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Comparison of carbon estimation methods for European forests

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ABSTRACT

National and international carbon reporting systems require information on carbon stocks of forests. For this purpose, terrestrial assessment systems such as forest inventory data in combination with carbon estimation methods are often used. In this study we analyze and compare terrestrial carbon estimation methods from 12 European countries. The country-specific methods are applied to five European tree species (*Fagus sylvatica* L., *Quercus robur* L., *Betula pendula* Roth, *Picea abies* (L.) Karst. and *Pinus sylvestris* L.), using a standardized theoretically-generated tree dataset. We avoid any bias due to data collection and/or sample design by using this approach. We are then able to demonstrate the conceptual differences in the resulting carbon estimates with regard to the applied country-specific method. In our study we analyze (i) allometric biomass functions, (ii) biomass expansion factors in combination with volume functions and (iii) a combination of both. The results of the analysis show discrepancies in the resulting estimates for total tree carbon and for single tree compartments across the countries analyzed of up to 140 t carbon/ha. After grouping the country-specific approaches by European Forest regions, the deviation within the results in each region is smaller but still remains. This indicates that part of the observed differences can be attributed to varying growing conditions and tree properties throughout Europe. However, the large remaining error is caused by differences in the conceptual approach, different tree allometry, the sample material used for developing the biomass estimation models and the definition of the tree compartments. These issues are currently not addressed and require consideration for reliable and consistent carbon estimates throughout Europe.

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1. Introduction

Forests play an integral role in the global carbon cycle. According to the Food and Agriculture Organization (FAO, 2013), forests cover about 31% of the land surface area. Forests store about 2.4 Pg of carbon per year (Pan et al., 2011) and sequester about 30% of the current global CO_2 emissions, thus reducing the atmospheric CO_2 concentration by almost a third (Canadell et al., 2007). In the past the production of timber and fuel wood was the primary objective of forest management (FOREST EUROPE, UNECE, FAO, 2011). Today non timber forest ecosystem services such as clean

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air and water, protection against natural hazards, and biodiversity are of increasing interest (EUROSTAT, 2012). Following the Kyoto Protocol the forest's ability to store carbon and produce renewable energy in the form of biomass became a focal point in natural resource management. Within Europe (EU-27), 18.3% of the energy is generated from renewable sources, with 67.7% of that consisting of biomass (including renewable waste; EUROSTAT, 2012).

The increasing demand on European forests and their services requires consistency in forest information and monitoring. The primary source of forest information is produced by National Forest Inventories (NFIs), which often vary in terms of their conceptual approaches, sampling designs and data collection systems (Tomppo et al., 2010). Aside from more traditional applications such as monitoring forest resources and the sustainability of forestry, NFI data are of increasing interest for assessing the role of forests in the carbon cycle (e.g., for Kyoto reporting or future climate-related treaties such as the REDD+ Programme; Mohren et al., 2012).

Forest inventories record tree data which are, in turn, used for estimating standing timber volume in m^3/ha. The same tree measures can be used to derive total biomass or carbon content of forest ecosystems in t/ha. Biomass is the dry weight of wood estimated for constant conditions (i.e., oven dried wood samples until a constant weight is reached; Bartelink, 1996; Repola, 2008, 2009 or Cienciala et al., 2006). Carbon accounts for approximately half of this oven dried biomass, which consists mainly of polysaccharides such as cellulose, lignin and hemicellulose (Lamlom and Savidge, 2003; McGroddy et al., 2004).

Two conceptually different approaches are used to assess carbon stocks of forests: (i) the biogeochemical-mechanistic approach, and (ii) the statistical empirical approach. The biogeochemical-mechanistic approach is based on physiological principles of carbon uptake through photosynthesis and carbon loss due to the respiration and decomposition processes. This approach uses energy, water, and nutrient cycles to determine the carbon fluxes of an ecosystem. This method is implemented in large scale carbon cycle models and requires soil data, daily climate information and ecophysiological parameters for the given vegetation or forest ecosystem.

Carbon related outputs include GPP (Gross Primary production), NPP (Net Primary production) as well as stem, root or leaf carbon. Any comparison with terrestrial data such as forest inventory data requires a transfer function (Eastaugh et al., 2013), i.e., converting the model output carbon into tree volume (usually biomass expansion factors). These principles have been implemented in large scale carbon cycle models to circumvent the problem of missing terrestrial data and to provide methodologically consistent carbon cycle information for large regions, continents or even for the whole globe (VEMAP Members, 1995). Examples of models that use such an approach are BIOME BGC (Thornton, 1998; Thornton et al., 2002; Pietsch et al., 2005), CLM (Lawrence et al., 2011) and C-FIX (Veroustraete et al., 2002). A related product, known as the MOD17 product, implements key components of BIOME BGC with additional use of satellite data and provides GPP and NPP estimates on a $0.0083^\circ \times 0.0083^\circ$ resolution (approx. 1×1 km) for the whole globe (Running et al., 2004; Zhao and Running, 2010).

The statistical empirical approach is probably more commonly used in forestry, since it was developed earlier than the biogeochemical approach and requires terrestrial data such as forest inventory data (Tomppo et al., 2010). With this approach, biomass and carbon are estimated by applying (i) allometric biomass functions and/or (ii) biomass expansion factors.

Allometric biomass functions use tree variables such as diameter at breast height and/or tree height for estimating tree biomass. The share of carbon is then estimated using tree carbon fraction factors. In contrast, when using biomass expansion factors, conversion factors are used to transform tree volume into biomass. Volume functions must be used before the application of the expansion factors.

These statistical principles in deriving terrestrial biomass and carbon are also implemented in tree population models such as succession or gap models and typical tree growth models. Predicted volume or tree dimensions such as diameter or height serve as input parameters to apply either biomass functions or biomass expansion factors for calculating the terrestrial biomass in t/ha. Typical examples are succession models like PICUS (Lexer and Hoenninger, 2001; Seidl et al., 2005), LANDCARB (Mitchell et al., 2012), the matrix model EFISCEN (Nabuurs et al., 2000) or tree growth models such as MOSES (Hasenauer, 1994), PROGNAUS (Sterba and Monserud, 1997), SILVA (Pretzsch et al., 2002) or BWINPro (Nagel, 1999).

Allometric biomass and volume functions as well as biomass expansion factors are derived empirically from tree sampling. Destructive sampling, extensive field and lab work are needed to obtain biomass data for the different tree compartments – stem, branches, roots and foliage. Based on these sample data, generalized statistical functions for the different tree compartments or expansion factors are developed and applied to inventory data. Every region or country has different resulting functions and factors (e.g. for Austria Pollanschütz, 1974; for Romania Giurgiu et al., 1972; for Sweden Marklund, 1988; for Finland Repola, 2008, 2009 or for France Vallet et al., 2006). Examples for biomass functions developed for larger regions are Wirth et al. (2004), Muukkonen (2007) or Wutzler et al. (2008). The resulting biomass and carbon estimates strongly depend on the samples, but also on the chosen conceptual approach (i.e., whether biomass functions or biomass expansion factors are used).

Previous studies have shown that throughout many parts of the world, the calculation methods have a large impact on the results for biomass and carbon, both for trees and for tree compartments (Araújo et al., 1999 for Brazil; Westfall, 2012 and MacLean et al., 2014 for Northeastern United States; Guo et al., 2010 for China; Jalkanen et al., 2005 for Sweden, or Thurnher et al., 2013 for Austria). This supports the necessity for a similar study for Europe; however such a study was not done until now.

In Europe, National Forest Inventory data is commonly used for country reporting for international statistics and programs such as the Forest Resource Assessment Program for the Food and Agriculture Organization (FAO), or the Land Use, Land-Use Change and Forestry (LULUCF) report for the United Nations Framework Convention on Climate Change (UNFCCC; Tomppo et al., 2010). However, consistent calculation methods are required to be able to integrate and assess data from various countries for the purpose of assessing climate change mitigation or carbon sequestration potential in European forests (McRoberts et al., 2009; Ståhl et al., 2012).

The purpose of this study is to analyze the different carbon estimation methods covering 12 different countries across Europe and assess the impact of the methodological differences in deriving biomass estimates. Five important tree species in Europe are selected for comparison (*Fagus sylvatica, Quercus robur, Betula pendula, Picea abies* and *Pinus sylvestris*). We are specifically interested in

(i) compiling and assessing country-specific calculation methods for deriving biomass and carbon from NFI data; and
(ii) quantifying the effect of the various calculation methods on resulting biomass and carbon estimates using a standardized theoretical data set.

2. Methods

Europe's forests consist of a variety of ecological and climatic conditions covering different tree species. For our study we select

5 species considered to be important European tree species because they have a large distributional range and a high ecological and economic value. The selected deciduous tree species are (i) *F. sylvatica* L. (European beech), (ii) *Q. robur* L. (Pedunculate oak) and (iii) *B. pendula* Roth (Silver birch) and the two coniferous species, (iv) *P. abies* (L.) Karst. (Norway spruce) and (v) *P. sylvestris* L. (Scots pine).

Q. robur also includes *Quercus petraea* L. and *B. pendula* includes *Betula pubescens* Ehrh., since these species are similar in terms of genetics, shape and properties and thus are usually not distinguished from one another by NFI systems or biomass studies (e.g., Muukkonen, 2007; Repola, 2009; Giurgiu et al., 1972; Ledermann and Neumann, 2006).

Within Europe, each country has its own statistical empirical approach for deriving carbon estimates from National Forest Inventory data (Tomppo et al., 2010). We obtain each of these procedures for our comparative analysis. Below, we describe the methods employed for the 12 countries. For a detailed presentation, by country, we refer to Appendices A–M.

2.1. General carbon calculation approach

Biomass is commonly estimated by separate tree compartments (e.g. Wirth et al., 2004; Seidl et al., 2005; Pietsch et al., 2005; Thurnher et al., 2013). We consider four tree compartments for estimating biomass: (i) stem, (ii) branches, (iii) foliage, and (iv) root (including stump). The general equation for calculating total tree carbon can be expressed as:

$$C_{tree} = CC * (dsm + dbm + dfm + drm) \quad (1)$$

where C_{tree} is the total carbon content of a tree [kg], CC is the carbon fraction [kg/kg] given for each country in Appendix A, dsm is the dry stem biomass [kg], dbm is the dry branch biomass [kg], dfm is the dry foliage biomass [kg] and drm is the dry root biomass [kg]. For each country the species specific carbon calculation methods are compiled (see Appendices A–M).

2.2. Carbon calculations by country

European forests cover a wide range of environmental conditions, as well as large elevation and latitudinal gradients. According to FOREST EUROPE, UNECE, FAO (2011) suggestions to limit the range of these environmental, elevation and latitudinal gradients, we cluster the 12 countries which provide biomass estimation methods for our study into four geographic regions: North Europe, Central-West Europe, Central-East Europe, and South Europe. The underlying assumption is that countries within each region should have similar climatic and biophysical conditions for tree growth and we expect that this will reduce the variation in tree allometry. Table 1 summarizes the 12 country-specific carbon estimation methods and the required tree variables.

All carbon calculation methods use diameter at breast height (DBH) and tree height (H) as input variables. In five countries (Finland, Austria, Germany, the Netherlands, and Romania) additional variables are used: crown ratio (CR), aboveground volume (V), and tree age (A). Six methods use allometric biomass functions, three use biomass expansion factors and four use a combination of both (see Table 1). The carbon calculation method, by country, including the coefficients and the definitions of the tree compartments are given in Appendices A–M. Below, we give a brief summary by region.

Table 1
Summary on calculation Methods (AF = allometric biomass functions, BEF = biomass expansion factors and volume functions, combi = combination of AF and BEF) and used Variables in the calculations (DBH = diameter at breast height, H = tree height, CR = crown ratio, A = tree age, V = aboveground tree volume), variables in brackets indicate that this variable is only used in some functions.

Region	Country	Method	Variables
North Europe	Finland	AF	DBH, H, (CR)
	Norway	AF	DBH, (H)
Central-West Europe	Austria	combi	DBH, (H, CR, A)
	Belgium	combi	DBH, (H)
	France	BEF	DBH, (H)
	Germany	combi	DBH, H, (V, A)
	Netherlands	BEF	DBH, A, (H)
Central-East Europe	Czech Republic	combi	DBH, (H)
	Poland	AF	DBH, (H)
	Romania	BEF	DBH, H, A
South Europe	Italy	AF	DBH, H
	Spain	AF	DBH, (H)

2.2.1. Northern Europe

Two countries, Finland and Norway, belong to Northern Europe. In Finland (also representing Estonia) the allometric biomass functions use DBH, tree height, and crown ratio. The models developed for Finland obtain carbon from biomass with a constant carbon fraction of 0.5 (see Appendix B). The carbon estimation approach of Finland is also applied in Estonia since forest biomass functions for Estonia are currently under development (Uri et al., 2010).

The Norwegian methodology uses allometric biomass functions. The method for Norway was developed in Sweden (Marklund, 1988; Petersson and Ståhl, 2006). The models use DBH and tree height as variables (see Appendix C).

F. sylvatica is not native in Finland or Norway, thus it is excluded from the analysis for Northern Europe.

2.2.2. Central-Western Europe

Five countries, Austria, Belgium, France, Germany and the Netherlands, belong to Central-Western Europe. The biomass calculation in Austria uses a combination of species-specific form factor functions, biomass expansion factors, and allometric biomass functions. The allometric biomass functions for branch biomass use crown ratio as an additional input variable (Ledermann and Neumann, 2006), while the functions for root biomass use tree age (Wirth et al., 2004). The volume and branch biomass functions use data from Austria, while the foliage and root biomass function obtain their data from other Central European countries (see Appendix D).

The Belgian biomass calculation method is a combination of volume estimation, expansion factors, and allometric biomass functions. The volume prediction (Dagnelie et al., 1985) and the biomass functions of *P. abies* depend on DBH and tree height. All other biomass functions use only DBH as input variable. The volume calculation method and most of the biomass functions mainly use data from Belgium. Some biomass functions are obtained from other countries such as Austria, the Czech Republic, Germany, France, and the Netherlands (see Appendix E).

In France, the biomass calculation method combines volume functions with biomass expansion factors derived from samples in France (INRA, 2004). Foliage biomass is assumed to be a constant proportion of total biomass (see Appendix F). For all species in France a carbon fraction of 0.475 is used (see Appendix A), which differs from most other countries.

In Germany, a combination of volume functions, biomass expansion factors and allometric biomass functions is applied. The volume calculation is implemented in the program BDAT 2.0 (Kublin, 2002). The expansion factors for tree volume vary by tree age and the expansion factors for root biomass vary by aboveground biomass (see Appendix A). The models (except foliage

biomass) are developed with sample material from Germany (see Appendix G).

The method for the Netherlands uses allometric biomass functions to calculate aboveground tree biomass. Aboveground biomass is then separated into tree compartments with proportional biomass fractions. The biomass fractions are derived from tree age and are calculated based on the allometric biomass functions of the EFISCEN project (Schelhaas et al., 1999; Vilén et al., 2005). The biomass calculations for aboveground biomass and the fraction coefficients come from sample material across Europe and the European part of Russia (see Appendix H).

2.2.3. Central-Eastern Europe

Three countries, Czech Republic, Poland, and Romania, belong to Central-Eastern Europe. The Czech Republic biomass calculation method is similar to Austria and Belgium, using a combination of volume functions, expansion factors, and allometric biomass functions. The functions were developed based on sample material from the Czech Republic or former Czechoslovakia (see Appendix I).

In Poland, allometric biomass functions are used for aboveground biomass and expansion factors for belowground biomass. The functions are developed with sample data from Poland, Finland and Central Europe (see Appendix J).

