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Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests

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Abstract

Assessments of forest resource in national inventories provide a firm basis for quantifying forest biomass and carbon stock. National statistics on forest resources provide estimates of forest area, timber volume, and growth of timber by age classes with known precision. Estimates of carbon stock are, however, obtained by expanding the total stemwood volume to total biomass with simple conversion factors. The objective of this study was to improve the accuracy and reliability of the biomass expansion factors (BEFs) and to develop expansion factors that are dependent on stand age and dominant tree species. For development of BEFs, we applied volume and biomass equations to describe the allometry of single trees and a systematic network of forest inventory data to determine variation in stand structure. The results of this study indicate that the proportions of most biomass components vary considerably during the rotation. We conclude that the reliability of the national carbon stock inventory could be improved by applying these age-dependent BEFs, which are formulated on the basis of representative data and which include an estimate of uncertainty.

Keywords: Boreal forests; Branch; Carbon; Foliage; Forest inventory; Kyoto protocol; Roots; Uncertainty

1. Introduction

Forest carbon sinks were included in the Kyoto Protocol as one of the mechanisms for mitigating climate change, since these sinks are known to play an important role in the global GHG balance. Globally, annual carbon sequestration by terrestrial ecosystems was estimated to be 2.3 Gt C in the 1990s, while emissions from land-use change were 1.6 Gt C per year (IPCC, 2000). The net terrestrial uptake of 0.7 Gt C per year corresponded to one-tenth of the emissions from combustion of fossil fuels (6.3 Gt C per year) (IPCC, 2000). Currently, the methods for calculating the carbon content of forests are too imprecise for estimating the carbon balance at the ecosystem level or the national level (Fang et al., 1998). Reliable estimates of changes in carbon stocks, and thereby fluxes, are necessary for understanding both the global carbon cycle (Schimel, 1998) and national inventories of greenhouse gases (IPCC, 2000).

In general, estimates of carbon stocks and stock changes in temperate and boreal forests are based on forest inventory data (Kauppi et al., 1992; Sedjo, 1992;

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Dixon et al., 1994; UN-ECE/FAO, 2000; Liski et al., in press). Systematic assessment of forest resources is a reliable source of information for the amounts of stem volume at country and regional levels and thus a suitable basis for biomass and carbon studies (Kauppi et al., 1992; Sedjo, 1992; Dixon et al., 1994; Laitat et al., 2000; Fang and Wang, 2001). As national forest inventories (NFI) are usually geared towards estimation of stem volumes, the disadvantage of using NFI data is the lack of direct measurements of biomass. With few exceptions (e.g. Gracia et al., 1997), representative estimates of biomass for larger areas do not exist.

The biomass stock of forest trees has been calculated by using biomass expansion factors (BEFs) that convert timber volumes to dry weight (density factor) and thereafter to whole tree biomass (expansion factor) (Johnson and Sharpe, 1983; Karjalainen and Kellomäki, 1996; Weiss et al., 2000). These two factors can be replaced with one factor that converts stem volumes directly to whole tree biomass (e.g. Schroeder et al., 1997; Fang and Wang, 2001). In general, constant BEFs have been applied (UN-ECE/FAO, 2000; FAO, 2001; Liski et al., in press), although it is known that BEFs vary depending on growth conditions and phase of stand development (Satoo and Madgwick, 1982).

Reliable methods are available for estimating both the biomass and volume of single tree in boreal forests (Laasasenaho, 1982; Marklund, 1988; Brandel, 1990; Korhonen and Maltamo, 1990; Hakkila, 1991). These single tree equations are not applicable for conversion of stem volume to biomass of trees at stand, regional or national scales.

In this study, we developed BEFs for this task. The objective was to improve the accuracy and the reliability of BEFs. We developed BEFs that are dependent on stand age and dominant tree species. The main results were species-specific stand-level BEFs for whole tree biomass, as well as for different biomass components as a function of stand age, with known precision.

2. Material and methods

2.1. Data

We used tree and stand variables from 3000 permanent sample plots measured by the Finnish National Forest Inventory in 1985–1986. Of these sample plots, those located on forest land (tree growth of more than 1 $m^3\ ha^{-1}$ per year) either on mineral soils or peatlands were included in our analysis.

This systematic sampling grid was denser in southern than in northern Finland. In southern Finland there were four plots in each cluster and the distance between clusters was 16 km. In northern Finland there were three plots in each cluster and the distance between clusters varied from 24 to 32 km. The denser sampling grid was located roughly below 66° latitude. The measurements of the permanent sample plots used in this study were diameter at breast height (dbh), tree species, size of the plot and age of the stand. In the younger stands, age was estimated visually from the whorls of the trees, and, in the older stands, from drillings of sample trees. The normal size of a plot was 300 m^2, but trees with a diameter less than 10.5 cm were measured from a 100 m^2 plot.

Only plots that had more than 70% of the basal area made up of Scots pine, Norway spruce or broadleaved species were included (Table 1). Since our analysis was focused on forests that were over 10 years, plots with a basal area less than 1 $m^2\ ha^{-1}$ were omitted from the sample. Trees with a diameter less than 5 cm were excluded from the calculations due to the limitations of the applied volume and biomass equations (Laasasenaho, 1982; Marklund, 1988).

2.2. Applied volume and biomass equations

The stem volume of each tree was calculated based on diameter at breast height by using equations from Laasasenaho (1982). A simple equation $V = a \times (\mathrm{dbh})^b$ was used in which V is stem volume over bark, dbh the diameter at breast height (1.3 m), and a and b are parameters.

The biomass of each component of a tree was estimated from dbh using Swedish equations for biomass (Marklund, 1988). These equations provide biomass estimates for Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), for the various biomass components (stem, stem bark, living branches, dead branches, needles, stump, roots more than 5 cm in diameter and roots less than 5 cm in diameter). For birch (*Betula pubescens*), however, only biomass equations of stem, stem bark, living branches and dead branches were available.

