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Generalized functions of biomass expansion factors for conifers and broadleaved by stand age, growing stock and site index

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ABSTRACT

Parties to the Kyoto Protocol and/or the United Nations Framework Convention on Climate Change (UNFCCC) are required to account for their direct human-induced carbon emissions and removals including those from forestry and other land use related activities. In most European countries, the forestry related greenhouse gas inventories are largely or exclusively based on converting tree volume data from national forest inventories to biomass using biomass conversion and expansion factors (BCEFs). However, country specific data for many species are often lacking, which considerably increases the uncertainties of the greenhouse gas inventories. The focus of this research was to develop, using internationally published datasets that cover a large geographical area, an extended set of generalized curves of such biomass expansion factors for several species or species groups by age, growing stock and site index.

1. Introduction

Forest ecosystems are increasingly recognized as important elements of the global carbon cycle, as well as the cycle of various other greenhouse gases (GHG) that are believed to considerably affect climate. The IPCC (2007) reports how globally, annual human-induced carbon dioxide emissions from fossil fuel burning increased from an average of 6.4 (6.0–6.8) GtC yr^{-1} in the 1990s to 7.2 (6.9–7.5) GtC yr^{-1} in 2000–2005. Carbon dioxide emissions associated with land-use change are estimated to be 1.6 (0.5–2.7) GtC yr^{-1} over the 1990s (both estimates having large uncertainties). The impact of forests on climate in future, including whether we can use forests as mitigation tools, depends on how we manage them.

The United Nation Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol (UNFCCC, 1997) recognize that forest ecosystems may contribute to mitigate the human-induced greenhouse effect. More specifically, the Kyoto Protocol requires Annex-I countries (i.e. developed countries) to account for the carbon emissions and removals caused by verifiable human-induced land use changes, and allows to account for emissions and removals from forestry and other land use related activities that have taken place since 1990. This requires, for each country, an annual GHG inventory for the land use, land-use change and forestry sector (LULUCF).

The estimates inventory is usually coupled with high uncertainty which largely arises from methodological problems, as well as the limitations of data availability worldwide. In most European countries, the LULUCF GHG inventories are largely or exclusively based on forest inventories (FIs) at the national, regional or sub-regional levels, and such inventory data are converted to carbon stock changes by various methods (IPCC, 2003, 2006). FI data is widely used in GHG inventories as they mainly collect tree volume related information that is related to biomass, which is usually the most important pool concerning carbon stock changes. However, most frequently, the objective of the FIs is to collect such data that are closely related to forest management, including forest area, tree-level data such as diameter, height and volume, and stand level data such as mean diameter and total volume. This data is obtained using field sampling or a combination of remote sensing and field sampling, each of them involving different levels of uncertainties. When converting information from the FI to GHG inventory, additional uncertainties are unavoidable.

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Table 1
Forest types, genera and species collected in the harmonized dataset.

Level of aggregation	Items
Forest type	Conifers Broadleaved
Genera	*Abies, Acacia, Acer, Alnus, Betula, Camellia, Carpinus, Castanopsis, Chamaecyparis, Cinnamomum, Cryptomeria, Cyclobalanopsis, Eucalyptus, Fagus, Fraxinus, Larix, Metasequoia, Nothofagus, Picea, Pinus, Populus, Pseudotsuga, Quercus, Shorea, Tectona, Tilia, Tsuga*
Species	*Acacia dealbata, A. mollissima, Acer spicatum, Alnus glutinosa, A. incana, A. rubra, Betula ermanii, B. maximowicziana, B. pendula, B. platyphylla, B. pubescens, Camellia japonica, Carpinus betulus, Castanopsis cuspidata, Chamaecyparis obtusa, Cinnamomum camphora, Cryptomeria japonica, Cyclobalanopsis myrsinaefolia, Eucalyptus diversicolor, E. fastigata, E. globulus, E. nitens, E. obliqua, E. regnans, E. sieberii, E. tereticornis, Fagus crenata, F. orientalis, F. sylvatica, Fraxinus excelsior, Larix cajanderi, L. czekanovskii, L. decidua, L. komarovii, L. gmelinii, L. leptolepis, L. olgensis, L. sibirica, L. sukaczewii, Metasequoia glyptostroboides, Nothofagus truncata, Picea abies, P. ajanensis, P. glauca, P. koraiensis, P. glehnii, P. mariana, P. obovata, P. orientalis, P. schrenkiana, P. sitchensis, Pinus banksiana, P. caribaea, P. densiflora, P. elliottii, P. koraiensis, P. nigra, P. palustris, P. pinaster, P. ponderosa, P. pumila, P. radiata, P. resinosa, P. sibirica, P. strobus, P. sylvestris, P. taeda, P. thunbergii, P. virginiana, Populus alba,, P. bachelieri, P. deltoides, P. euramericana, P. grandidentata, P. laurifolia, P. tremula, P. tremuloides, P. trichocarpa Pseudotsuga menziesii, Quercus castaneifolia, Q. mongolica, Q. pedunculiflora, Q. pubescens, Q. robur, Shorea robusta, Tectona grandis, Tilia amurensis, T. cordata, T. platyphyllos, Tsuga heterophylla*

One important source of such additional uncertainty is that FIs typically focus only on commercially important stem volume and rarely include quantitative estimates of other important biomass components such as root fractions, branches, leaves, which makes it necessary to estimate these elements of total biomass using conversion and expansion factors (IPCC, 2003, 2006; Somogyi et al., 2006). However, country specific factors are often lacking sometimes even at national levels, but more often at regional levels.

Carbon stocks and their changes of the biomass pool can be estimated from forest inventory data by using either biomass equations (BE) or biomass expansion factors (BEF) and conversion factors (i.e. wood density). These latter two factors can be combined into one factor, i.e. biomass conversion and expansion factors (BCEFs; Somogyi et al., 2006; IPCC, 2006). In the first case, tree level data like diameter at breast height (DBH) or, additionally height, age, etc. is required (Zianis et al., 2005; Somogyi et al., 2006), whereas in the second case, volume data from the forest inventory is needed (Somogyi et al., 2006; IPCC, 2006). BEs are only used in a few countries that run a high precision forest inventory. In these cases, locally derived BEs are usually available. On the other hand, for converting volume most countries must rely on the application of BCEFs.

The application of BCEFs involves two components. One is that both tree or stand biomass compartments that are converted and/or expanded *from*, and those that are converted and/or expanded *to*, must correctly be defined, and appropriate factors are to be used (Somogyi et al., 2006). The other component is that the factors to be used are usually species specific (*e.g.* Levy et al., 2004), however, they may also depend on site (e.g. Wirth et al., 2004), forest history and tree size or age (IPCC, 2003; Levy et al., 2004), because these all affect the biomass allocation strategies of the trees.

Although these interdependences can be considered as well documented in general, there is a general lack of information concerning country specific data due to the very large variation of the factors worldwide, and the scale and resource limitations of data collection. This is especially true for BEF values, and is also obvious from many papers reporting BCEF values, as well as the recent methodological guidelines of IPCC (2003, 2006). Although these guidelines contain sets of so called default values for BEFs and BCEFs, they recognize that high variation of the published average values must be expected.