The calculation in Romania uses a combination of volume functions, biomass expansion factors and biomass fractions similar to the Netherlands. The volume functions based on data from Romania (Giurgiu et al., 1972) provide tree volume. After applying biomass expansion factors, the biomass of tree compartments is estimated using biomass fractions from the EFISCEN project (Schelhaas et al., 1999; Vilén et al., 2005) (see Appendix K).

2.2.4. Southern Europe

Two countries, Italy and Spain, belong to Southern Europe. Italy uses allometric biomass functions developed with sample material from Italy for aboveground biomass and expansion factors for root biomass (see Appendix L).

In Spain allometric biomass functions developed with Spanish sample data are used. Similar to France, the carbon fractions in Spain differ from the other countries. Species-specific carbon fractions given by Montero et al. (2005) are used (see Appendix A, and for further details Appendix M).

3. Data

Forests across Europe vary by site conditions, age, and genetics and usually have experienced different forest management. Furthermore, available forest inventory data sets differ according to (i) the sampling design (i.e., fixed area plots vs. angle count sampling), (ii) the measurement methods (i.e., minimum diameter threshold for recording trees) or (iii) the data collection and processing method (i.e., measurement of tree height for every tree vs. applying diameter–height relationships, etc.). These differences in forest data from country to country make a theoretical comparison of the different regional biomass calculation methods difficult (Tomppo et al., 2010).

In order to circumvent this problem we produce a standardized input dataset, which provides all necessary input data for the country-specific models (see Appendices A–M). This ensures that any differences in the results are a consequence of the carbon calculation methods.

3.1. Stand data generation

For creating a standardized data set we use STANDGEN (Kittenberger, 2003), a tool implemented in the framework of the single tree simulation model MOSES (Hasenauer, 1994; Klopf et al., 2011). The STANDGEN tool generates stand data including diameter and location of single trees based on information on diameter distribution (mean and standard deviation), spatial distribution, and aggregation of trees. For each of the five selected tree species, three stands are generated, each with a size of 0.25 hectare (2500 m^2). The three stands differ in mean and standard deviation of tree diameter and represent forest stands at different ages. This takes into account that stand age affects eco-physiological processes such as biomass allocation, stem number, or stocking density. For each species, we generate a young stand (quadratic mean DBH 10 cm with standard deviation 1 cm), a middle-aged stand (30 cm ± 5 cm), and an old stand (50 cm ± 10 cm). Note that we use the quadratic mean DBH to refer to the "average or central tree" representing the tree with the mean basal area. For convenience we consider that a tree with quadratic mean DBH represents a tree with "mean tree biomass". We follow here Eastaugh (2014) showing that the error in this assumption is small. Tree height and age are estimated using species-dependent relationships, crown length is estimated using the DBH-, and height-dependent functions implemented in the MOSES framework (Sterba, 1976; Marschall, 1992; Klopf et al., 2011).

3.2. Stand variables

The generated stands are characterized by the stand variables: mean tree height, height–diameter ratio, crown ratio, stand age, stem number per hectare (N), and basal area per hectare (BA). The two latter variables are calculated as follows.

$$BA = 1/S * \Sigma(DBH^2 * \pi/400) \quad (2)$$

$$N = 1/S * ni \quad (3)$$

where *BA* is the basal area per hectare [m^2/ha], *S* is equal to 0.25 ha (the size of the generated stand), *DBH* is the diameter at breast height (at 1.3 m) [cm], *N* is the stem number per hectare [trees/ha], and *ni* is the number of trees per stand. Summary statistics of the generated stand properties available for our study are given in Table 2. Tree height, stand age and basal area increase with increasing DBH, while the height–diameter ratio, crown ratio and stem number decrease, meaning that these stand properties change with age (Table 2).

4. Analysis and results

4.1. Tree carbon estimation

We start our analysis by applying the 12 country specific carbon calculation methods as outlined in Appendices B–M to our standardized tree data set. The data set covers five tree species: (i) *F. sylvatica* L., (ii) *Q. robur* L., (iii) *B. pendula* Roth, (iv) *P. abies* (L.) Karst. and (v) *P. sylvestris* L. (Table 2). We calculate biomass for the tree compartments stem, branch, foliage and roots. The biomass results by compartment are added and multiplied with the carbon fraction (Appendix A) to derive total tree carbon. Since the input data set is identical by species, we ensure that any differences in the results represent (i) differences in the calculation approach, (ii) the statistical coefficients and/or (iii) any additional regional biophysical differences by species. Fig. 1 provides the total carbon in kg per tree versus diameter at breast height (DBH) by

Table 2
Properties of the generated standardized tree dataset separated by stands and species, first column properties of stand with quadratic mean diameter (DBH) of 10 cm, second for DBH of 30 cm, third for DBH 50 cm, Stand age [year] derived from yield tables (see Method section), Stem number is number of trees per hectare [ha^{-1}], Basal area is the area of trees at breast height (1.3 m) per hectare [m^2/ha], Mean height is Lorey's mean height (Lorey, 1878) of all trees in stand [m], Mean H/DBH is the mean height-to-diameter ratio [m/m], Mean CR is mean crown ratio (crown height divided by tree height) [m/m].

	Stand age [year]			Stem number [ha^{-1}]			Basal area [m^2/ha]		
	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm
Picea abies	25	70	150	3404	740	304	27	52	65
Pinus sylvestris	35	115	>130	2776	576	240	22	41	50
Fagus sylvatica	40	85	>140	3064	496	188	24	35	37
Quercus robur	35	90	>130	2248	440	212	18	31	39
Betula pendula	17	75	>120	2148	412	160	17	29	31
	Mean height [m]			Mean H/DBH [m/m]			Mean CR [m/m]		
Picea abies	8.5	22.6	30.9	83	75	59	0.73	0.58	0.46
Pinus sylvestris	6.6	18.8	26.6	65	62	52	0.79	0.61	0.48
Fagus sylvatica	8.7	20.8	26.7	87	69	54	0.71	0.59	0.48
Quercus robur	8.4	25.2	31.5	82	84	66	0.73	0.55	0.47
Betula pendula	8.4	25.3	31.9	81	84	65	0.73	0.55	0.46

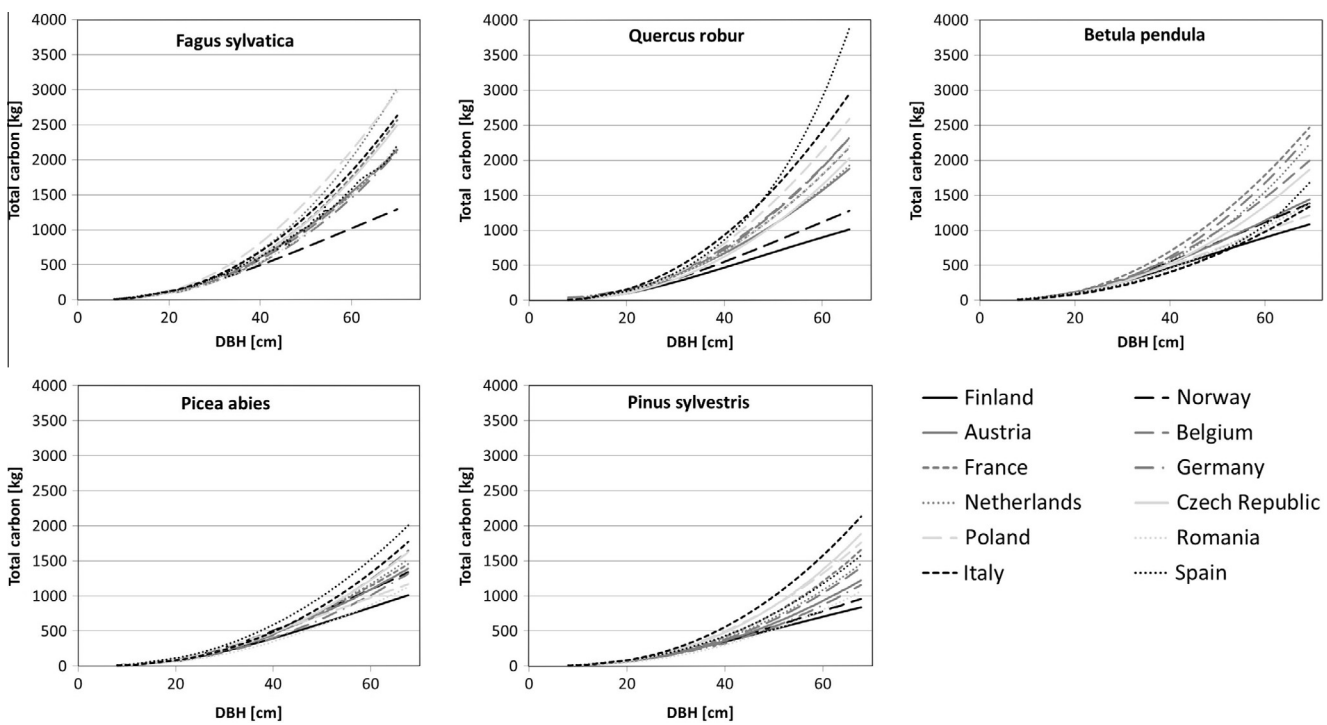

Fig. 1. Tree carbon on tree level [kg/tree] for all countries in this study and for all analyzed tree species, results are grouped by ecoregions (black – North Europe and South Europe, dark gray – Central-West Europe, light gray – Central-East Europe).

species and country. In Fig. 1, and in the following Figs. 2–7, we present curves that originate from the smoothed single tree results.

Strong discrepancies with increasing DBH are evident (Fig. 1) by country. Thus we subsequently group the country-specific results by European forest regions following the definition of the State of Europe's Forests 2011 (FOREST EUROPE, UNECE, FAO, 2011) to address regional biophysical growing conditions resulting from the geographic location, soil and climate conditions, and genetic differences by species across Europe. Country specific biomass estimation methods (Appendices B–M) were developed and calibrated with regional data. Thus the resulting carbon and biomass estimates are expected to capture the different regional biophysical growing conditions. We assign each tree species and country-specific estimation method to each of the four European forest regions. The results for tree carbon in kg per tree versus DBH are ordered by country and grouped by European forest region as shown in Figs. 2–5.

4.2. Tree biomass estimation by compartment

Total tree carbon (Figs. 1–5) is calculated as the sum of the estimated biomass of each compartment (stem, branches, foliage and roots) multiplied by the carbon fraction factor (Eq. (1) and Appendices A–M). Next we evaluate the proportions of the compartment results and their respective discrepancies by species and country across Europe. Since *P. abies* and *F. sylvatica* are the most important coniferous and broadleaf species and cover the vast majority of forest area in Central-East and Central-West Europe, we focus and display here only these two species within these two regions. Fig. 6 presents the trend in the four compartments versus DBH for *P. abies* in Central-West Europe, and Fig. 7 for *F. sylvatica* for Central-East Europe, respectively. We use the identical scaling to show (i) the effect of the different functions by compartment applied and (ii) their contribution to the total tree carbon.

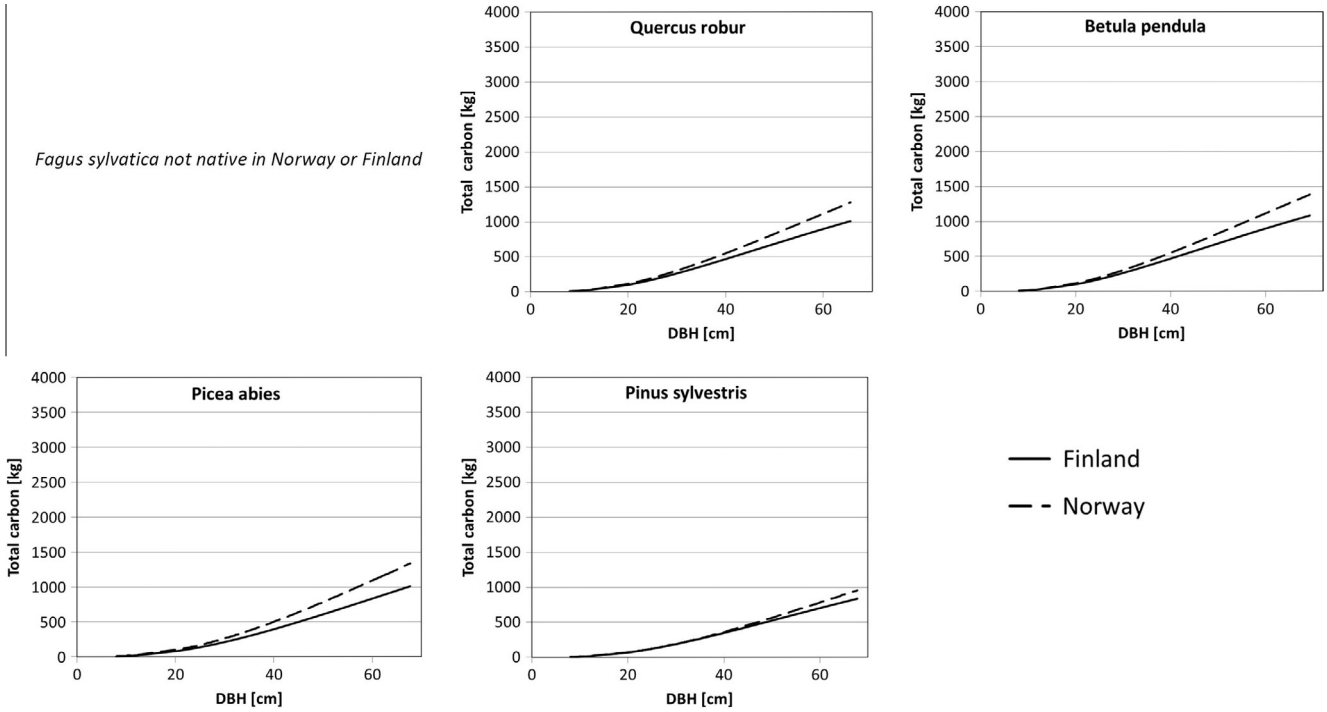

Fig. 2. Tree carbon on tree level [kg/tree] for North Europe and for all analyzed tree species.