Table 1
Mean density (trees per ha) and median diameter of the forest stands used in this study[a]

Age of stand	Dominant tree species[b]					
	Scots pine ($n = 782$)		Norway spruce ($n = 459$)		Broadleaved ($n = 153$)	
	Trees per ha	Median dbh[c]	Trees per ha	Median dbh[c]	Trees per ha	Median dbh[c]
10–19	1514	11.60	2500	8.94	1825	11.18
20–29	1603	11.45	1641	13.44	2783	10.65
30–39	1655	12.85	1661	13.25	2245	10.40
40–49	1470	12.95	1580	16.15	2222	11.85
50–59	1463	13.90	1336	19.45	1834	12.50
60–69	1361	14.35	1376	21.50	1882	14.70
70–79	1252	17.29	1173	22.35	1383	18.39
80–89	1107	19.25	1077	24.86		
90–99	895	22.18	1232	22.36	941	22.63
100–119	880	23.10	1106	24.15		
120–139	785	22.08	1189	19.37		
140–	588	24.17	879	21.50		

[a] The age classes of the oldest broadleaved forests were wider than the others due to smaller sample.
[b] The dominant tree species was defined as having a threshold of 70% of basal area.
[c] The median dbh is the basal area median diameter of trees in each age class.

2.3. BEFs at stand level and by age class

In this study, we were developing stand-level BEFs that convert stem volume directly to the dry weight of biomass component. We consider expansion from stem volume, V, to dry weight of tree component i, W_i, and consequently define BEF, B_i, as

$$B_i = \frac{W_i}{V} \tag{1}$$

for biomass components i (foliage, branches, stem, dead branches, bark, stump, coarse roots, small roots or whole tree). Eq. (1) was applied both at stand level and by age classes. In the computation of stand-level BEFs, W_i was the sum of the estimated tree level biomasses of component i over trees measured in one sample plot and V was the corresponding sum of tree level stem volumes. To obtain BEFs for different age classes (Table 2), these sums were extended over trees measured from all sample plots belonging to the relevant class.

2.4. Error estimates of BEFs by age class

The accuracy of BEFs by age classes (Table 2) was assessed, taking into account sampling error of the inventory, model error of the biomass equations and model error of the volume equations (see Appendix A).

Model error of the total biomass estimate was assessed by assuming that the errors of the biomass components are mutually uncorrelated at tree level. This is not the case exactly, but this assumption was made for practical reasons.

Model error was assessed by estimating both its maximum and minimum values. This was done with two approaches, one in which we assumed (1) zero correlation between estimation errors of trees in a cluster and another where we assumed (2) full correlation between errors at the cluster level. Sampling error was assessed by estimating the residual variance of biomass estimates by age classes (Appendix A, Table 2). Confidence intervals for BEFs by classes were calculated based on maximum relative standard error (RSE).

2.5. Functions for age-dependent BEFs

Modelling of age-dependence in BEFs was based on stand-level BEFs calculated according to Eq. (1). Due to the fact that stand age—BEF relations are heteroscedastic and non-linear, we made comparisons between different logarithmic transformations of variables and also comparisons between different types of

Table 2
BEFs, their RSEs, and 95% confidence intervals (conf. int.) for Scots pine, Norway spruce and broadleaf dominated forests[a]

Age of stand	Dominant tree species											
	Scots pine				Norway spruce				Broadleaved			
	BEF	Minimum RSE (%)	Maximum RSE (%)	95% conf. int.	BEF	Minimum RSE (%)	Maximum RSE (%)	95% conf. int.	BEF[b]	Minimum RSE (%)	Maximum RSE (%)	95% conf. int.
10–19	0.697	3.41	8.82	±0.12	0.862	6.35	21.34	±0.37	0.544	5.60	10.14	±0.11
20–29	0.705	1.26	4.59	±0.06	0.860	2.50	9.90	±0.17	0.551	4.86	7.55	±0.08
30–39	0.710	1.31	3.90	±0.06	0.841	1.47	6.79	±0.11	0.554	4.27	5.35	±0.06
40–49	0.702	1.38	4.96	±0.07	0.820	1.50	3.65	±0.06	0.556	1.65	3.88	±0.04
50–59	0.701	0.97	4.14	±0.06	0.816	1.41	3.51	±0.06	0.552	1.94	4.60	±0.05
60–69	0.710	0.79	3.87	±0.05	0.791	1.65	3.17	±0.05	0.554	5.03	5.76	±0.06
70–79	0.708	0.86	3.54	±0.05	0.784	1.29	2.91	±0.05	0.545	3.32	4.28	±0.05
80–89	0.707	1.07	3.98	±0.06	0.777	1.34	2.94	±0.05				
90–99	0.704	0.98	4.06	±0.06	0.782	1.59	3.37	±0.05	0.544	3.86	5.30	±0.06
100–119	0.703	0.81	3.15	±0.04	0.784	1.84	2.73	±0.04				
120–139	0.698	1.27	4.17	±0.06	0.782	3.75	4.58	±0.07				
140–	0.690	1.25	4.15	±0.06	0.788	2.18	3.41	±0.05				

[a] The minimum and the maximum RSEs were estimated by assuming independence and full correlation between trees in a cluster of sites of the National Forest Inventory, respectively. The confidence intervals (conf. int.) were calculated on the basis of maximum relative standard error.

[b] Accounts for aboveground biomass only.

function forms, in order to obtain the best fit for the data.

Eq. (2) was fitted (Tables 3–5) using linear regression with the time-dependent term $e^{-0.01t}$ as the independent variable. Its rate coefficient (−0.01) was determined by trial and error so that it gave the minimum sum of squares in the regression fit. The BEF for component i as a function of stand age is thus

$$B_i = a_i + b_i\,e^{-0.01t} \qquad (2)$$

where a_i and b_i are parameters, and i is the stem, foliage, living branches, dead branches, bark, stump, coarse roots, small roots, total biomass or total aboveground biomass.