The average values report by the IPCC guidelines (IPCC, 2003, 2006) are for some main species or species groups. In addition to the fact that specific data are lacking for many species, the application of these reported IPCC values include uncertainties that are also due to missing information concerning stand structure, age and compartments included in the values.

In this study, we report an extended set of BEF values and provide generalized curves of these values for several species or species groups over age, growing stock and site index. The curves were developed using thousands of stand-level measured biomass compartments from a large geographical coverage. Through a meta-analysis, we have developed reliable statistical information to estimate BEFs that could be applied in GHG inventories in countries where national data is not available. By applying the curves reported in this paper, or using them in selecting appropriate values from other data sources, one can reduce some of the uncertainty for species, age, growing stock and site index, which may be available in the FI, thus, more accurate estimation of the carbon stocks and their changes can be done for the biomass pool.

2. Material and methods

2.1. Data and statistical analysis

2.1.1. General issue

The application of factors to estimate biomass depends on local tree and stand characteristics; therefore, there is no purely theoretical formula that relates them to species, site index, age and growing stock. Moreover, no unique formula has been reported, up to now, to fit empirical data.

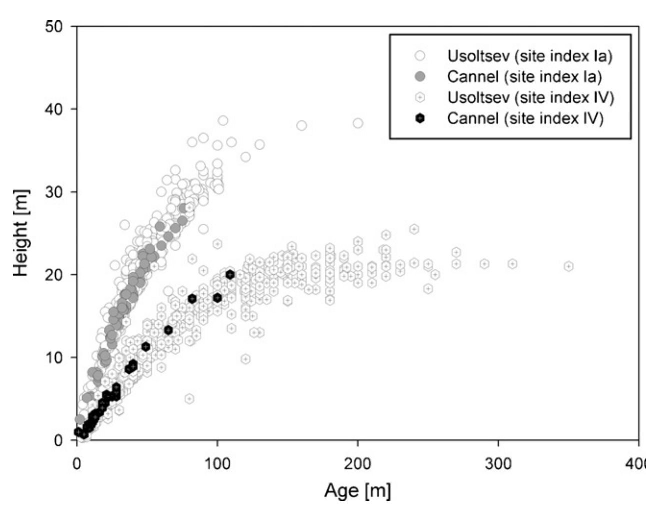

Fig. 1. Relationship between mean stand age and top height for the Usoltsev and the Cannell datasets of Conifers and Broadleaved in the *Ia* and *IV* general bonitaet (site index) scales (Shvidenko et al., 2007).

Table 2

Age dependent BEF functions by forest type and genera. All cases were processed using four different non-linear regression models. The no. of plots and the min and max age (i.e. the range of utilization of proposed equations) of original data used for the analysis are also reported; the terms BEF_{il} and BEF_{el} means that the leaf compartment were respectively included and not included in the computation of BEFs (see text for the list of models used and the definition of BEFs); mean, median and standard deviation of BEF_{il} and BEF_{el} are also reported. BIC is the Bayesian Information Criterion, LogLik the maximum log likelihood and RSE the root standard error of the estimation; *a*, *b*, *c* are the parameters estimated by the non-linear regression analysis, SD the standard error and p the statistical significance of the estimation ($^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$). The symbol "–" used in some cells (see columns related to the c parameter) denote that the term is not included in the model while NS means Not statistically Significant ($p > 0.05$). See also Appendices A and B for a complete list of equations developed during this research.

ID	No. of plots	Age		BEF				Model	BIC	LogLik	RSE	*a*			*b*			*c*		
		Minimum	Maximum	Type	Mean	Median	SD					Mean	SD	*p*	Mean	SD	*p*	Mean	SD	*p*
Broadleaved	1493	2	400	BEF_{il}	1.2506	1.1969	0.183	1	−1578.90	804.07	0.537	0.168	0.003	***	1.338	0.086	***	–	–	–
								2	−1583.86	806.55	0.529	1.177	0.004	***	1.896	0.134	***	–	–	–
								3	−1576.84	806.69	0.527	1.174	0.009	***	1.749	0.310	***	0.952	0.095	***
								4	−1590.94	813.74	0.528	1.199	0.004	***	0.577	0.069	***	0.095	0.010	***
	1530	2	400	BEF_{el}	1.19484	1.16195	0.137	1	−2036.23	1032.78	0.342	0.156	0.003	***	0.553	0.075	***	–	–	–
								2	−2036.47	1032.90	0.341	1.168	0.004	***	0.693	0.098	***	–	–	–
								3	−2029.17	1032.92	0.341	1.166	0.008	***	0.654	0.232	***	0.963	0.206	***
								4	−2036.97	1036.82	0.342	1.175	0.004	***	0.216	0.048	***	0.092	0.020	***
Conifers	3491	2	380	BEF_{il}	1.35396	1.2305	0.463	1	−1738.96	885.80	2.620	0.137	0.002	***	4.612	0.107	***	–	–	–
								2	−1710.29	871.46	2.579	1.132	0.003	***	6.793	0.200	***	–	–	–
								3	−1782.71	911.75	2.516	1.166	0.004	***	17.400	1.782	***	1.367	0.041	***
								4	−1760.46	900.63	2.589	1.194	0.003	***	1.924	0.121	***	0.090	0.004	***
	3493	2	380	BEF_{el}	1.19457	1.1428	0.174	1	−5392.27	2712.45	0.783	0.107	0.002	***	2.140	0.074	***	–	–	–
								2	−5396.02	2714.33	0.764	1.109	0.002	***	2.726	0.101	***	–	–	–
								3	−5400.64	2720.72	0.777	1.118	0.003	***	4.156	0.558	***	1.180	0.057	***
								4	−5454.32	2747.56	0.761	1.135	0.002	***	0.692	0.052	***	0.085	0.005	***
Abies & Picea	761	3	283	BEF_{il}	1.40837	1.2589	0.708	1	−902.76	464.65	6.906	0.156	0.004	***	6.690	0.283	***	–	–	–
								2	−873.55	450.04	8.016	1.160	0.007	***	9.146	0.610	***	–	–	–
								3	−924.84	479.01	6.642	1.205	0.006	***	49.575	8.936	***	1.545	0.066	***
								4	−930.87	482.02	6.818	1.236	0.004	***	3.398	0.414	***	0.084	0.006	***
	762	3	283	BEF_{el}	1.21431	1.1578	0.2	1	−1586.68	806.61	2.047	0.115	0.003	***	3.240	0.227	***	–	–	–
								2	−1584.07	805.31	1.965	1.117	0.004	***	4.177	0.330	***	–	–	–
								3	−1590.63	811.90	2.067	1.134	0.005	***	10.074	2.611	***	1.318	0.097	***
								4	−1624.45	828.82	1.817	1.153	0.003	***	1.190	0.169	***	0.077	0.007	***
Larix	363	9	380	BEF_{il}	1.24075	1.153	0.272	1	−270.55	147.07	4.685	0.108	0.008	***	5.428	0.711	***	–	–	–
								2	−269.85	146.71	4.709	1.109	0.010	***	6.849	1.005	***	–	–	–
								3	−265.15	147.31	4.646	1.127	0.015	***	15.737	11.906	NS	1.269	0.247	***
								4	−266.17	147.82	4.354	1.150	0.007	***	1.223	0.380	***	0.056	0.011	***
	364	9	380	BEF_{el}	1.17961	1.12245	0.179	1	−459.96	241.77	1.353	0.096	0.007	***	3.602	0.481	***	–	–	–
								2	−459.33	241.46	1.358	1.098	0.008	***	4.366	0.638	***	–	–	–
								3	−454.86	242.18	1.348	1.112	0.012	***	10.390	7.889	NS	1.301	0.266	***
								4	−457.08	243.28	1.293	1.127	0.006	***	0.812	0.243	***	0.061	0.013	***
Pinus	2177	2	310	BEF_{il}	1.3529	1.2241	0.386	1	−975.20	502.97	1.705	0.130	0.003	***	4.211	0.109	***	–	–	–
								2	−998.74	514.74	1.476	1.113	0.005	***	6.735	0.204	***	–	–	–
								3	−1040.46	539.45	1.536	1.148	0.006	***	13.224	1.396	***	1.289	0.046	***
								4	−1097.10	567.76	1.496	1.186	0.004	***	2.100	0.130	***	0.101	0.004	***
	2177	2	310	BEF_{el}	1.19638	1.143	0.169	1	−3477.40	1754.07	0.606	0.097	0.002	***	2.176	0.076	***	–	–	–
								2	−3495.17	1762.95	0.564	1.095	0.003	***	2.865	0.105	***	–	–	–
								3	−3493.31	1765.87	0.582	1.104	0.004	***	3.724	0.488	***	1.120	0.058	***
								4	−3581.87	1810.15	0.547	1.126	0.002	***	0.778	0.054	***	0.091	0.005	***

