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Indirect methods of large-scale forest biomass estimation

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Abstract Forest biomass and its change over time have been measured at both local and large scales, an example for the latter being forest greenhouse gas inventories. Currently used methodologies to obtain stock change estimates for large forest areas are mostly based on forest inventory information as well as various factors, referred to as biomass factors, or biomass equations, which transform diameter, height or volume data into biomass estimates. However, while forest inventories usually apply statistically sound sampling and can provide representative estimates for large forest areas, the biomass factors or equations used are, in most cases, not representative, because they are based on local studies. Moreover, their application is controversial due to the inconsistent or inappropriate use of definitions involved. There is no standardized terminology of the various factors, and the use of terms and definitions is often confusing. The present contribution aims at systematically summarizing the main types of biomass factors (BF) and biomass equations (BE) and providing guidance on how to proceed when selecting, developing and applying proper factors or equations to be used in forest biomass estimation. The contribution builds on the guidance given by the IPCC (Good practice guidance for land use, land-use change and forestry, 2003) and suggests that proper application and reporting of biomass factors and equations and transparent and consistent reporting of forest carbon inventories are needed in both scientific literature and the greenhouse gas inventory reports of countries.

Keywords Biomass · Biomass expansion factor · Biomass equation · Biomass function · Forest carbon inventory · Greenhouse gas inventory

Introduction

Forest biomass and its change over time have long been considered as key characteristics of forest ecosystems (Reichle 1982; Cannell 1982). During recent decades, the amount of carbon stored in the biomass has gained special attention as a result of the UN Framework Convention on Climate Change (UNFCCC) as well as its Kyoto Protocol. Under these agreements, countries are requested to estimate and report CO_2 emissions and removals of forest, and the credited sinks may be used as emission reductions.

Unlike in other sectors or with other greenhouse gases, carbon emissions and removals from the Land Use, Land Use Change and Forestry (LULUCF) sector can only be indirectly measured as changes in the forest carbon stocks. Although alternative methods have been tried before (like aerial photogrammetry) and new approaches [e.g. light detection and ranging (LiDAR), Patenaudea et al. 2004] are emerging to estimate the carbon content of forests and its change, the currently used methodologies remain important. They are based on the estimation of the change in biomass stocks, using forest inventory information, which is multiplied by the carbon fraction[1] of the biomass to establish the change

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[1] The carbon fraction is defined as the carbon content of a unit of biomass. Most frequently, a value of 0.5 is used (see FCCC/SBSTA/2004/INF.7 at http://www.unfccc.de).

in the corresponding carbon stocks. This method is also promoted by the IPCC "Good Practice Guidance for Land Use, Land-Use Change and Forestry" (IPCC 2003).

The change in biomass stocks can be assessed either as a difference between the biomass increment and biomass removals or as a change of biomass stocks between consecutive inventories (IPCC 2003). Due to the high requirements on the resources for measurements, biomass assessment under field conditions in practice is done in either of two indirect ways. One is to use the volume data of certain compartments of trees or stands as reported by forest inventories or other national statistics and to multiply it with an appropriate factor or factors, referred to in this paper as biomass factors (BF) to convert and, if necessary, expand or reduce the available volume estimates to the required biomass estimates:

$$B = P \times \mathrm{BF}, \tag{1}$$

where B is the biomass (fresh or dry plant mass, kg or t), P an available tree or stand parameter (e.g. tree volume, m^3) and BF an appropriate biomass factor that may include a conversion and, if necessary, an expansion component (see later).

Note that there are many terms used for these factors in the literature. Probably the most frequently used name is biomass expansion factor (BEF). However, BEF is only one type of biomass factors. A factor to be used to estimate biomass may or may not expand, but it always converts the available tree or stand parameter, unless this parameter is biomass of some sort. The term biomass factor is to be used to refer to any factor that can be used alone or in combination with other factors to estimate biomass from volume, and "biomass expansion factor" is to be used to only refer to factors that expand.

The other way to estimate biomass is to apply an appropriate biomass equation (BE) that predicts tree biomass as a function of diameter at breast height (DBH), or DBH together with other data of measured sample trees, again practically from forest inventories:

$$B = f(P_1, P_2, \ldots, p_1, p_2, \ldots), \tag{2}$$

where B is the biomass (fresh or dry plant mass, kg or t); P_1, P_2, etc. the available tree data (e.g. DBH, cm; height, m) and p_1, p_2, etc. the parameter(s) of the equation.

The first method can be used if only aggregated volume estimates, e.g. volume of growing stock by tree species, are available, whereas biomass equations are preferred if one has access to representative sample of tree-wise data from target population. This paper focuses on the biomass factors and equations taking volume, DBH and all other forest inventory information as known input data.

Since biomass represents one of the key variables in the ecosystem studies, a lot of effort has been made to facilitate its estimation. Recently published BFs include Fang et al. (2001), Lehtonen et al. (2004), Levy et al. (2004) and Sabaté et al. (submitted). Numerous stand-specific biomass equations are also available and most recent efforts have been focused on the development of comprehensive databases on these equations, e.g. Araújo et al. (1999), Parresol (1999), Zianis and Mencuccini (2004), Joosten et al. (2004), Jenkins et al. (2004) and Zianis et al. (2005). Stand biomass can also be modelled as a function of stem volume, as shown by Smith et al. (2003) for the USA and by Lehtonen et al. (2004) for Finland.

