Ann. For. Sci. 61 (2004) 677–682
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DOI: 10.1051/forest:2004066

Original article

Inventory-based carbon stock of Flemish forests: a comparison of European biomass expansion factors

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(Received 2 June 2003; accepted 6 February 2004)

Abstract – Different European Biomass Expansion Factors (BEFs) were compared for the inventory-based quantification of total aboveground and belowground biomass in forests. Therefore a qualitative analysis is performed on the biomass results obtained through the BEF approach and those from experimentally established allometric relations based on destructively sampled and fully excavated trees. Total organic carbon (OC) stock in aboveground and belowground living biomass of Flemish forests amounts to 12 Mt on average, with a significantly larger OC stock per hectare in deciduous forests compared to coniferous or mixed forest types. Total forest biomass seems to be fairly well approximated by a multiplication of the standing stock with either one of the applied BEFs. However an indication of the volume and age class for which the BEFs are established and a refined diameter-volume-biomass relation for oak trees in Europe, are required to gain more accurate results.

forest inventory / carbon stock / biomass expansion factor / allometric relation

Résumé – Stocks de carbone dans la biomasse des forêts en Flandre à partir d'un inventaire permanent des ressources forestières : une comparaison des facteurs européens d'expansion. Différents facteurs européens d'expansion pour la biomasse (FEB) sont utilisés pour la quantification de la biomasse aérienne et souterraine des écosystèmes forestiers à partir d'un inventaire permanent. Une analyse comparative des résultats obtenus, d'une part, par l'approche des FEB et d'autre part, par l'utilisation de relations expérimentales à l'aide d'un échantillon d'arbres complètement découpés et déterrés est effectuée. Dans les forêts en Flandre le stock de carbone dans la biomasse aérienne et souterraine est estimé à 12 Mt en moyenne ; le stock de carbone des forêts d'essences feuillues est significativement plus élevé que celui des bois de conifères ou des forêts mixtes. La biomasse des forêts est relativement bien évaluée par la multiplication du volume à l'hectare sur écorce par l'un des FEB européens. Néanmoins les valeurs des FEB dépendent de l'âge et du volume des peuplements qui ont permis de les évaluer. L'utilisation des relations circonférence-volume-biomasse affinées pour le chêne en Europe semble indispensable pour obtenir des résultats plus précis.

inventaire des ressources forestières / stock de carbone / facteur d'expansion / relation allométrique

1. INTRODUCTION

Throughout the world countries are seeking to comply with the agreements under the United Nations Framework Convention on Climate Change (UNFCCC) and to implement the commitments under the Kyoto Protocol. As parties are allowed to offset their emission reduction targets by increasing biological carbon (C) sequestration in terrestrial ecosystems including forests, there has been an increasing interest in accurate measurement of the regional carbon stocks in forest biomass [2].

Accurate estimates of the amount of carbon sequestered in forest ecosystems are easily accomplished by applying the available, consecutive forest inventory data of a region [13, 20]. As such the measurements of forest carbon pools are based on well-established techniques of conventional forest inventory, soil sampling and ecological surveys [3, 16, 30]. However forest inventories are traditionally intended to monitor economically interesting wood volumes for the purpose of making sound management plans. No biomass measurements are performed on a regional basis. As such the inventory-based carbon budgetting methods generally rely on (uncertain) conversion techniques to expand stemwood volume into estimates for total tree carbon and litterfall rates [10].

Two different methods are generally applied to convert easily measurable tree or stand characteristics to total biomass. When the experimental diameter to biomass relation for each species in the stand is known and the individual tree diameter measurements exist, biomass can be found by applying directly

