SILVA FENNICA
Silva Fennica 41(3) research articles
www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

Modelling Mean Above and Below Ground Litter Production Based on Yield Tables

Thomas Wutzler and Martina Mund

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

Estimates of litter production are a prerequisite for modeling soil carbon stocks and its changes at regional to national scale. However, the required data on biomass removal is often available only for the recent past. In this study we used yield tables as a source of probable past forest management to drive a single tree based stand growth model. Next, simulated growth and timber volume was converted to tree compartment carbon stocks and biomass turnover. The study explicitly accounted for differences in site quality between stands. In addition we performed a Monte Carlo uncertainty and sensitivity analysis. We exemplify the approach by calculating long-term means of past litter production for 10 species by using yield tables that have been applied in Central Germany during the last century. We found that litter production resulting from harvest residues was almost as large as the one from biomass turnover. Differences in site quality caused large differences in litter production. At a given site quality, the uncertainty in soil carbon inputs were 14%, 17%, and 25% for beech, spruce, and pine stands, respectively. The sensitivity analysis showed that the most influential parameters were associated with foliage biomass and turnover. We conclude that rates of mean past litter production and their uncertainties can reliably be modeled on the basis of yield tables if the model accounts for 1) full rotation length including thinning and final harvest, 2) differences in site quality, and 3) environmental dependency of foliage biomass and foliage turnover.

Keywords biomass turnover, carbon accounting, soil carbon, harvest residues, sensitivity analysis, thinnings, uncertainty
Addresses Max Planck Institute for Biogeochemistry, Jena, Germany
Email thomas.wutzler@bgc-jena.mpg.de
Received 29 August 2006 **Revised** 18 May 2007 **Accepted** 5 July 2007
Available at http://www.metla.fi/silvafennica/full/sf41/sf413559.pdf

1 Introduction

Estimates of litter production are a prerequisite modeling forest soil carbon stocks and its changes. Most dynamic soil carbon models of mineral forest soils are driven by carbon inputs from plant litter production, which is usually estimated by forest inventories (de Wit et al. 2006, Liski et al. 2006, Ågren et al. 2007). The combination of forest inventories and modeling is a viable option to compile soil carbon stock changes from regional to national and global scales (Peltoniemi et al. 2007). Models, which allow for reliable estimates of changes in soil carbon stocks at different spatial scales, are of particular interest, because they could be used for national annual greenhouse gas reports according to the UN Framework Convention on Climate Change and the Kyoto Protocol (UNFCCC 1997). In addition to the application in climate modeling, estimates of mean past litter production can be useful to study the sustainability of intensively managed energy plantations with respect soil carbon protection (Reijnders 2006). The derivation of long-term mean litter input rates requires data on forest biomass and on past forest thinning operations and harvest. For many regions, these data are available for the recent past only. A model for forest timber volume, yield and growth under defined site conditions and a defined management regime is recorded in yield tables, which are used in this study as an approximation tool of former forest management.

Yield tables were developed for many species, many site classes, and many regions (e.g. Tjurin and Naumenko 1956, e.g. McArdle 1961, Nishizono et al. 2005). They list expected stand characteristics such as tree height, basal area, and standing timber volume, as well as proposed timber volume of thinning and harvesting for several stand age classes and tree species. Because of environmental changes over the last 50 to 60 years some older yield tables do not reflect current tree growth (Mund et al. 2002, Jandl et al. 2007). However, their common use in forestry practice and for forest planning indicate their usefulness at least in the past.

The objective of this study is to demonstrate how yield tables can be used to estimate long-term means of past litter production. This proposed methodology is significant for all studies on soil carbon balance where no better data on former forest management or biomass is available. The intended spatial scale is the regional level with calculations based on single stands or single strata of the forested area. We investigate the following questions: 1) How relevant is litter production resulting from self-thinning, precommercial thinning, commercial thinning, and final harvest compared to litter production resulting from foliage, fine roots, and branches turnover? 2) How large is the influence of different tree species and of different site qualities on the estimates of litter production? And 3) how large are the uncertainties of the estimates and which factors contribute most to them?

We exemplify the approach using yield tables that have been applied to forests in Eastern Germany (Nicke 1997) to drive a forest growth model and convert simulated timber volume and harvest to rates of litter production. Further we study the uncertainty of the results and the sensitivities to parameters and assumptions.

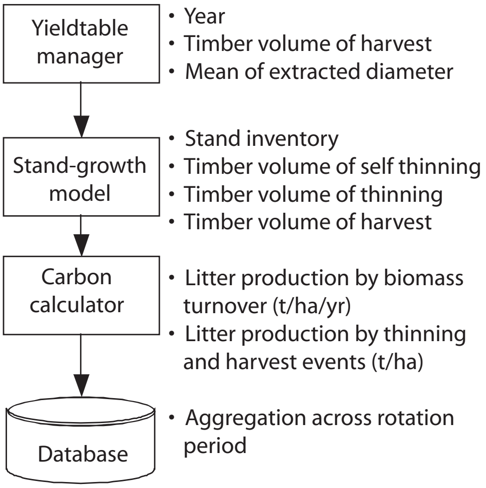

Fig. 1. Overview of modeling mean litter production by yield tables. Information on forestry management, as represented by yield tables was used to drive a stand growth model. The model outputs were used to calculate litter production by biomass turnover and management operations during stand growth. Finally, the outputs were aggregated across one rotation period.

Table 1. Yield tables that have been used in this study to simulate standard rotation and litter inputs. Several site indices were used. Additionally the table lists the prescribed rotation length and the stand age from which commercial thinning with biomass removal was applied. a) taken from (Nicke 1997).

Tree group	Yield table (mostly grey literature)	Site index (m)	Length of rotation (yrs)	Begin of biomass removal (% of rotation)
Spruce	Wenk et al. (1985) (a)	36/30/24	120/120/130	40
Beech	Dittmar et al. (1986) (a)	36/30/24	160/160/160	40
Pine	Lembcke et al. (1976) (a)	32/26/20	130/130/140	40
Oak	Ertelt (1962) (a)	23.4/20/15.7	200/200/160	30
Larch	Schober R (1987) (a)	34/29.5/25	140/140/140	40
Douglas fir	Bergel (1985) (a)	43.8/38.7/34.1	100/100/100	40
Linden/Maple	Böckmann (1990)	33.5/29.2/23.1	90/120/120	60
Birch	Tjurin and Naumenko (1956) (a)	31.8/25.1/17.1	100/100/90	40
Ash	Wimmenauer (1919) in (Erteld 1962) (a)	29.9 / 24.8	120/120	40
Poplar	Knapp (1973) in (Autorenkollektiv 1982) (a)	37/30.5/24.1	50/50/50	70

2 Methods

An overview of the general approach of this study is given in Fig. 1. The details are explained in the following sections.