Experience shows that, unlike forest inventory data, which are designed to represent forest conditions over large areas, the various BFs and BEs are highly dependent on local conditions (e.g. Wirth et al. 2003; Zianis et al. 2005). This is not only because they may largely depend on species, site, age, management regime, etc. but also because the definitions involved are markedly different. In addition, the majority of the BFs and BEs that are available in the literature are based on case studies in specific conditions using only very few trees (from under ten to a few hundreds, see Wirth et al. 2003). The objective of these studies was to represent only the local conditions, not those of large areas. Because of all these, specific considerations are required when applying any BF or BE for large forest areas, often in millions of hectares.

It must also be noted that the BFs and BEs can be defined in many ways (see below) and, partially because of this, many factors and terms are used. However, neither the application nor the reporting of the applications is consistent in either the scientific literature or the greenhouse gas inventory reports of countries to the UNFCCC and KP. This can lead to highly biased and uncertain biomass estimates.

The effect of using different BFs for the same species to estimate biomass is well demonstrated by Wirth et al. (2003) who estimated biomass from the same forestry inventory database using biomass factors from the IPCC default database (see below) and five other different sources. The various biomass estimates differed by as much as 40% from the one based on the IPCC data. Somogyi (in NIR Hungary 2004) also concluded that the greenhouse gas inventory of Hungary was sensitive to the biomass factors used with forest inventory data as, for example, a 20% change in the value of the biomass factor resulted in a 12.0% change in the overall carbon sink for the country. On the other hand, representative BFs and representative BEs applied for the estimation of tree biomass in Sweden gave consistent estimates (Jalkanen et al. 2005).

Because of the above, proper application and transparent and consistent reporting of BFs and BEs would be needed in both the scientific literature and the reports of countries to the UNFCCC and KP. However, a study (see FCCC/SBSTA/2004/INF.7) that analysed the recent (2003) practice of reporting the estimation methods used in the National Communications[2] (NC) clearly

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[2] All national communications of the Annex I countries can be accessed at the UNFCCC website, http://www.unfccc.int.

showed the lack of proper definition, use and reporting of the various estimators applied. While some countries correctly reported the applied factors, their values and/or dependence on species and size, and even whether the same values were applied for standing biomass, increment or harvested values, other countries have only supplied incomplete or even fractional information. Almost half the Annex I countries have not reported their BF values at all. Furthermore, applied values might have been changed without proper reasoning and without recalculation of time-series as requested by the guidance of IPCC (2003).

The present contribution aims at introducing the main types of factors and equations at a general, theoretical level and providing guidance on how to proceed when selecting, developing and applying proper factors or equations to be applied in forest biomass estimation. The contribution builds on the guidance given by the IPCC (2003) and state-of-the-art analyses in the biomass estimation in the context of the national GHG inventories to the UNFCCC.

General definitions

In estimating biomass for large forest areas, and in applying Eqs. 1 and 2 above, biomass can be defined in many ways. Strictly speaking, when the objective is to estimate the biomass of plants, as is the case of carbon inventories, then the correct term to be used is phytomass. It would also be possible to estimate the total biomass of an ecosystem, which would have to include fauna also. However, with the carbon content of the ecosystem in focus in this paper, we use the term "biomass"[3] in the sense of "phytomass" as is also the common use in forestry.

Transparent biomass estimation requires the specification of the included components of trees or stand. For biomass assessment of *trees*, the following components are usually considered: roots (thick and thin, up to a certain diameter, but excluding fine roots), stump, stem up to a certain threshold diameter, bark, tree top (which is the thin part of the stem above the threshold diameter), thick branches up to a certain threshold diameter, thin branches (twigs) above the threshold diameter and, finally, the foliage. Fine roots are generally not included in the tree-wise estimation of biomass, among others, because the methods applied for estimation of the fine root biomass are stand specific rather than tree specific. The total biomass of a *stand* includes tree biomass, but may also include the biomass of understorey vegetation (shrub layer, dwarf shrubs, grasses, herbs, bryophytes and lichens).

Both the available tree or stem parameter, as well as the biomass to be estimated, can include any or all of the previously mentioned compartments and components. Depending on which tree components or which stand components are meant, different biomass factors or equations should be used. Note also that excluding certain tree or stand fractions is also important. For example, dead wood mass is in general excluded from stand biomass.

For the correct application of the biomass values, and also that of BFs and BEs, the definition of both the biomass and the value(s), from which biomass is calculated, is crucial. In each case, biomass is converted from the available tree or stand values. However, it may also happen that the available volume data (in case of using BFs), or the calculated biomass value, contain less biomass fractions than needed. In these cases an expansion is also needed. The conversion and the expansion can be done in consecutive steps or in one combined step. This is demonstrated by the systemized examples below that show the large variety of possible definitions of the various factors and equations.[4]

Biomass factors

Depending on the availability of tree or stem values *from* which the estimation is made, and also on the desired output *to* which the estimation leads, various factors must be used for biomass estimation. In the simplest case, conversion is enough using wood density values. If total biomass estimate is needed, but only merchantable tree volume data are available, then an expansion factor is also necessary. In such cases, the conversion and expansion can be done in several ways. For example, the estimation of the total aboveground tree biomass from the merchantable tree volume can be done in the following ways: (1) expansion from merchantable to total tree volume followed by the conversion to biomass or (2) conversion of the merchantable tree volume to biomass of the merchantable part of the tree followed by the expansion of this biomass to the total tree biomass or (3) conversion and expansion, in one step, from merchantable tree volume to tree biomass (Fig. 1). Thus, BFs may have either just an expansion or just a conversion component, or both components can be included in one combined value.[5] The most frequent expansion and conversion factors that are involved in the estimation of biomass are further detailed below.