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these allometric equations to all trees or diameter classes. The equations might be species-specific or more general in nature (pooled by species group). Caution is necessary though when extrapolating these allometric relations to other sites or outside the range of diameters for which they were established [18, 25]. Destructive sampling of mature trees on a regional basis, in mixed uneven-aged forests and especially the excavation of their root system, is extremely time-consuming and no option in a normal management regime. Thus most countries have but a few studies on allometric relations obtained from destructive sampling of a few species in a few sites [4]. For forests where such experimental relations are not available, simple models have been developed which convert merchantable volume to total aboveground and belowground dry matter using a combination of expansion and conversion factors [3]. An expansion factor is used to scale up from a lower (e.g. stem) to a higher level (e.g. total aboveground). Conversion factors on the other hand are used to translate the data in another unit (e.g. from m^3 to t DM). There are several reported combinations of expansion and conversion factors to calculate total carbon stock in a forest stand, starting from the known total stem volume: (i) stem volume can be converted into stem dry matter followed by an expansion to total aboveground and belowground dry matter and a conversion to total carbon stock; (ii) total tree volume can be calculated by expanding the stem volume followed by a conversion into total dry matter and carbon stock; (iii) stem volume can also be converted directly into the amount of carbon in the stems followed by an expansion to the total aboveground and belowground carbon stock. The factors and their combinations are mostly referred to as Biomass Expansion Factors (BEFs). They are generally based on a combination of measurements for broad species groups or specific species in different countries. The use of these BEFs is foreseen by the IPCC guidelines in those cases where no biomass information is readily available [12].

The aim of this study was to compare reported BEFs from European literature with allometric relations [17] in producing a good approximation of total aboveground and belowground carbon stock in living biomass for a typical Flemish deciduous forest stand. Based on destructively sampled stems and branches and fully excavated coarse roots of oak, beech and ash, a qualitative comparison explored the possibilities of European BEFs for the quantification of the total carbon stock in regional forest biomass. A forest inventory-based carbon quantification was performed and evaluated for the aboveground and belowground living biomass of Flemish forest ecosystems.

2. METHODS AND DATA

The analysis was based on available data in the mixed deciduous Aelmoeseneie forest (Gontrode, East-Flanders, Belgium), property of the Ghent University [23, 28] and the regional Flemish forest inventory [9]. Tested BEFs were taken from European literature [17].

The Aelmoeseneie forest dates back to the year 864. Overfelling during World War I (1914–1918) necessitated a replantation. As such most of the mature trees are now about 80 years old. In 1993 a scientific zone was installed comprising two forest types: an oak-beech stand, with mainly pedunculate oak (*Quercus robur* L.) and common beech (*Fagus sylvatica* L.) on sandy loam soil and an ash stand with mostly common ash (*Fraxinus excelsior* L.) and common sycamore (*Acer pseudoplatanus* L.) on a sandy loam soil covered with alluvium. These stands contain a Level II plot of the forest condition monitoring program, as part of the "International co-operative program on the assessment and monitoring of air pollution effects on forests" (ICP-plots, UN/ECE).

Table I. General biomass expansion factors (t DM in aboveground and belowground biomass m^{-3} stem volume) for both deciduous and coniferous tree species [17].

BEF	Deciduous species	Coniferous species
1	0.72	0.48
2	0.77	0.49
3	0.84	0.57
4	0.86	0.60
5	0.93	0.69

Table II. Species-specific biomass expansion factors (SBEF) (t DM in above- and belowground biomass m^{-3} stem volume) for the main tree species of the experimental forest Aelmoeseneie [17].

SBEF	Oak	Beech	Maple	Larch
1	0.87	0.74	0.87	0.68
2	1.02	0.76		
3		0.99		

Destructive sampling of 12 oaks, 6 beeches and 6 ashes from the oak-beech stand in 1997 provided information on the stem volume, based on Simpson's formula [22], circumference – volume relations between stem volume (V) and circumference at breast height (CBH), wood density and total dry weight of stems and branches [28]. Two of the sampled oak trees were excavated and all coarse roots (diameter > 5 mm) were meticulously collected. The coarse root system of both trees amounted to 16.3% and 17.6% of total tree biomass [28]. Duvigneaud (1984) found a similar root fraction of 17.0% in a *Querceto-Coryletum* of 80 years. Literature values of root fractions were used to assess the carbon stored in the coarse roots of the other species: 16.8% for beech and 16.3% for ash [8].