Table 3

Growing stock dependent BEF functions by forest type and genera. All cases were processed using four different non-linear regression models; The no. of plots and the min and max growing stock (i.e. the range of utilization of proposed equations) of original data used for the analysis are also reported; the terms BEF_{il} and BEF_{el} means that the leaf compartment were respectively included and not included in the computation of BEFs (see text for the list of models used and the definition of BEFs); mean, median and standard deviation of BEF_{il} and BEF_{el} are also reported. BIC is the Bayesian Information Criterion, LogLik the maximum log likelihood and RSE the root standard error of the estimation; *a, b, c* are the parameters estimated by the non-linear regression analysis, SD the standard error and p the statistical significance of the estimation (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$). The symbol "–" used in some cells (see columns related to the c parameter) denote that the term is not included in the model while NS means Not statistically Significant ($p > 0.05$). See also B for a complete list of equations developed during this research.

ID	No. of plots	Growing stock		BEF				Model	BIC	LogLik	RSE	*a*			*b*			*c*		
		Minimum	Maximum	Type	Mean	Median	SD					Mean	SD	*p*	Mean	SD	*p*	Mean	SD	*p*
Broadleaved	1365	1	772	BEF_{il}	1.247	1.194	0.189	1	−1707.70	868.29	1.718	0.173	0.002	***	0.681	0.095	***	–	–	–
								2	−1795.29	912.08	1.774	1.171	0.003	***	4.423	0.392	***	–	–	–
								3	−1934.08	985.09	0.950	1.049	0.027	***	1.581	0.213	***	0.436	0.056	***
								4	−1930.24	983.17	0.905	1.175	0.004	***	0.500	0.046	***	0.018	0.002	***
	1402	1	772	BEF_{el}	1.194	1.160	0.144	1	−2095.09	1062.04	0.932	0.152	0.002	***	0.448	0.086	***	–	–	–
								2	−2117.91	1073.44	0.970	1.159	0.003	***	1.578	0.239	***	–	–	–
								3	−2186.19	1111.21	0.707	1.073	0.030	***	0.797	0.152	***	0.393	0.088	***
								4	−2185.86	1111.05	0.701	1.154	0.004	***	0.263	0.038	***	0.017	0.003	***
Conifers	3252	1	1294	BEF_{il}	1.333	1.224	0.361	1	−2500.50	1266.43	6.024	0.179	0.002	***	0.090	0.018	***	–	–	–
								2	−3125.93	1579.14	6.296	1.153	0.002	***	12.400	0.466	***	–	–	–
								3	−3509.98	1775.21	2.759	1.051	0.011	***	3.791	0.302	***	0.566	0.026	***
								4	−3542.73	1791.58	2.789	1.172	0.003	***	0.739	0.033	***	0.014	0.001	***
	3253	1	1294	BEF_{el}	1.189	1.142	0.159	1	−5993.92	3013.13	1.966	0.123	0.001	***	0.066	0.014	***	–	–	–
								2	−6309.67	3171.01	2.584	1.113	0.001	***	4.358	0.225	***	–	–	–
								3	−6802.55	3421.50	1.033	1.024	0.011	***	1.297	0.106	***	0.437	0.031	***
								4	−6837.67	3439.05	1.017	1.114	0.002	***	0.337	0.016	***	0.013	0.001	***
Abies & Picea	730	1	1294	BEF_{il}	1.371	1.258	0.399	1	−695.73	361.05	9.983	0.208	0.003	***	0.294	0.088	***	–	–	–
								2	−1471.13	748.75	4.621	1.126	0.003	***	8.002	0.823	***	–	–	–
								3	−969.13	501.05	4.610	1.063	0.024	***	5.648	1.058	***	0.579	0.051	***
								4	−945.42	489.19	4.545	1.201	0.005	***	0.754	0.073	***	0.009	0.001	***
	730	1	1294	BEF_{el}	1.205	1.157	0.161	1	−1399.95	713.16	2.810	0.139	0.002	***	0.193	0.068	***	–	–	–
								2	−1472.33	749.35	5.254	1.123	0.003	***	9.064	0.891	***	–	–	–
								3	−1604.93	818.95	1.392	1.012	0.028	***	1.700	0.309	***	0.419	0.061	***
								4	−1598.91	815.94	1.258	1.131	0.004	***	0.394	0.039	***	0.009	0.001	***
Larix	363	1	965	BEF_{il}	1.245	1.153	0.282	1	−411.18	217.38	5.093	0.126	0.004	***	1.125	0.222	***	–	–	–
								2	−461.64	242.61	6.237	1.104	0.005	***	8.797	1.016	***	–	–	–
								3	−486.49	257.98	3.993	1.023	0.036	***	2.058	0.756	***	0.508	0.117	0.000
								4	−474.55	252.01	4.616	1.101	0.009	***	0.263	0.043	***	0.007	0.002	0.000
	364	1	965	BEF_{el}	1.183	1.122	0.191	1	−617.25	320.42	2.720	0.105	0.003	***	0.872	0.184	***	–	–	–
								2	−650.06	336.82	3.372	1.093	0.004	***	4.987	0.680	***	–	–	–
								3	−681.34	355.42	2.120	1.012	0.038	***	1.173	0.404	***	0.434	0.124	0.001
								4	−670.97	350.23	2.418	1.084	0.008	***	0.185	0.030	***	0.007	0.002	0.000
Pinus	2039	1	735	BEF_{il}	1.333	1.216	0.361	1	−1754.41	892.45	9.682	0.154	0.002	***	0.108	0.021	***	–	–	–
								2	−2611.04	1320.76	8.256	1.102	0.003	***	17.990	0.548	***	–	–	–
								3	−2927.43	1482.77	3.564	0.949	0.020	***	3.791	0.361	***	0.501	0.032	***
								4	−2899.71	1468.91	3.827	1.128	0.003	***	0.674	0.028	***	0.011	0.000	***
	2039	1	735	BEF_{el}	1.187	1.139	0.155	1	105776.00	−52872.60	NS	0.084	0.000	***	3.795	0.109	***	–	–	–
								2	−4235.90	2133.19	3.132	1.092	0.002	***	6.456	0.297	***	–	–	–
								3	−4623.22	2330.66	1.095	0.948	0.026	***	1.234	0.106	***	0.351	0.041	***
								4	−4631.42	2334.76	1.110	1.095	0.002	***	0.325	0.015	***	0.011	0.001	***