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[3] The term "biomass" suggests that just mass (weight) unit is employed when speaking about biomass quantity. Although volume units are also frequently used in this respect, the amount of biomass in this paper is always expressed in mass units (kilograms, metric tons, etc.).

[4] Note that, as shown later, biomass factors can also be functions of tree characteristics like age, diameter and volume, or site. Thus, Eqs. 1 and 2 are similar, and biomass is estimated as a function of the known parameter values and other known stand or tree characteristics.

[5] Note that it is also possible to estimate volume from biomass, for which similar factors may be needed; however, this paper focuses on the estimation of biomass from volume.

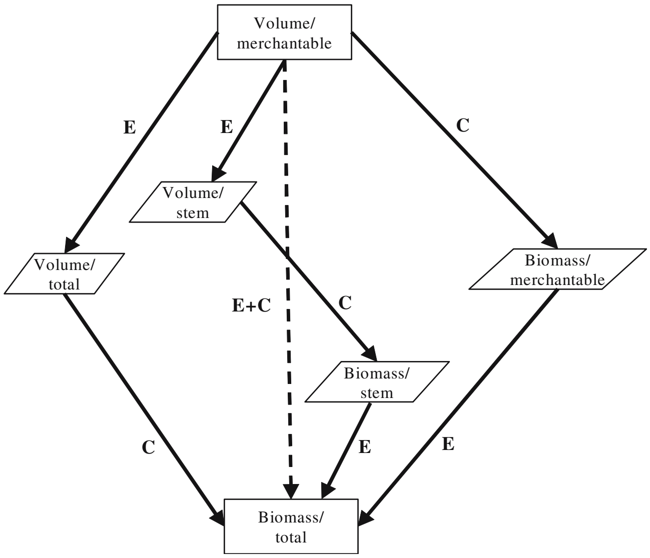


Fig. 1 Various ways to estimate total biomass from merchantable volume. *E* stands for expansion, *C* for conversion. *Stem* refers to the frequently used definition, when all parts of the stem are included, but all branches and leaves are excluded. The examples do not cover all possible combinations of including various tree parts as listed in the text

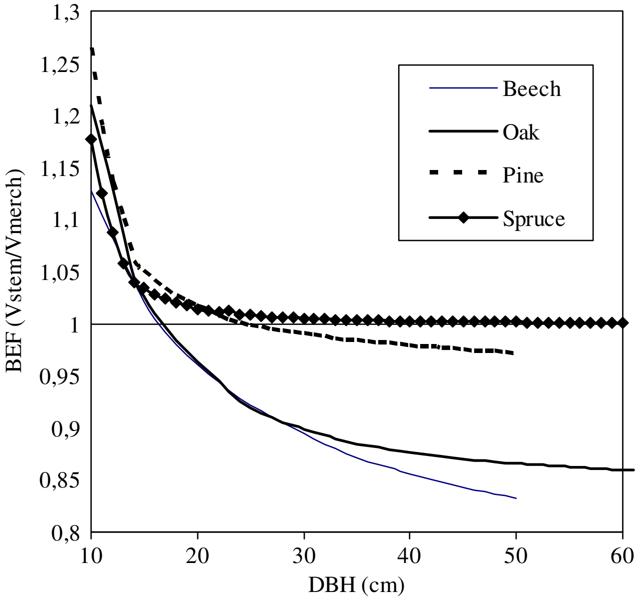


Fig. 2 Example of species-specific volume expansion factors for estimating stem volume (V_{stem}) from merchantable volume (V_{merch}) as defined in the Czech Republic (derived from Parez et al. 1990). These expansion factors are size-dependent (*DBH* diameter at breast height)

Expansion from stem or merchantable volume to total volume

Frequently, stem volume over bark is estimated during forest inventories. However, different clients may require different volumes such as stem volume under bark, total stem and branch volume or merchantable wood volume. Also, it may be necessary to calculate the total volume of wood removed in harvests from the harvested wood volume. Naturally, there may be several different cases of expanding the original volume (V_0) to the desired volume (V_1) in different countries and instances, but the formula in each case is the same:

$$V_1 = V_0 \times \text{volume expansion factor.} \tag{3}$$

It is worth noting that volume to volume estimation may be needed to obtain larger or smaller volume than the originally available volume. An example for the latter case is the estimation of stem volume from merchantable volume in the Czech Republic. The merchantable volume includes both branch and stem wood above the threshold diameter of 7 cm and, to obtain stem volume only, one has to discount branch wood of the noted dimension threshold. This involves application of species-specific and size-specific factors. Since branch biomass is only significant in the case of broadleaved species, the applied expansion factor is approximately one for conifers, but may be significantly smaller for beach and oak trees with sufficiently large stem diameter (Fig. 2).

Conversion from volume to biomass

Converting volume to biomass of the same tree components is done using the density of the appropriate tree components. The factor that can be used for conversion, ρ (Mg m^{-3}), is defined as

$$\rho = B/V, \tag{4}$$

where B is the biomass (Mg) and V the volume (m^3) of the specified tree components.