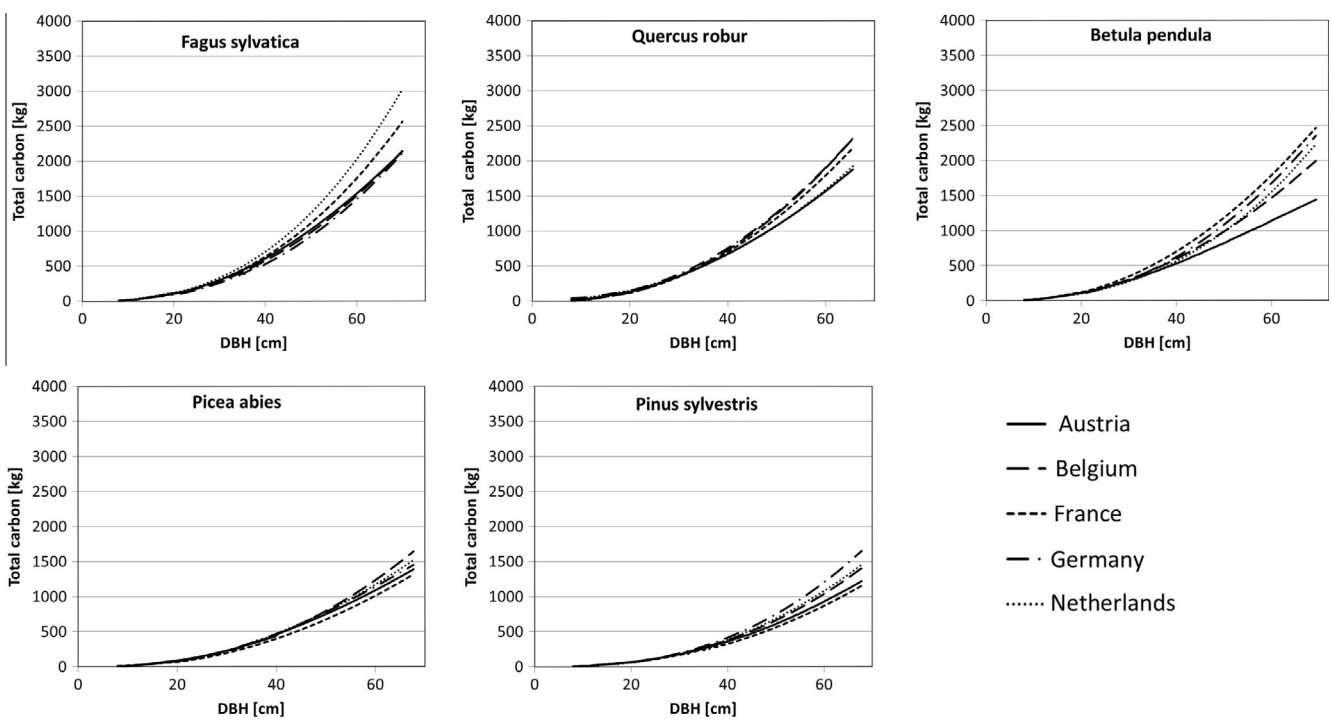

Fig. 3. Tree carbon on tree level [kg/tree] for Central-West Europe and for all analyzed tree species.

4.3. Carbon and biomass of forest stands

The deviations found in the country-specific tree carbon estimates by DBH (see Figs. 1–7) may differ from carbon estimates at the forest stand-level since the number of trees by DBH class varies. In addition, most carbon studies focus on stand level estimates (e.g. t/ha). Therefore, we assess the methodological implications at the forest stand level by country and the species-specific carbon calculation method by deriving forest stand carbon estimates for our generated forest stands. Again, we choose to focus on *P. abies* and *F. sylvatica* and the corresponding three reference stands with a quadratic mean DBH of 10 cm (standard deviation (SD) of DBH distribution 1 cm), 30 cm (SD 5 cm) and 50 cm (SD 10 cm) generated with the tool STANDGEN (see Table 2).

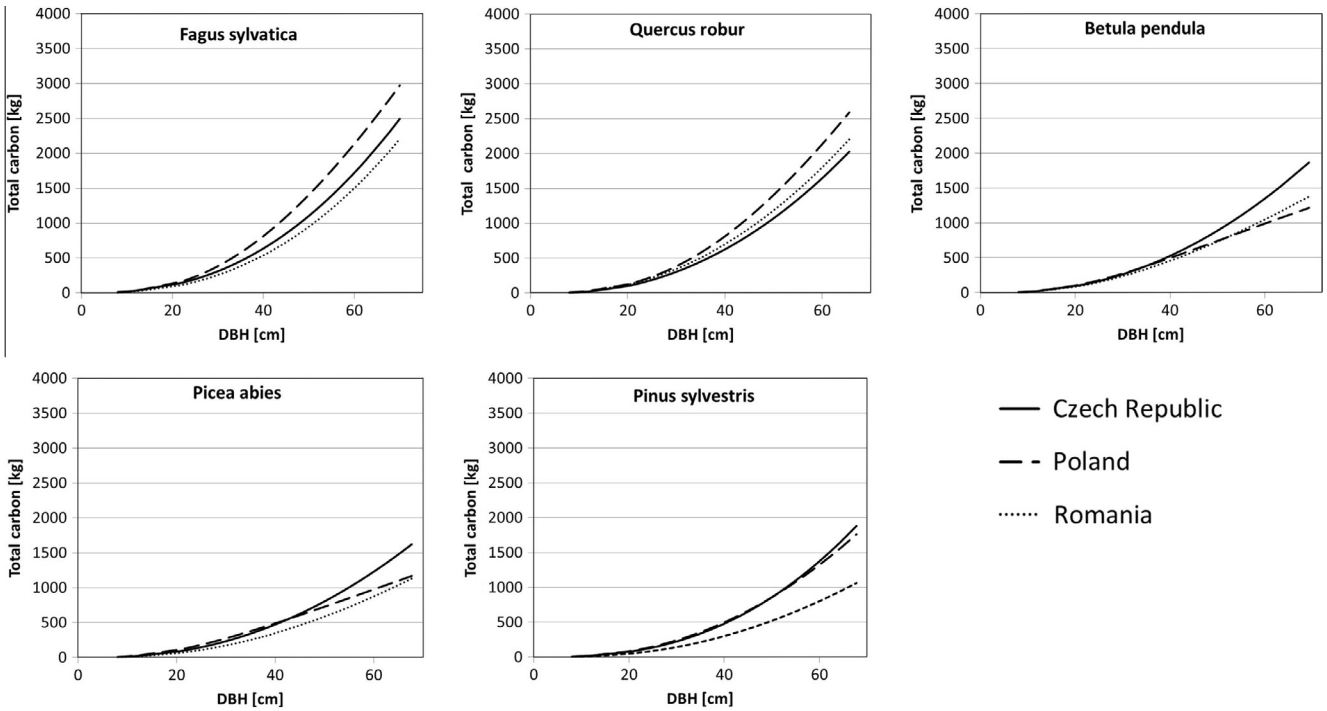

Fig. 4. Tree carbon on tree level [kg/tree] for Central-East Europe and for all analyzed tree species.

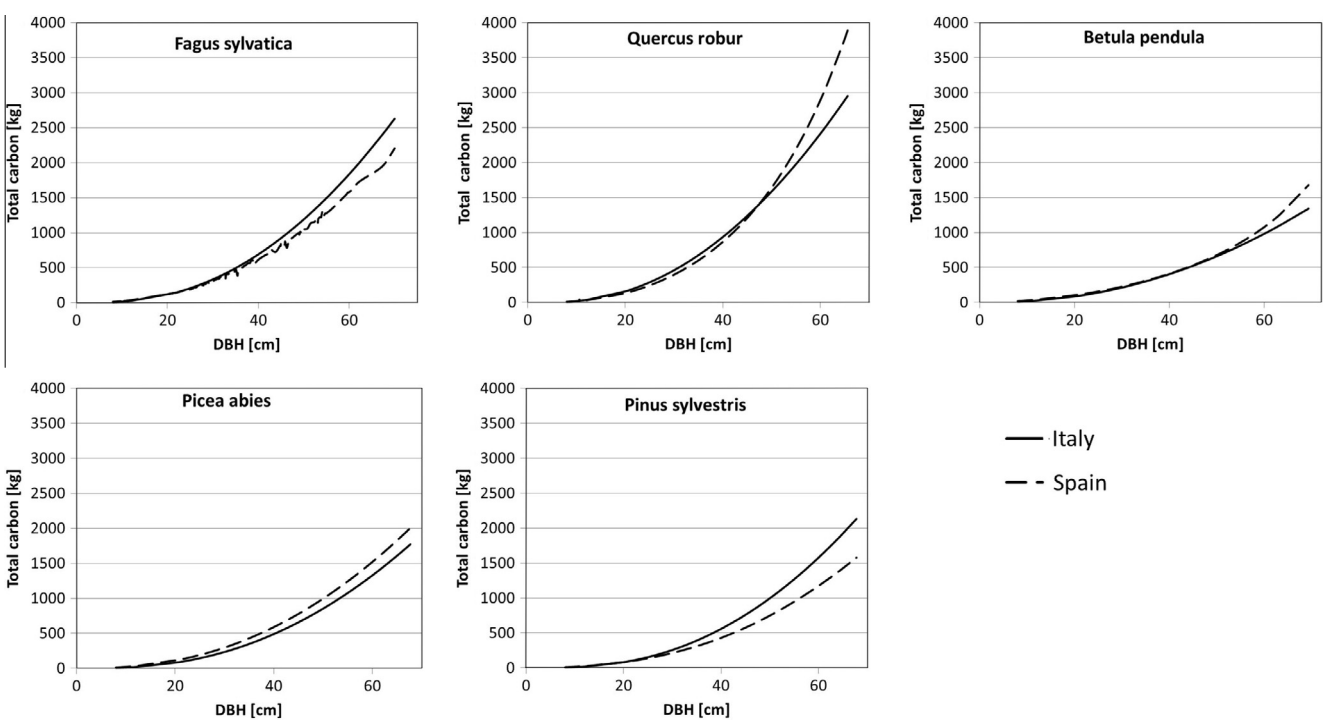

Fig. 5. Tree carbon on tree level [kg/tree] for South Europe and for all analyzed tree species.

For each tree, the biomass and carbon estimation methods are applied. The results for *P. abies* and *F. sylvatica* covering the stem, branch, foliage, root, and total tree biomass plus the tree carbon estimates for each reference stand are given in Tables 3 and 4. Again, we use the quadratic mean DBH representing the tree with mean basal area and mean tree biomass (Eastaugh, 2014). Tables 3 and 4 also provide summary statistics for *P. abies* and *F. sylvatica*. Similar tables for the other species, we provide in Supplementary material (Tables S.1–S.3).

5. Discussion

Carbon estimates by tree species differ substantially by country (see Fig. 1). After grouping the countries by main forest region in Europe (FOREST EUROPE, UNECE, FAO, 2011) to address regional differences, the deviations by species and country within the forest region are found to be smaller, but still evident (Figs. 2–5). The smallest deviations are detected for the North Europe and South

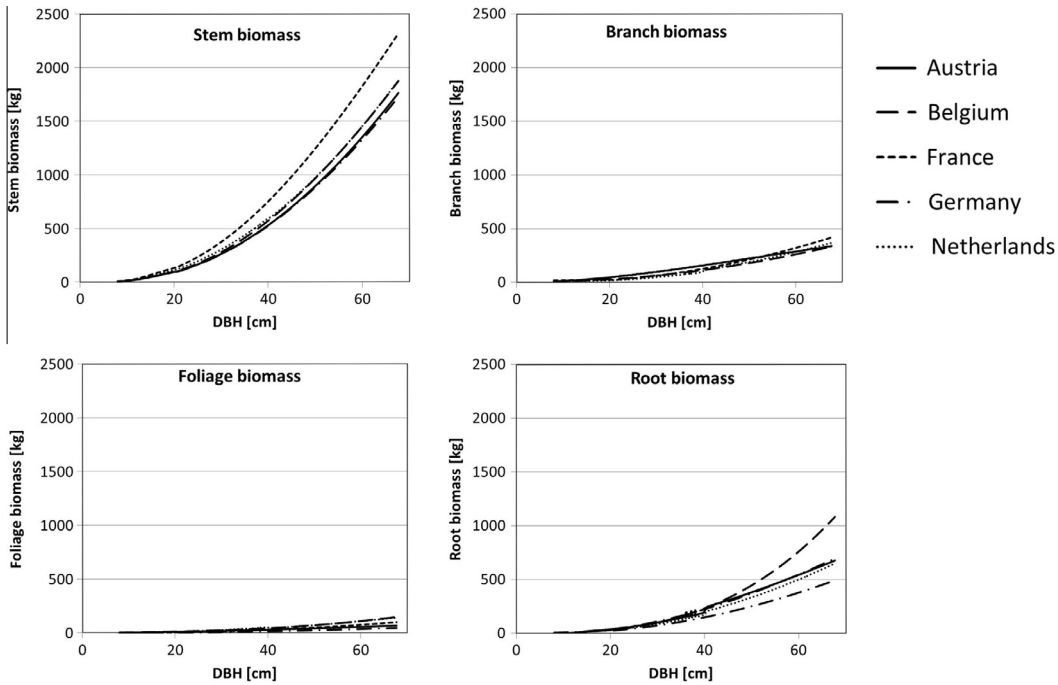

Fig. 6. Biomass in tree compartments on tree level [kg/tree] for *Picea abies* and Central-West Europe.

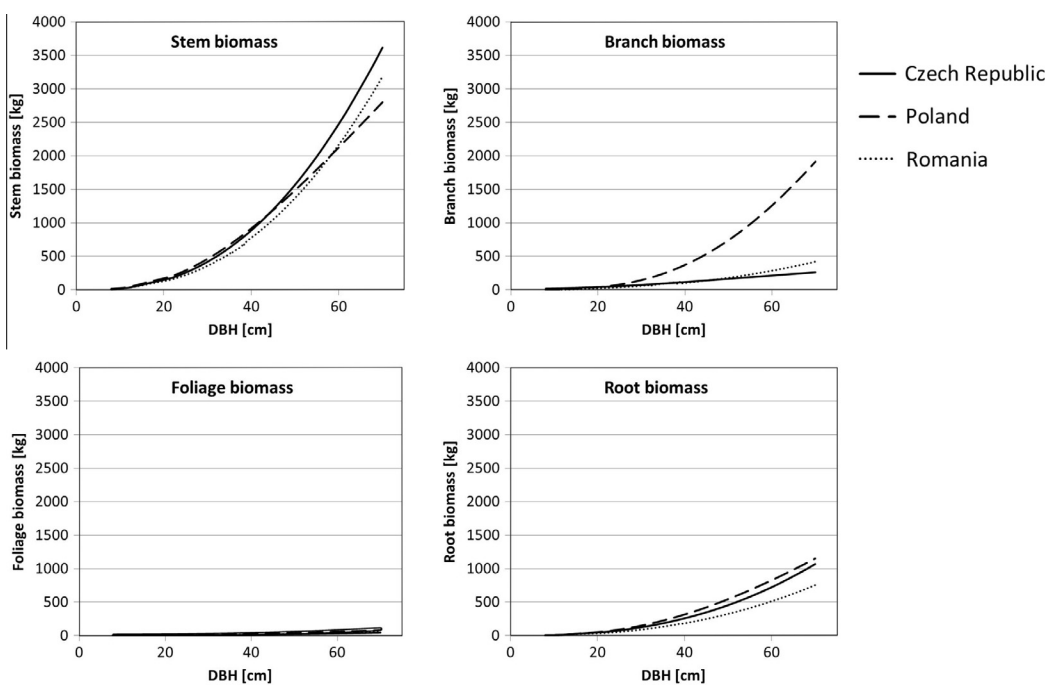

Fig. 7. Biomass in tree compartments on tree level [kg/tree] for *Fagus sylvatica* and Central-East Europe.

Europe regions (Figs. 2 and 5), as compared to Central-West Europe (Fig. 3) and Central-East Europe (Fig. 4). This supports the hypothesis that part of the observed differences can be attributed to environmental growing conditions. The remaining error is caused by the conceptual approach. Stem biomass contributes the largest proportion of total biomass followed by root, branch, and foliage biomass (Figs. 6 and 7). Some unrealistic results are detected, for example in the case of branch biomass for *F. sylvatica* in Poland (Fig. 7).

The results at the stand level (Tables 3 and 4 and Tables S.1–S.3 in Supplementary material) confirm that the differences in tree carbon and biomass in tree compartments at the tree level (Figs. 1–7) can be observed also on the stand level. Tables 3 and 4 further allows quantifying the discrepancies in carbon and biomass observed merely visually in Figs. 1–7. For both *P. abies* and *F. sylvatica,* stem biomass add the largest part to the existing discrepancies in total biomass and carbon followed by branch and root biomass. The average range of stem biomass estimates for all countries and

Table 3
Results for biomass in tree compartments, tree biomass (sum of all compartments) and tree carbon on stand level [t/ha] for *Picea abies*, results arranged according to the 4 Forest regions, first column give the results for the stand with quadratic mean diameter (DBH) of 10 cm, second column for DBH of 30 cm and third column for DBH of 50 cm. At the end of table selected statistics are given for each stand and each biomass and carbon estimate: Mean and Range (Maximum–Minimum) of the country estimates and variation expressed as Range divided by Mean.