For the conversion of stem volume (m^3 ha^{-1}) into total aboveground and belowground dry matter (t DM ha^{-1}) five comparable European BEFs, termed *general* BEFs in this article, were used [17] for both coniferous and deciduous tree species (Tab. I). All exclude the amount of dry matter in leaves and needles. For the main tree species of the Aelmoeseneie experimental forest, comparable *species-specific* BEFs were also retained [17] for further calculations (Tab. II). As the aim is to assess the influence of different expansions from volume to biomass, rather than the carbon content in biomass, the default IPCC carbon content value of 0.5 t t^{-1} DM was used [30].

2.1. Comparison of BEFs

To compare the biomass results obtained through application of different European BEFs for the calculation of the regional Flemish forest biomass carbon stock, the Aelmoeseneie forest served as test case. A comparison was made between total forest biomass derived from experimentally obtained diameter-biomass relations and total forest biomass calculated through multiplication of the stem volumes with general (Tab. I) as well as species-specific (Tab. II) BEFs.

For all destructively sampled trees allometric relations were established between stem diameter at breast height (*DBH* in cm) and total biomass of stems, branches and coarse roots (kg DM). The most frequently found function in biology that describes the allometric diameter-biomass relation is the power function [5, 6, 14, 15, 21, 24, 26, 27, 29]. This function is biologically reasonable and takes on the following simple form:

$$B = aD^b$$

with B being the total aboveground and belowground biomass (kg DM), D is the diameter at breast height (cm) and a en b the coefficients of the equation. For each relation the 95% confidence and 95% prediction intervals on the regression line were calculated. Consecutively tree biomass for all sampled trees was calculated by multiplying the stem volume with the corresponding general or species-specific BEF and the obtained results were related to the above prediction intervals.

Total aboveground and belowground forest biomass for the Aelmoeseneie stand was then calculated by applying general BEFs, species-specific BEFs and the experimental allometric relations on all trees in the stand. Significant differences between the means of the obtained biomass calculations were assessed by an analysis of variances (ANOVA). Post hoc tests determined which means differed (SPSS11.0). For ash, for which no species-specific BEFs were found, only two techniques were tested.

2.2. OC stock in Flemish forests

Based on the recent Flemish regional forest inventory (RFI) [9], a detailed description was obtained of the forest type distribution, age classes, species distribution and standing stock. The inventory is based on a regular 50 ha grid of permanent sample plots encompassing all forest types and age classes [9]. Silvicultural measurements include: circumference (cm^2), height (m), basal area (m^2 ha^{-1}), stand density (number ha^{-1}) and stem volume (m^3 ha^{-1}) for all tree and shrub species with a threshold of 7 cm (*DBH*). Each sample plot (2517 in total) is classified in a specific stand type. A distinction is made between the following stand types with their corresponding species composition [9]:

Deciduous (D): > 80% of the basal area is represented by deciduous species; Coniferous (C): > 80% of the basal area is represented by coniferous species; Mixed deciduous (MD): 20–50% mixture with coniferous species; Mixed coniferous (MC): 20–50% mixture with deciduous species.

For each forest grid, stem volume per species per unit area is known. Multiplying this volume with the corresponding BEF gives the total biomass for that species (t DM ha^{-1}). This calculation was performed for the 5 different general BEFs (Tab. I) and for all species of each forest type and age class (1–20 years; 21–40 years; 41–60 years; 61–80 years; 81–100 years; 101–120 years; 121–140 years; 141–160 years; >160 years and uneven-aged), generating a range for the total biomass in each forest type and age class. The total area for each forest type was derived from the updated Flemish forest map [9]. As well as for the trees in the Aelmoeseneie forest, the IPCC default carbon content of 50% of the dry matter is used. Summation of the OC stocks over the different forest types generated the range of the total actual carbon stock in the aboveground and belowground biomass of the Flemish forests. An analysis of variances with post-hoc tests was performed to identify significant differences in biomass content between forest types and age classes (SPSS11.0).

OC stock calculations in the national communications to the UNFCCC for the Flemish region will be based on the above methodology. The question is whether those obtained OC stocks will be a good approximation of the actual carbon stock for the Flemish forests. Based on the available stand volume data for the Aelmoeseneie experimental forest and the available BEFs, the carbon stocks in the Aelmoeseneie forest were compared to those of the RFI mixed deciduous forest type of the same age class.