2.1 Yield Tables and Study Area

We used yield tables as a source of data on probable past forest management. In general, yield tables describe the "regular growth" of forest stands for: 1) distinct tree species; 2) under constant environmental conditions; 3) according to a defined management regime. In a first step, we compiled a relational database of yield tables, which provides amongst others the following attributes.

- meta information: region, where the data that was used to construct the table data was collected, genus and species, and citation
- absolute site index: the expected height of trees (m) at stand age 100 years (Kramer and Akça 1995)
- stand attributes: stand age (yr), dominant height (m), basal area (m²), tree number per hectare (1/ha), and timber volume (m³/ha), quadratic mean of tree diameters at breast height (dbh) (cm), and stand height (m)

The database currently contains 228 yield tables out of 49 yield table collections. Each yield table collection contains several tables corresponding to different site qualities. Site quality is expressed by the site index as defined above. In this study we used yield tables that have been applied in the past in Eastern Germany (Table 1). Hence, the study area of the application example is defined by the set of stands, where these yield tables have guided the management, which comprises most of the forest area of Eastern Germany. The approach of inferring biomass removal by yield tables can be extended to other regions in a straightforward way, by using the yield tables that have been applied in the corresponding region.

2.2 Stand Development Simulations

Stand development was simulated with the TreeGrOSS model (Nagel 1999, Nagel 2003). The empirical stand growth model simulates diameter and height development of single trees and explicitly takes account for competition. By these simulated competition indices also self-thinning is simulated. The stand was initialized according to the first age that was recorded in the yield table and had a tree diameter (dbh) ≥ 7 cm. We implemented thinning and harvesting operations according to the yield tables in the following way. We simulated tree growth with environmental conditions of the former century, which well matched the growth recorded in the yield tables. Tree growth was simulated in periods of at most 5 years. Shorter periods occurred when the time to the next date that was recorded in the corresponding yield table was less than 5 years. We simulated tree dimensions before the growing season. In each of these simulation cycles, first growth was projected, next self-thinning during this period was calculated, and finally thinning was applied. Basal area of thinned trees was derived by comparing the yield table target basal area with the simulated basal area. Type of thinning (from above/below/neutral) was determined by comparing diameter from yield table with the simulated diameter. We assumed a clearcut of the stand at the last age that was listed in the corresponding yield table. In addition we specified the stand age until precommercial thinning has been applied by a fraction of the rotation period (Table 1). At precommercial thinning all biomass is left in the forest, at commercial thinning a defined fraction of branches and stem is removed from the forest.

2.3 Calculation of Litter Production by Tree Biomass Turnover

Yield tables and the stand growth model provided data on timber volume. Our focus, however, was on litter production, which originated from biomass turnover of all tree compartments. Hence, the timber volume was converted to dry timber biomass by species specific basic wood densities. Next, biomass of different tree compartments were estimated by multiplying timber biomass by site and age specific expansion factors. Finally, biomass stocks were converted to carbon stocks by species specific carbon concentrations. The product of wood density and expansion factor is termed conversion-expansion (ce-factor) factor in this study. For spruce we used the functions of expansion or conversion factors developed for Central Europe (Wirth and Schumacher 2002, Wirth et al. 2004) and for pine the functions developed for Finish forests (Lehtonen et al. 2004a). For beech, only ce-factors for whole tree carbon stock were available. Hence, we re-examined the dataset of Wirth et al. (2004) to derive ce-factors for other tree compartments as well (Table 2). The factors depend on species, stand age, and site quality. Biomass of other tree species was calculated using ce-factors of either spruce, pine, or beech, but using species specific dry wood densities and carbon contents. Basic wood densities and carbon contents were taken from Weiss et al. (2000).

Table 2. Coefficients and standard errors of the conversion-expansion factor function $ce_{Beech} = b_0 + b_1 e^{-b2xAge}$ (t C/m³ dry wood), stratified by tree compartment and site index. Site indices: 0 – across all, 1 – good (> 28 m), 2 – average (20...28 m), 3 – low (< 20 m); rmse – root mean square error of the residuals; cv – rmse / mean (ce_{Beech})

Compartment	Site index	b_0	b_1	b_2	rmse	cv
Total	0	0.741	0.636	0.018	0.113	12.7%
	1	0.735	1.320	0.020	0.152	14.6%
	2	0.760	0.649	0.022	0.079	9.2%
	3	0.827	0.922	0.067	0.065	7.2%
Stem	0	0.479	0.380	0.020	0.073	8.2%
	1	0.445	0.765	0.021	0.155	14.9%
	2	0.464	0.289	0.014	0.052	6.0%
	3	0.530	0.496	0.050	0.042	4.7%
Branches	0	0.137	0.235	0.037	0.044	5.0%
	1	0.164	0.361	0.027	0.054	5.2%
	2	0.142	1.341	0.091	0.029	3.4%
	3	0.107	0.274	0.054	0.026	2.9%
Leaves	0	0.005	0.107	0.042	0.005	0.6%
	1	0.004	0.137	0.033	0.005	0.4%
	2	0.006	0.286	0.075	0.002	0.3%
	3	0.006	0.141	0.067	0.001	0.1%
Root	0	0	0.185	0.002	0.292	32.7%
	1	0	0.258	0.004	0.189	18.1%
	2	0	0.199	0.003	0.281	32.6%
	3	0	0.118	–0.004	0.301	33.5%

The above ground litter production was derived by multiplying branch and foliage biomass by a mean turnover time (Table 3). We did not calculate the turnover of stem and coarse root because this was accounted for by self-thinning, thinning and harvest. The production of below ground litter was derived by multiplying the above ground litter production by a species specific factor (Table 3). For Pine and Spruce forests we adapted the factor 1.5 from Ågren et al. (2007). We did not find a similar study for beech. However, in a first approximation we assumed that the soil carbon inputs by litter production are balanced by outputs by soil respiration, i.e. the storage is very small

Table 3. Coefficients for estimating biomass turnover. Numbers in brackets denote the standard deviation, used in the sensitivity analysis (a) (Muukkonen and Lehtonen 2004) with assuming standard deviation of 1/2 of the range to minimum; (b) (Ågren et al. 2007); (c) (Heinsdorf et al. 1993); (d) based on equation 4 from (Lehtonen et al. 2004b); mean across trees with dbh from 7 to 40 cm; (e) all leaves biomass is shed each year unless some carbon that is translocated before leaves senescence (f) based on data of (Mund 2004) (g) based on (Bowden et al. 1993) and (Fahey et al. 2005).

Species	Turnover [1/yr] Foliage	Branches	Belowground / Aboveground litter production
Spruce	0.10 (0.015) (a)	0.0125 (0.008) (a)	1.5 (0.3) (b)
Pine	0.4 (0.1) (c)	0.015 (0.01) (d)	1.5 (0.3) (b)
Beech	0.9 (0.09) (e)	0.013 (0.01) (f)	1.0 (0.2) (g)

compared to the input/output fluxes. Bowden et al. (1993) found that 37% of the annual soil respiration of a North American broadleaved forest can be attributed to above ground litter and 30% to belowground litter. A more recent study confirms this ratio of about 0.8 of below ground to above ground litter production but indirectly infers an additional carbon flow from roots to rhizosphere (Fahey et al. 2005). Because our focus is on soil carbon inputs by litter production, we included this flux in the below ground litter production and used a ratio of 1.0 for beech.