2.1.2. Data collection

In this study we derived various BEFs using area specific (i.e. stand level) data of forests selected from the Biomass Compartment Database (Teobaldelli, 2008). Biomass data included the following tree's compartments: stem, bark, branches and foliage. The expansion was done either from stem overbark to the sum of stem overbark and branches (i.e. total aboveground woody biomass, or BEF_{el}), or from stem overbark to the sum of stem overbark, branches and leaves (i.e. total aboveground biomass, or BEF_{il}).

The Biomass Compartment Database (Teobaldelli, 2008), containing at the moment data of 6392 plots, represents a harmonized collection of existing datasets (Cannell, 1982; Usoltsev, 2001). It is a database that will be freely available during 2009 in the AFOLU clearinghouse (European Commission, DG-Joint Research Centre, Institute for Environment and Sustainability, Climate Change Unit).

The dataset from Cannell (1982) includes biomass values (6 compartments: stem overbark, branches, foliage, fruits, roots and understorey) for temperate forest stands (809 pure forest, 504 mixed forest; 129 genera, 95 species) of various ages, gathered from forest inventories from around the world (46 countries).

The Usoltsev (2001) dataset represents one of the most extensive databases (5085 plots) of forest biomass for the forest-forming species of Northern Eurasia (37 countries). It includes biomass values (7 compartments: stem, stem's bark, branches, branch's bark, foliage, roots and understorey) from forest stands (3462 Conifers, 1617 Broadleaved; 4476 pure forest; 609 mixed forest; 12 genera: 4 Conifers and 8 Broadleaved; 49 species: 28 Conifers and 21 Broadleaved). Most data in this database (81%) are from the territory of the Russian Federation.

The data was obtained using standard methodologies applied in measuring forest biomass. Despite some methodical uncertainties and discrepancies, caused by the fact that forest biomass was determined by experts of different scientific areas for different purposes, specific to each of them, the majority of harvest biomass data are considered as information from reliable and sound scientific studies.

Other studies also extensively used the Cannell (1982) and Usoltsev (2001) databases to investigate the relation of biomass allocation and growth of different species (Usoltsev et al., 1995; Usoltsev and Hoffmann, 1997a,b, 1998; Hoffmann and Usoltsev, 2000, 2001, 2002; Niklas, 2005; Pilli et al., 2006).

2.1.3. Data preparation for the analysis of the effect of age, growing stock and site index

The analysis of variance component showed no significant random effect explained by the study factors, i.e. two datasets (Cannell, 1982; Usoltsev, 2001) used to run the meta-analysis.

In order to analyse the effect of age and growing stock we aggregated biomass data to species and genus level. Moreover, we also aggregated data to broad forest type categories such as Conifers and Broadleaved (Table 1).

These aggregations seemed necessary to enable one to apply these categories to any species that are not represented in our database. The IPCC (2003) itself also reports these broad categories.

The aggregation by site index of the two dataset was made using the Orlov's general bonitaet (site index) scales (Shvidenko et al., 2007). In this classification there are two site index scales: one for coniferous and deciduous species of seed origin, and the second, for deciduous species of coppice origin. The scales indicate different levels of productivity based on average age and height of dominant species of stands (Shvidenko et al., 2007).

The Usoltsev (2001) plots, used in our analysis, originally reported site index based on the Orlov's site index scales. As no site index was reported by Cannell (1982), a site index value was assigned to each plots by using the mean stand height and age as proxy variables, and, as look up table, the site index scale for coniferous and deciduous species of seed origin (Shvidenko et al., 2007). By applying this procedure we assumed that all the plots were originated from seed. Although this assumption could be not true for some stand of vegetative origin, like for instance poplar stands, we found a good relationship of the mean total stand height *vs* age between the data of the Cannell dataset and the data of the same site classes of the Usoltsev dataset (Fig. 1).

2.1.4. Fitting the data with non-linear models

All the data grouped by site index, were fitted over age and growing stock by forest-types, genera and species to four types of non-linear models.

In these formulas, which are detailed below, y (dimensionless) is BEF, as defined before, x is the mean age (yr) or the mean growing stock ($m^3\ ha^{-1}$) of the stand, and a, b and c are coefficients of the non-linear regression models.

2.1.4.1. Schumacher's equation.

$$y = e^{(a+b/x)} \quad (1)$$

The Eq. (1) was developed by F.X. Schumacher in 1939 for modelling volume-yield of an even-aged timber stand (Sit and Poulin-Costello, 1994). The equation assumes that the rate of change of y (i.e. BEF) is inversely proportional to x (age or growing