2.6. BEFs and diameter distribution of stands

We tested how detailed information on stand structure (diameter distribution) of each age classes is

Table 3
BEFs = $B_i(t)$ for Scots pine (*P. sylvestris*) stands[a]

Tree compartment (i)	a	S.E.	b	S.E.	r^2	RMSE	Mean of response
Stem	0.4194	0.0016	−0.0798	0.0025	0.4902	0.0198	0.3729
Foliage	0.0177	0.0010	0.0499	0.0015	0.5026	0.0121	0.0468
Branches	0.0706	0.0006	0.0212	0.0010	0.3021	0.0078	0.0830
Branches, dead	0.0104	0.0001	0.0059	0.0002	0.4356	0.0016	0.0138
Bark	0.0254	0.0005	0.0221	0.0007	0.4589	0.0059	0.0383
Stump	0.0472	0.0001	−0.0039	0.0002	0.3169	0.0014	0.0449
Roots, coarse >5 cm	0.0838	0.0007	−0.0365	0.0011	0.5065	0.0088	0.0626
Roots, small <5 cm	0.0272	0.0006	0.0269	0.0009	0.2884	0.0068	0.0429
Total	0.7018	0.0015	0.0058	0.0024	0.0053	0.0191	0.7051
Total ABVG	0.5436	0.0012	0.0193	0.0019	0.0873	0.0152	0.5548

[a] BEF is expressed in Mg m^{-3} and the independent variable (t) in years. Total ABVG is the total aboveground biomass, including stem, foliage, living branches, dead branches and bark. Equation: $B_i(t) = a + b\,e^{-t/100}$. The functions were developed using data from stands between 10 and 150 years of age and with stemwood volume less than 250 m^3 ha^{-1}.

Table 4
BEFs $= B_i(t)$ for Norway spruce (*P. abies*) stands[a]

Tree compartment (i)	a	S.E.	b	S.E.	r^2	RMSE	Mean of response
Stem	0.4000	0.0016	−0.0462	0.0031	0.3101	0.0139	0.3774
Foliage	0.0388	0.0027	0.0849	0.0050	0.3596	0.0229	0.0805
Branches	0.0905	0.0024	0.0719	0.0046	0.3137	0.0210	0.1257
Branches, dead	0.0088	0.0001	0.0040	0.0002	0.3470	0.0011	0.0107
Bark	0.0353	0.0006	0.0125	0.0011	0.2114	0.0049	0.0414
Stump	0.0488	0.0002	0.0044	0.0004	0.2030	0.0018	0.0470
Roots, coarse >5 cm	0.1024	0.0010	−0.0271	0.0018	0.3045	0.0083	0.0891
Roots, small <5 cm	0.0201	0.0014	0.0448	0.0026	0.3622	0.0120	0.0421
Total	0.7406	0.0060	0.1494	0.0114	0.2530	0.0518	0.8139
Total ABVG	0.5734	0.0049	0.1272	0.0092	0.2735	0.0418	0.6358

[a] BEF is expressed in Mg m^{-3} and the independent variable (t) in years. Total ABVG is the total aboveground biomass, including stem, foliage, living branches, dead branches and bark. Equation: $B_i(t) = a + b\,e^{-t/100}$. The functions were developed using data from stands between 10 and 150 years of age and with stemwood volume less than 250 m^3 ha^{-1}.

needed for calculation of BEFs. Data were grouped, according to dominant tree species and age of the stand, into classes with a 10-year interval in stand age.

For each age class, BEFs were calculated by three different methods (Fig. 1). In the first method, BEFs were calculated on the basis of the measured diameters of trees on the NFI sample plots, as described earlier; this was used as a reference for comparison with other methods.

The second method was to estimate BEFs using only basal area median diameter and stocking density (trees per ha) of each age class.

The third method was based on use of the Weibull distribution. All the trees of a single class were sorted according to diameter. Then the shape of the two-parameter Weibull distribution was established on the median (d_{med}) and maximum diameter (d_{max}), which was defined as the 99% percentile diameter. Parameters $b = f(d_{50\%}, d_{99\%})$ and $c = f(d_{50\%}, d_{99\%})$ were obtained for each age class. The estimates for parameters were calculated by using a method based on percentiles (Bailey and Dell, 1973). Stocking of each class was also used. The estimated Weibull distribution was then used to calculate BEFs.

2.7. Biomass as a function of stem volume

We developed equations at stand-level for the relationships between biomass components and stem volume. Eq. (3) was formulated for the relationship between stem volume and biomass (Tables 6–8). These equations are applicable for coniferous forests that have a stem volume up to 250 m^3 ha^{-1}. For broadleaved forests the equations should not be

Table 5
BEFs $= B_i(t)$ for broadleaved stands[a]

Tree compartment (i)	a	S.E.	b	S.E.	r^2	RMSE	Mean of response
Stem	0.3964	0.0028	−0.0186	0.0039	0.0830	0.0129	0.3833
Branches	0.1011	0.0021	−0.0180	0.0029	0.1339	0.0096	0.0885
Branches, dead	0.0053	0.0007	0.0082	0.0009	0.2399	0.0030	0.0110
Bark	0.0588	0.0009	0.0105	0.0013	0.2045	0.0043	0.0662
Total ABVG	0.5616	0.0041	−0.0179	0.0056	0.0377	0.0190	0.5490

[a] BEF is expressed in Mg m^{-3} and the independent variable (t) in years. Total ABVG is the total aboveground biomass, including stem, living branches, dead branches and bark (foliage excluded). Equation: $B_i(t) = a + b\,e^{-t/100}$. The functions were developed using data from stands between 10 and 100 years of age and with stemwood volume less than 200 m^3 ha^{-1}.