Picea abies	Stem biomass [t/ha]			Branch biomass [t/ha]			Foliage biomass [t/ha]			Root biomass [t/ha]			Tree biomass [t/ha]			Tree carbon [t/ha]		
	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm
North Europe																		
Finland	49.6	186.3	232.0	17.1	41.7	42.5	12.6	18.0	12.0	29.8	85.7	118.9	109.0	331.6	405.4	48.2	155.9	197.7
Norway	48.2	217.7	316.6	40.1	80.4	80.1	16.3	27.1	25.0	27.4	91.9	113.0	132.1	417.1	534.6	57.9	193.8	256.1
Central-West Europe																		
Austria	45.8	194.3	300.9	45.4	71.4	70.9	11.9	14.1	13.8	13.9	75.3	125.4	117.0	355.0	510.9	52.6	169.7	249.3
Belgium	43.4	206.9	323.5	29.7	47.5	59.8	18.7	18.6	24.6	14.2	76.1	159.1	105.9	349.1	567.1	43.6	164.0	272.6
France	60.2	276.7	412.2	–	–	–	1.2	5.5	8.2	18.1	83.0	123.7	79.5	365.3	544.1	37.8	172.2	259.7
Germany	37.1	192.1	296.2	68.7	46.5	71.7	4.2	11.5	17.0	33.9	54.9	84.6	143.9	304.9	469.5	69.8	145.6	227.4
Netherlands	41.8	224.6	325.7	22.6	36.1	63.7	12.1	20.2	24.6	11.6	64.8	112.3	88.1	345.7	526.3	44.0	171.9	264.1
Central-East Europe																		
Czech Republic	41.1	215.2	346.9	17.5	21.6	26.4	3.5	5.1	6.6	26.7	83.7	133.8	88.8	325.6	513.7	44.4	161.6	258.1
Poland	73.9	278.5	311.2	14.9	32.2	53.0	10.3	15.5	15.5	22.8	75.0	87.3	121.9	401.2	466.9	60.9	199.5	234.6
Romania	29.9	167.0	246.3	16.2	26.8	45.2	8.7	15.0	18.8	8.3	48.2	81.9	63.1	257.0	392.2	31.6	127.6	197.0
South Europe																		
Italy	45.0	210.4	348.5	24.9	60.7	102.6	–	–	–	20.3	78.6	130.8	90.2	349.7	581.9	45.1	173.4	292.4
Spain	55.1	282.8	483.7	60.3	78.9	87.9	4.2	12.3	19.0	34.7	66.9	83.6	154.3	440.9	674.2	77.1	218.8	338.7
Mean [t/ha]	47.6	221.0	328.6	32.5	49.4	64.0	9.4	14.8	16.8	21.8	73.7	112.9	107.8	353.6	515.6	51.1	171.2	254.0
Range [t/ha]	44.0	115.9	251.7	53.8	58.9	76.2	17.5	22.0	18.4	26.4	43.7	77.3	91.2	183.9	282.0	45.6	91.2	141.8
Range/Mean [%]	92	52	77	166	119	119	185	149	109	121	59	68	85	52	55	89	53	56

Table 4
Results for biomass in tree compartments, tree biomass (sum of all compartments) and tree carbon on stand level [t/ha] for *Fagus sylvatica*, for details on the table and the content please see explanations provided for Table 3.

Fagus sylvatica	Stem biomass [t/ha]			Branch biomass [t/ha]			Foliage biomass [t/ha]			Root biomass [t/ha]			Tree biomass [t/ha]			Tree carbon [t/ha]		
	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm
North Europe																		
Finland	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Norway	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Central-West Europe																		
Austria	55.9	185.4	241.1	36.0	87.9	110.5	3.3	3.5	3.1	12.7	26.3	32.9	107.8	303.1	387.6	53.9	149.9	195.4
Belgium	48.0	189.8	248.0	19.1	46.9	63.4	3.6	6.5	8.8	21.2	47.7	61.8	91.9	290.8	382.0	45.0	141.0	188.7
France	80.8	247.6	345.6	–	–	–	1.6	5.0	6.9	22.6	69.3	96.8	105.1	321.9	449.2	49.9	151.1	215.2
Germany	43.5	168.9	241.8	29.7	38.7	37.2	3.6	6.5	8.8	31.5	49.8	67.0	108.3	263.9	354.7	54.1	130.2	179.1
Netherlands	79.2	233.1	349.7	13.2	39.7	46.1	5.8	5.4	6.3	34.4	58.6	82.8	132.7	336.8	485.0	66.1	166.4	244.6
Central-East Europe																		
Czech Republic	56.1	209.7	299.5	62.0	36.5	30.6	3.0	3.6	4.0	23.4	62.2	87.2	144.6	312.1	421.2	72.3	154.3	212.3
Poland	80.2	229.7	277.2	14.6	74.7	143.1	3.4	6.4	7.7	23.6	74.6	102.7	121.8	385.3	530.7	60.9	190.4	267.7
Romania	54.1	178.9	262.0	9.0	30.5	34.6	4.0	4.1	4.7	23.5	45.0	62.0	90.6	258.5	363.3	45.3	127.7	183.2
South Europe																		
Italy	63.9	230.2	312.6	21.4	48.8	65.0	–	–	–	17.1	55.8	75.5	102.3	334.8	453.1	51.2	165.5	228.5
Spain	69.3	198.9	260.8	46.5	65.1	76.8	5.0	4.9	4.3	32.4	47.2	50.0	153.2	316.2	391.9	76.6	155.6	198.4
Mean [t/ha]	63.1	207.2	283.8	27.9	52.1	67.5	3.7	5.1	6.1	24.2	53.7	71.9	115.8	312.3	421.9	57.5	153.2	211.3
Range [t/ha]	37.3	78.7	108.6	53.0	57.4	112.5	4.2	3.0	5.6	21.8	48.2	69.8	62.5	126.8	176.1	31.6	62.7	88.6
Range/Mean [%]	59	38	38	190	110	167	114	59	92	90	90	97	54	41	42	55	41	42

stands is 137.2 t/ha for *P. abies* (branch 63.0, root 49.1, and foliage 19.3 t/ha) and 74.8 t/ha for *F. sylvatica* (branch 74.3, root 46.6, and foliage 4.3 t/ha). Although the differences of the root, branch and foliage biomass are smaller in absolute terms, the relative differences are even higher as compared to the stem biomass estimates (Average Range/Mean for stem biomass and all stands for *P. abies* 74% (branch 135%, root 83%, and foliage 148%) and for *F. sylvatica* 45% (branch 156%, root 92%, and foliage 88%) (Tables 3 and 4). Therefor the choice of stem biomass function contributes most to total carbon in absolute terms, but the other compartments have an impact as well, especially in proportion to their results.

Tables 3 and 4 further indicate that these discrepancies differ between the different stands. In the younger forest stands (DBH 10 cm) the ratio of Range and Mean of the tree carbon estimates for *P. abies* is 85% and for *F. sylvatica* of 54% and thus highest as opposed to the two older stands. The same patterns are also visible in the biomass compartments (Tables 3 and 4 and Tables S.1–S.3). This is not detectable from the single tree results (Figs. 1–7) since the scaling hides the results at small DBH. The results for the young trees are very small in absolute values compared to the results of bigger trees (Figs. 1–7). Still the total carbon results of the young stands with DBH 10 cm amount for about a fourth of the results of the old stands with DBH 50 cm (21% for *P. abies* and 28% for *F. sylvatica*; Tables 3 and 4). The large amount of carbon in young stands is caused by the large number of trees per unit area (Table 2), which have an amplifying effect on the single tree results and the differences on forest stand level. Comparing only the carbon of single trees would be misleading because the stem number decreases with age due to competition. Such effects need to be considered if the task is to optimize carbon storage for the purposes of climate change mitigation, such as REDD+ (Canadell et al., 2007; Mohren et al., 2012).

Stand-level results for branch and foliage biomass do not show the same increase based upon DBH as do stem and root biomass. The results show that foliage and branch biomass are constant with a modest increase with stand age. This is consistent with the Pipe Model Theory (Shinozaki et al., 1964a,b) and other research indicating that after canopy closure Leaf Area Index (LAI) is a constant (Waring et al., 1982; He et al., 2012).

Our analysis confirms that the general carbon calculation approach (biomass functions vs. conversion factors) in combination with the specific parameter estimates for deriving biomass functions or conversion factors (Appendices A–M) influences the country-specific results. Differences in carbon estimates across countries are affected by regional conditions. However determining the proportion of the detected deviation that is due to the sampling procedure and methods versus the deviation from environmental conditions (e.g. climate, soil or genetics) or differences in tree allometry remains a key question. Since it is very difficult to know the true biomass amount by compartment and tree species, plausibility checks, such as a careful assessment of the (i) original sample material for calibrating and developing regional biomass estimation methods and the (ii) statistical approach are essential. The empirical sample material for the country-specific estimation methods has large discrepancies (see Tables 5 and 6 for *P. abies* and *F. sylvatica* and Tables S.4–S.6 in the Supplementary material for the remaining species).

Most biomass estimation methods applied in this study use sample data mostly within a DBH range between 10 and 40 cm and lack data from very small or very big trees. Tree heights and ages have similar deficiencies in sample data range (Tables 5 and 6, Tables S.4–S.6 in Supplementary material). This range limitation results in regression functions derived from sample data that may lead to unrealistic estimates if they are extrapolated, particularly for larger, but also smaller tree diameters. Analogously, differences in tree allometry due to forest management or tree genetics can be possible sources of deviation in the carbon and biomass results. Within Europe both management practices (FOREST EUROPE, UNECE, FAO, 2011) and tree genetics vary strongly by tree species (Skrøppa, 2003; Mátyás et al., 2004). This may affect biomass allocation and growth rates (Schmidt-Vogt, 1977; Gruber, 1987; Müller-Starck et al., 1992). Since hardly any references provide information on allometric properties such as crown length, crown width or stem taper or even tree genetics, we cannot examine this in more detail.

The type of estimation method has a large effect on any results and we want to illustrate this for biomass expansion factors versus allometric biomass functions. Biomass expansion factors convert tree volume into biomass by applying a species-specific average conversion factor, independent of age, tree height, etc. Forest management strongly affects the growth rates of stands and thus the tree ring width (Assmann, 1970). Wood density is strongly correlated to tree ring width (MacPeak et al., 1990; Repola, 2006; Ledermann and Neumann, 2006) but also to tree age. It is well known that constant biomass expansion factors tend to overestimate biomass for young trees and underestimate biomass for older trees (Pietsch and Hasenauer, 2002). Allometric biomass functions which derive tree biomass from DBH and/or height were developed to circumvent this problem and include the effect of age in the biomass predictions.

Biomass in tree compartments show higher differences among countries than total biomass estimates (Figs. 6 and 7). Again part of these discrepancies in biomass estimates may be caused by environmental drivers while the rest is an effect of sample material and the estimation methodology. Here it is also important to know the definition of the various tree compartments by country as this also affects the results (Jenkins et al., 2003). For example, the definition of branch or stem biomass for *F. sylvatica* in Poland could be different than in other countries, since the results for total biomass in Poland did not show clear differences in Fig. 4. Unfortunately, in the case of Poland (Muukkonen, 2007) we could not test this hypothesis, since the definition of stem and branch biomass is not given. But there is some evidence in the results of other countries. In France stem biomass includes all branches (Vallet et al., 2006). In most other countries the definition of stem excludes branches as well as the stump (e.g. for Austria Pollanschütz, 1974; for Norway Marklund, 1988). This explains why France has the highest results for stem biomass for *P. abies* (Fig. 6) but only average results for total tree biomass (see Fig. 3 and Table 3).

Similarly, the assigned minimum diameter for root biomass (see Appendices B–M) influences the deviations in root biomass results (Figs. 6 and 7, Tables 3 and 4). For Austria as well as for Norway it is assigned 2 mm (Wirth et al., 2004; Petersson and Ståhl, 2006), while for the Czech Republic or Belgium it is assigned 5 mm (Drexhage and Gruber, 1999; Drexhage and Colin, 2001; Xiao et al., 2003).

All functions in this study use tree diameter to predict the biomass or volume, with many also using tree height (Table 1 and Appendices B–M). Any additional predictor variable decreases the remaining variation and improves the performance of the model (e.g. Ketterings et al., 2001; Ledermann and Neumann, 2006 or Lang et al., 2007). Some models use additional variables such as tree age (Wirth et al., 2004) or tree crown parameters (i.e., crown ratio or crown length; Repola, 2008, 2009; Ledermann and Neumann, 2006). Without tree height or crown height as additional variables the models will assume a constant DBH/height ratio or DBH/crown height ratio. This is an unrealistic assumption since height increment culminates earlier than diameter increment and trees in general modify their crown according to stand density and the light availability (Assmann, 1970). A good example to illustrate the effect of additional variables are root biomass estimates of *P. abies* from Austria and Belgium. Both countries use

Table 5
Properties of the sample material used for volume and biomass functions for *Picea abies* by country and region: if multiple references are used for the compartments in one country, each reference is covered by one row. Given for each reference is DBH (diameter at breast height) and tree height of the sample material, the Origin of the samples (the country where the sample material was collected), the Number of samples, the Age of the sample trees in years as well as the Reference. Boxes with a endash (–) indicate that this information is not given by the reference. For the volume functions used in Czech Republic only the maximum diameter and height of the samples is given (Petráš and Pajtík, 1991).

Forest region	Country	Compartments	DBH [cm]	Height [m]	Origin	No. samples	Age [a]	References
North Europe	Finland	All	1.7–41.7	2.1–35.0	Finland	613	15–164	Repola (2009)
	Norway	Aboveground	0.3–63.4	1.3–35.6	Sweden	551	1–223	Marklund (1988)
		Roots	0.3–63.4	1.3–35.6	Sweden	342	1–223	Petersson and Stahl (2006)
Central-West Europe	Austria	Stem volume	5.0–78.0	10.0–44.0	Austria	9972	–	Pollanschütz (1974)
		Branches	2.4–65.9	2.8–42.6	Austria	3753	35–126	Ledermann and Neumann (2006)
		Foliage	1.8–98.2	2.1–44.8	Switzerland	189	15–270	Burger (1947, 1953)
		Roots	7.6–41.2	6.8–31.7	Temperate Europe	85	16–142	Wirth et al. (2004)
	Belgium	Stem volume	–	–	Belgium	991	–	Dagnelie et al. (1985)
		Branches	2.4–65.9	2.8–42.6	Austria	3753	35–126	Ledermann and Neumann (2006)
		Foliage	4.0–38.0	6.7–25.9	Netherlands	23	9–39	Bartelink (1996)
		Roots	7.6–41.2	6.8–31.7	Temperate Europe	85	16–142	Wirth et al. (2004)
	France	Aboveground	14.3–71.6	–	France	309	–	Vallet et al. (2006)
	Germany	Wood volume	–	–	Germany	–	–	Kublin (2002)
		Foliage	25.0–55.6	22.0–29.8	Germany	7	–	Schwarzmeier (2000)
	Netherlands	Aboveground	0.5–52.0	–	European Russia	222	20–155	Hamburg et al. (1997)
Central-East Europe	Czech Republic	Wood volume	−74.0	−46.0	Czechoslovakia	2111	–	Petráš and Pajtík (1991)
		Foliage, twigs	4.0–92.0	4.0–48.0	Czechoslovakia	265	–	Petráš et al. (1985)
		Roots	5.0–25.0	15 (mean)	N Germany	15	10–40	Drexhage and Gruber (1999)
	Poland	All	0.0–67.5	2.0–42.7	Europe	~1800	–	Muukkonen (2007)
	Romania	Aboveground	–	–	Romania	5403	–	Giurgiu et al. (1972)
South Europe	Italy	All	8.1–81.7	6.0–40.1	NE Italy	93	–	Tabacchi et al. (2011)
	Spain	All (excl. foliage)	9.0–57.5	8.0–29.0	Spain	29 (roots 10)	–	Ruiz-Peinado et al. (2011)
		Foliage	5.3–49.2	7.1–23.8	NW Spain	125	34–44	Diéguez-Aranda et al. (2009)

Table 6
Properties of the sample material used for volume and biomass functions for *Fagus sylvatica* by country and region: for details on the table and the content please see explanations provided for Table 5.