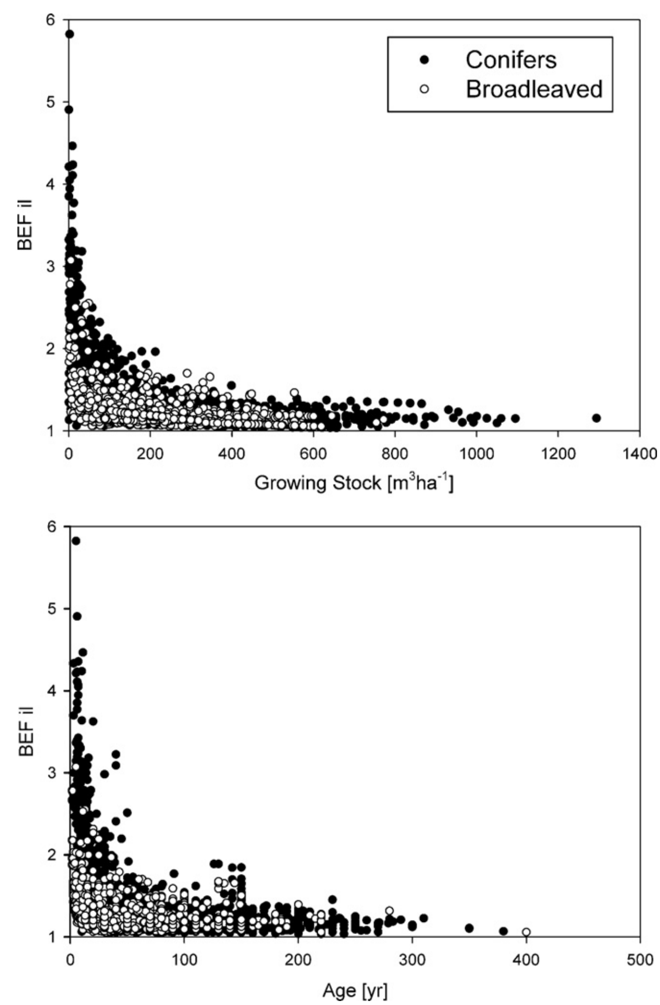

Fig. 2. Growing stock and age dependent BEFs for Conifers and Broadleaved stands.

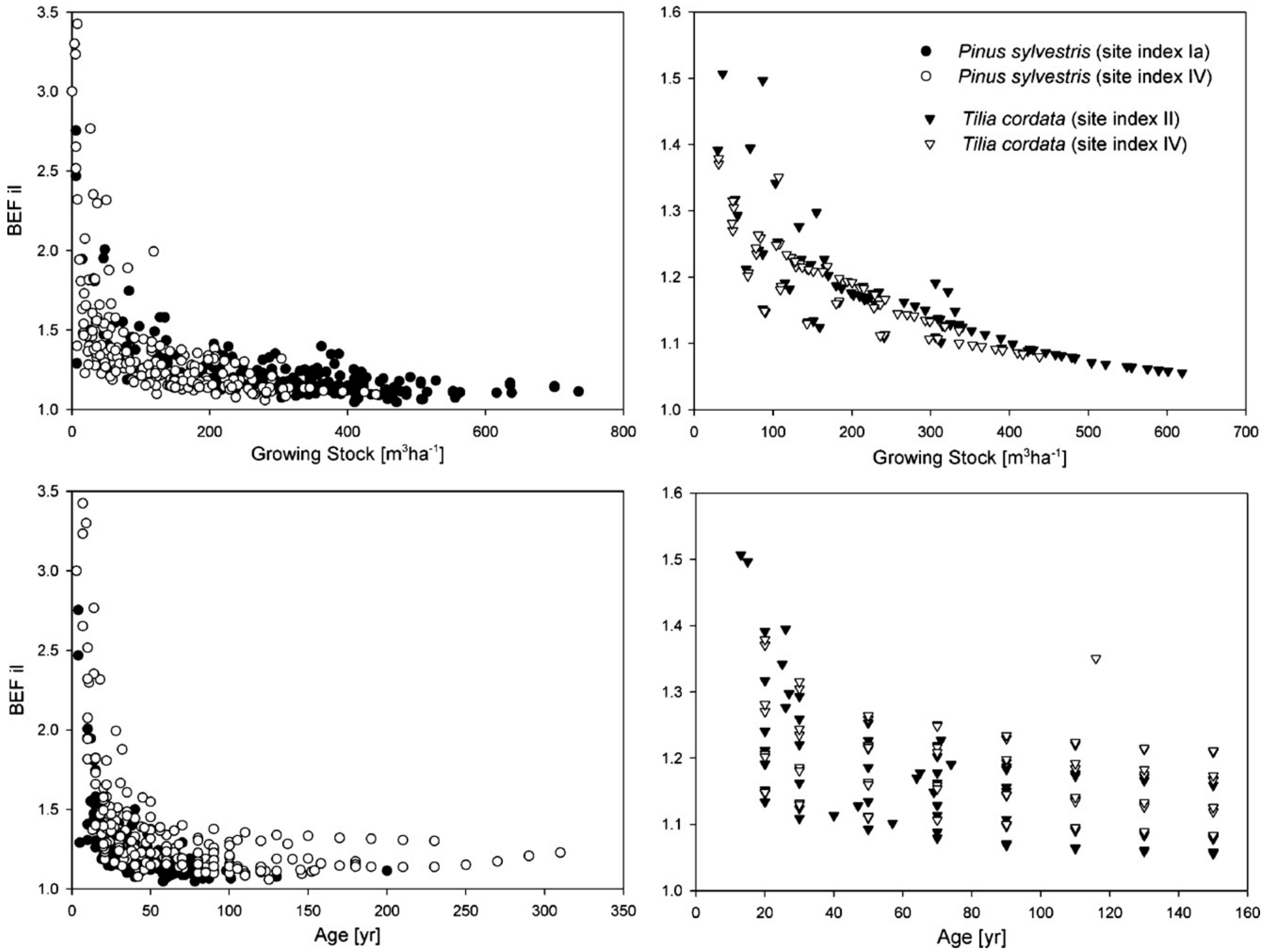

Fig. 3. Growing stock and age dependent BEFs for *Pinus sylvestris* and *Tilia cordata*, growing in stands characterized by different site index.

stock). Parameter a is the logarithm of the maximum y-value as x approaches infinity (Sit and Poulin-Costello, 1994).

2.1.4.2. Reciprocal equations.

$$y = a + \frac{b}{x} \tag{2}$$

The Eq. (2) was previously used by Fang et al. (1998, 2001, 2005) and by Fang and Wang (2001) to express the relationship between BEF (parameter y of the equation), defined here as the ratio of tree biomass compartment to stand volume, and timber volume (parameter x of the equation) for calculating China's forest biomass. In their study a and b parameters were considered constants for a specific forest type.

$$y = a + \frac{b}{x^c} \tag{3}$$

The Eq. (3) is a modification of Eq. (2) and it was developed for this study.

2.1.4.3. Specific equation for age-dependent biomass expansion factors.

$$y = a + b \cdot e^{-x \cdot c} \tag{4}$$

Considering that BEF relations are heteroscedastic and non-linear, Lehtonen et al. (2004) made comparisons between different logarithmic transformations of variables and different types of form. Finally they proposed Eq. (4) to predict BEFs, defined here as the ratio of tree biomass compartment (foliage, branches, stem, dead branches, bark, stump, coarse roots, small roots or whole tree) to tree stem volume, of Scots pine, Norway spruce and Birch. In particular tree stem volume and biomass compartments were computed respectively using Laasasenaho (1982) and Marklund (1988) equations and DBH as proxy variable. The equation was fitted using linear regression with the time dependent term $e-0.01 \times$ age as the independent variable and BEF as the dependent variable.