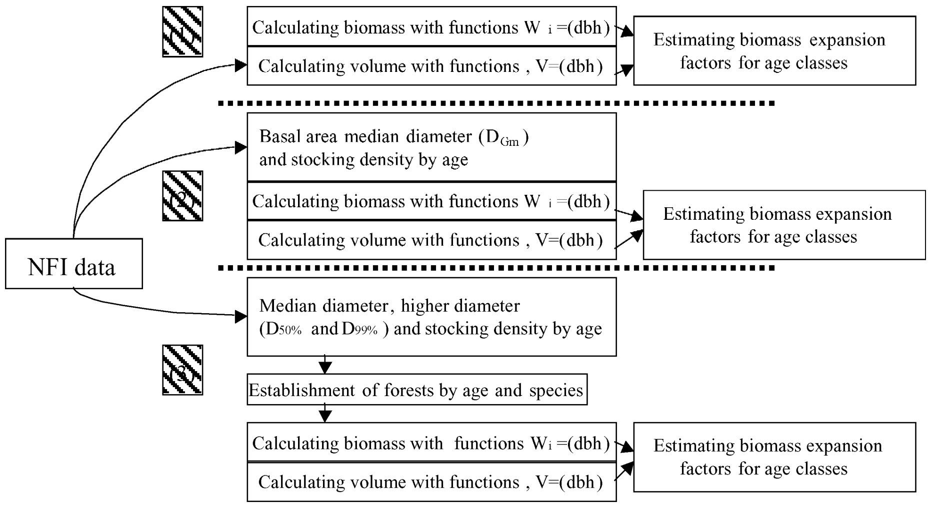

Fig. 1. The approach to evaluate the effect of diameter distribution on BEFs, using three methods: (1) estimation of BEFs based on tree-level data from the National Forest Inventory, (2) estimation of BEFs based on basal area median diameter and (3) estimation of BEFs based on Weibull distribution.

applied in cases where stem volume is more than 200 m^3 ha^{-1}. The estimate for biomass W_i is

$$W_i(V) = aV^b \tag{3}$$

where W_i is the dry weight of the biomass component i (i is the stem, foliage, living branches, dead branches, bark, stump, coarse roots, small roots) or an aggregate of those components, a and b are parameters and V the stem volume. Formula (3) is a power function and was estimated in linear form.

Due to this transformation of variables, a correction coefficient has to be added to parameter a. It was assumed that $\ln(W_i)$ is normally distributed and therefore variance divided by 2 was applied as a correction coefficient ($\sigma^2/2$).

3. Results

3.1. BEFs by stand age and biomass by stem volume

The BEF for the total biomass of Scots pine stand was only slightly age-dependent, while the BEF for

Table 6
Biomass for Scots pine (*P. sylvestris*) stands[a]

Tree compartment	ln(a)	S.E.	b	S.E.	r^2	RMSE	Mean of response
Stem	−1.1576	0.0052	1.0444	0.0013	0.9984	0.0514	2.8332
Foliage	−2.2532	0.0298	0.7802	0.0074	0.9143	0.2918	0.6864
Branches	−2.3012	0.0104	0.9504	0.0026	0.9924	0.1019	1.3264
Branches, dead	−3.9252	0.0122	0.9056	0.0030	0.9885	0.1195	−0.4708
Bark	−2.8289	0.0154	0.8842	0.0038	0.9810	0.1505	0.5397
Stump	−3.1697	0.0032	1.0171	0.0008	0.9994	0.0316	0.7178
Roots, coarse >5 cm	−3.3197	0.0138	1.1400	0.0035	0.9906	0.1355	1.0287
Roots, small <5 cm	−2.6589	0.0173	0.8686	0.0043	0.9752	0.1691	0.6469
Total	−0.3453	0.0028	0.9989	0.0007	0.9995	0.0277	3.4727
Total ABVG	−0.5632	0.0028	0.9932	0.0007	0.9995	0.0279	3.2329

[a] Stem volume (V) as an independent variable gives biomass components (W_i) in tonnes of dry weight. Total ABVG is the total aboveground biomass, including stem, foliage, living branches, dead branches and bark. Equation: $W_i(V) = aV^b$. The functions were developed using data from stands between 10 and 250 m^3 ha^{-1}.

Table 7
Biomass for Norway spruce (*P. abies*) stands[a]

Tree compartment	ln(a)	S.E.	b	S.E.	r^2	RMSE	Mean of response
Stem	−1.1154	0.0066	1.0298	0.0014	0.9991	0.0329	3.7352
Foliage	−1.4772	0.0399	0.7718	0.0083	0.9450	0.1986	2.1388
Branches	−1.4447	0.0245	0.8642	0.0051	0.9827	0.1221	2.6186
Branches, dead	−4.1336	0.0158	0.9141	0.0033	0.9935	0.0787	0.1696
Bark	−2.8200	0.0201	0.9221	0.0042	0.9898	0.0998	1.5189
Stump	−2.9410	0.0061	0.9750	0.0013	0.9991	0.0305	1.6513
Roots, coarse >5 cm	−2.8028	0.0185	1.0810	0.0038	0.9936	0.0922	2.2853
Roots, small <5 cm	−2.1205	0.0410	0.7707	0.0085	0.9420	0.2040	1.4893
Total	0.0230	0.0103	0.9511	0.0021	0.9975	0.0512	4.5022
Total ABVG	−0.2086	0.0103	0.9478	0.0021	0.9975	0.0510	4.2549

[a] Stem volume (V) as an independent variable gives biomass components (W_i) in tonnes of dry weight. Total ABVG is the total aboveground biomass, including stem, foliage, living branches, dead branches and bark. Equation: $W_i(V) = aV^b$. The functions were developed using data from stands between 10 and 250 m^3 ha^{-1}.