Our aim was to come up with a mean of litter production across the entire rotation cycle. Hence, we aggregated the litter input rates of all the simulation periods by Eq. 1.

$$\overline{l}_p = \frac{\sum_i 0.5\left(l_{p,i-1} + l_{p,i}\right) \cdot t_i}{\sum_i t_i} \tag{1}$$

In Eq. 1 the absolute amount litter production for each simulated period *i*, was calculated by multiplying the mean rate of litter production of this period $0.5\left(l_{p,i-1} + l_{p,i}\right)$ by the length of the period t_i. Finally the sum of the litter across all simulation periods was divided by sum of the length of all simulation periods, i.e. the rotation length.

2.4 Calculation of Litter Production by Thinning and Harvesting Events

In addition to litter production by foliage, fineroot, and branch turnover, also self-thinning and residues after harvesting or thinning operations contribute to litter production and carbon inputs to the soil (Harmon et al. 1996, Nishizono et al. 2005). In each simulation period the stand growth model simulated the timber volume of a) trees that died by self-thinning, b) trees cut by precommercial thinnings, and c) trees extracted by commercial thinning and harvest. Carbon stocks of tree compartment of tree volumes a) and b) were calculated with previously presented conversion factors. We excluded foliage and fineroot carbon stocks from input to the soil to avoid double counting with turnover. This led to a small underestimation of litter input rates for coniferous trees.

During commercial thinning and harvest a part of the stem and branch biomass is removed and another part is left at the side as harvest residues. Information about the proportion of the removed wood is based on timber volume and does not distinguish between stem and branch. At coarse scale removal statistics can be used to obtain extracted timber volume (Dieter and Elsasser 2002). However, at stand scale, we used values of a guideline of the forest administration (Weber 2003) to interpolate proportion of the removed timber volume by species and stand age (Fig. 2).

The carbon in harvest residues was calculated in the following way. We multiplied the sum of stem and branch carbon by proportion of removed timber wood (Fig. 2). Next we partitioned the remaining carbon to fine woody litter and coarse woody litter with the proportions 40% and 60% respectively. We did not find suitable studies to back up this subjective partitioning. However, we will discuss with the sensitivity analysis that changes in this partitioning do not affect the result-

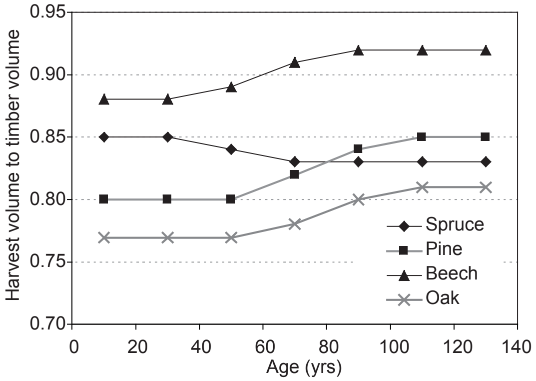

Fig. 2. Regional estimates of extracted timber volume in relation to timber volume of trees that died during commercial thinning operation according to Weber (2003). Having regional species and age-specific estimates of this factor improves the estimate for the litter production resulting from harvest residues.

ing equilibrium soil carbon stocks very much. All the litter produced by thinning/harvesting events was summed over the rotation period and divided by the rotation length to obtain a mean annual rate of litter production.

2.5 Uncertainty Analysis

Uncertainty of the calculated litter production was studied by the Monte Carlo method. This method investigates the distribution of a random variable by simulating random numbers (Gentle 1985). In our case the random variable, in which we are interested in, is the sum litter production over all litter compartments and the simulated random numbers represent the parameters that were used to calculate litter production. Monte Carlo simulation involves the generation of a large number of realizations of the parameters from their joint probability distribution. The distribution of the calculated results, i.e. rates of litter production, across all the realizations of parameters represents the result's empirical joint probability distribution. This empirical distribution can be used to describe the uncertainty of the result.

We studied the propagation of the uncertainty of converting timber volume to carbon stocks in stem, branch, foliage, and root by varying the product of expansion-factor, wood density, and carbon content (ke-factor). The precision of this product is dominated by the biomass expansion factor. The precision listed in Table 4 actually describes the uncertainty of predicting an intermediate expansion factor for a given combination of site factors such as stand age and site quality. We also included uncertainty of biomass turnover by varying the mean lifetime of foliage and branches and by varying the proportion of belowground litter input. In addition we included uncertainty of information on management to our analysis by varying the proportion of removed timber, the proportion of remaining coarse wood that is collected for firewood, and the proportion of fine wood in harvest residues. We prescribed a log-normal distribution for each parameter with a mean according to standard parameterization and a coefficient of uncertainty (*cv*) according to Table 4. The mean of simulated litter production varied less than 0.3% after 4000 runs. Hence we used 5000 runs for one Monte Carlo simulation. In a first scenario we assumed all parameters to be independent. In a second scenario we introduced positive correlations between the ce-factors of stem, root, and foliage, and a negative correlation between the ce-factors of stem and branches. The correlations at the scale of the normal distribution were 0.7 and –0.4 respectively. This reflected our experiences from examining uncertainty with constructing biomass functions for Common beech (Wutzler and Wirth 2007).

2.6 Sensitivity Analysis

The data generated by the Monte Carlo simulation was also used to assess which parameters had the largest influence on the uncertainty of litter production. We assessed the importance of each parameter by calculating the rank-based correlation, called Spearman's rho (Conover 1980), between each input parameter and the calculated litter production. The strength of this correlation reflects how strongly the parameter influences the uncertainty in the results (Vose 1996). In order to compare the correlations we normalized the squared correlation to 100%. We refer to this value as importance index.

Table 4. Coefficient of uncertainty (standard deviation divided by the mean) of the parameters used in the uncertainty analysis. ke: product of wood density, expansion factor, and carbon content; (a) according to Table 3 (b) G. Weber pers. communication, see also Fig 2 (c) unknown, reasonable number (d) unknown, conservative number (e) (Wirth et al. 2004) with regional density error and site specific factors (f) according to Table 3 in (Lehtonen et al. 2004a) (g) medium site index of Table 2.