ρ and even a combined BF are frequently approximated by wood density, which itself can be defined in many ways. The GPG LULUCF (IPCC 2003) recommends basic (conventional) wood density to be used, which corresponds to dry matter at zero moisture conditions (oven-dried) divided by the volume estimated at fresh conditions (fresh volume). In any case, as volume is most often measured on fresh wood, care must be taken that the used density values refer to fresh wood conditions. If the used density values are based on absolute dry wood conditions the volume values need to be shrunk with typical shrinkage values before converting with the wood density.

Note that, strictly speaking, ρ is only equal to wood density if the thick stem wood under bark alone is considered in both B and V. Indeed, several countries have converted, in their national inventories, stem volume to stem biomass using country-specific wood density values or values recommended by IPCC (2003). In case the density of the other tree compartments, from bark to branches, considerably differ from the density of the wood itself, an adjustment of ρ may be necessary (e.g. correction for knots and bark by Hakkila 1979).

Expansion from stem or merchantable biomass to total tree biomass

"Total" biomass can mean either total aboveground biomass, or whole tree biomass, when the biomass of roots is also included. Total aboveground biomass can be expanded from the stem using an appropriate expansion factor. Whole tree biomass including roots can be assessed from aboveground biomass with the help of root–shoot ratio (e.g. IPCC 2003). However, whole tree biomass can be directly estimated from stem biomass using one combined value, too. The choice of method is highly dependent on the availability of appropriate and representative factors to be applied in national inventories. Wirth et al. (2003) have developed BEF for Norway spruce which is defined as the ratio of total stand biomass to stem wood biomass of the stand. Levy et al. (2004) reported BEF values for 13 conifer species in the UK, defined as a ratio between total aboveground tree fresh mass and the fresh mass of the merchantable timber, as well as root–shoot ratios based on an extensive tree pulling database.

Estimation of biomass using combined factors

In the estimation of total biomass, conversion and expansion can also be included in one value, which allows the calculation from stem volume to total biomass in one step. Such combined factors are applied, e.g. in the NC of Germany. Wirth et al. (2003) also report factors that convert stem volumes directly to total carbon stock of trees for most common tree species of Germany. Here, one combined conversion factor includes biomass expansion, wood density and even the carbon content of the biomass.

The major advantage of the combined BFs is that biomass expansion and density values originate from the same destructive biomass measurement. Thus, the error budget estimation is also much easier due to fact that the correlation between errors of wood density and expansion does not have to be assessed.

The development of combined factors may rely on stand-level volume and biomass estimates obtained with the help of volume and biomass equations that are first applied to tree-wise data of sample plots and thereafter summed up to get stand-level estimates (Lehtonen et al. 2004). The development of both volume and biomass equations requires destructive measurements (volume or biomass) of sampled trees, where the measurements include, for example, estimates of dry weight of biomass components as in Sabaté et al. (submitted). However, comprehensive databases on species-specific biomass and volume equations are already available (Ter-Mikaelian and Korzukhin 1997; Zianis et al. 2005), and appropriate biomass equations and volume equations with tree-level data of target population can be used for formulation of factors that are to be used in regional or national biomass inventories (Lehtonen et al. 2004).

A comparison of the various BFs

The various BFs used to estimate biomass may differ considerably (Fig. 3). This is not only due to the already mentioned definition which changes depending on "from what" and "to what" the conversion and expansion is done. In general, BFs vary by species and according to tree size. The relative share of biomass components (e.g. foliage and branches) varies during stand development, and the relative share of stem in total biomass usually increases during stand development (Satoo and Madgwick 1982). BFs may also differ due to the varying density of the compartments involved, as mentioned above. Lehtonen et al. (2004) found that the factors used to estimate biomass were dependent on stand age, while Fang et al. (2001) and Schroeder et al. (1997) reported BEFs as a function of stem volume. The BFs reported for Norway spruce in Germany by Wirth et al. (2003) varied according to site fertility, with fertile sites having relatively less biomass compared to poor sites.

When selecting or developing BF values, care should be taken that they are representative of the forest population to which they will be applied with respect to the

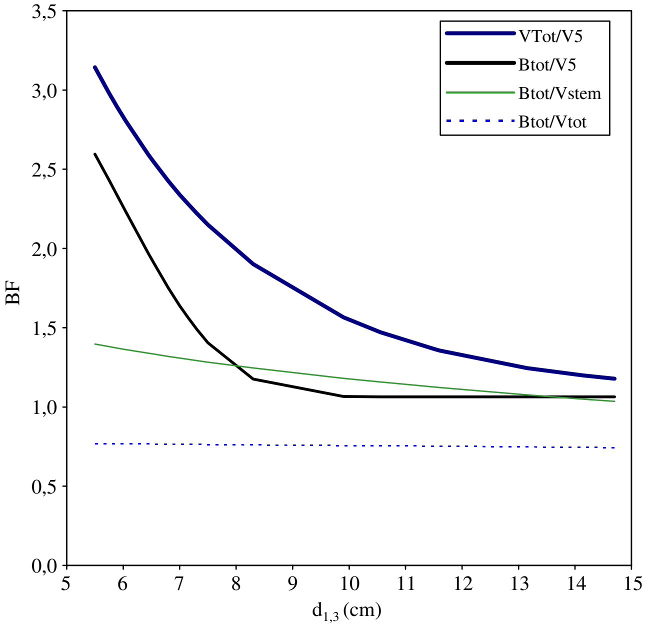


Fig. 3 Various tree-level BF values for Black locust (*Robinia pseudoacacia* L.) in Hungary over DBH. *V* is for volume and *B* for biomass, while *5* in the terms means 5 cm of threshold (top) diameter, *stem* means stem and *tot* means total. Note that the *continuous line* represents an example for an expansion factor, while the *dashed* and *dotted lines* represent conversion or combined conversion and expansion factors

above and other factors on which BFs depend (see Guidance on the selection and application of appropriate BFs and BEs).