3. RESULTS AND DISCUSSION

3.1. Comparison of BEFs

The species-specific diameter-biomass relations for oak, beech and ash in the Aelmoeseneie forest are best described by the power function:

$$TDM = a\,(DBH)^b$$

Table III. Parameter values of the species-specific linearized models. The standard errors of the estimates (SEa and SEb) are significant at the 1%-level. *Adj.* R^2 = adjusted coefficient of determination, SEr = standard error of regression, E = correction factor [1, 26].

Tree species	ln a	b	E	*Adj.* R^2	SEa	SEb	SEr
Oak	–2.180	2.554	0.002	0.943	0.640	0.188	0.147
Beech	–1.897	2.489	0.003	0.996	0.217	0.068	0.118
Ash	–0.867	2.157	0.003	0.950	0.767	0.219	0.117

where *TDM* = total aboveground and belowground dry matter (kg DM) and *DBH* = diameter at breast height (cm). A log transformation was performed to remove heteroscedasticity. This results in the following equation:

$$\ln TDM = \ln a + b \times \ln DBH.$$

To express estimated values of *TDM* in arithmetic (untransformed) units a back transformation is necessary. When transforming back, the intercept of the linear regression has to be corrected for logarithmic bias. Otherwise the estimate after retransformation will yield a systematic underestimation of the actual *TDM* value. To correct for this bias a correction term was added [1, 26, 31]. This results in the final equation:

$$\ln TDM = \ln a + b \times \ln DBH + \mathrm{E}$$

where E = SEr^2/2 and SEr the standard error of regression. Table III gives the linear regression results for the different tree species.

Figures 1 to 3 show the relations for each tree species in arithmetic units, including the 95% confidence and 95% prediction intervals on the regression. Superimposed, the biomass results based on the general and the species-specific BEFs are shown for each sampled tree. As can be seen, the prediction interval is always wider than the confidence interval and even widens exponentially with increasing diameter. This is inherently connected to the nature of the power function where the standard deviation of predicted biomass is proportional to the mean biomass per diameter class [14, 15]. Biomass predictions for trees in the deciduous stand within the experimental diameter range and based on these equations, will have a 95% probability of occurring within these prediction intervals on the regression. From the graphs it is also obvious that *TDM* calculations for the sampled trees by expanding stem volume to total aboveground and belowground biomass based on general BEFs are also found well within these 95% prediction intervals for the diameter range as found in the deciduous forest Aelmoeseneie.

Furthermore when the experimental allometric relations, the general BEFs and species-specific BEFs were applied to all trees in the Aelmoeseneie stand, no significant differences were found (ANOVA) between the *TDM* results (Tab. IV).

Although biomass expansion factors are correctly situated among the most uncertain variables in the carbon budgetting methods [10, 11], the reported European general and species-specific BEFs enable a good approximation of total aboveground and belowground forest biomass in the typical deciduous stands of the Aelmoeseneie forest. It is expected that the reported BEFs will perform evenly well in other Flemish mixed deciduous forest

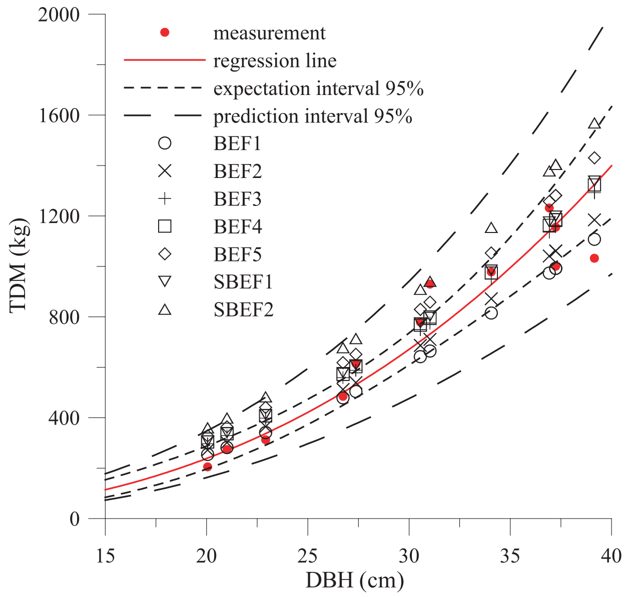

Figure 1. Allometric relationship for oak, with corresponding prediction intervals, superimposed with the total biomass as calculated from reported general BEFs (Tab. I) and species-specific BEFs (Tab. II).