Identifier	Description	Spruce	Pine	Beech
Biomass to Carbon Conversion				
keStem	ke of Stem	13.3% (e)	5.3% (f)	6.0% (g)
keBranch	ke of Branch	13.3% (e)	9.7% (f)	3.4% (g)
keFoliage	ke of Foliage	13.3% (e)	25.9% (f)	0.3% (g)
keRoot	ke of Root	13.3% (e)	11.3% (f)	33.0% (g)
Biomass Turnover				
lifetimeBranches	lifetime of branches (a)	63.0%	67.0%	70.0%
lifetimeFoliage	lifetime of foliage (a)	15.0%	25.0%	10.0%
pBelow	ratio of below ground to above ground litter production (a)	20.0%	20.0%	25.0%
Thinning and Harvest				
harvExt	ratio of harvest volume to timber volume(b)	5.0%		
pWoodPicked	proportion of collected remaining coarse wood (c)	25.0%		
fwlShare	proportion of fine wood in harvest residues (d)	30.0%		

In addition to the Monte Carlo study, we investigated how the uncertainty of stand growth affected the litter production. We represented the uncertainty of stand growth by varying the site index. The soil carbon inputs for the uncertain site index were linearly interpolated between the site indices, for which the soil carbon inputs have been calculated previously from yield tables.

2.7 Comparison with Measured Leaves Litterfall

To validate our model results we compared the estimated litter production by leaves turnover with measured litter fall data of a case study on European beech forests (*Fagus sylvatica* L.) in Thuringia, Germany, under different silvicultural management (regular shelterwood system, selection system, unmanaged forest; Mund (2004). In that study annual litter fall of two years was measured by litter traps at four study sites including 3 or 5 forest stands. The mass of leaf litterfall was converted to carbon by measured carbon contents. Growing conditions are described as optimal for beech forests and corresponding to site indices above 28 m.

3 Results

The three major sources of litter production, which were investigated in this study, were continuous biomass turnover, self-thinning, and residues remaining after thinning operations and harvest. Simulated self-thinning differed between species. For spruce and beech stands, which were dominating at the study area, carbon inputs from self-thinning was negligible compared to harvest and thinning residues.

The comparison of litter production by species revealed large differences (Fig. 3). The comparison also confirmed that the sum of litter production resulting from thinning and harvest was smaller but of the same magnitude as large as the sum of litter production by turnover of foliage, fine root, and branches across the rotation period. In the comparison of litter production by different litter compartments, the largest contributions were found with fine root litter production, followed by foliage litter production (Fig. 4). Branch turnover contributed minor parts only. When comparing litter production by site quality, we found that differences were in the same magnitude as the mean for all compartments (Fig. 4). The calculated litter production for the three

Table 5. Calculated litter production (tC/ha/yr).

Species	Site index	Turnover			Thinning and harvesting		
		Foliage	Fine root	Branch	Fine wood	Coarse wood	Coarse root
Spruce	24.0	0.57	0.89	0.20	0.25	0.22	0.43
	30.0	0.79	1.18	0.22	0.38	0.38	0.62
	36.0	1.25	1.83	0.30	0.57	0.69	0.74
Pine	20.0	1.46	1.96	0.13	0.24	0.74	0.53
	26.0	2.15	2.87	0.19	0.31	0.95	0.70
	32.0	2.88	3.83	0.25	0.40	1.22	0.90
Beech	24.0	0.77	0.89	0.24	0.23	0.24	0.52
	30.0	1.56	1.79	0.42	0.42	0.48	0.81
	36.0	2.15	2.45	0.55	0.65	0.81	1.15

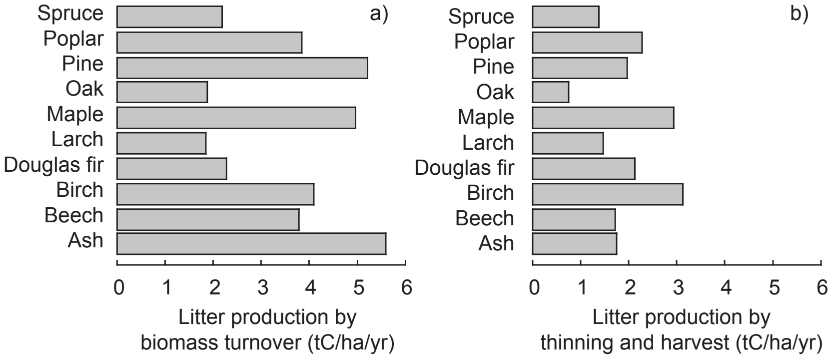

Fig. 3. Comparison of litter production between different monospecific stands of medium site quality. Litter production by the biomass turnover a) are of the same magnitude as litter production by thinning events b) for all species. Differences between species are of the same magnitude as the litter production itself.

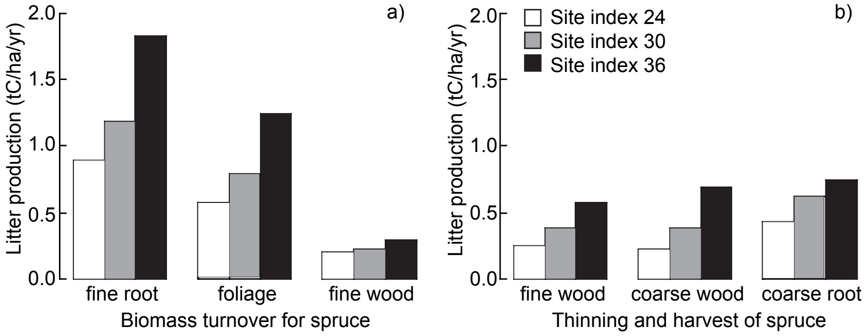

Fig. 4. Comparison of litter production between different site qualities (site index) by litter compartments for spruce. The difference in litter production between site qualities is of the same magnitude as the litter production itself.

most important species for three different site qualities are listed in Table 5.

In the following presentation of the results of the Monte Carlo uncertainty analysis, we concentrate on the sum of litter production across all litter compartments. Fig. 5 displays the resulting empirical distribution of two Monte Carlo simulations for spruce of site index 30 m. The first simulation was performed with sampling from a parameter distribution that assumed independent parameters, the second one from a parameter distribution that included correlations between the parameters. From the first distribution, we calculated a mean litter production of 3.9 tC/ha/yr, a standard deviation of 0.65 tC/ha/yr, giving a coefficient of uncertainty (cv) of 17%. The variance of the second simulation did not differ from the first simulation within two significant digits. Similarly, we inferred a cv of 14% and 25% for beech and pine respectively from their empirical distributions. These uncertainties were in the same magnitude as the uncertainty of stand growth, as represented by a 5% increase of the site index.

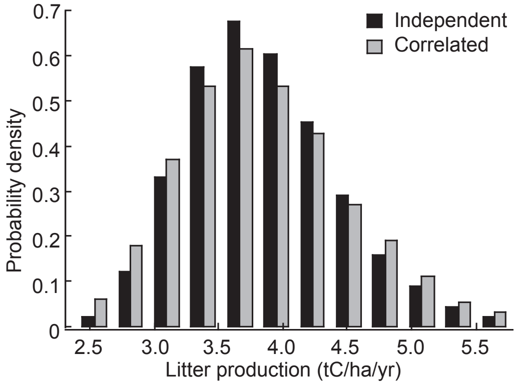

Fig. 5. Histogram litter production for Spruce of site index 30 m when accounting for uncertainty in model parameters. The distribution deviates slightly from normal by having a stronger positive tail. In the case where correlations between input parameters were accounted for, the distribution has slightly stronger tails.