Norway spruce stands decreased as stand age increased (Fig. 2a and b). For the youngest stands, less than 20 years of age, the BEFs were rather imprecise (Table 2). This may be a result of higher variance and greater heterogenity in the structure of these stands and perhaps also of the smaller number of stands in these age classes (Tables 1 and 2). The RSEs of BEFs developed for broadleaved forests were higher than those for coniferous forests.

The biomass components of Scots pine, especially stem and foliage, were age-dependent; whereas the BEFs of roots and branches varied less during stand development (Table 3 and Fig. 2). The biomass components of Norway spruce, especially branches and foliage, varied according to age (Table 4 and Fig. 2). This can be seen by comparing the r^2 and parameter b values in the tables mentioned above.

In general, our equations for Scots pine have higher r^2 values than the equations for Norway spruce and broadleaved species (Tables 3–5). This is because the development of pine stands over time is more homogenous and there was a larger number of Scots pine stands in our sample. On the basis of the low values of parameter b and r^2, we conclude that in some cases (e.g. when the biomass of broadleaved species or that of the stump and bark for Norway spruce are estimated) it is better to apply constant values over the time of stand development. The mean of the response (see Tables 3–5) can be used as such constant BEF for these components.

In the coniferous stands, the relationship between stem volume and different biomass components was nearly linear, with low variance (Tables 6 and 7). The equation that describes the relationship between stem

Table 8
Biomass for broadleaved stands[a]

Tree compartment	ln(a)	S.E.	b	S.E.	r^2	RMSE	Mean of response
Stem	−0.9818	0.0067	1.0062	0.0017	0.9993	0.0356	2.7225
Branches	−2.6242	0.0181	1.0534	0.0046	0.9950	0.0964	1.2499
Branches, dead	−3.8654	0.0519	0.8197	0.0133	0.9364	0.2761	−0.8855
Bark	−2.5764	0.0109	0.9621	0.0028	0.9978	0.0581	0.9643
Total ABVG	−0.4852	0.0074	0.9921	0.0019	0.9991	0.0394	3.1669

[a] Stem volume (V) as an independent variable gives biomass components (W_i) in tonnes of dry weight. Total ABVG is the total aboveground biomass, including stem, living branches, dead branches and bark. Equation: $W_i(V) = aV^b$. The functions were developed using data from stands between 10 and 200 m^3 ha^{-1}.

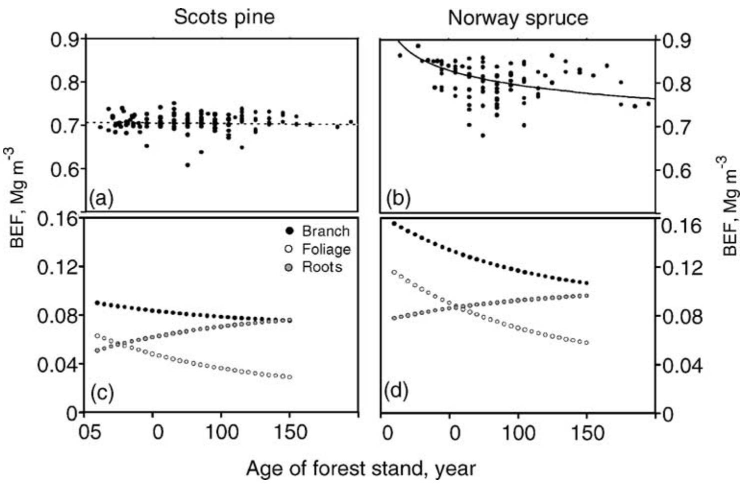

Fig. 2. BEFs for Scots pine (a and c) and Norway spruce (b and d) stands as a function of stand age. BEF is the ratio between the dry weight of biomass and stem volume (Mg m^{-3}). Figures (a) and (b) illustrate the modelled BEFs for whole tree biomass of pine and spruce stands and the actual observations; (c) and (d) describe the modelled BEFs for living branches, foliage and roots (more than 5 cm in diameter). The parameter values of these functions and their standard errors are shown in Tables 3 and 4.

volume and total biomass started to saturate only slightly with higher stem volumes (Fig. 3). For broad-leaved stands the correlation between stem volume and aboveground biomass was also strong (Table 8).

3.2. Estimating diameter distribution

In order to understand the role of diameter distribution when BEFs were estimated we compared different methods to generalise information on stand structure (Fig. 4).

Comparison of the three methods to describe the diameter distribution of stands indicates that using Weibull, a more sophisticated method compared to use of basal area median diameter, improved the accuracy of BEFs only slightly (Fig. 5). The other method based on the basal area median diameter and stocking density resulted in almost equally accurate BEF estimates.

If one is looking for average estimates for large areas, it is feasible to determine volume and biomass based on the basal area median tree. In most age classes, the relative difference of Mg m^{-3} ratio was less than 3% (Fig. 5). On the other hand, when the estimates were made for the youngest age classes, the difference increased to 9%. Thus, for young stands diameter distribution cannot be predicted easily. In general, when representative treewise inventory data are not available, these methods can be applied for estimating of BEFs.

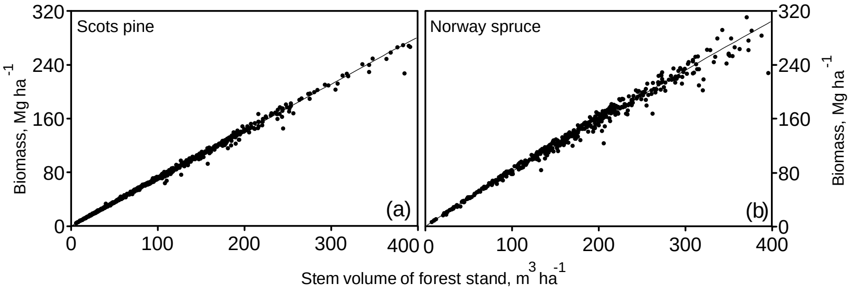

Fig. 3. Stand-level biomass (Mg ha^{-1}) of Scots pine (a) and Norway spruce (b) stands as a function of stem volume (m^3 ha^{-1}). The parameter values of the functions and their standard errors are shown in Tables 6 and 7.