Tree-level versus stand-level factors

Most of the countries that use the GPG LULUCF for reporting to UNFCCC estimate the changes in the biomass carbon stocks by deducting losses (e.g. due to harvests and disturbances, etc.) from gains (i.e. the increment). In order to estimate the biomass of losses and gains, one needs to have stand-level BFs due to the fact that the tree-level data of these variables is not usually known. On the other hand, tree-level factors can be used when tree-level data are available, but appropriate BEs do not exist (e.g. monitoring carbon stock changes in afforestation projects).

Biomass factors can thus be defined for both tree level and stand level. For the tree level, BFs are defined as

$$\mathrm{bf} = m_1/m_2, \tag{5}$$

where bf is the tree-level biomass factor, m_1 the appropriate measure of the tree (e.g. biomass) and m_2 the other measure of the tree (e.g. volume).

Note that we used small letters in Eq. 5 to refer to individual *tree*, rather than stand, characteristics.

The general form of stand-level BFs is

$$\mathrm{BF} = M_1/M_2, \tag{6}$$

where BF is the stand-level biomass factor, M_1 the appropriate measure of the stand (e.g. biomass) and M_2 the other measure of the stand (e.g. volume).

Frequently, stand-level BFs are developed from individual tree data:

$$BF = \frac{M_1}{M_2} = \frac{\sum_i m_{1i}}{\sum_i m_{2i}}, \tag{7}$$

where i is the index of a single tree, M the appropriate stand-level measures and m the appropriate tree-level measures.

While it is quite possible to develop tree-level factors by species, tree size, management regime and/or site, etc. and use these with tree-level inventory data, much more common is to use BFs that are developed to estimate *stand* biomass from other stand characteristics. However, the importance of using tree-level factors is increasing, and new studies will most probably favour the use of tree-level factors or equations.

It is important to note that at tree level, BFs are developed using sample trees, from which generalized curves are constructed (Wirth et al. 2003). At the stand level, either tree-level biomass measurements or BEs can be used to estimate biomass (i.e. m_1). In both cases, however, the development of BFs that can be applied for the estimation of biomass at larger scale involves two samplings, i.e. sampling of stands and sampling of trees within the selected stands. Thus, the uncertainty of using the developed factors will include both the uncertainty of tree-level estimation of biomass and that resulting from the sampling of stand from target population.

BFs suggested by the good practice guidance of IPCC (2003)

The good practice guidance prepared by IPCC (2003) suggests the use of two types of biomass factors, referred to in IPCC (2003) as BEFs. Equation 3.2.3 on page 3.24 in the guidance of IPCC (2003) applies the following definition for BEFs:

$$\begin{aligned}\mathrm{BEF}_2 = {} & \text{biomass expansion factor for conversion}\\ & \text{of merchantable volume to}\\ & \text{aboveground tree biomass, dimensionless.}\end{aligned}$$

Thus, Eq. 3.2.3 of the IPCC (2003) requires, in addition to BEF_2, basic wood density, D (applied appropriately, eventually including a further parameter for the necessary adjustment for the wood shrinkage, see above), to convert merchantable volume (V, m^3) to aboveground tree biomass (B, ton dry matter):

$$B = V \times \mathrm{BEF}_2 \times D. \tag{8}$$

To estimate the total, i.e. above and belowground biomass, B must further be multiplied by $(1 + R)$, a specific expansion factor, where R is the root–shoot ratio (dimensionless).

Equations 3.2.7 and 3.2.8 on page 3.27 use the same definition of BEF_2 to estimate the annual loss of biomass due to commercial fellings and annual loss of biomass due to fuelwood gathering, respectively.

Equation 3.2.5 on page 3.26 in the guidance (IPCC 2003) includes the following factor:

$$\begin{aligned}\mathrm{BEF}_1 = {} & \text{biomass expansion factor for conversion}\\ & \text{of annual net increment (including bark)}\\ & \text{to aboveground tree biomass increment,}\\ & \text{dimensionless.}\end{aligned}$$

Here again, the available volume data ("average annual net increment in volume suitable for industrial processing", I_{V}) is converted to "average annual aboveground biomass increment in tonnes dry matter ha^{-1} year^{-1}" (G_{W}) using both BEF_1 and D:

$$G_{\mathrm{W}} = I_{\mathrm{V}} \times D \times \mathrm{BEF}_1. \tag{9}$$

The IPCC (2003) provides tables of default values for both BEF_1 and BEF_2 (Table 3A.1.10), D (Table 3A.1.9-2) and R (Table 3A.1.8). The default values have high uncertainties when applied to specific cases and can only be applied as a first approximation (e.g. when the so-called Tier 1 method as suggested by IPCC 2003 is allowed), but they may not be representative for the local conditions at all. Therefore, rightly, the GPG for LULUCF always suggests that locally derived BEFs (e.g.