The comparison of the importance index, a combined measure of parameter uncertainty and parameter sensitivity, provided a measure of the relative importance of the parameters for the uncertainty in the soil carbon inputs. Fig. 6 displays the importance index for all the parameters that were included in the sensitivity analysis. Uncertainty of foliage turnover (lifeTimeFoliage) was an important cause of the uncertainty in litter production for all species. Contrary, uncertainty in harvest information (harvest, pWoodPicke, fwlShare) was not important with all species. For Pine, the comparatively high uncertainties of both, expansion factor for foliage and mean life-

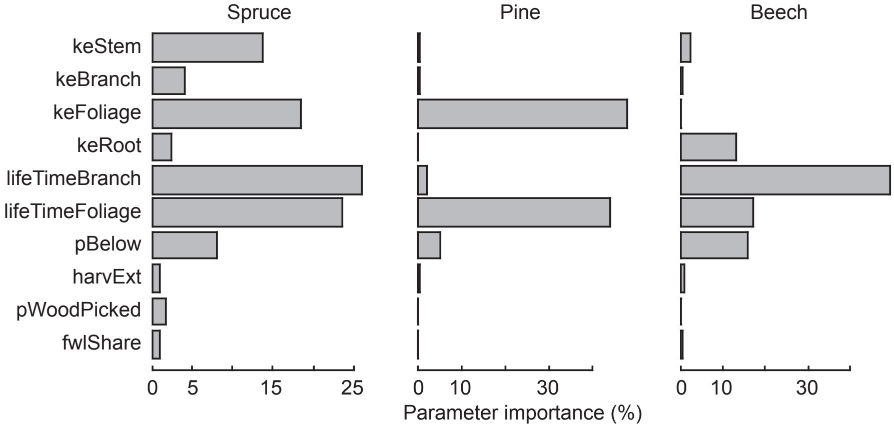

Fig. 6. Importance index, i.e. relative influence of the parameter uncertainty on the results uncertainty, for litter production of intermediate site quality. Parameter identifiers are described in Table 3. For all species the mean lifetime of foliage is very important (lifeTimeFoliage), for Pine also the conversion from timber to foliage biomass (keFoliage) is important. The mean life time of branches (lifeTimeBranch) is the most important factor for Spruce and Beech. Uncertainty in information on harvest (last three parameters) is not contributing much to the uncertainty in results in all three cases.

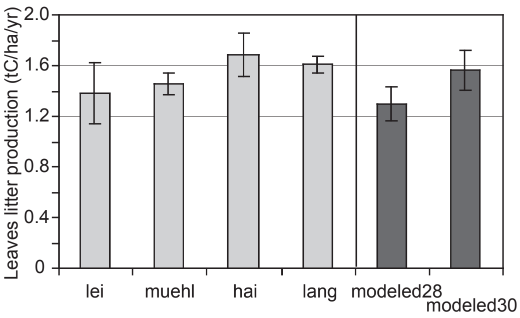

Fig. 7. Comparison of calculated litter production by leaves for beech with litter fall data from Mund (2004). Both, the mean and the standard deviation (error bars) of values calculated for two site indices 28 m and 30 m (modeled28, modeled30) well match the range of carbon in measured litter fall at the sites Leinefelde (lei), Muehlhausen (muehl), Hainich (hai), and Langula (lang).

time of foliage (Table 4) were important causes of the large uncertainties in the result and are dominating over all the other factors.

We further studied how the uncertainty of litter production would decrease if we were able to better constrain foliage biomass and turnover. We repeated the Monte Carlo analysis with double precision of the ke-factor, i.e. product of expansion factor, wood density and carbon content, for foliage and double precision of the foliage turnover time compared to Table 4. This resulted in a reduction of the relative error (cv) of the sum of soil carbon inputs by 3%, 11%, and 0% for spruce, pine, and beech, respectively. For spruce and beech, the lifetime of branches became the most important parameter. For pine, the foliage parameters still had the highest importance index.

The reliability of the applied model approach is shown by the comparison with field data given in Fig. 7. The modeled data well matched the range of measured annual leaf litter fall at for beech study sites.

4 Discussion

Forest soil carbon inputs by litter production are usually derived using forest inventories (de Wit et al. 2006, Liski et al. 2006, Ågren et al. 2007). However, in most countries, forest inventories are only available for the very recent past. Therefore, this study presented an alternative approach that is based on yield tables instead of forest inventories. We exemplified the approach by estimating long-term mean past litter production based on yield tables that have been used in Eastern Germany. Further we assessed the uncertainties of the results and the importance of several input parameters.

The litter production by residues from thinning and harvest was smaller than the litter production by biomass turnover but of the same magnitude (Fig. 3, Fig. 4). Self-thinning did not significantly affect soil carbon inputs in forests of the most common tree species. This can be explained by the fact, that the management proposed in yield tables result in stand densities at which no or only slight competition for light occurs. For birch, maple and pine self-thinning contributed to soil carbon inputs in the same magnitude as harvest residues. However, most of the self-thinning occurred in the period of precommercial thinning, where all wood remains at the site. And soil carbon stocks do not depend much upon whether tree biomass entered the forest floor by self-thinning or as harvest residues. Allocation has been studied extensively before (Burschel et al. 1993, Baritz and Strich 2000, Löwe et al. 2000, Lehtonen et al. 2004a, Levy et al. 2004, Jalkanen et al. 2005, Zianis et al. 2005) and also estimating turnover of leaves and branches has been studied (Lehtonen et al. 2004b, Muukkonen and Lehtonen 2004, Ågren et al. 2007). However, only minor research has been done to quantify harvest residues. At regional or national scale forest statistics have been used (Ågren et al. 2007), but at stand level it is difficult to use regional forest statistics. Hence, in many studies a fixed portion of stemwood is extracted and the other compartments are left on site. For example Kaipainen et al. (2004): transferred 10–15% of stemwood from the thinnings and the final cuttings to litter. In contrast, the presented study explicitly takes into account first, the distinction between precommercial and commercial thinning (Table 1), second, the age-dependency of the proportion of remaining wood (Fig. 2), and third, self-thinning.

Site quality, as expressed by the site index, had a large influence on both, litter production by biomass turnover and litter production by harvest residues (Fig. 4). The effect of site quality is of the same magnitude as differences by species and as the mean of soil carbon inputs. Published soil carbon studies at the national scale consider age classes and species, but often site quality is not taken into account explicitly (e.g. de Wit et al. 2006, Liski et al. 2006, Ågren et al. 2007). However, our results suggest that site index should be explicitly accounted for.