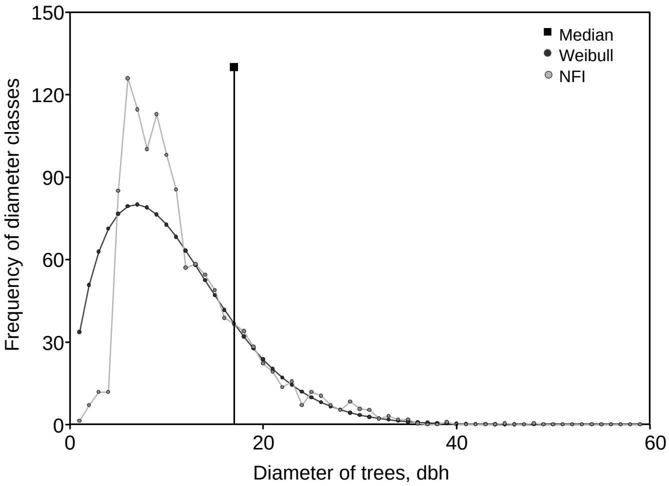

Fig. 4. Diameter distribution of Scots pine stands of the age class (70–80 years). The grey line represents the measured diameter distribution on 87 sample plots of the National Forest Inventory. The black line is an approximation of the diameter distribution using Weibull distribution (estimated with median and 99th diameter). The black bar indicates the basal area median diameter.

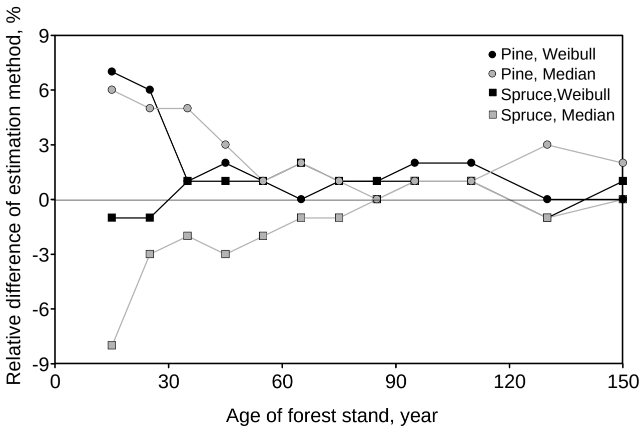

Fig. 5. Relative differences in BEFs determined with different methods to describe diameter distribution. Median refers to the method based on a basal area median diameter and stocking density, while Weibull is a modelled diameter distribution. The relative difference was calculated by dividing the difference between the reference and the estimate obtained with the method applied (median or Weibull) by the reference (based on measured diameters).

4. Discussion

In general, national and regional estimates of forest carbon stocks and sinks are calculated on the basis of growing stock and gross increment estimates using simple conversion factors (Kauppi et al., 1992, 1995; Löwe et al., 2000; Tomppo, 2000b; UN-ECE/FAO, 2000; Liski et al., in press). NFI can provide accurate and unbiased estimates of timber volume and increment with known precision (EC, 1997; Laitat et al., 2000). According to a review by Laitat et al. (2000), the RSE in national estimates of timber volume ranges from 0.54% in France to 5.1% in Belgium, whereas errors related to conversion factors are unknown. Use of the current conversion factors, which are based on relatively few sites sampled in various ecosystem studies, may lead to biased estimates of forest carbon stocks.

Reliability of a biomass estimate in the US was facilitated by compiling of a large dataset on aboveground biomass of temperate forests by pooling published and unpublished biomass studies of the region (Schroeder et al., 1997). Regionally representative data on the allometry of trees have been collected and used to develop equations for tree level volume (e.g. Laasasenaho, 1982; Brandel, 1990; Kaufmann, 1992) and biomass (e.g. Bartelink, 1997; Ter-Mikaelian and Korzukhin, 1997).

In this study, we have shown that reliable stand-level BEFs with known precision can be formulated on the basis of the information summarised in the existing volume and biomass functions. Compared to previous methods for estimation of conversion factors, the strength of this study lies in (1) the volume and biomass equations, which describe allometry of trees on the basis of regionally representative data and in (2) the systematic forest inventory data that describe regional variation in diameter distribution and stocking density by stand age. Furthermore, by using information on model errors and variation in stand structure, we can provide an estimate of uncertainty for the BEFs. This approach can also be used to formulate BEFs in other regions and countries where reliable biomass and volume equations are available.

The BEFs currently applied in the assessments of forest carbon stocks in Finland (0.595 Mg m^{-3} for Scots pine and 0.716 Mg m^{-3} for Norway spruce) (Tomppo, 2000b) have been generated on the basis of a few ecosystem studies (Karjalainen and Kellomäki, 1996) and are slightly lower than those obtained here. Stump and root BEFs published by UN-ECE/FAO (2000) for Finland are also lower compared with the BEFs obtained in this study. According to UN-ECE/FAO (2000), for Finland the stump and root BEF was 0.10 for all tree species, whereas in the present study it was 0.16 and 0.18 for Scots pine and Norway spruce, respectively. We were not able to formulate continuous BEFs for belowground biomass of birch, since we relied on biomass equations provided by Marklund (1988), and equations for roots of birch were not obtained. According to Laitakari (1935), the average estimate for the root system of birch was about half the volume of stem, which means that BEF for the stump and roots of birch would be 0.19, assuming the same wood density for roots and stem (Bhat, 1982) and using our mean of response for estimation of stem BEF (Table 5).