Haripriya 2000) should preferably be used if available, which always leads to a more accurate biomass assessment. Default values may deviate from the local averages due to differences between the local population and the one that was used for the development of default values. Furthermore, the applicability of the default values may be limited if national definition of, for example, stem volume may deviate from that assumed for default values.

Biomass equations

Biomass equations (BE) can also be constructed at both tree and stand levels. Tree-level equations usually relate the biomass of sampled trees (*b*) to dimensions that are easy to measure for a large number of trees such as diameter at breast height (*d*) and tree height (*h*). There are comprehensive collections of biomass equation for conditions corresponding to those in North America (Tritton and Hornbeck 1982; Ter-Mikaelian and Korzukhin 1997; Jenkins et al. 2004), Australia (Eamus et al. 2000; Keith et al. 2000) and Europe (Zianis et al. 2005). Generic biomass equations for Norway spruce were developed by Wirth et al. (2004), Schulze et al. (2004) and for some other species by Muukkonen (2005). Databases of biomass equations are also available on the Web: http://www.metla.fi/hanke/3306/tietokanta.htm for Europe and http://www.fs.fed.us/ne/global/pubs/books/dia_biomass/index.shtml for North America.

The most common mathematical model for biomass equation takes the form of the power function

$$b_i = \beta_0 x^{\beta_1} \tag{10}$$

or its simple linear form

$$\log b_i = \beta_0 + x\beta_1, \tag{11}$$

where β_0 and β_1 are the equation parameters, *b* the biomass of tree component *i* and *x* the independent variable, e.g. *d* (Zianis and Mencuccini 2004).

The logarithm is either the natural or the 10-base transformation of the component. In most cases the variability of b_1 is largely explained by the variability of the diameter at breast height (*d*), the tree height (*h*) or their combinations (Zianis et al. 2005). For example, the values of parameters β_0 and β_1 are reported to vary by species, site conditions, climate and stocking of stands.

Corresponding to the most common type of the biomass equation, the model form developed by Marklund (1987, 1988) might in some cases give more reliable biomass estimates than the most used power function (Muukkonen 2005):

$$\log b_i = \beta_0 + \beta_1 \left(\frac{x}{x + \beta_2} \right), \tag{12}$$

where *x* is the independent variable, and the logarithm is the natural transformation of the biomass component.

With respect to stand-level equations, Pan et al. (2004) report, using the idea of Brown and Lugo (1984), a method of estimating stand-level biomass from stand-level volume. They apply a linear equation similar to Eq. 11 above, where the dependent variable is stand-level biomass, and the independent variable is stand-level volume. Pan et al. (2004) also report equation parameters for main forest types (characterized by species groups or species), age classes and volume ranges in China. Further equations and equation parameters for living and standing dead trees at the stand level are reported for the USA by Smith et al. (2003) at http://www.treesearch.fs.fed.us/pubs/5179.

Like with BFs, BEs also depend on local conditions; therefore, care should be taken when selecting and developing BEs. The majority of the published BEs are developed using trees sampled from specific study sites or from sites that represent a small region only (Zianis et al. 2005). Reliable BEs to be used on large spatial scale exist only for Scandinavia and have been developed by Marklund (1987, 1988).The definition of size classes of roots and branches as well as lower and upper diameter threshold values may have varied among studies where BEs were developed. Thus, it might result in biased biomass estimates if site-specific BEs are used with forest inventory data at large spatial scales where several age classes and structural types of stands coexist for which the used BEs are no more valid (Pastor et al. 1983/1984; Jenkins et al. 2003; Wirth et al. 2003). Unless an equation was developed exclusively for the species and study region of interest, and in conditions typical of the study sites, it is difficult to know which of the several potentially applicable equations to choose. Compiled databases on biomass equations can help in comparisons and evaluations of potential equations that might be applicable in large-scale inventories. If BEs from other regions or stand characteristics are used, their applicability under local conditions needs to be evaluated, for instance, in terms of the fit of the biomass allocation between the different georegions or stands, the fit of the dimensions of the sampled trees to the dimensions for which the used BEs are valid as well as the fit of the applied definitions (Zianis et al. 2005). Thereafter these BEs can be used for approximation of biomass in an area, where biomass studies of that particular species do not exist.

Uncertainty of BFs and BEs

Biomass factors and biomass equations are widely applied when countries are reporting their carbon stocks and stock changes, but very little is known about the uncertainty involved. The estimation of uncertainty is needed when countries report their greenhouse gas emissions and sinks according to GPG LULUCF (IPCC 2003). The uncertainty of tree biomass will also be utilized when estimating the overall uncertainty of forest carbon budget, including soil carbon stock, such as presented by Monni et al. (2006). However, as Phillips et al. (2000) note it may be practically impossible to quantify all sources of errors of applying BFs or BEs applications at regional or national levels.

Jenkins et al. (2003) listed several sources of errors that are involved when BEs are applied to national scale. Similar errors can increase the uncertainty of biomass estimates when using BFs. In addition to sampling, measurement and data processing, which may introduce random errors, as well as measurement bias, further bias may be caused, inter alia, by the following:

- Factors or equations developed for one site may not apply to another one.
- Factors or equations developed for one species (or species group) may not apply to another one.
- Sample trees and wood density samples may not be representative of the target population with respect to size range or other characteristics of sample trees that result from stand history and management.
- Form of mathematical formula in the case of BEs.
- The multiplication of several BFs (e.g. wood density and expansion factor) instead of the use of combined factor.