We used the Monte Carlo approach to study the uncertainty of the calculated soil carbon. An alternative approach would have been error propagation methods. However, error propagation methods assume specific distributions of the parameters and all intermediate results, and they have problems with non-linearity, because they are usually based on a first order Taylor expansion (Winzer 2000). Contrary, Monte Carlo analysis is an effective method to assess uncertainty when models are complex with non-linearity and with different types of correlations (Morgan and Henrion 1990, Vose 1996). When we compare our estimates of litter production of spruce of intermediate site quality (3.8 t/ha/yr) with an estimate across all forests in Finland (Peltoniemi et al. 2006), their estimates are slightly lower (2.7–3.0 tC/ha/yr). This is reasonable, because we expect forests in the region of our study to be more productive. Peltoniemi et al. (2006) also performed an Monte Carlo analysis and quantified the standard deviation of litter production, i.e. soil carbon inputs, to be 0.36 tC/ha/yr, corresponding to a 13% relative error. Our higher estimate of relative error of 18% is probably because we used a higher uncertainty of foliage turnover. When aggregating the results of a set of stands or strata to a larger forest area, the precision of the aggregated value increases with the square root of the number of stands or strata (Kurth et al. 1994). Smith and Heath (2001) found with an uncertainty analysis of ecosystem carbon stocks, that introducing temporal correlations decreased uncertainty very much. Peltoniemi et al. (2006) demonstrated, that estimating litter from standing biomass overestimates temporal correlation and underestimates uncertainty of annual results. In our study, temporal correlations were not as important, because we aggregated results across an entire rotation period (Eq. 1). In our results, also the inclusion of correlations between model biomass expansion factors of different compartments did not change the distribution of soil carbon inputs significantly (Fig. 5).

The results of the sensitivity analysis strongly depend on the assumptions about the distribution of the parameters. We assumed a right-skewed log-normal shape for all parameters. This distribution is more suitable than a normal distribution especially for the conversion factors and the lifetimes of foliage and branches than a normal distribution. On the one side, values below zero, which can occur in the normal distribution, are clearly not valid. On the other side values larger than twice the mean are observed occasionally. However, we expect the shape of the distribution to not affect the distribution of the results very much (e.g. Smith and Heath 2001). For some of the parameters we assigned subjective values. In the Monte Carlo simulations we therefore assigned rather high relative errors to these parameters in order to reflect our lack of knowledge about these parameters. However, in the sensitivity analysis, some of these uncertain parameters did not influence the calculated litter production very much (proportion of fine wood in harvest residues, proportion of coarse harvest residues that are collected for private combustion, and to some extent also uncertainty of the ratio of below ground litter production). The importance index reflects both, the uncertainty of the parameter and the sensitivity of the parameter (Hamby 1994). On the one side there are parameters that are uncertain but not sensitive (e.g. collected coarse wood). They are not very important for the uncertainty of the results. On the other side, there are sensitive parameters. Small changes in these parameters have a substantial influence on the results. However, if their precision is high, i.e. they have a low relative error, then they are also not important for the uncertainty in the results. Hence, we should concentrate on the parameters that are important, i.e. sensitive and uncertain.

For all species, the lifetime of foliage was a very important parameter (Fig. 6). Mean lifetime is the reciprocal of the turnover. Ågren et al. (2007) found, that the mean lifetime of needles of spruce and pine is correlated to latitude. However, Wachter (1985) found that mean lifetime of spruce needles varied by 13% already at regional scale and that lifetime increased with altitude and water availability. A combined observation and modeling study (Muukkonen and Lehtonen 2004) quantified a range of turnover times of spruce needles of 0.7 to 0.13 yr^{-1} for southern Finland, which corresponds to a relative error of 15%. Bornkamm et al. (2003) cited 8 studies of pine needles in which a mean lifetime between 2 and 3 years was found in Slovakia, Estonia, southern Finland, England and northern Germany. However, their own measurements in Germany resulted in a mean life time of pine needles of 1.7 years. They attributed this low value to periods of hot and dry weather conditions. Therefore, we used a relative error of 25% for pine, which is considerably higher than the 11% that was used for foliage by Peltoniemi et al. (2006). For broadleaved forests most studies assume a turnover rate of 1 yr^{-1} because all foliage is shed. However, some of the carbon is translocated during leaves senescence or consumed by herbivores before reaching the ground. Fahey et al. (2005) reported 16 to 26% maximum extent of carbon resorption from the differences in leaf area to weight ratio between late-season live foliage and fresh litterfall for northern American hardwood forest. Similar to Fahey's approach, we quantified a value of 9% of carbon resorption from data of a Common beech forest in northern Spain (Regina and Tarazona 2001). Hence, in this study we used a beech foliage carbon turnover rate of 0.9 yr^{-1} instead of 1.0 yr^{-1}. In order to improve precision of soil carbon inputs, environmental dependencies of foliage carbon turnover should be studied further and incorporated into the carbon turnover calculation.

For beech and spruce, also the lifetime of branches had a substantial influence on litter production (Fig. 6). Because we did not find explicit literature on beech branch turnover, we estimated branch turnover and its error by dividing branch biomass by branch litterfall for each of 16 stands from the study of Mund (2004). The turnover had a large variability (cv = 74%) and declined with stand age ($r^2 = 0.52$). The correlation between branch turnover and tree diameter was studied for spruce (Muukkonen and Lehtonen 2004) and pine (Lehtonen et al. 2004b) in southern Finland. A next step in improving the estimates of soil carbon inputs is to perform similar studies in other regions too, and to implement the derived results in the carbon turnover calculation.

In the following we discuss how and why some aspects of the used methods differed from previous studies. Other studies calculated fine root litter production similar as foliage litter production by estimating biomass and turnover (e.g. Peltoniemi et al. 2004). However, both, the estimation of fine root biomass and the turnover is still very uncertain (Matamala et al. 2003, Hutchings and John 2004, Majdi et al. 2005, Godbold et al. 2006, Mulia and Dupraz 2006). Hence, some studies use the idea of functional scaling, which suggests a stable proportion between foliage and root biomass, to estimate fineroot biomass (Vanninen and Mäkelä 1999, de Wit et al. 2006). However, with this approach there is still the uncertainty of fineroot turnover. Therefore, we followed an approach of Ågren et al. (2007), which extends the idea of functional scaling to litter production. Hence, we use a fixed ratio of below ground litter production to above ground litter production. Our study, as well as previous studies, did not distinguish between soil carbon inputs by fine root litter production and by root exudates. However, evidence is accumulating that the carbon transport by root exudates is a major carbon flux with a different dynamics in soil (Fahey et al. 2005, Högberg and Read 2006).