Forest region	Country	Compartments	DBH [cm]	Height [m]	Origin	No. Samples	Age [a]	References
North Europe	Finland	–	–	–	–	–	–	–
	Norway	–	–	–	–	–	–	–
Central-West Europe	Austria	Stem (volume)	–	–	Austria	933	–	Pollanschütz (1974)
		Branches	2.0–67.1	3.6–39.0	Austria	4213	35–125	Ledermann and Neumann (2006)
		Foliage	0.8–57.0	2.6–39.6	Switzerland	91	14–128	Burger (1953)
		Roots	4.0–53.0	7.0–28.0	Germany	27	44–127	Bolte et al. (2004)
	Belgium	Stem (volume)	–	–	Belgium	–	–	Dagnelie et al. (1985)
		Branches	5.7–62.1	9.2–33.9	Czech Republic	20	40–114	Cienciala et al. (2005)
		Foliage	2.0–33.0	3.5–22.5	Netherlands	38	8–59	Bartelink (1997)
		Roots	3.0–38.0	7.0–29.0	Central Europe	48	21–160	Wutzler et al. (2008)
	France	Aboveground	1.6–81.2	–	France	1293	–	Vallet et al. (2006)
	Germany	Wood volume	–	–	Germany	–	–	Kublin (2002)
		Foliage	2.0–33.0	3.5–22.5	Netherlands	38	8–59	Bartelink (1997)
	Netherlands	Aboveground	2.0–33.0	3.5–22.5	Netherlands	38	8–59	Bartelink (1997)
Central-East Europe	Czech Republic	Wood volume	−74.0	−38.0	Czechoslovakia	1886	–	Petráš and Pajtík (1991)
		Foliage, twigs	8.0–84.0	8.0–36.0	Czechoslovakia	285	–	Petráš et al. (1985)
		Roots	3.0–20.0	9.9 (mean)	NE France	16	24–35	Le Goff and Ottorini (2001)
	Poland	All	2.0–64.0	3.5–29.0	Europe	68	–	Muukkonen (2007)
	Romania	Aboveground	–	–	Romania	7070	–	Giurgiu et al. (1972)
South Europe	Italy	All	5.0–60.7	7.2–31.6	Italy	91	–	Tabacchi et al. (2011)
	Spain	All (excl. foliage)	9.5–74.8	9.0–30.9	Spain	72 (roots 14)	–	Ruiz-Peinado et al. (2011)
		Foliage	9.9–21.0	12.6–26.2	NW Spain	16	–	Diéguez-Aranda et al. (2009)

the same reference (Wirth et al., 2004), but Austria use in addition to DBH also the tree age for root biomass prediction. The additional variable has rather little effect for small diameters, while the results for Austria and Belgium strongly deviate after DBH of 40 cm (Fig. 6) and the root biomass of the oldest stand is for Belgium 33.7 t/ha (+27%) higher than for Austria. The choice of biomass or carbon estimation method is restricted to the availability of the input data. If a forest inventory does not provide certain

variables (e.g. age or crown height) then more general estimation methods must be used.

Carbon is derived by multiplying biomass with the carbon fraction (Eq. (1)). Research indicated that the carbon fraction in biomass differs by ecoregion (Thomas and Martin, 2012), tree species (Lamlom and Savidge, 2003) or by tree compartment (Lamlom and Savidge, 2006). Besides France, Belgium and Spain, most countries in this study use a carbon fraction of 0.5 as suggested by IPCC (2006) (Appendix A). Considering the literature this is a simplification of the complexity of nature, but necessary since no comprehensive studies exist.

Carbon reporting systems such as the FAO Statistics, the Kyoto protocol or the UNFCCC (United Nations Framework – Convention on Climate Change) are not only concerned with carbon stocks but mainly with changes in carbon stocks (fixation vs. emissions). The effect of the calculation methods presented in this study might be substantially smaller for estimating changes in carbon. Still since the tree results in Figs. 2–5 show different inclination across the DBH range, one can expect that the different methods procure different carbon increment rates for the same change in tree properties like an increase in DBH of 1 cm.

6. Conclusions

We present and compare the official biomass estimation methods from 12 different countries across Europe as they are used for the carbon reporting duties within the Kyoto Protocol under UNFCCC. True tree or stand biomass estimates are impossible to obtain so we compare and assess the country-specific estimation methods to provide a conceptual understanding of the different estimation procedures and how these differences may affect carbon predictions at the European scale. After addressing regional differences by clustering into European forest regions, deviations of single tree carbon and biomass as well as stand-level results decrease but remain throughout Europe (Figs. 2–5, Tables 3 and 4). These discrepancies can be explained with (i) differences in the sample material (Tables 5 and 6), (ii) the variables used in the biomass functions and (iii) the definition of the compartments (Appendices B–M). No additional patterns according to the biomass calculation methods (allometric biomass functions or biomass expansion factors) are evident.

The quality of tree carbon calculations in Europe needs to be improved and systematic quality checks for providing consistent carbon estimation methods are required. These checks must include (i) the definition of the tree compartments, (ii) additional variables to capture differences in site conditions, management impacts, and age effects, (iii) the performance of biomass functions when applied beyond the range of the data set available for parametrization, (iv) representativeness of the functions and the used sample material in terms of covering the tree allometry and specific variability of trees in the region of interest and (v) plausibility checks with local sample material, especially when estimation systems from other regions are applied.

We strengthen the findings of the FPS COST ACTION E43 on "Harmonisation of National Inventories in Europe: Techniques for Common Reporting" (McRoberts et al., 2009; Ståhl et al., 2012) by quantifying the deviation caused by different carbon calculation methods in Europe, which can lead to differences in tree carbon up to 140 t/ha for *P. abies* and 90 t/ha for *F. sylvatica*. We also highlight new issues discovered like the high discrepancies in young stands or the effect of additional tree variables such as crown length or tree age. Choosing and modifying the carbon calculation methodology is the responsibility of each country and NFI organization. However, this is a critical task that should be coordinated across countries because it has such significant ramifications such as its influence on climate change mitigation policy.

Conflict of interests

The authors declare that they have no conflict of interest.

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Appendix A. General details on carbon estimation

Tree carbon gets calculated according to the following general equation.

Table A.1
Carbon fraction (CC) for converting biomass into carbon.

Carbon fraction [/]					
Country	*Picea abies*	*Pinus sylvestris*	*Fagus sylvatica*	*Quercus robur*	*Betula pendula*
Austria	0.5	0.5	0.5	0.5	0.5
Belgium	0.5	0.5	0.49	0.5	0.5
Czech Republic	0.5	0.5	0.5	0.5	0.5
Finland	0.5	0.5	0.5	0.5	0.5
France	0.475	0.475	0.475	0.475	0.475
Germany	0.5	0.5	0.5	0.5	0.5
Italy	0.5	0.5	0.5	0.5	0.5
Netherlands	0.5	0.5	0.5	0.5	0.5
Norway	0.5	0.5	0.5	0.5	0.5
Poland	0.5	0.5	0.5	0.5	0.5
Romania	0.5	0.5	0.5	0.5	0.5
Spain	0.506	0.509	0.486	0.484	0.485

Table A.2
Dry wood density (wd) for converting volume into biomass.

Dry wood density [t dry biomass/m^3]					
Country	*Picea abies*	*Pinus sylvestris*	*Fagus sylvatica*	*Quercus robur*	*Betula pendula*
Austria	0.362	0.450	0.561	0.579	0.551
Belgium	0.380	0.480	0.560	0.600	0.550
Czech Republic	0.380	0.430	0.570	0.550	0.520
France	0.438	0.438	0.546	0.546	0.546
Germany – branch	0.490	0.490	0.540	0.570	0.540
Germany – stem	0.360	0.360	0.490	0.540	0.490
Romania	0.370	0.420	0.585	0.560	0.525

Table A.3
Root-to-shoot ratio (RS) for deriving root biomass with aboveground biomass (BM).

Root-to-shoot ratio [/]					
Country	*Picea abies*	*Pinus sylvestris*	*Fagus sylvatica*	*Quercus robur*	*Betula pendula*
France	0.30	0.30	0.28	0.28	0.28
Germany – BM < 50 t/ha (*Picea, Pinus*), BM < 75 t/ha (*Fagus, Betula*)	0.46	0.46	0.43	0.35	0.43
Germany – BM 50–150 t/ha (*Picea, Pinus*), BM 75–150 t/ha (*Fagus, Betula*)	0.32	0.32	0.26	0.35	0.26
Germany – BM > 150 t/ha	0.23	0.23	0.24	0.35	0.24
Italy	0.29	0.36	0.20	0.20	0.24
Poland	0.23	0.23	0.24	0.24	0.24

$$C_{tree} = CC * (dsm + dbm + dfm + drm) \quad (A.1)$$

where C_{tree} is the total carbon content of a tree [kg], *CC* is the carbon fraction [/] given for each country in Table A.1, *dsm* is the dry stem biomass [kg], *dbm* the dry branch biomass [kg], *dfm* the dry foliage biomass [kg] and *drm* the dry root biomass [kg].

If applicable in the country-specific methodology, dry wood density *wd* to derive biomass using volume estimates are provided in Table A.2 and root-to-shoot ratio *RS* for deriving root biomass in Table A.3.

Some of the biomass calculation methods consider different compartments than the above mentioned. To get comparable results, the results of these sub-compartments are aggregated to the compartments stem, branch and roots according to the following equations:

$$dsm = dswm + dsbm \quad (A.2)$$

$$dbm = dabm + ddbm \quad (A.3)$$

$$drm = dstm + dcrm + dfrm \quad (A.4)$$

with *dsm* dry stem biomass, *dswm* dry stem wood biomass, *dsbm* dry stem bark biomass, *dbm* dry branch biomass, *dabm* dry alive branch biomass, *ddbm* dry dead branch biomass, *drm* dry root biomass, *dstm* dry stump biomass, *dcrm* dry coarse root biomass, *dfrm* dry fine root biomass, all quantities in [kg].

The biomass functions of the Czech Republic and Spain separate branches into different diameter classes (e.g. Spain Ruiz-Peinado et al., 2011, 2012; Diéguez-Aranda et al., 2009 and Balboa-Murias et al., 2006a,b; for the Czech Republic Petráš et al., 1985). As foliage biomass is included in the branch biomass, for calculating branch biomass solely foliage biomass get substracted, see Eq. (A.5).

$$dbm = dbm1 + dbm2 + dbm3 + dbm4 + dbm5 - dfm \quad (A.5)$$

With *dbm*1 thick branches with diameter >7 cm, *dbm*2 medium branches with diameter 2–7 cm, *dbm*3 thin branches and twigs with diameter <2 cm, *dbm*4 thin branches with diameter 0.5–2 cm, *dbm*5 twigs with diameter <0.5 cm, *dfm* foliage biomass.

In the following chapters the biomass calculations are described for each country in detail. Often used variables are *DBH* diameter at breast height, at 1.3 m above ground, *H* tree height from ground to tree top, *HC* crown height from ground to living crown (first living branch), *CR* crown ratio calculated $CR = (H - HC)/H$, *wd* dry wood density.

Carbon fraction (*CC*), dry wood density (*wd*) and Root-to-shoot ratios (*RS*) are coefficients most calculation methods use and are therefore presented accumulated for all calculation methods here.

Appendix B. Biomass calculation in Finland

Allometric biomass functions dependent on DBH, tree height and crown length are used for calculating biomass for tree compartments (stem wood, stem bark, living branches, dead branches, foliage (leaves/needles), stump, coarse roots (diameter >1 cm)) (Repola, 2008, 2009) and fine roots (diameter <1 cm) (Härkönen et al., 2011) (see Table B.1).

The chosen methodology is largely identical then the method from the Finnish NIR report. It differs merely in the choice of coefficients used for estimating fine root biomass (Härkönen et al., 2011; Statistics Finland, 2013). It uses allometric biomass functions developed in Finland.

Model type 1:

$$dswm, dsbm, \ldots = cf * exp(c0 + c1 * dk/(dk + c2) + c3 * ln(H) + c4 * H + cf2) \quad (B.1)$$

Model type 2:

$$dswm, dsbm, \ldots = cf * exp(c0 + c1 * dk/(dk + c2) + c3 * H/(H + c4) + c5 * ln(CL) + cf2) \quad (B.2)$$

$$dk = 2 + 1.25 * DBH \quad (B.3)$$

$$dfrm = f_{fr} * dfm \quad (B.4)$$

with *dk* stump diameter [cm], *DBH* [cm], *H* [m], *CL* crown length [m], *CR* crown ratio [/], coefficients *ci, cf, cf*2 and f_{fr} are given below. f_{fr} are valid for semi-fertile sites (Härkönen et al., 2011).

For broadleaf trees and *dfm CR* is used instead ln(*CL*). For broadleaf trees and *dabm CL* instead ln(*CL*).

F. sylvatica is not native in Finland. Therefore Finland is excluded from analysis for this tree species.

Table B.1
Coefficients for calculating biomass for Finland (Repola, 2008, 2009).

Coefficients for biomass by compartments for Finland									
Compartment	*c*0	*c*1	*c*2	*c*3	*c*4	*c*5	*cf*	*cf*2	Model type
Picea abies									
dswm	−3.555	8.042	14	0.869	0.015	0	1	0.009	1
dsbm	−4.437	10.071	18	0.261	0	0	1	0.029	1
dabm	−3.023	12.017	14	−5.722	5	1.033	1	0.0425	2
dfm	−0.085	15.222	4	−14.446	1	1.273	1	0.0575	2
ddbm	−5.317	6.384	18	0.982	0	0	1.208	0	1
dstm	−3.964	11.73	26	0	0	0	1	0.0615	1
dcrm	−2.294	10.646	24	0	0	0	1	0.1095	1
Pinus sylvestris									
dswm	−3.721	8.103	14	5.066	12	0	1	0.0055	2
dsbm	−4.695	8.727	12	0.228	0	0	1	0.0355	1
dabm	−5.166	13.085	12	−5.189	8	1.11	1	0.0415	2
dfm	−1.748	14.824	4	−12.684	1	1.209	1	0.0625	2
ddbm	−5.318	10.771	16	0	0	0	0.913	0	1
dstm	−6.753	12.681	12	0	0	0	1	0.027	1
dcrm	−5.55	13.408	15	0	0	0	1	0.0395	1
Betula pendula, *Quercus robur*									
dswm	−4.879	9.651	12	1.012	0	0	1	0.004035	1
dsbm	−5.433	10.121	12	2.647	20	0	1	0.02739	2
dabm	−5.067	14.614	12	−5.074	12	0.092	1	0.035855	2
dfm	−20.856	22.32	2	0	0	2.819	1	0.027185	2
ddbm	−7.996	11.824	16	0	0	0	2.1491	0	1
dstm	−3.574	11.304	26	0	0	0	1	0.03348	1
dcrm	−3.223	6.497	22	1.033	0	0	1	0.07477	1

Table C.1
Coefficients for calculating biomass for Norway (Marklund, 1988; Petersson and Ståhl, 2006).