In our study, to take into account the error structure and the heteroscedasticity of error variance, the proposed formulas [Eqs. (1)–(4)] were fitted using the generalized non-linear least square (GNLS) method, included into the R-nlme packages (R, version 2.7.2). In fact using the GNLS function, errors are allowed to be correlated and/or have unequal variances (Pinheiro and Bates, 2000). Finally the heteroscedasticity structure was assumed to be proportional to the age and growing stock and it was described using a power function as regression weight.

The performance of the proposed formulas [Eq. (1)–(4)] were analyzed using the Bayesian Information Criterion (BIC) which is a way to estimate the best model formulation as a function of model explanatory power and model complexity.

The BIC (Schwartz, 1978), based on maximization of a log likelihood function, was preferred to the widely used Akaike Information Criterion (AIC) (Akaike, 1974) because the latter is biased in large dataset since the relative weight of the penalty term (i.e. the second term of the AIC formulation) becomes very small compared to that one related to maximum log likelihood (Shono, 2005) and as a consequence AIC tends to select the complicated model (e.g. many explanatory variables exist in regression analysis).

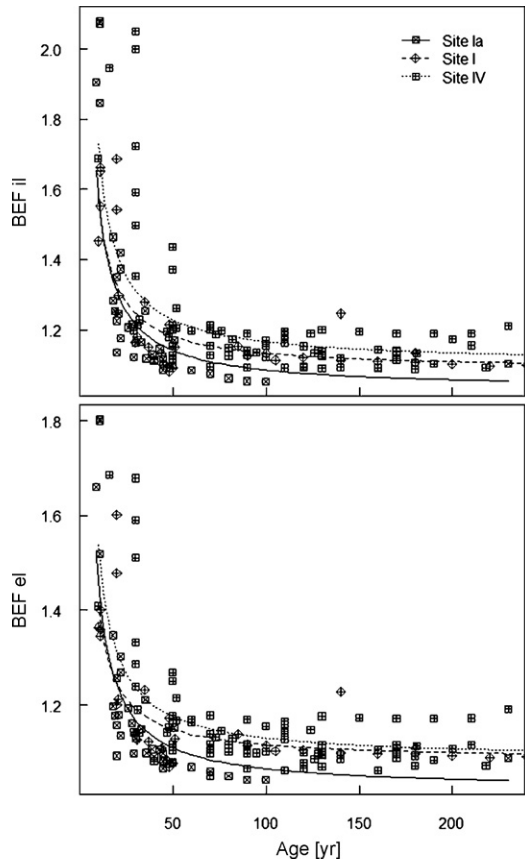

Fig. 4. Age dependent BEFs for *Larix*, growing in stands characterized by different site index. BEF_{il} (i.e. BEF "including leaves") is the ratio of total aboveground biomass (stem overbark, branches and leaves) to stem overbark biomass; BEF_{el} (i.e. BEF "excluding leaves) is the ratio of stem overbark and branches biomass to stem overbark biomass. The fitting curves have been produced using the model 2, i.e. $y = a + b/x$, where x is the mean age (yr) of the stand, and a and b are coefficients of the non-linear regression models.

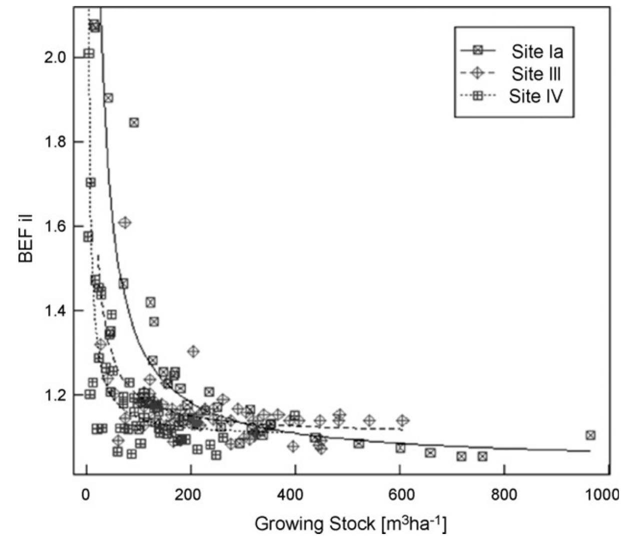

Fig. 5. Growing stock dependent BEFs for *Larix* growing in stands characterized by different site index. The fitting curves have been produced using the model 2, i.e. $y = a + b/x$, where x is the mean growing stock ($m^3\ ha^{-1}$) of the stand, and a and b are coefficients of the non-linear regression models.

3. Results

3.1. The effect of age, growing stock and site index

The analysis of the biomass compartments datasets (i.e. Cannell, 1982; Usoltsev, 2001) permitted us to describe and model the variation of BEFs (i.e. BEF_{il} and BEF_{el}) at different age or growing stock in forest stands growing in site with different index; mean, median and RSE (Root Standard Error) of estimation of growing stock and age dependent BEF functions for some selected level of aggregation, are reported in Tables 2 and 3; all the output data are instead reported in Appendices A and B.

The highest variability of BEFs was found on young forests or in stand with lower growing stock, especially during the analysis of broad categories like Conifers and Broadleaved.

This variability decreased from forest type (i.e. Conifers and Broadleaved) through genera to the species level.

Higher BEF values were found, for Conifers and Broadleaved forest types in young stands or in stands with lower growing stock (Fig. 2); BEFs of Conifers ranged between 5.8 and 1.03 while Broadleaved's BEFs ranged between 3.07 and 1.05.

The analysis at species level showed that growing stock dependent BEFs is less variable than age dependent BEFs (Fig. 3).

We found higher BEFs in less productive stands (lower site index), especially in mature (>20 years old) and older forests (Figs. 3 and 4).

On the contrary we did not find any influence of site index on BEFs of Conifers and Broadleaved stands at different level of growing stock (Fig. 3; Fig. 5).

3.2. Comparison of proposed model

The four model, utilized during the statistical analysis has shown different results in relation to the level of aggregation of data (forest type, genera and species) and to the independent variable (i.e. age or growing stock) used during the analysis.

Growing stock and age dependent BEF functions for some selected level of aggregation, are reported in Tables 2 and 3; all the output data are instead reported in Appendices A and B.

In some cases (49 of 912 for BEFs *vs* Age and 80 of 744 for growing stock dependent BEFs), the proposed models were not significant (NS) or not able to fit the data (NA) (Tables 2 and 3 and Appendices A and B).

In all the other cases the proposed models fitted the data with different level of accuracy.

Excluding leaves during the estimation of biomass expansion factors (i.e. BEF_{el}) with age (Fig. 4) or growing stock as independent variable reduced the variability observed in the biomass dataset and increased the accuracy of the model (higher Loglike and lower BICs and RSE values) (Tables 2 and 3 and Appendices A and B).

The comparison of the four models showed no statistically significant differences between the proposed non-linear equations. For each level of aggregation the estimated BICs where statistically not different.

However the analysis of BICs permitted to rank the four models according to the number of cases with lower BICs, estimated during each analysis.