BEFs (biomass component/stem volume) change as a stand ages, especially in Norway spruce stands. The variation in these factors with increasing stand age was also proposed by Kauppi et al. (1995), who compiled information from the literature. However, they assumed higher variation for Scots pine than for Norway spruce stands, mainly due to an assumed greater variation in the proportion of root biomass in Scots pine. In general, BEFs applied for different age classes of Norway spruce stands by Kauppi et al. (1995) were lower than these in this study. For Scots pine stands their BEFs by age classes were 0.80 Mg m^{-3} for stands under 40 years, 0.67 Mg m^{-3} for 41–80-year-old stands, and 0.59 Mg m^{-3} for stands over 81 years, being higher for younger stands and lower for middle aged and old stands than our BEFs were (Table 2).

Kauppi et al. (1995) estimated BEFs by age classes, and their assumption of decreasing proportion of root biomass over the age gradient was opposite to our results (Fig. 2). Our finding that BEF decreases in branches and foliage is in agreement with the trend suggested by Kauppi et al. (1995). The proportions of some biomass components (e.g. aboveground biomass of broadleaved species as well as the stump and bark of Norway spruce) are fairly stable during the rotation, and constant factors for biomass expansion can be applied for rough estimation of the biomasses of these components. When stand development and, e.g. biomass turnover are modelled, it is, however, important to notice these slight trends in the BEFs.

Our functions for BEFs can be applied to coniferous forests aged between 10 and 150 years and with less than 250 m^3 ha^{-1}. An upper limit is given since the number of older stands (>150 years) in our data was small (Fig. 2a and b). For stands less than 10 years, BEF of 10 years should be applied. For a broadleaved forest, the functions are applicable for age classes ranging from 10 to 100 years and with less than 200 m^3 ha^{-1}.

Information on forest resources might be available in the form of mean volumes according to the development classes. Since the relationship between stem volume and whole tree biomass was found to be very strong, the biomass can be estimated from mean volumes with the help of equations presented in Tables 6–8. Stem volume does not determine the biomass of the foliage and roots, but it certainly has several build-in factors that affect the biomass of the tree components (e.g. water and nutrient supply, fertility, competition, moisture and length of growing season) (Mäkelä et al., 1995). The equations describing the relationship between biomass of the tree components and stem volume at stand level are applicable for conifer forests that have a stem volume up to 250 m^3 ha^{-1}. With broadleaved forests, the equations should not be applied if the stem volume is more than 200 m^3 ha^{-1}.

Our equations may overestimate biomass in stands with high stemwood volumes, because they are based only on diameter. The relationship between diameter growth and height growth changes during stand development (Assmann, 1970). This may not be accounted for adequately, because the tree level equations we employed have relatively small sample of larger trees (more than 30 cm dbh) (Marklund, 1988).

The BEFs in this study were formulated on the basis of volume and biomass equations and on appropriate information concerning diameter distribution and stocking density of the stands, all of which might introduce some errors in the BEFs. The volume equations applied in our study (Laasasenaho, 1982) were developed by minimising error in large trees, which constitute the main part of the standing volume. Therefore, volume estimates for small trees might be biased and our BEFs might introduce bias to biomass estimation in young stands.

Applied biomass equations (Marklund, 1988) are based on a representative sample of forested stands in Sweden; and differences in stem form might have resulted a systematic bias in our BEF values. The assumption that the allometry of Swedish and Finnish trees is the same was tested by comparing volume equations for southern Sweden formulated by Brandel (1990) with those for Finland by Laasasenaho (1982). We were especially interested in the stem form in southern Sweden, since there the climatic conditions are more favourable and Marklund's (1988) sampling was quite dense there. We found that the difference in stem volume based on diameter and height between trees in southern Sweden and Finland on the stand level was less than 5% for pine and spruce.

The BEF equations presented here are applicable for a region where the diameter distribution and tree allometry is similar to the diameter distribution and tree allometry for which these volume and biomass equations were developed and applied (Parresol, 1999). Thus, major changes in silvicultural practices that might lead to changes in tree allomerty could also influence BEF values. In Finland, the stocking density of forests has increased during recent decades as a result of intensified forest management (Tomppo, 2000a). This change may lead to overestimation of canopy biomass with our BEFs, since the ratio of canopy biomass to stem volume might differ from that in Marklund's and Laasasenaho's data. Furthermore, BEFs by stand age are also sensitive to changes in diameter distributions and in stocking density of the stands. In our study this information originated from the permanent sample plots measured in 1985–1986 by the National Forest Inventory.

For developing BEFs, we used treewise measurements from the permanent sample plots of the National Forest Inventory, however, detailed information on stand structure might not always be available. Thus, we also tested approaches, in which the stand structure by age classes was simplified for a median tree (assuming all trees in an age class are of equal size) or where it was described by a Weibull distribution (in this case the information needed was the median and the 99th percentile of diameter distribution for each age class). Based on this evaluation, we conclude that BEFs can also be obtained with this limited information on stand structure.

In addition to regional carbon stock assessments, the BEFs formulated in our study are needed and can be used in analysis of the carbon dynamics of forest ecosystems that make use of inventory data on forest resources. Stand-level estimates of biomasses according to tree components are needed when biomass production and litterfall by biomass components of different quality are modelled and linked to a soil (e.g. Liski et al., 2002) model describing decomposition of dead organic matter. For these purposes it is important to be able to observe the dynamics of carbon stocks in different tree components, such as foliage, branches, bark, stem, stump and roots, according to stand age.

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Appendix A. Error estimation of BEFs by age classes

Let us denote by v_{ij} the estimate of stem volume for tree j in cluster i and by m_{ij} the biomass estimate for the same tree.