Coefficients for biomass by compartment for Norway					
	*a*0	*a*1	*a*2	*a*3	*a*4
Picea abies					
dswm	−2.3032	7.2309	14	0.0355	0.7030
dsbm	−3.4020	8.3089	15	0.0147	0.2295
dabm	−1.2063	10.9708	13	−0.0124	−0.4923
ddbm	−4.6351	3.6518	18	0.0493	1.0129
dfm	−1.8551	9.7809	12	0	−0.4873
drm	4.58761	10.4404	138	0	0
Pinus sylvestris					
dswm	−2.6864	7.6066	14	0.02	0.8658
dsbm	−3.2765	7.2482	16	0	0.4487
dabm	−2.5413	13.3955	10	0	−1.1955
ddbm	−5.8926	7.1270	10	−0.0465	1.106
dfm	−3.4781	12.1095	7	0.0413	−1.565
drm	3.4428	11.0654	113	0	0
Quercus robur, *Betula pendula*					
dswm	−3.3045	8.1184	11	0	0.9783
dsbm	−4.0778	8.3019	14	0	0.7433
dabm	−3.3633	10.2806	10	0	0
ddbm	−6.6237	11.2872	30	−0.3081	2.6821
drm	6.1708	10.0111	225	0	0

Appendix C. Biomass calculation in Norway

The methodology is taken from the Norwegian NIR report (Climate and Pollution Agency, 2013; oral communication Rasmus Astrup, 2013). It uses allometric biomass functions developed in Sweden. For aboveground biomass the functions from Marklund (1988) and for belowground biomass (minimum root diameter 2 mm) from Petersson and Ståhl (2006) are used. The functions for alive branches for *P. abies* and *P. sylvestris* also contain the biomass of needles (Marklund, 1988). To compare with other results the foliage biomass is calculated with separate functions.

$$dswm, dsbm, \ldots = exp(a0 + a1 * DBH/(DBH + a2) + a3 * H + c4 * ln(H)) \quad (C.1)$$

For the broad leaf species foliage biomass is assumed to be a constant proportion of stem biomass (de Wit et al., 2006):

$$dfm = dswm * 0.021 \quad (C.2)$$

DBH [cm] (for *drm DBH* [mm]), *H* [m], *drm* [g dry weight], coefficients *a*0–*a*4 are given in Table C.1 (Marklund, 1988; Petersson and Ståhl, 2006).

Appendix D. Biomass calculation in Austria

The presented method corresponds widely with the method for forest carbon calculation used in the Austrian National Inventory report for the Kyoto reporting (Umweltbundesamt, 2013) (see Tables D.1–D.3).

Dry stem biomass (dsm) get calculated using stem volume and species-specific wood density (Gschwantner et al., 2010).

$$dsm = V * wd \tag{D.1}$$

$$V = (DBH/200)^2 * \pi * H * FF \tag{D.2}$$

with *DBH* [cm] and *H* [m]

$$FF = c1 + c2 * ln^2(DBH) + c3/H + c4/DBH + c5/DBH^2 + c6/DBH/H + c7/DBH^2/H \tag{D.3}$$

with *DBH* and *H* [dm] where *V* stem volume [m^3], *FF* form factor, *wd* dry wood density given in Appendix A [kg dry BM/m^3], which is calculated using wood density and shrinkage factor by tree species from Wagenführ and Scheiber (1985), *ci* coefficients for form factor calculations (Pollanschütz, 1974; Schieler, 1988; Gabler and Schadauer, 2008) are given below.

Dry branch mass (*dbm*) is calculated for *P. abies* (including foliage biomass), *F. sylvatica, B. pendula* (same function as for *F. sylvatica)* and *Q. robur* using allometric functions from Ledermann and Neumann (2006):

$$dbm = cf * exp(a + b * ln(DBH) + c * H/DBH + d * ln(CR)) \tag{D.4}$$

with *DBH* [cm], *H* [m], the species-specific parameters *a–d* and *cf* given below in the following table.

For *P. abies dfm* is substracted from *dbm* to get comparable results.

Foliage biomass (*dfm*) is calculated for *P. abies*, *F. sylvatica, B. pendula* and *Q. robur* using allometric functions of Burger (1947, 1949, 1953) modified after Lexer and Hoenninger (2001).

$$dfm = a * DBH^b \tag{D.5}$$

dbm and *dfm* for *P. sylvestris* after Hochbichler et al. (2006):

$$dbm, dfm = cf * exp(a + b * ln(DBH) + c * ln(H)) \tag{D.6}$$

with *DBH* [cm], *H* [m], the species-specific parameters *b*0, *b*1, *cf* and *a–d* are given below.

Root mass (*drm*) get calculated for *P. abies*, *F. sylvatica, B. pendula* and *Q. robur* using the biomass functions of Wirth et al. (2004), Bolte et al. (2004) and Offenthaler and Hochbichler (2006). Only Bolte et al. (2004) provide the minimum diameter of the samples (2 mm).

$$drm = cf * exp(a + b * ln(DBH) + c * ln^2(DBH) + d * ln(A) \tag{D.7}$$

And for *P. sylvestris* (Offenthaler and Hochbichler, 2006):

$$drm = 0.038872 * DBH^{2.066783} \tag{D.8}$$

with *DBH* [cm], *A* is tree age [a], the species-specific parameters *a–d* and *cf* are given below.

Appendix E. Biomass calculation in Belgium

The below presented methodology is the result of a literature review. The volume calculation method is identical in the Belgium NIR report (Flemish Environment Agency, 2013). It is a combination of volume functions, expansion factors and allometric biomass functions from Belgium, Austria, the Czech Republic, Germany, France and Netherlands (see Tables E.1 and E.2).

$$V = b0 + b1 * c_{130} + b2 * c_{130}^2 + b3 * c_{130}^3 + b4 * H + b5 * c_{130}^2 * H \tag{E.1}$$

$$dsm = V * wd \tag{E.2}$$

with *V* merchantable timber volume [m^3] with a minimal diameter of 7 cm (circumference 22 cm), c_{130} (circumference at 1.3 m height) = $DBH \cdot \cdot \pi$, *H* [m], *b*0–*b*5 coefficients according to Dagnelie et al. (1985) given below in the following table, *wd* dry wood density are taken from Vande Walle et al. (2005) are given in Appendix A.

If there are no appropriate biomass functions for Belgium available, the allometric functions from other countries are used. The functions are selected to give realistic results across the DBH and height range of the analysed trees.

For *dbm*, *dfm* and *drm* of *P. sylvestris* (Xiao et al., 2003 cited in Zianis et al., 2005), for *dbm* of *F. sylvatica, B. pendula* and *Q. robur* (Cienciala et al., 2005 cited in Zianis et al., 2005), for *dfm* Bartelink (1997) and for *drm* Wutzler et al. (2008):

$$dbm = b0 * DBH^{b1} \tag{E.3}$$

$$dfm = f0 + f1 * DBH^{b2} \tag{E.4}$$

$$drm = r0 * DBH^{r1} \tag{E.5}$$

The coefficients are given in the following table.

For *P. abies* and *dbm* (including needles) Ledermann and Neumann (2006), for *dfm* (not added to total biomass to avoid double counting) Bartelink (1996), for *drm* Wirth et al. (2004):

$$dbm = b0 * exp(b1 + b2 * ln(DBH) + b3 * H/DBH) \tag{E.6}$$

$$dfm = exp(f0 + f1 * ln(DBH) + f2 * ln(H)) \tag{E.7}$$

$$drm = r0 * exp(r1 + r2 * ln(DBH)) \tag{E.8}$$

with *DBH* [cm], *H* [m], coefficients given below.

Minimum diameter for root biomass is only provided by Xiao et al. (2003) and is 5 mm.

Appendix F. Biomass calculation in France

The below presented methodology is selected based on available literature on biomass in forests for France (INRA, 2004). It is largely identical then the method from the French NIR report (CITEPA, 2013). It combines volume functions with expansion factors developed in France (see Table F.1).

$$FF = (a + b * CBH + c * CBH^{0.5}/H) * (1 + d/CBH^2) \tag{F.1}$$

$$V = FF * (\pi/40000) * CBH^2 * H \tag{F.2}$$

$$dsm + dbm = V * wd \tag{F.3}$$

$$dfm = V * wd * 0.02 \tag{F.4}$$

$$drm = RS * (dsm + dbm + dfm) \tag{F.5}$$

Table D.1
Coefficients for calculating form factor for Austria (Pollanschütz, 1974; Schieler, 1988; Gabler and Schadauer, 2008).

Coefficients for form factor for Austria							
	*c*1	*c*2	*c*3	*c*4	*c*5	*c*6	*c*7
Picea abies	0.46818	−0.013919	−28.213	0.37474	−0.28875	28.279	0
Pinus sylvestris	0.435949	−0.014908	5.21091	0	0.028702	0	0
Fagus sylvatica	0.686253	−0.037151	−31.0674	−0.386321	0.219462	49.6163	−22.3719
Quercus robur	0.115631	0	65.9961	1.20321	−0.930406	−215.758	168.477
Betula pendula	0.42831	−0.06643	0	0	0	8.4307	0

Table D.2
Coefficients for calculating branch and foliage biomass for Austria (Ledermann and Neumann, 2006 and Burger, 1947, 1949, 1953 modified after Lexer and Hoenninger, 2001)

Coefficients for branch biomass for Austria						For foliage biomass			
	a	*b*	*c*	*d*	*cf*	*a*	*b*	*c*	*cf*
Picea abies	−1.9576	2.0252	0.1451	0.9154	1.051	0.0956	1.56	–	–
Pinus sylvestris	−3.2856	2.1684	0.1473	–	1.041	−3.8876	1.5904	0.2348	1.0417
Fagus sylvatica, Betula pendula	−3.3205	2.5568	−0.1092	0.6002	1.212	0.0217	1.7	–	–
Quercus robur	−1.2943	1.9445	0	1.2137	1.280	0.0270	1.7	–	–

Table D.3
Coefficients for calculating root biomass for Austria (Wirth et al., 2004; Bolte et al., 2004; Offenthaler and Hochbichler, 2006).

Coefficients for root biomass for Austria					
	a	*b*	*c*	*d*	*cf*
Picea abies	−8.35049	4.56828	−0.33006	0.28074	1.0406
Fagus sylvatica, Betula pendula	−4	2.32	0	0	1.08
Quercus robur	−3.97478	2.52317	0	0	1.0505

Table E.1
Coefficients for calculating stem volume for Belgium (Dagnelie et al., 1985).

Coefficients for stem volume for Belgium						
	b0	*b1*	*b2*	*b3*	*b4*	*b5*
Picea abies	−0.01093	0.001395	−9.6E−06	−2.5E−07	−0.00279	4.9E−06
Pinus sylvestris	−0.03984	0.001551	−6.2E−06	4.8E−08	7.4E−05	2.96E−06
Fagus sylvatica	−0.01557	0.000923	−7.1E−06	−7.7E−08	−0.00135	4.04E−06
Quercus robur	−0.00227	0.000124	1.26E−05	−5.9E−08	−0.00167	3.75E−06
Betula pendula	−0.01139	−0.0001	2.83E−05	−1.9E−07	−0.0006	3.08E−06

Table E.2
Coefficients for calculating branch, foliage and root biomass for Belgium (Ledermann and Neumann, 2006; Wirth et al., 2004; Bartelink, 1997; Wutzler et al., 2008; Cienciala et al., 2005; Xiao et al., 2003).

Coefficients for branch biomass					For foliage biomass			For root biomass		
	b0	*b1*	*b2*	*b3*	*f0*	*f1*	*f2*	*r0*	*r1*	*r2*
Picea abies	1.102	−1.1635	1.7459	−0.9499	−1.346	3.351	−2.201	1.0554	−5.3789	2.9211
Pinus sylvestris	0.0022	2.9122	0	0	0	0.00445	2.2371	0.3399	1.4728	0
Fagus sylvatica, Quercus robur, Betula pendula	0.021	2.471	0	0	0.375	0.0024	2.517	0.0282	2.39	0

Table F.1
Coefficients for calculating tree volume for France (Vallet et al., 2006).

Coefficients for tree volume for France				
	a	*b*	*c*	*d*
Picea abies	0.631	−0.000946	0	0
Pinus sylvestris	0.297	0.000318	0.384	204
Quercus robur, Betula pendula	0.471	−0.000345	0.377	0
Fagus sylvatica	0.395	0.000266	0.421	45.4

with *FF* Form factor for tree volume estimation, $CBH = DBH \cdot \pi$ (circumference at 1.3 m height), *H* [m], *V* [m^3] aboveground tree volume, *a–d* coefficients according to Vallet et al. (2006) given in the following table, *wd* wood density and *RS* root-to-shoot ratio given in Appendix A. Minimum root diameter is not defined.

Foliage biomass *dfm* is considered to be 2% of the total aboveground biomass.

Appendix G. Biomass calculation in Germany

The methodology presented below is identical to the method used in the German NIR report (Federal Environmental Agency, 2012) using the same volume functions as the German Forest Inventory (Bundeswaldinventur) (see Table G.1).

Wood volume, wood density and expansion factors are used to calculate biomass. Raw wood volume (minimum diameter 7 cm) (Kublin, 2002) is calculated with the functions implemented in the program BDAT 2.0 (Kublin, 2002) depending on species, DBH, tree height and *d*7 (diameter at height of 7 m). The estimation of the variable *d*7 is done by the program BDAT 2.0 for trees, as these values are not included in the dataset. Tree wood volume is calculated with raw wood volume and expansion factors (see Table G.1) derived from Grundner and Schwappach (1952) cited in Federal Environmental Agency (2012).

Foliage biomass is included in the estimates for coniferous species. Its share can be estimated with respective biomass functions for foliage, for *P. abies* from Schwarzmeier (2000), for *P. sylvestris* from Xiao et al. (2003), for *B. pendula* from Hytönen et al. (1995), for *F. sylvatica* from Bartelink (1997) and for *Q. robur* from Curiel Yuste et al. (2005). The volume functions are from Germany, the functions for the remaining compartments from other European countries.

$$dsm = V_{RW} * wd_stem \quad (G.1)$$

$$V_{TW} = a + V_{RW} * b \quad (G.2)$$

$$dbm = (V_{TW} - V_{RW}) * wd_branch \quad (G.3)$$

$$drm = RS * (dsm + dbm + dfm) \quad (G.4)$$

$$dfm = a + b * DBH^c * H^d \quad (G.5)$$

Table G.1
Coefficients for converting raw wood volume to tree wood volume (Federal Environmental Agency, 2012) and for calculating foliage biomass for Germany (Schwarzmeier, 2000; Xiao et al., 2003; Hytönen et al., 1995; Bartelink, 1997; Curiel Yuste et al., 2005).

Coefficients for tree wood volume for Germany			Coefficients for foliage biomass			
	a	*b*	*a*	*b*	*c*	*d*
Picea abies, age <60 years	0.036697	1.148143	0	0.0026146	2.6763	0
Picea abies, age >60 years	0	1.177947	0	0.0026146	2.6763	0
Pinus sylvestris, age <60 years	0.009946	1.156659	0	0.112269	2.2371	0
Pinus sylvestris, age >60 years	0.036883	1.076103	0	0.112269	2.2371	0
Betula pendula	0.017493	1.121933	0	0.0003	2	0.9583
Fagus sylvatica, age <60 years	0.011942	1.207371	0.375	0.0024	2.517	0
Fagus sylvatica, age 61–100 years	0.008184	1.196184	0.375	0.0024	2.517	0
Fagus sylvatica, age >100 years	0.030255	1.128104	0.375	0.0024	2.517	0
Quercus robur	0.101879	1.051529	0	0.0024	2.6081	0

with V_{RW} rawwood volume [m^3], V_{TW} total wood volume [m^3], *DBH* [cm], *H* [m], *wd_stem* is wood density stem, *wd_branch* wood density branch (Kollmann, 1982 cited in Federal Environmental Agency, 2012) and *RS* root-to-shoot ratio are given in Appendix A, *a, b* coefficients for calculating V_{TW} (Federal Environmental Agency, 2012) and for *dfm* are given in Table G.1. Minimum root diameter is not defined.