Model 1 was 1st ranked during the analysis of BEFs *vs* Age (82 cases with lower BICs of 242) and 4th ranked (25 cases with lower BICs of 185) during the analysis of BEFs *vs* Growing Stock; in particular during the last analysis (BEFs *vs* Growing Stock) some of the estimated equations, even if statistically significant, seemed not able to fit the data accurately (Figs. 6 and 7) (Tables 2 and 3 and Appendices A and B).

Model 2 was 2nd ranked in both analysis (52 of 185 and 72 of 242 cases with lower BICs respectively during the BEFs *vs* Growing Stock and Age analysis) (Tables 2 and 3 and Appendices A and B).

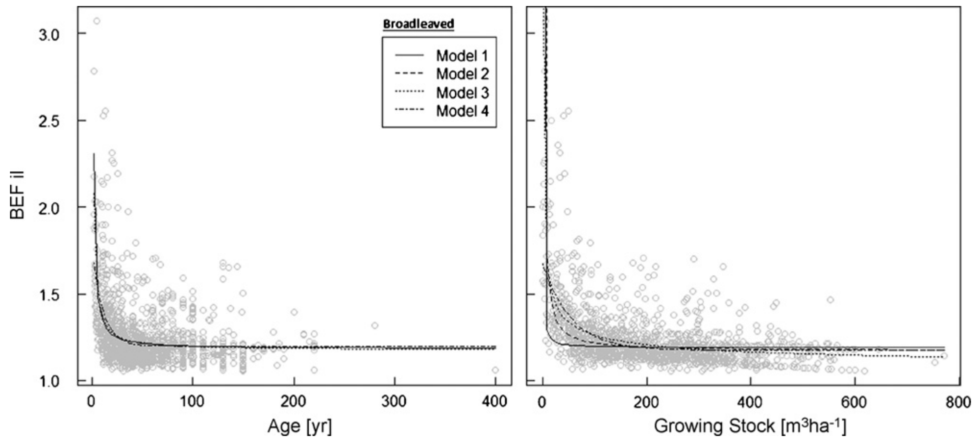

Fig. 6. Age and growing stock dependent BEFs for Broadleaved stands. The fitting curves have been produced using four non-linear regression models, i.e. Model 1: $y = \exp(a + b/x)$, Model 2: $y = a + b/x$, Model 3: $y = a + b/(x^c)$ and Model 4: $y = a + b \times \exp(-x \times c)$, where y is the age or growing stock dependent BEF, x is the mean age (yr) or growing stock ($m^3\ ha^{-1}$) of the stand, and a, b and c (only for models 3 and 4) are coefficients of the non-linear regression models.

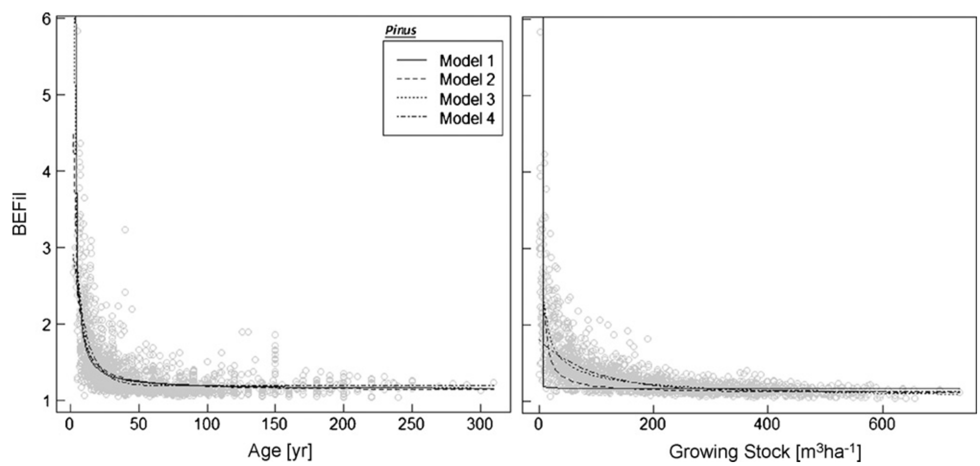

Fig. 7. Age and growing stock dependent BEFs for *Pinus* stands. The fitting curves have been produced using four non-linear regression models, i.e. Model 1: $y = \exp(a + b/x)$, Model 2: $y = a + b/x$, Model 3: $y = a + b/(x^c)$ and Model 4: $y = a + b \times \exp(-x \times c)$, where y is the age or growing stock dependent BEF, x is the mean age (yr) or growing stock ($m^3\ ha^{-1}$) of the stand, and a, b and c (only for models 3 and 4) are coefficients of the non-linear regression models.

Model 3 was 3rd and 4th ranked (37 of 185 and 24 of 242 cases with lower BICs) respectively during the BEFs *vs* Growing Stock and Age analysis (Tables 2 and 3 and Appendices A and B)

Finally Model 4 was 1st and 3rd ranked (70 of 185 and 65 of 242 cases with lower BICs) respectively during the BEFs *vs* Growing Stock and Age analysis (Tables 2 and 3 and Appendices A and B).

4. Discussion

The main objective of this study was to reduce uncertainties and possible sources of errors for forest biomass estimation by providing biomass expansion factors to be used at stand level in connection with forestry inventory data (stand stem biomass, age or growing stock of the stand) collected in different climatic zones.

The meta-analysis we conducted included the largest amount of statistical information available in literature for estimating generalized BEF curves, including data from large geographical areas with different ecological and management conditions, thus, inherently involving large variation. This was sometimes supplemented by uncertainties resulting from the unknown quality of the data. In order to minimize uncertainties, we fixed the minimum number of stands to be used for developing a generalized function to any species and species group to 30.

A conceptual model would describe the effect of age on biomass allocation possibly by demonstrating a decrease of BEF with an increase of tree size, or age, with an asymptotic BEF value. The variation of BEF at different growing stock level of the stand should be, instead more related to different silviculture practises (stand tree density, thinning, etc.).

Concerning the effect of site on BEFs, we found higher age dependent BEFs in stands growing on sites of lower productivity, both in Conifers (Fig. 2), as well as in Broadleaved (Fig. 3) stand. This is consistent with findings of Wirth et al. (2004). Presumably, this is due to a bigger ratio of branches/stem of trees growing in poor sites. In fact trees growing on poor sites are generally characterized by a higher degree of branchiness and modification of stem architecture (presence of fork, etc.), which inevitably increases the value of BEF. This age and site dependence of BEF was also reported by many authors (e.g. IPCC, 2003, 2006; Levy et al., 2004).

Stand level BEF values were also decreasing with an increase of growing stock. Forest stands characterized by an identical growing stock may have different tree's age and dimensions (mean DBH and top height) and horizontal (density) stand structure. Also site index of stands could be different even if growing stock level is similar, but as reported growing stock dependent BEFs did not show any dependencies on site index. The reported lower variability of growing stock dependent BEFs as well the absence of dependencies on site index, are probably related to the fact that growing stock integrates the effects of stand age, site index and other biotic and abiotic factors on forest biomass (Zhang et al., 2002). The differences between growing stock and age dependent BEFs should be more investigated especially because if our findings could be generalized, in order to reduce uncertainties during the expansion to stand level tree biomass, growing stock dependent BEFs should be preferred to age dependent BEFs.