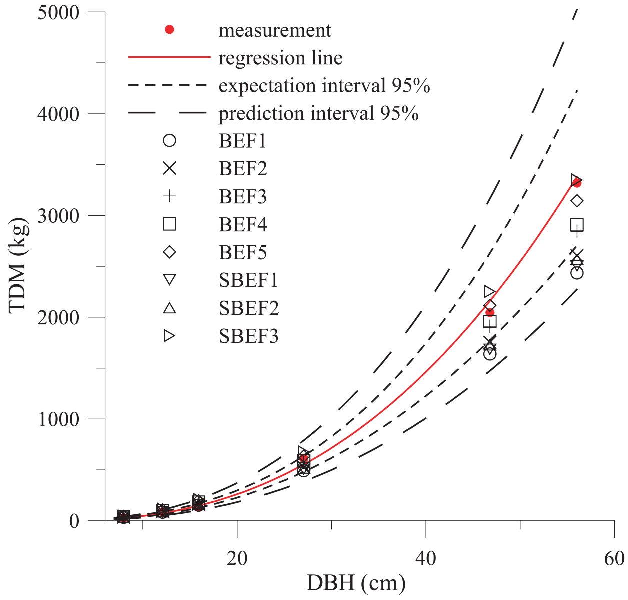

Figure 2. Allometric relationship for beech, with corresponding prediction intervals, superimposed with the total biomass as calculated from reported general BEFs (Tab. I) and species-specific BEFs (Tab. II).

stands. This can be verified as soon as more biomass assessments in other typical Flemish deciduous forest stands come available. Caution is necessary for oak trees though, where the second species-specific BEF is systematically higher compared to the other BEFs. Furthermore, Tamhane's T2 post hoc tests (ANOVA) reveal only for oak significant differences between *TDM* values obtained through general BEFs and species-specific BEFs (Tab. IV). *TDM* values calculated with the minimum and maximum general BEFs are also significantly different for oak (Tab. IV). This might indicate that the actual reported European BEFs for deciduous forests are too general for oak trees. More research on other oak stands in mixed deciduous forests would clarify this finding. Refinement of the diameter-volume-biomass relation for oak will certainly improve the assessment of general BEFs for deciduous forests.

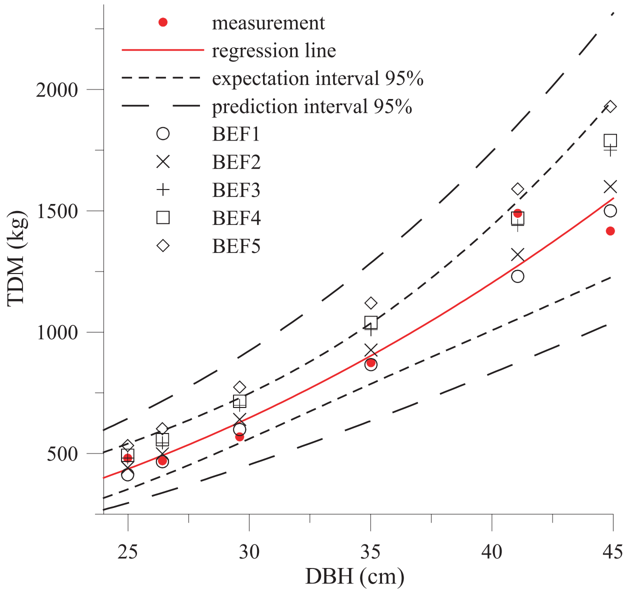

Figure 3. Allometric relationship for ash, with corresponding prediction intervals, superimposed with the total biomass as calculated from reported general BEFs (Tab. I).