An estimate of BEF is

$$\hat{b} = \frac{\sum_{i,j} m_{ij}}{\sum_{i,j} v_{ij}} = \frac{\sum_i m_i}{\sum_i v_i},$$
$$\text{where } v_i = \sum_j v_{ij} \text{ and } m_i = \sum_j m_{ij} \tag{A.1}$$

and its variance can be approximated with the formula (Cochran, 1977)

$$\mathrm{Var}(\hat{b}) \approx \frac{\mathrm{Var}\left(\sum_i m_i - b\sum_i v_i\right)}{\left(\sum_i v_i\right)^2} \tag{A.2}$$

Sampling error was estimated by evaluating the variance of the residuals of biomass by clusters, assuming random sampling

$$\widehat{\mathrm{Var}}_{\mathrm{s}}\left(\sum_i m_i - b\sum_i v_i\right) = n\widehat{\mathrm{Var}}_{\mathrm{s}}(e_i) \tag{A.3}$$

where n is the number of clusters and $\widehat{\mathrm{Var}}_{\mathrm{s}}(e_i)$ is estimated by the sampling variance of the residuals $e_i = m_i - \hat{b}v_i$. In this data there are four sample plots in one cluster in southern Finland and three sample plots per cluster in northern Finland.

Model errors were estimated by assuming independent trees and also by assuming that all trees in one cluster were fully correlated with each other. This approach made it possible to find upper and lower limits for model errors. The assumption of independent trees:

$$\mathrm{Corr}_{\mathrm{m}}(v_{ij}, v_{ik}) = \mathrm{Corr}_{\mathrm{m}}(m_{ij}, m_{ik}) = 0, \qquad k \neq j \tag{A.4}$$

gives the formula

$$\mathrm{Var}_{\mathrm{m}}\left(\sum_i m_i - b\sum_i v_i\right) = \sum_{i,j}\mathrm{Var}_{\mathrm{m}}(m_{ij}) + b^2\sum_{i,j}\mathrm{Var}_{\mathrm{m}}(v_{ij}) - 2b\sum_{i,j}\mathrm{Cov}_{\mathrm{m}}(m_{ij}, v_{ij}) \tag{A.5}$$

for tree model error.

Variance of model errors for volume is $\mathrm{Var}_{\mathrm{m}}(v_{ij}) = s_{\mathrm{r,v}}^2 v_{ij}^2$ (Laasasenaho, 1982) and for biomass $\mathrm{Var}_{\mathrm{m}}(m_{ij}) = s_{\mathrm{r,m}}^2 m_{ij}^2$ (Marklund, 1988), where $s_{\mathrm{r,v}}$ and $s_{\mathrm{r,m}}$ are the relative mean square errors of the model estimates. Covariance of volume and biomass estimates can be estimated using the model variances and correlation of the errors in volume and biomass estimates.

$$\widehat{\mathrm{Cov}}_{\mathrm{m}}(m_{ij}, v_{ij}) = r_{\mathrm{tree,mv}}\sqrt{\widehat{\mathrm{Var}}_{\mathrm{m}}(m_{ij})\widehat{\mathrm{Var}}_{\mathrm{m}}(v_{ij})} = s_{\mathrm{r,m}} s_{\mathrm{r,m}} r_{\mathrm{tree,mv}} m_{ij} v_{ij} \tag{A.6}$$

where $r_{\mathrm{tree,mv}}$ is the estimate for the correlation between biomass and volume models, which is assumed to be constant for all trees.

Assumption of perfect correlation between model errors within each cluster,

$$\mathrm{Corr}_{\mathrm{m}}(v_{ij}, v_{ik}) = \mathrm{Corr}_{\mathrm{m}}(m_{ij}, m_{ik}) = 1, \quad k \neq j \tag{A.7}$$

leads to

$$\mathrm{Var}_{\mathrm{m}}\left(\sum_i m_i - b\sum_i v_i\right) = \sum_i \mathrm{Var}_{\mathrm{m}}(m_i) + b^2\sum_i \mathrm{Var}_{\mathrm{m}}(v_i) - 2b\sum_i \mathrm{Cov}_{\mathrm{m}}(m_i, v_i) \tag{A.8}$$

where estimates for variance based on (Laasasenaho, 1982) and (Marklund, 1988) are

$$\widehat{\mathrm{Var}}_{\mathrm{m}}(v_i) = s_{\mathrm{r,v}}^2 \sum_{j,k} v_{ij} v_{ik} \quad \text{and}$$
$$\widehat{\mathrm{Var}}_{\mathrm{m}}(m_i) = s_{\mathrm{r,m}}^2 \sum_{j,k} m_{ij} m_{ik} \tag{A.9}$$

and where covariance is estimated

$$\widehat{\mathrm{Cov}}_{\mathrm{m}}(m_i, v_i) = r_{\mathrm{cl,mv}}\sqrt{\widehat{\mathrm{Var}}_{\mathrm{m}}(m_i)\widehat{\mathrm{Var}}_{\mathrm{m}}(v_i)} = s_{\mathrm{r,m}} s_{\mathrm{r,m}} r_{\mathrm{cl,mv}} \sqrt{\sum_{j,k} m_{ij} m_{ik} \sum_{j,k} v_{ij} v_{ik}} \tag{A.10}$$

by calculating the correlation $r_{\mathrm{cl,mv}}$ between the error of volume and the error of biomass at the cluster level. Total variance of BEF is

$$\widehat{\mathrm{Var}}(\hat{b}) \approx \frac{\widehat{\mathrm{Var}}_{\mathrm{s}}\left(\sum_i m_i - b\sum_i v_i\right) + \widehat{\mathrm{Var}}_{\mathrm{m}}\left(\sum_i m_i - b\sum_i v_i\right)}{\left(\sum_i v_i\right)^2} \tag{A.11}$$

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