Finally the study showed that including the leaves biomass compartment during the meta-analysis added some degree of uncertainty in the estimation of age and growing stock dependent BEFs, especially in young stands.

The generalized functions of BEFs derived for species or species groups (genera and forest type) by age, growing stock and site index can be used in case no local or country-specific data are available for either a certain species or genus, or for different age groups or site types. From the analysis the proposed non-linear equations, used to predict age and growing stock dependent BEFs showed no statistically significant differences. Nevertheless, Model 1 seemed not able to fit the growing Stock dependent BEFs accurately and probably the equation should be used only to predict age dependent BEFs. Finally the min and max growing stock or age reported in the tables are related to the original dataset used for the analysis and they must be considered as the range of application of proposed equations.

The generalized functions can also be used for validating existing values that, e.g. may not come from a representative study. However, although the derived functions are based on representative data and include an estimate of uncertainties, they are not meant to replace local data, which must always be preferred if they are available.

Care should also be taken with respect to the type of BEF that should be used in a country with merchantable volume data that is to be expanded to get total biomass. The two types of BEF that could be developed in this study expand stem biomass overbark to aboveground woody biomass or total aboveground biomass, respectively. If a user has stem biomass to be converted, the BEF values we have developed ("stem-based BEFs") can be directly applied for expansion. However, if merchantable volume is to be expanded ("merchantability-based BEF"), then the expansion depends on the definition of merchantability.

This definition inherently involves two elements at the stand level. One is the merchantability limit for any tree (e.g. 10 cm top diameter). This element may mean 10–20% expansion or more in addition to the expansion by the stem-based BEF. The other element is related to the distribution of trees of different size within the stands, and also to the quality of the trees from a merchantability point of view. Due to the unusable small and bad quality trees, the merchantable volume needs again a further expansion. Depending on the definition of these elements in the various countries, the difference between the BEFs developed in this study and those to be applied for merchantable timber can vary substantially. We also note here that the BEFs to be applied for stands of merchantability limit are greater than our BEFs if only the biomass of the merchantable part of the stem is known. Less or even no difference can occur if also some parts of branches are included in the merchantable biomass. However, in most cases, the stem-based BEFs underestimate the required expansion rate when merchantable wood is to be expanded. (Unless significant differences in stem and branch density are found, the same BEFs can be used for expanding volume and biomass.)

Because of the above, the values of the stem-based BEFs that we developed are not to compare with BEFs including different definitions (see for instance Fang et al., 1998, 2001, 2005; Fang and Wang, 2001; Lehtonen et al., 2004).

Except than for Larch forest (Fig. 8) with growing stock higher than 20 m^3 ha^{-1}, where our data were lower than IPCC default values, the comparison of our BEFs with default IPCC values (IPCC, 2006) for Boreal Forest, showed a general good agreement (Fig. 8), presumably because of the higher percent (81%) of data in the

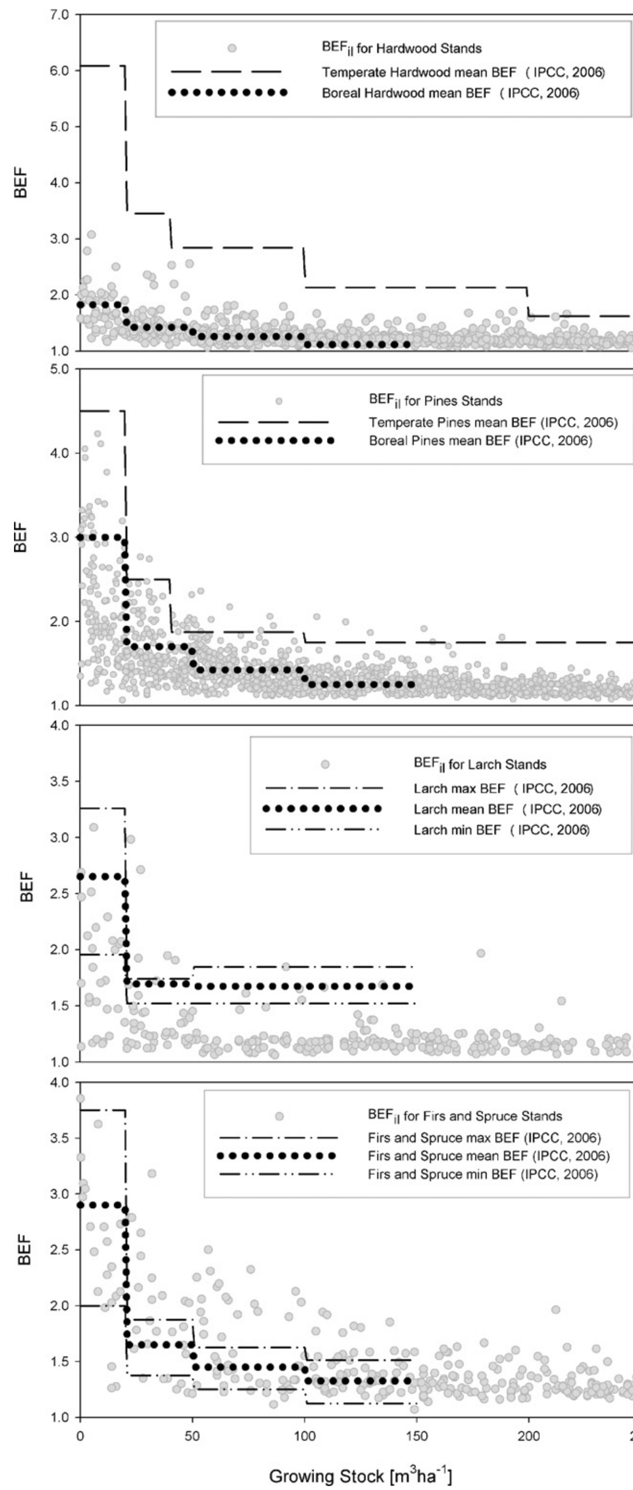

Fig. 8. Comparison between growing stock dependent BEFs estimated in this study (BEF_{il}) with IPCC default values (IPCC, 2006). The IPCC default values (max, min and mean) have been estimated from BCEFs (Table 4.5; IPCC, 2006) using default wood density values: Hardwood (Temperate and Boreal): 0.493; Pines (Temperate and Boreal): 0.4; Larch (Boreal): 0.46; Firs and Spruce (Boreal): 0.4.

Usoltsev database (2001) related to the territory of the Russian Federation; nevertheless, the above stem-based BEFs are not to compare with the BEFs reported in IPCC (2003) or with those BEFs that can be calculated from reported BCEF and wood density values by IPCC (2006) because both IPCC reports refer to merchantability-based BEFs which, moreover, are not exactly defined.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2008.11.002.

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