3.2. OC stock in Flemish forests

The total forest area in Flanders amounts to 146 381 ha (10.8% of the territory), with 732 ha temporarily not forested [9]. The deciduous forest type occupies 51% of the total forested area, followed by the coniferous (38%) and the mixed types (10%) (Fig. 4). Dependent on which pair (deciduous and coniferous species) of general BEFs is chosen from Table I, the total regional OC content in the aboveground and belowground living biomass of the Flemish forests ranges from 10 to 14 Mt. 6 to 8 Mt OC is stored in deciduous forests, 3 to 5 Mt OC in coniferous forests, 0.4 to 0.5 Mt OC in the mixed deciduous and 0.5 to 0.7 Mt OC in the mixed coniferous forests. Figure 4 shows the distribution of the total OC stock per hectare over the different forest types. Tamhane's T2 post hoc tests (ANOVA) revealed significantly more OC per hectare in the living biomass of deciduous forests compared to coniferous forests for all age classes other than the first one (1–20 years). This is in accordance with previous studies at stand level [19, 28].

The comparison of the OC stock in the deciduous Aelmoeseneie forest stands (oak and ash in the age class 81 to 100 years) with the RFI deciduous forests of the same age class, reveals no significant differences between the average OC stocks per

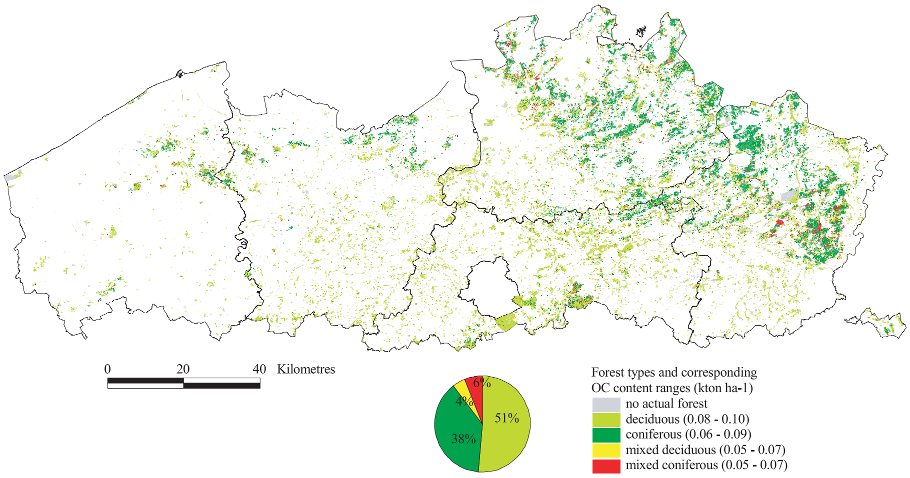

Figure 4. Forest types in Flanders with their corresponding OC stock range in aboveground and belowground living biomass, based on the minimum (BEF1) and maximum (BEF5) general European BEFs applied in this study.

Table IV. Total aboveground and belowground DM (*TDM*, t DM ha^{-1}) for the oak, beech and ash trees of the oak-beech stand in the Aelmoeseneie experimental forest based on three conversion techniques, with indication of the significant differences (a and b) that occur (*TDM*1 is calculated based on the experimental diameter-biomass relations, *TDM*2–*TDM*6 are based on the general BEFs and *TDM*7–*TDM*9 on the species-specific BEFs).

	Oak	Sign	Beech	Sign	Ash	Sign
*TDM*1	135.89	–	97.51	–	10.48	–
*TDM*2	118.09	a, b	62.00	–	9.34	–
*TDM*3	126.29	b	66.31	–	9.98	–
*TDM*4	137.77	–	72.33	–	10.89	–
*TDM*5	141.05	–	74.06	–	11.15	–
*TDM*6	152.53	a	80.08	–	12.06	–
*TDM*7	142.69	–	63.72	–		
*TDM*8	167.29	b	65.44	–		
*TDM*9			85.25	–		