Appendix H. Biomass calculation in the Netherlands

The chosen method is a combination of the allometric biomass functions published in Nabuurs et al. (2005) also used in the NIR report of the Netherlands (National Institute for Public Health and the Environment, 2013) and biomass fractions calculated using results from the EFISCEN project (Schelhaas et al., 1999; Vilén et al., 2005). The allometric biomass functions published in Nabuurs et al. (2005) use publications providing species-dependent allometric biomass functions and conversion factors from Europe and the European part of Russia. For *Q. robur* the allometric function of Hochbichler (2002) is used, for *F. sylvatica* of Bartelink (1997), for *B. pendula* of Johansson (1999), for *P. sylvestris* and *P. abies* of Hamburg et al. (1997) (see Tables H.1 and H.2).

$$BM_{ABG} = a0 * DBH^{a1} * H^{a2} \quad (H.1)$$

$$BM_{total} = BM_{ABG} * (1 + RS) \quad (H.2)$$

with *DBH* [cm] (for *B. pendula DBH* [mm], *H* [m], BM_{ABG} total aboveground biomass [kg dry weight], BM_{total} total tree biomass [kg dry weight], *RS* age-dependent root-to-shoot ratio calculated using biomass fractions from Vilén et al. (2005) given in the next table. Minimum root diameter is not defined. The species-specific publications given above provide the coefficients for the aboveground biomass (*a*0–*a*2) and are cited in Nabuurs et al. (2005).

Total above ground biomass get divided into tree compartments by multiplying with estimates for biomass fractions.

$$dsm, dbm, \ldots = f_i * BM_{total} \quad (H.3)$$

f_i are given below.

Biomass fractions were calculated within the EFISCEN project (Schelhaas et al., 1999; Vilén et al., 2005) and are based on the biomass allocation functions. For *P. abies* based on the functions of Wirth et al. (2004) for aboveground biomass and for coarse roots on Lehtonen et al. (2004) for fine roots. For *P. sylvestris* on the

Table H.1
Coefficients for calculating aboveground biomass for the Netherlands (Hochbichler, 2002; Bartelink, 1997; Johansson, 1999 and Hamburg et al., 1997 cited in Nabuurs et al., 2005).

Coefficients for aboveground biomass for the Netherlands			
	*a*0	*a*1	*a*2
Quercus robur	0.41354	2.14	0
Fagus sylvatica	0.0798	2.601	0
Betula pendula	0.00029	2.50038	0
Pinus sylvestris	0.0217	1.9634	0.9817
Picea abies	0.0533	1.791	0.8955

Table H.2
Age-dependent fraction values for calculating biomass in tree compartments for the Netherlands.

Biomass fractions dependent on tree age [years] for the Netherlands											
Picea abies	20	30	40	50	60	70	80	90	100	110	1000
f_stem	0.385	0.474	0.562	0.617	0.642	0.650	0.644	0.639	0.634	0.628	0.619
f_branch	0.349	0.256	0.173	0.130	0.111	0.104	0.106	0.108	0.111	0.115	0.121
f_roots	0.100	0.132	0.166	0.178	0.182	0.188	0.195	0.201	0.205	0.209	0.213
f_foliage	0.167	0.138	0.099	0.077	0.065	0.058	0.055	0.052	0.050	0.048	0.047
RS	0.111	0.152	0.199	0.216	0.223	0.231	0.243	0.251	0.258	0.264	0.271
Pinus sylvestris	30	40	50	60	80	100	120	1000			
f_stem	0.357	0.504	0.583	0.624	0.661	0.679	0.688	0.691			
f_branch	0.368	0.258	0.195	0.163	0.135	0.125	0.123	0.127			
f_roots	0.109	0.138	0.154	0.163	0.169	0.171	0.168	0.165			
f_foliage	0.167	0.101	0.068	0.050	0.035	0.026	0.021	0.018			
RS	0.122	0.160	0.182	0.195	0.204	0.206	0.203	0.197			
Fagus sylvatica, Quercus robur, Betula pendula	40	60	80	100	120	140	1000				
f_stem	0.600	0.674	0.692	0.693	0.712	0.721	0.721				
f_branch	0.100	0.108	0.118	0.129	0.108	0.095	0.089				
f_roots	0.261	0.191	0.174	0.165	0.167	0.171	0.176				
f_foliage	0.044	0.022	0.016	0.014	0.013	0.013	0.014				
RS	0.350	0.237	0.211	0.198	0.200	0.206	0.214				

functions of Cienciala et al. (2006) for aboveground biomass and on Marklund (1988) for root biomass. For *F. sylvatica, B. pendula* and *Q. robur* on Bartelink (1997) and Cienciala et al. (2005) for aboveground biomass and Le Goff and Ottorini (2001) for root biomass.

In the EFISCEN database there are no specific biomass fractions for the Netherlands available. Therefore the conversion factors developed for Germany/Austria were selected as these are probably most comparable with the conditions of forests in the Netherlands.

Appendix I. Biomass calculation in the Czech Republic

The presented method of calculating carbon is developed using volumetric functions applied in volume tables for Czechoslovakia (Petráš and Pajtík, 1991), density of wood and bark of tree species (Klement et al., 2010) and published allometric biomass functions (Drexhage and Colin, 2001; Petráš et al., 1985). It combines volume functions, biomass expansion factors and allometric biomass functions from the Czech Republic (see Tables I.1–I.3).

$$dswm, dsbm, \ldots = V_i * wd * I_i \tag{I.1}$$

$$dfm, drm, dbm5 = b1 * (DBH + b2)^{b3} * H^{b4} * b5 \tag{I.2}$$

where V_i is the volume of a certain compartment [m^3], *wd* is wood density [kg/m^3] given in Appendix A and I_i correction index (if applicable) derived from Požgaj et al. (1993), Chmelař (1992) and Miles and Smith (2009).

Minimum root diameter is 5 mm (Drexhage and Collin, 2001). The correction indices for individual tree species and *b*1–*b*5 coefficients for biomass calculation are given below.

$$dsm = BM_{wood>7cmUB} + dsbm \tag{I.3}$$

$$dbm = BM_{wood<7cmUB} + dbm5 \tag{I.4}$$

where $BM_{wood>7cmUB}$ is the biomass of wood under bark with diameter equal to or above 7 cm [kg dry BM], *dsbm* is biomass of bark [kg dry BM], $BM_{wood<7cmUB}$ is biomass of wood under bark with diameter below 7 cm [kg dry BM], *dbm*5 is biomass of green twigs [kg dry BM] as previously described. The individual biomass parts are calculated as follows:

$$BM_{wood>7cmUB} = V_{wood>7cmUB} * wd \tag{I.5}$$

$$BM_{wood<7cmUB} = V_{wood<7cmUB} * wd * I_{wood<7cm} \tag{I.6}$$

$$dsbm = V_{bark} * wd * I_{bark} \tag{I.7}$$

The volume of individual parts of the tree were calculated using two-parameter regressions applied in volume tables for Czechoslovakia and compiled or modified by Petráš and Pajtík (1991). The volume of the different parts of tree (tree, stem, wood with diameter equal to or above 7 cm under bark, wood with diameter below 7 cm under bark) is calculated using volumetric equations.

The compartment is indicated by the lower index. *OB* indicate volume over bark and *UB* under bark. If this is not stated, the used formula is valid for both *OB* and *UB*.

General equation for all different volumes of *P. abies* is:

$$V_i = a0 * (DBH + a1)^{a2} * H^{a3} - a4 * (DBH + a5)^{a6} * H^{a7} \tag{I.8}$$

For *F. sylvatica*:

$$V_i = FF_i * \pi * DBH^2 * H/40000 \tag{I.9}$$

$$FF_{stem} = a0 + a1 * DBH + a2 * DBH^2 + a3 * DBH^3 + a4 * H + a5 * H * DBH + a6 * DBH^2 * H + a7 * DBH^3 * H \tag{I.10}$$

$$FF_{wood>7cm} = a0 + a1/DBH + a2/DBH^2 + a3/DBH^3 + a4 * H + a5 * H * DBH + a6 * DBH^2 * H + a7 * DBH^3 * H \tag{I.11}$$

$$FF_{treeOB} = a0 + a1/H + a2/H^2 + a3/DBH + a4 * H/DBH + a5 * H^2/DBH + a6/DBH^2 + a7/DBH^2/H + a8/DBH^2/H^2 + a9/DBH^3 + a10/DBH^3 * H + a11/DBH^3 * H^2 \tag{I.12}$$

For *Q. robur*:

$$FF_{stem} = a0 + a1/DBH + a2/DBH^2 + a3/DBH^3 + a4 * H + a5 * H * DBH + a6 * DBH^2 * H + a7 * DBH^3 * H \tag{I.13}$$

$$FF_{wood>7cm}, FF_{treeOB} = a0 + a1/H + a2/H^2 + a3/DBH + a4 * H/DBH + a5 * H^2/DBH + a6/DBH^2 + a7/DBH^2/H + a8/DBH^2/H^2 + a9/DBH^3 + a10/DBH^3 * H + a11/DBH^3 * H^2 \tag{I.14}$$

Table I.1
Correction indices of wood density for the Czech Republic (Požgaj et al., 1993; Chmelař, 1992; Miles and Smith, 2009).

Correction indices of wood density for the Czech republic					
	Picea abies	*Pinus sylvestris*	*Fagus sylvatica*	*Quercus robur*	*Betula pendula*
I bark	1.25	0.95	1.2	1	1.13
I wood <7 cm	1.2	1.1	1.1	1.1	1.1

Table I.2
Coefficients for calculating biomass for the Czech Republic (Drexhage and Colin, 2001; Petráš et al., 1985).

Coefficients for biomass calculations for the Czech republic							
		*b*1	*b*2	*b*3	*b*4	*b*5	Reference
Picea abies	Twigs	0.016	1	1.788	0.679	0.468	Petráš et al. (1985)
Picea abies	Foliage	0.015	1	1.831	0.564	0.426	Petráš et al. (1985)
Picea abies	Roots	0.020	0	2.360	0	1	Drexhage and Colin (2001)
Pinus sylvestris	Twigs	0.236	1	1.842	−0.434	0.457	Petráš et al. (1985)
Pinus sylvestris	Foliage	0.119	1	1.857	−0.360	0.425	Petráš et al. (1985)
Pinus sylvestris	Roots	0.013	0	2.740	0	1	Drexhage and Colin (2001)
Fagus sylvatica, Quercus robur, Betula pendula	Twigs	0.076	1	2.245	−0.559	0.401	Petráš et al. (1985)
Fagus sylvatica, Quercus robur, Betula pendula	Foliage	0.029	1	2.432	−0.600	0.365	Petráš et al. (1985)
Fagus sylvatica, Betula pendula	Roots	0.022	0	2.540	0	1	Drexhage and Colin (2001)
Quercus robur	Roots	0.028	0	2.440	0	1	Drexhage and Colin (2001)

Table I.3
Coefficients for volume calculation for the Czech Republic (Petráš and Pajtík, 1991).

Regression coefficients for volumetric equations for the Czech Republic														
	Compartment	*a*0	*a*1	*a*2	*a*3	*a*4	*a*5	*a*6	*a*7	*a*8	*a*9	*a*10	*a*11	*a*12
Fagus sylvatica	stemOB	6.77E−01	−1.43E−02	2.92E−04	−2.11E−06	−3.13E−03	2.67E−04	−5.91E−06	4.19E−08					
Fagus sylvatica	stemUB	5.84E−01	−1.14E−02	2.49E−04	−1.88E−06	−2.77E−03	2.40E−04	−5.40E−06	3.87E−08					
Fagus sylvatica	wood ⩾7cm OB	5.65E−01	−2.33E+00	3.93E+01	−2.34E+02	−1.42E−03	−1.83E−06	6.21E−07	−4.77E−09					
Fagus sylvatica	wood ⩾7cmUB	5.42E−01	−3.12E+00	4.43E+01	−2.36E+02	−1.07E−03	−1.86E−05	8.81E−07	−6.00E−09					
Fagus sylvatica	treeOB	5.99E−01	−2.02E−01	4.49E+00	5.99E+00	−4.41E−01	6.10E−03	−2.97E+00	−1.09E+02	8.99E+01	6.66E+01	−1.09E+01	6.35E−01	
Pinus sylvestris	stemOB	3.03E−05	2.08E+00	−1.25E−02	9.61E−01									
Pinus sylvestris	stemUB	2.26E−05	2.12E+00	−1.27E−02	9.80E−01									
Pinus sylvestris	wood ⩾7cmOB					7.20E−02	−2.12E+00	1.37E+00						
Pinus sylvestris	wood ⩾7cmUB					6.43E−02	−2.12E+00	1.37E+00						
Pinus sylvestris	treeOB					3.60E+01	8.11E−01	1.38E+00	3.03E−05	2.08E+00	−1.25E−02	9.61E−01	1.00E+02	
Betula pendula	stemOB	0.00E+00	1.32E+00	−2.30E−04	6.43E+01	−2.04E+01	8.00E+00	−2.32E−01						
Betula pendula	stemUB								1.00E+00	−1.00E−02	1.73E+01	5.05E−03	1.00E−01	−2.06E+00
Betula pendula	wood ⩾7cmOB	−4.50E+00	1.08E+00	−1.15E−03	3.12E+04	−2.32E+01	5.50E+00	−1.43E−01						
Betula pendula	wood ⩾7cmUB								1.00E+00	−1.00E−02	1.73E+01	5.05E−03	1.00E−01	−2.06E+00
Betula pendula	treeOB	0.00E+00	1.11E+00	−4.80E−04	8.30E+04	−2.60E+01	8.00E+00	−1.50E−01						
Quercus robur	stemOB	4.62E−01	4.31E−01	7.46E−01	−9.06E−01	9.96E−04	−6.73E−06	−9.82E−07	7.75E−09					
Quercus robur	stemUB	3.59E−01	−5.25E−01	3.09E+00	−3.14E+00	3.21E−03	−5.84E−05	2.66E−07	−1.96E−09					
Quercus robur	wood ⩾7cmOB	4.47E−01	5.98E+00	−2.09E+00	−1.49E+01	8.70E−02	1.06E−03	−2.69E+01	1.68E+01	−2.21E−01	2.23E+02	−5.39E+01	−1.01E+00	
Quercus robur	wood ⩾7cmUB	4.53E−01	2.16E+00	9.10E+00	−1.21E+01	1.81E−01	−4.01E−03	−6.83E+00	9.44E+00	−2.44E−02	3.37E+01	−9.10E+00	−2.16E+00	
Quercus robur	treeOB	5.24E−01	4.24E+00	−6.60E+00	−7.81E+00	2.67E−01	−7.01E−03	3.74E+01	−2.14E+00	1.15E−01	−2.95E+01	1.73E+00	−9.29E−02	
Picea abies	stemOB	4.01E−05	1.00E+00	1.82E+00	1.13E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00					
Picea abies	stemUB	3.20E−05	1.00E+00	1.85E+00	1.15E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00					
Picea abies	wood ⩾7cmOB	4.01E−05	1.00E+00	1.82E+00	1.13E+00	9.29E−03	1.00E+00	−1.02E+00	8.96E−01					
Picea abies	wood ⩾7cmUB	3.20E−05	1.00E+00	1.85E+00	1.15E+00	8.29E−03	1.00E+00	−1.02E+00	8.96E−01					
Picea abies	treeOB	4.45E−05	1.00E+00	1.81E+00	1.13E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00					

For *B. pendula*:

$$V_{OB} = (H + a0)^{a1} * (a2 + a3 * exp(a4 * (DBH + a5)^{a6})) \quad (I.15)$$

$$V_{UB} = V_{OB} * (a7 + a8 * (a9 * exp(a10 * (V_{OB} + a11)^{a12}))) \quad (I.16)$$

For *P. sylvestris*:

$$V_{stem} = a0 * (DBH + 1)^{a1+a2*log(DBH+1)} * H^{a3} \quad (I.17)$$

$$V_{wood>7cm} = V_{stem} - a4 * (DBH + 1)^{a5} * H^{a6} \quad (I.18)$$

$$V_{treeOB} = V_{stemOB} + a4 * (DBH + 1)^{a5}/H^{a6} * a7 * (DBH + 1)^{a8+a9*log(DBH+1)} * H^{a10}/a11 \quad (I.19)$$

In case no regression equation was available, the required volume was calculated from the available volumes following the principles below:

$$percent_bark = max\{V_{wood>7cmOB} - V_{wood>7cmUB})/V_{wood>7cmOB}; V_{stemOB} - V_{stemUB})/V_{stemOB}\} \quad (I.20)$$

$$V_{wood<7cmOB} = V_{treeOB} - V_{wood>7cmOB} \quad (I.21)$$

$$V_{wood<7cmUB} = (1 - percent_bark) * V_{wood<7cmOB} \quad (I.22)$$

$$V_{bark} = V_{treeOB} - V_{wood>7cmUB} - V_{wood<7cmUB} \quad (I.23)$$

In the listed equations, FF_i the form factor for volume estimates [/], V_i volume of tree compartments [m^3], *percent_bark* is proportional content of bark [/], *DBH* is tree diameter at breast height in [cm], and *H* is tree height in [m] and parameters *a*0 to *a*12 are regression coefficients derived for the respective species and listed in the following table.