Two important factors were not taken into account explicity in this study. These are ground vegetation and natural disturbances. Peltoniemi et al. (2006) applied a mean biomass stock of ground vegetation of 3.8 t/ha and a mean turnover rate of 0.33 yr^{-1} based on more detailed data for forests in southern Finland (Peltoniemi et al. 2004). Application of the same numbers together with 50% carbon content to this study would lead to an additional increase of non woody litter production of 0.63 tC/ha/yr. A part of the natural disturbances is accounted for by the yield tables, which state that only 80% of the given basal area should be thinned. The other 20% of the thinned basal area will be killed due to other reasons such as disturbance (Wenk et al. 1985). However, if there are larger scale disturbances, litter production will be larger compared to the values presented in this study.

The good agreement between calculated and measured leaf litter production (Fig. 7) increases our confidence in the calculated soil carbon inputs. While the sites Leinefele (lei) and Muehlhausen (muehl) have been managed according to yield tables, the Hainich site (hai) represents an unmanaged forest and the Langula site (lang) a selection cutting system. However, leaf litterfall is estimated quite well for all the sites with the yield table based approach showing that the uncertainty of the modelled values are in the range of the variability caused by the studied management activities.

5 Conclusions

- Residues left after thinning and harvest contributed to litter production in the same magnitude as the continuous biomass turnover. Therefore, it is important to consider at least one full rotation period including thinning operations and final harvest for estimating long-term mean litter production.
- Both, different species and differences in site quality for the same species caused variability in litter production that was of the same magnitude as the mean of litter production. Hence, site quality is very important for estimating litter production at stand scale, but should also be taken into account at broader scales.
- We quantified the relative error of the presented litter production to be 14%, 17%, and 25% for beech, spruce, and pine stands respectively. This uncertainty was mainly due to the large natural variability in foliage biomass and foliage lifetime. A better explanation of this variability by environmental conditions will improve the precision.
- Long-term means of past litter production rates and their uncertainty can be reliably estimated for the former century on the basis of yield tables. The presented approach can provide a new tool to establish the baseline carbon stocks in dynamic soil carbon models (Peltoniemi et al. 2007, Wutzler and Reichstein 2007), which in turn can be used for soil carbon monitoring.

Acknowledgements

We want to thank two anonymous referees for their constructive comments, which helped to improve the manuscript.

References

Ågren, G.I., Hyvönen, R. & Nilsson, T. 2007. Are Swedish forest soils sinks or sources for CO_2 – model analyses based on forest inventory data. Biogeochemistry in press (online first) DOI 10.1007/s10533-006-9064-0.

Autorenkollektiv 1982. Ertragstafelauszüge 1982. Zentrale Betriebsakademie Forstwirtschaft, Abt. Aus- und Weiterbildung, Markleeberg. 96 p.

Baritz, R. & Strich, S. 2000. Forests and the National Greenhouse Gas Inventory of Germany. Biotechnology, Agronomy, Society and Environment 4: 267–271.

Bergel, D. 1985. Douglasien-Ertragstafel fuer Nordwestdeutschland. 1985. 157(3/4): 149–159.

Böckmann, T. 1990. Wachstum und Ertrag der Winterlinde (Tilia cordata Mill) in Nordwestdeutschland. Dissertation Georg August University, Göttingen.

Bornkamm, R., Faensen-Thiebes, A. & Nino, M. 2003. Changes of macroscopic symptoms during the lifetime of pine needles (Pinus sylvestris L.). Forstwissenschaftliches Centralblatt 122(6): 376–388.

Bowden, R.D., Nadelhoffer, K.J., Boone, R.D., Melillo, J.M. & Garrison, J.B. 1993. Contributions of aboveground litter, belowground litter, and root respiration to total soil respiration in a temperature

---

List of Symbols

dbh	diameter at breast height (1.3 m)
h	tree height (m)
si	site index (m)
ς	stem wood density (t/m^3)
l_P	litter production for litter compartment p (tC/ha/yr)
p	litter compartment (Table 4)
i	index of ration periods
t_i	length of simulation period i (yr)
ce	carbon per timber volume (tC/m^3 dry wood)
b_j	regression coefficients

mixed hardwood forest. Canadian Journal of Forest Research 23(7): 1402–1407.

Burschel, P., Kürsten, E. & Larson, B.C. 1993. Die Rolle von Wald und Forstwirtschaft im Kohlenstoffhaushalt – Eine Betrachtung für die Bundesrepublik Deutschland. Forstliche Forschungsberichte München – Schriftenreihe der Forstwissenschaftlichen Fakultät der Universität München und der forstlichen Versuchs- und Forschungsanstalt 126: 1–135.

Conover, W.J. 1980. Practical nonparametric statistics. John Wiley & Sons, New York. 493 p.

de Wit, H.A., Palosuo, T., Hylen, G. & Liski, J. 2006. A carbon budget of forest biomass and soils in southeast Norway calculated using a widely applicable method. Forest Ecology and Management 225(1–3): 15–26.

Dieter, M. & Elsasser, P. 2002. Carbon stocks and carbon stock changes in the tree biomass of Germany's forests. Forstwissenschaftliches Centralblatt 121(4): 195–210.

Dittmar, O., Knapp, E. & Lembcke, G. 1986. DDR Buchenertragstafel 1983. IFE-Berichte aus Forschung und Entwicklung 4: 1–59.

Erteld, W. 1962. Ertragstafelauszüge für den Gebrauch in der Praxis. Neumann Verlag. 170 p.

Fahey, T.J., Siccama, T.G., Driscoll, C.T., Likens, G.E., Campbell, J., Johnson, C.E., Battles, J.J., Aber, J.D., Cole, J.J. & Fisk, M.C. 2005. The biogeochemistry of carbon at Hubbard Brook. Biogeochemistry 75: 109–176.

Gentle, J.E. 1985. Monte Carlo methods. In: Kotz, S. & Johnson, N.L. (eds.). Encyclopedia of statistics 5. John Wiley & Sons, New York. p. 612–617.

Godbold, D.L., Hoosbeek, M.R., Lukac, M., Cotrufo, M.F., Janssens, I.A., Ceulemans, R., Polle, A., Velthorst, E.J., Scarascia-Mugnozza, G., De Angelis, P., Miglietta, F. & Peressotti, A. 2006. Mycorrhizal hyphal turnover as a dominant process for carbon input into soil organic matter. Plant and Soil 281(1–2): 15–24.

Hamby, D.M. 1994. A review of techniques for parameter sensitivity analysis of environmental-models. Environmental Monitoring and Assessment 32(2): 135–154.

Harmon, M.E., Garman, S.L. & Ferrell, W.K. 1996. Modeling historical patterns of tree utilization in the Pacific Northwest: Carbon sequestration implications. Ecological Applications 6(2): 641–652.

Heinsdorf, M., Heinze, M. & Fiedler, H.J. 1993. Changes of nutrient element dynamics in the needles of a pine plantation. Forstwissenschaftliches Centralblatt 112(3): 179–190.

Högberg, P. & Read, D.J. 2006. Towards a more plant physiological perspective on soil ecology. Trends in Ecology & Evolution 21(10): 548–554.