Recent work by Levy et al. (2004) makes an exception compared to previous studies, as the minimum, maximum, mean, median and standard deviation of BEFs and root–shoot ratios for conifers in the UK were reported based on felled trees. This information could be utilized when the uncertainty of carbon stocks in the UK is studied. Relative standard error of average BEFs by Levy et al. (2004) varied between 4 and 15% from the mean depending on the tree species.

According to an extensive biomass measurement done in Catalonia, Spain, relative standard error of aboveground BEFs varied between 5 and 17% for Mediterranean tree species. Relative standard errors for aboveground factors were less than 13% with most species, while it was up to 17% for species that had rather small sample (Sabaté et al., submitted). These reported uncertainties can be used as lower limit of possible uncertainty when uncertainty estimates are lacking and need to be covered by expert judgement.

A study by Lehtonen et al. (2004) had a different approach for uncertainty estimation for BFs. Here, biomass equations by Marklund (1988) were applied for tree-level NFI data of Finland, and the relative standard error was assessed by combining model errors and sampling error of NFI by age classes. The relative standard error of BEFs in this study varied from 20 to 2%, being in general less than 5% depending on the tree species and age class. In this study it was assumed that BEs by Marklund (1988) developed in Sweden are representative for Finland.

The common feature of extensive biomass measurement data sets, such as those for the UK (Levy et al. 2004), Finland (Hakkila 1979) and Sweden (Marklund 1988), is that these were not originally designed to fulfil the needs of national greenhouse gas reporting. Therefore, the representativeness and sampling methods of these studies can be questioned. Anyhow, systematic errors of the factors that are developed for biomass estimation are difficult to quantify, because it requires an independent set of data of biomass measurements to be compared against BFs. In a study by Lehtonen (2005) systematic errors of BFs for foliage by Lehtonen et al. (2004) were assessed, and the BEs by Marklund (1988) and Hakkila (1991) were tested against independent biomass data from Southern Finland, totalling ca. 400 felled conifers. It was found out that systematic errors for foliage biomass varied from − 40 to + 20%. However, foliage biomass is the most difficult aboveground biomass pool to be estimated and therefore systematic errors are likely to be lower for the total aboveground biomass.

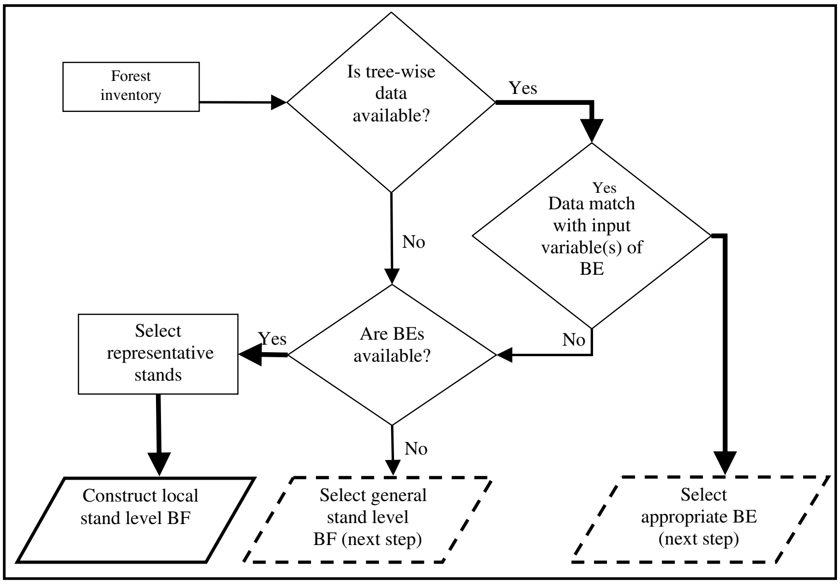
With respect to BEs, most of them lack information on the error estimates of the empirical parameters. According to Keith et al. (2000), the main sources of error in implementing allometric BEs could occur at the tree scale and when biomass estimates are extrapolated from plot to regional scale. It should be noticed that when a logarithmic or any other transformation is applied to the raw data, biomass predictions are biased (Baskerville 1972; Sprugel 1983). Mathematical formulae for correcting bias provide accurate estimates even though assumptions about the distribution of statistical errors must be made (Zianis et al. 2005). Thus, prior to the use of BEs for biomass predictions at the stand, regional or continental scales one should evaluate the status of data deficiencies and the possible methodological inconsistencies to avoid biased biomass estimates.

Guidance on the selection and application of appropriate BFs and BEs

In the estimation of forest biomass over large areas by appropriate factors or equations, methodological options should be carefully evaluated and understood in order to avoid obtaining biased estimates. Figures 4, 5 and 6 are designed to guide any practitioner to select and apply proper methods for biomass estimation at regional or national scale. Figure 4 suggests to check if available forest inventory data and BF/BE inputs are both at the same level, i.e. tree or stand, and to use as much tree-level information as possible. Figure 5 suggests that it is necessary to check species and fitting for ecoregion. Finally, Fig. 6 should be used to check the representativeness of stand structure. Note that optimal cases are marked by thick lines in the figures.