hectare. The OC stock in the Aelmoeseneie deciduous oak stand, as calculated based on the 5 different BEFs and the available stand volume, ranges from 112 to 146 t OC ha^{-1} for the minimum and maximum BEF respectively. The OC stock in the ash stand ranges from 120 to 155 t OC ha^{-1} and the OC stock as calculated from the RFI data for this forest type and age class ranges from 118 to 152 t OC ha^{-1}. Calculation of biomass OC stock based on inventory data and reported BEFs appears to be a good approximation for the biomass in the Aelmoeseneie forest. This leads one to suspect that the OC stock as calculated from the RFI data and BEFs render a good approximation of the actual OC stock in deciduous forests. More experimental information on other deciduous forests for different age classes would enable the verification of this finding. The use of general BEFs and regional forest inventory data is undoubted the most practical way to quantify total aboveground and belowground carbon stock in Flemish forests. However special attention is drawn to research conducted by Brown (2002) on US forests. She found that the magnitude of the BEFs varies with the merchantable volume of the stand. More precisely the BEFs follow a reverse power function. Low volumes correspond with high BEFs, which generally decrease exponentially to a constant BEF at high volumes. Since general BEFs were applied here, with no information on the volume class for which they were established, the same BEFs were used for all volume classes. Consequently an overestimation of the total biomass for the older stands and an underestimation of the biomass for the young forest stands might have arisen. Therefore when reporting general BEFs for use in regional carbon budgetting, the volume and age class for which they were established should be communicated. Furthermore, although not significant in this case, the occurring differences in mean OC stock values between the case study and the RFI calculation are largely due to different volume calculations between both studies. The RFI volume calculation is based on height and diameter measurements for all trees in the permanent plot and the volume equation of Dagnelie [7]. For the main tree species of the Aelmoeseneie forest on the other hand, an allometric volume equation was established between circumference and volume of several model trees. For the secondary species beech, maple and larch, height was calculated based on an allometric relation between diameter and height, and the volume equation of Dagnelie [28]. Comparison of these volume calculations for oak in the oak-beech and ash stand, revealed an underestimation of the volumes, and consequently biomass and carbon stock, for bigger trees when the allometric volume equation of Vande Walle et al. [28] was used compared to the equation of Dagnelie. Thus information on how the commercial volumes in a forest stand are calculated seems very important for accurate carbon budgetting.

4. CONCLUSIONS

Qualitative analysis of different biomass assessments leads one to suspect that the biomass carbon stock in the Flemish forests can be approximated by a multiplication of the standing stock with a general European BEF. The application of species-specific BEFs did not significantly alter the biomass calculations for beech and ash. However, identical BEFs (grouped per species group) applied to oak, beech and ash gave rise to higher variability within the oak population. The reported species-specific BEFs for oak also are more variable than those for beech. This draws the attention to the fact that more refinement on the diameter-volume-biomass relationship for oak trees might be necessary in order to establish general BEFs for deciduous trees that better reflect the oak population then they seem to do now. It would be worthwhile checking these findings in other European forest stands since the use of general BEFs would facilitate the biomass calculations and would improve European transparency in calculations. Attention could be focused then on improving the existing general BEFs instead of searching for another best species-specific BEF in each country.

It is concluded that the most practical way to assess carbon stock in the Flemish forests based on forest inventory data is by use of the reported general BEFs. Since no statistical difference was found between the five tested general BEFs no further conclusions on the choice of BEF can be drawn. However, more accurate biomass calculations would be possible if BEFs were reported together with the corresponding volume classes for which they were derived and if uncertainties on the factor were included. Furthermore regional and national continuous forest inventory monitoring programmes should be based on a well-defined methodology, including information on how the commercial volumes are estimated and accuracy assessments. Based on general BEFs and forest inventory data, the total OC stock in aboveground and belowground living biomass of Flemish forests is estimated at 12 Mt and a significant higher amount of OC per hectare is found in the deciduous forest type compared to the coniferous type.

Acknowledgements: This research was carried out as part of the CASTEC project (Carbon Sequestration potential in Belgian Terrestrial Ecosystems: quantification and strategic exploration) of Ghent University and CLO, financed by the Belgian OSTC (Second Multiannual Scientific Support Plan for a Sustainable Development Policy – SPSD II, contract nr. EV/02/12). Martine Waterinckx (Forest and Green Areas Division – FGAD) significantly contributed to this research by providing the necessary RFI data and by helpful and clarifying discussions.

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