Hutchings, M.J. & John, E.A. 2004. The effects of environmental heterogeneity on root growth and root/shoot partitioning. Annals of Botany 94(1): 1–8.

Jalkanen, A., Mäkipää, R., Ståhl, G., Lehtonen, A. & Petersson, H. 2005. Estimation of the biomass stock of trees in Sweden: comparison of biomass equations and age-dependent biomass expansion factors. Annals of Forest Science 62(8): 845–851.

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

Kaipainen, T., Liski, J., Pussinen, A. & Karjalainen, T. 2004. Managing carbon sinks by changing rotation length in European forests. Environmental Science & Policy 7(3): 205–219.

Knorr, W. & Kattge, J. 2005. Inversion of terrestrial ecosystem model parameter values against eddy covariance measurements by Monte Carlo sampling. Global Change Biology 11(8): 1333–1351.

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

Kurth, H., Gerold, D. & Ulbricht, R. 1994. Forsteinrichtung – Nachhaltige Regelung des Waldes. Deutscher Landwirtschaftsverlag Berlin GmbH, Berlin. ISBN 3-331-00589-4.

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R. & Liski, J. 2004a. 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.

— , Sievänen, R., Mäkelä, A., Mäkipää, S., Korhonen, K.T. & Hokkanen, T. 2004b. Potential litterfall of Scots pine branches in southern Finland. Ecological Modelling 180(2–3): 305–315.

Lembcke, G., Knapp, E. & Dittmar, O. 1976. DDR-Kiefern-Ertragstafel 1975. Institut für Forstwissenschaften Eberswalde.

Levy, P.E., Hale, S.E. & Nicoll, B.C. 2004. Biomass expansion factors and root : shoot ratios for coniferous tree species in Great Britain. Forestry 77(5): 421–430.

Liski, J., Lehtonen, A., Palosuo, T., Peltoniemi, M., Eggers, T., Muukkonen, P. & Mäkipää, R. 2006. Carbon accumulation in Finland's forests 1922–2004 – an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil. Annals of Forest Science 63(7): 687–697.

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.

Majdi, H., Pregitzer, K., Moren, A.S., Nylund, J.E. & Ågren, G.I. 2005. Measuring fine root turnover in forest ecosystems. Plant and Soil 276(1–2): 1–8.

Matamala, R., Gonzalez-Meler, M.A., Jastrow, J.D., Norby, R.J. & Schlesinger, W.H. 2003. Impacts of fine root turnover on forest NPP and soil C sequestration potential. Science 302(5649): 1385–1387.

McArdle, R.E. 1961. The yield of Douglas fir in the Pacific Northwest. USDA Technical Bulletin 201. Washington, D.C. 74 p.

Morgan, M. & Henrion, M. 1990. Uncertainty. A guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge University Press.

Mulia, R. & Dupraz, C. 2006. Unusual fine root distributions of two deciduous tree species in southern france: What consequences for modelling of tree root dynamics? Plant and Soil 281(1–2): 71–85.

Mund, M. 2004. Carbon pools European beech forests (Fagus sylvatica) under different silvicultural management. Berichte des Forschungszentrums Waldökosysteme A 189. University Göttingen. 255 p.

— , 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.

Muukkonen, P. & Lehtonen, A. 2004. Needle and branch biomass turnover rates of Norway spruce (Picea abies). Canadian Journal of Forest Research 34(12): 2517–2527.

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. 122 p.

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

Nicke, A. 1997. Ertragstafelauszüge. Lehrmaterial Fachhochschule für Forstwirtschaft in Schwarzburg. 255 p.

Nishizono, T., Iehara, T., Kuboyama, H. & Fukuda, M. 2005. A forest biomass yield table based on an empirical model. Journal of Forest Research 10(3): 211–220.

Peltoniemi, M., Mäkipää, R., Liski, J. & Tamminen, P. 2004. Changes in soil carbon with stand age – an evaluation of a modelling method with empirical data. Global Change Biology 10(12): 2078–2091.

— , Palosuo, T., Monni, S. & Mäkipää, R. 2006. Factors affecting the uncertainty of sinks and stocks of carbon in Finnish forests soils and vegetation. Forest Ecology and Management 232(1–3): 75–85.

— , Thürig, E., Ogle, S., Palosuo, T., Schrumpf, M., Wutzler, T., Butterbach-Bahl, K., Chertov, O., Komarov, A., Mikhailov, A., Gardenäs, A., Perry, C., Liski, J., Smith, P. & Mäkipää, R. 2007. Models in country scale carbon accounting of forest soils. Silva Fennica 41(3).

Regina, I.S. & Tarazona, T. 2001. Nutrient cycling in a natural beech forest and adjacent planted pine in northern Spain. Forestry 74(1): 11–28.

Reijnders, L. 2006. Conditions for the sustainability of biomass based fuel use. Energy Policy 34(7): 863–876.

Schober, R. 1987. Ertragstafeln wichtiger Baumarten 3. erw. Aufl. J. D. Sauerländers Verlag, Frankfurt (a. Main).

Smith, J.E. & Heath, L.S. 2001. Identifying influences on model uncertainty: an application using a forest carbon budget model. Environmental Management 27(2): 253–267.

Tjurin, A. & Naumenko, I. 1956. Forstliches Hilfsbuch für Waldtaxation. Moskva.

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

Vanninen, P. & Mäkelä, A. 1999. Fine root biomass of Scots pine stands differing in age and soil fertility in southern Finland. Tree Physiology 19(12): 823–830.

Vose, D. 1996. Quantitative risk analysis: a guide to Monte Carlo simulation modelling. John Wiley & Sons. 328 p.

Wachter, H. 1985. Zur Lebensdauer von Fichtennadeln in einigen Waldgebieten Nordrhein-Westfalens. Forst- und Holzwirt 40: 420–425.

Weber, G. 2003. Hilfstafeln zur naturalen Betriebssteuerung. Thüringer Landesanstalt für Wald, Jagd und Fischerei. Gotha. 107 p.

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.

Wenk, G., Römisch, K. & Gerold, D. 1985. DDR-Fichtenertragstafel1984. Series DDR-Fichtenertragstafel1984. Technische Universität Dresden – Sektion Forstwissenschaft, Agrarwissenschaftliche Gesellschaft der DDR. 64 p.

Wimmenauer. 1919. Wachstum und Ertrag der Esche. Allgemeine Forst- und Jagdzeitschrift: 2–17.

Winzer, P.J. 2000. Accuracy of error propagation exemplified with ratios of random variables. Review of Scientific Instruments 71(3): 1447–1454.

Wirth, C. & Schumacher, J. 2002. Biomass functions for Norway spruce in Central Europe. Präsentation COST E21 Workshop 4–5 July 2002, Besalu.

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

— & Wirth, C. 2007. Generic biomass functions for common beech (Fagus sylvatica L.) in Central Europe – predictions and components of uncertainty. Canadian Journal of Forest Research submitted.

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

Total of 67 references