When selecting factors or equations to be used in the estimation of biomass, the user should stay at tree level if data are available for this resolution and use BEs in the first place. If they are not available or not repre-

Fig. 4 Decision tree to help select appropriate factors or equations. I. Checking for availability of data, factors and/or equations



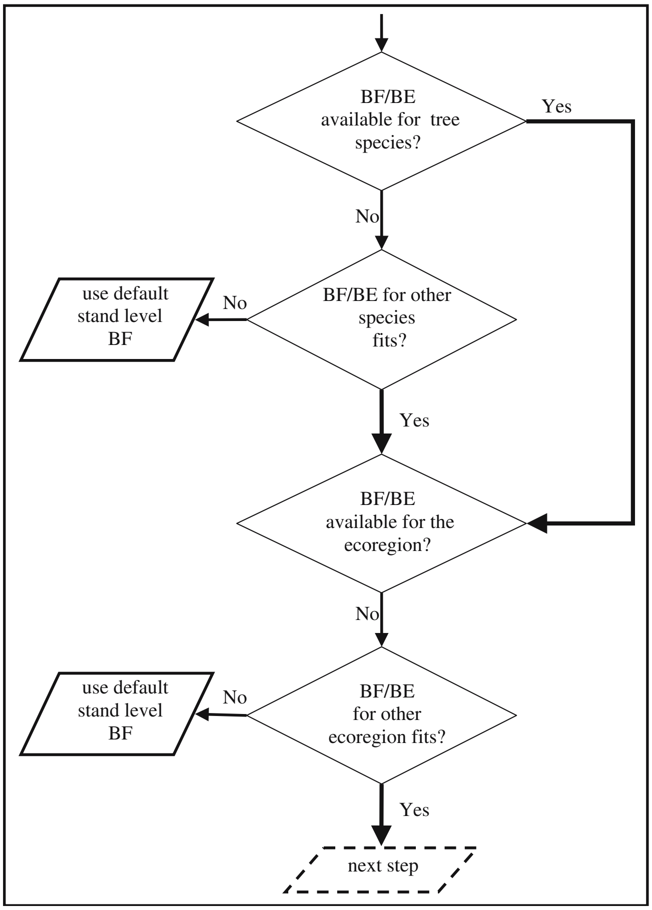


Fig. 5 Decision tree to help select appropriate factors or equations. II. Checking for species and ecoregion (applicable for both tree and stand levels)

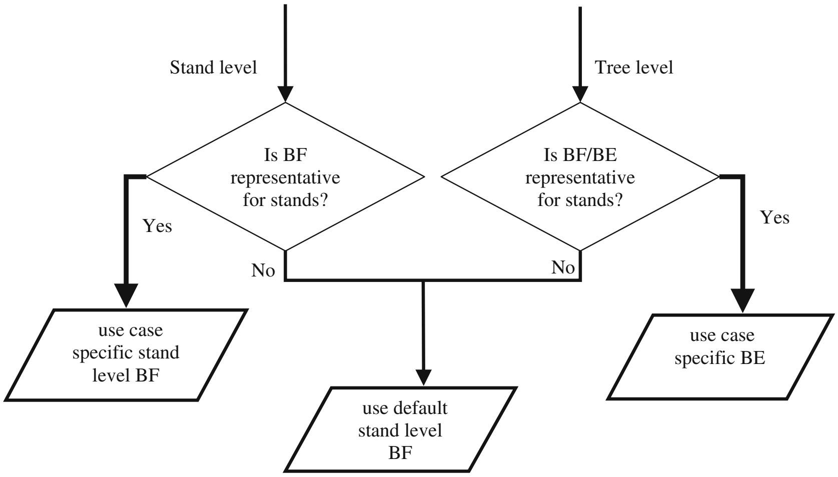
sentative, developing local factors or equations should be considered. Studies on belowground biomass are especially rare, and investigating root-to-shoot ratios and their dependence on stand and site characteristics would be needed. When local data are not available, information from databases should be used to approximate local conditions. If representative information cannot be found default values (IPCC 2003) should be applied. Also, care should be taken to define the values as a basis of the estimation and the biomass that is to be estimated (i.e. what fractions and/or merchantable limits they contain).

It must be noted that in forest carbon inventories, BFs and BEs may be used with different values like volume increment and harvested volume. The definition of these values may differ, and the forest carbon inventory only gives unbiased estimates if the BFs and BEs are applied consistently, taking into account the possible differences in definitions.

Finally, the reporting of complete information on the definition, development and use of BFs and BEs is needed both in scientific publications, as well as any national inventory reports or national communications. At least the following information is needed when reporting on any factor or equation that is used in biomass estimation:

- Tree species and origin (seed, coppice) for which the factors or equations are applied, and for which the factors or equations were developed
- Compartments that are included in the definition of biomass and, in case of BFs, the compartments that are included in the variable from which the biomass is calculated
- How sampling was applied for the development of BF or BE: number of trees, range of sites covered, range of tree sizes, range of ages of sample trees, main stand characteristics, management type and disturbance history of sample stands, etc.
- Any information on uncertainty of the factor or equation

Fig. 6 Decision tree to help select appropriate factors or equations. III. Checking for representativeness of stands used for developing BFs/BEs (applicable for both tree and stand levels)



For BFs, the following additional information is also needed:

- How is biomass estimated: with destructive measurements or using BEs
- If the BF is of stand level or tree level
- In case of stand-level BF, how sampling was made with respect to represent stand information: as in the previous list

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