Appendix J. Biomass calculation in Poland

Allometric biomass functions using tree height and/or diameter are used for estimating aboveground biomass in Poland. For *P. sylvestris* models developed with sample material from 18 Scots pines stands in Bory Lubuskie (western Poland) are used (Zasada et al., 2008). Due to lack of appropriate published biomass functions for *P. abies, F. sylvatica* and *Q. robur* in Poland generalized biomass functions for Europe are applied (Muukkonen, 2007). For *B. pendula* height- and diameter-dependent functions developed in Finland are used (Repola, 2008) (see Table J.1).

For *P. sylvestris*:

$$dswm, dsbm, \ldots = a0 * DBH^{a1} * H^{a2} \quad (J.1)$$

With *DBH* [mm], *H* [m]

For *P. abies*, *F. sylvatica* and *Q. robur*:

$$dsm, dsbm, \ldots = exp(a0 + a1 * DBH/(DBH + a2)) \quad (J.2)$$

With *DBH* [cm]

For *B. pendula*:

Model type 1:

$$dswm, dsbm, \ldots = cf * exp(a0 + a1 * dk/(dk + a2) + a3 * ln(H) + cf2) \quad (J.3)$$

Model type 2:

$$dswm, dsbm, \ldots = cf * exp(a0 + a1 * dk/(dk + a2) + a3 * H/(H + a4) + cf2) \quad (J.4)$$

$$dk = 2 + 1.25 * DBH \quad (J.5)$$

dk and *DBH* [cm], *H* [m], all parameters are given below.

Root-to-shoot ratios are the official values used in official Polish reportings on changes in carbon stocks of the living biomass under the Kyoto Protocol which are the weighted average of the default coefficients proposed by IPCC (2006).

$$drm = RS * (dswm + dsbm + dfm + dabm + ddbm) \quad (J.6)$$

RS is given in Appendix A. Minimum root diameter is not defined.

Appendix K. Biomass calculation in Romania

Tree biomass is calculated using the volume functions developed in Romania by Giurgiu et al. (1972) used in the Romanian NIR report combined with biomass expansion factors. The

Table J.1
Coefficients for calculating biomass for Poland (Zasada et al., 2008; Repola, 2008; Muukkonen, 2007).

Coefficients for biomass calculation for Poland								
	*a*0	*a*1	*a*2	*a*3	*a*4	*cf*	*cf*2	Model type
Pinus sylvestris								
dswm	0.00041	1.627725	1.390374	–	–	–	–	–
dsbm	0.000192	2.117192	–	–	–	–	–	–
dabm	0.0000038	3.653659	−1.6008	–	–	–	–	–
ddbm	0.0000072	2.433082	–	–	–	–	–	–
dfm	0.000212	2.30978	−0.58099	–	–	–	–	–
Picea abies								
dsm	−3.043	11.784	9.328	–	–	–	–	–
dbm	−0.537	10.093	40.426	–	–	–	–	–
dfm	−1.360	7.308	19.662	–	–	–	–	–
Fagus sylvatica, Quercus robur								
dsm	−0.657	10.730	17.394	–	–	–	–	–
dbm	−2.128	13.295	26.095	–	–	–	–	–
dfm	−2.480	9.511	26.771	–	–	–	–	–
Betula pendula								
dswm	−4.879	9.651	12	1.012	–	1	0.004035	1
dsbm	−5.401	10.061	12	2.657	20	1	0.02743	2
dabm	−4.152	15.874	16	−4.407	10	1	0.051975	2
ddbm	−8.335	12.402	16	–	–	2.0737	0	2
dfm	−29.566	33.372	2	–	–	1	0.0385	2

calculated volume includes above ground tree compartments excluding foliage. Wood density values from the Global wood density database (Zanne et al., 2009; Chave et al., 2009) and biomass fractions calculated using results from the EFISCEN project (Vilén et al., 2005) (see Tables K.1 and K.2).

$$log10(V_{abg}) = a0 + a1 * log10(DBH) + a2 * (log10(DBH))^2 + a3 * log10(H) + a4 * (log10(H))^2 \quad (K.1)$$

$$BM_{ABG} = V_{ABG} * wd \quad (K.2)$$

$$dsm, dbm, \ldots = f_i * BM_{ABG} \quad (K.3)$$

where V_{ABG} aboveground tree volume [m^3], BM_{ABG} aboveground tree biomass [kg], *DBH* [cm], *H* [m], *wd* dry wood density [kg/m^3] from the Global wood density database (Zanne et al., 2009; Chave et al., 2009) in Appendix A, coefficients *a*0–*a*4 and *f_i* age-dependent biomass fractions are given below. Minimum root diameter is not defined.

Appendix L. Biomass calculation in Italy

The methodology is a combination of the allometric biomass functions developed with sample material from Italy from Tabacchi et al. (2011) and the conversion parameters from Federici et al. (2008). *dsm* includes stem and branches > 5 cm diameter and *dbm* includes foliage and branches < 5 cm diameter (Tabacchi et al., 2011). The Italian NIR report for the Italian Greenhouse Gas Inventory for the period 1990–2010 (ISPRA, 2013) use growing stock reported by the NFI (MAF-ISAFA, 1988) in combination with biomass expansion factors, wood density and root-shoot ratios citing Federici et al. (2008). Growing stock is calculated with allometric functions, which are developed with a subset of the sample material used for the models used in this work (Tabacchi et al., 2011). Since *Q. robur* and *B. pendula* are not covered in Tabacchi et al. (2011), we use the models from *Quercus pubescens* Willd. for the first and from "Altre latifoglie" (other broadleaves) for the second species from the same reference (see Table L.1).

$$dsm = s0 + s1 * DBH^2 * H + s2 * DBH \quad (L.1)$$

$$dbm = b0 + b1 * DBH^2 * H + b2 * DBH \quad (L.2)$$

$$drm = RS * (dsm + dbm) \quad (L.3)$$

with *DBH* [cm], *H* [m], *s*0–*s*2 and *b*0–*b*2 according to Tabacchi et al. (2011) given in table below, *RS* according to Federici et al. (2008) in Appendix A. Minimum root diameter is not defined.

Table K.1
Coefficients for aboveground volume calculation for Romania (Giurgiu et al., 1972).

Coefficients for aboveground volume for Romania					
	*a*0	*a*1	*a*2	*a*3	*a*4
Picea abies	−4.18161	2.08131	−0.11819	0.70119	0.14818
Pinus sylvestris	−3.84672	1.82103	−0.04107	0.35677	0.33491
Fagus sylvatica	−4.11122	1.30216	0.23636	1.26562	−0.07966
Quercus robur	−4.13329	1.88001	0.04880	0.95371	−0.06364
Betula pendula	−4.16999	2.27038	−0.21540	0.30765	0.36826

Appendix M. Biomass calculation in Spain

Until now for international reporting, carbon stock in living biomass was calculated using the method of "Change in Carbon Stocks" described in the GPG-LULUCF (IPCC, 2006). Biomass expansion factors were based on large dataset collected in the Ecological Forest Inventory of Catalonia, Spain (Gracia et al., 2002; Mäkipää et al., 2005). Root biomass is estimated with an expansion factor according to IPCC methodology (IPCC, 2006) (see Table M.1).

In future for international reporting on forest biomass allometric functions are probably used. These functions are developed in Spain and are dependent on DBH and/or tree height (Ruiz-Peinado et al., 2011, 2012; Diéguez-Aranda et al., 2009).

For *P. abies* (functions from *Abies alba*), *P. sylvestris* and *F. sylvatica* the functions from Ruiz-Peinado et al. (2011) and Ruiz-Peinado et al. (2012) are used, for *B. pendula* (functions from *Betula alba*) from Diéguez-Aranda et al. (2009) and for *Q. robur* from Balboa-Murias et al. (2006a, 2006b). The minimum root diameter is not given; the authors state however that fine roots are not captured by their excavation method (Ruiz-Peinado et al., 2011, 2012).

As there are no explicit functions for foliage biomass given in Ruiz-Peinado et al. (2011, 2012), the foliage biomass functions from Diéguez-Aranda et al. (2009) are used. For *P. abies* and for *P. sylvestris* the function from *Pinus pinaster* are used, for *F. sylvatica* the function from *Betula alba* (Diéguez-Aranda et al., 2009).

The general equation for *P. abies* and *P. sylvestris* is:

$$dsm, dbm1, \ldots = a * DBH^b * H^c + d * H \quad (M.1)$$

For *P. sylvestris*, *dbm1* = 0 for *DBH* <= 37.5 cm, if DBH > 37.5 cm:

$$dbm1 = 0.54 * (DBH - 37.5)^2 - 0.0119 * (DBH - 37.5)^2 * H \quad (M.2)$$

The general equation for *F. sylvatica*, *Q. robur* and *B. pendula* is:

$$dsm, dbm1, \ldots = a * DBH^b * H^c + d * DBH^2 + e \quad (M.3)$$

Table K.2
Age-dependent biomass fractions for calculating biomass in compartments for Romania.

Biomass fractions dependent on tree age [years] for Romania											
Picea abies	20	30	40	50	60	70	80	90	100	110	1000
Stem	0.525	0.649	0.765	0.826	0.853	0.862	0.859	0.855	0.851	0.845	0.836
Branches	0.475	0.351	0.235	0.174	0.147	0.138	0.141	0.145	0.149	0.155	0.164
Roots	0.136	0.180	0.226	0.238	0.242	0.249	0.260	0.269	0.275	0.281	0.288
Foliage	0.227	0.189	0.135	0.103	0.086	0.077	0.073	0.070	0.067	0.065	0.063
Pinus sylvestris	30	40	50	60	80	100	120	1000			
Stem	0.493	0.661	0.749	0.793	0.830	0.845	0.848	0.845			
Branches	0.507	0.339	0.251	0.207	0.170	0.155	0.152	0.155			
Roots	0.150	0.181	0.198	0.208	0.213	0.213	0.208	0.201			
Foliage	0.230	0.132	0.087	0.063	0.044	0.032	0.026	0.022			
Fagus sylvatica, Quercus robur, Betula pendula	40	60	80	100	120	140	1000				
Stem	0.857	0.862	0.855	0.843	0.869	0.883	0.890				
Branches	0.143	0.138	0.145	0.157	0.131	0.117	0.110				
Roots	0.373	0.244	0.215	0.201	0.204	0.209	0.218				
Foliage	0.063	0.028	0.020	0.017	0.016	0.016	0.017				

Table L.1
Coefficients for calculation biomass for Italy (Tabacchi et al., 2011).

Coefficients for biomass calculations for Italy						
	s0	*s1*	*s2*	*b0*	*b1*	*b2*
Picea abies	−5.9426	0.01321	0.78369	5.9459	0.0040669	−0.21054
Pinus sylvestris	0.65786	0.017176	0	2.1336	0.0045864	0
Fagus sylvatica	−0.83814	0.024865	0	2.504	0.0051283	0
Quercus robur	1.0832	0.029634	−0.49794	−8.2101	0.0030396	1.7561
Betula pendula	−9.1098	0.0073484	2.3666	−3.6118	0.004319	0.74127

Table M.1
Coefficients for calculating biomass for Spain (Ruiz-Peinado et al., 2011, 2012; Diéguez-Aranda et al., 2009; Balboa-Murias et al., 2006a, 2006b).

Coefficients for biomass calculation in Spain					
Picea abies	*a*	*b*	*c*	*d*	
dsm	0.0189	2	1	0	
dbm1 + dbm2	0.0584	2	0	0	
dbm3	0.0371	2	0	0.968	
dfm	0.1081	1.51	0	0	
drm	0.101	2	0	0	
Pinus sylvestris					
dsm	0.0154	2	1	0	
dbm2	0.0295	2.742	−0.899	0	
dbm3	0.53	2.199	−1.153	0	
dfm	0.1081	1.51	0	0	
drm	0.13	2	0	0	
Fagus sylvatica	*a*	*b*	*c*	*d*	*e*
dsm	0.0182	2	1	0.0676	0
dbm2	0.0792	2	0	0	0
dbm3	0.00226	2	1	0.093	0
dfm	0.0346	1.645	0	0	0
drm	0.106	2	0	0	0
Quercus robur					
dswm	0.01823	2	1	0	−5.714
dsbm	0.00111	2	1	0.03154	−1.5
dbm1	3.427E−09	4.959	2.31	0	0
dbm2	0.00341	2	1	0	4.268
dbm4	0.03851	1.784	0	0	0
dbm5	0.00012	2	1	0	1.379
dfm	0.0101985	1.667	0.7375	0	0
drm	0.0116	1.949	0.9625	0	0
Betula pendula					
dswm	0.1485	2.2223	0	0	0
dsbm	0.031	2.186	0	0	0
dbm2	0.1374	1.76	0	0	0
dbm4	0.05	1.618	0	0	0
dbm5	0.0372	1.581	0	0	0
dfm	0.0346	1.645	0	0	0
drm	1.042	1.254	0	0	0

For *F. sylvatica dbm1* = 0 for *DBH* <= 22.5 cm, if *DBH* > 22.5 cm:

$$dbm1 = 0.83 * (DBH - 22.5)^2 - 0.0248 * (DBH - 22.5)^2 * H \quad (M.4)$$

For *B. pendula*:

$$dbm1 = 1.515 * exp(0.0904 * DBH) \quad (M.5)$$

All functions with biomass in [kg], *DBH* [cm] and *H* [m], coefficients *a–e* are given below.

Appendix N. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2015.11.016.

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