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Original article

Growing stock-based assessment of the carbon stock in the Belgian forest biomass

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Abstract – Belgian forests covered 693 181 ha in 2000, representing 22.7% of the total land area. As no biomass or carbon stock data are included in the Flemish and Walloon regional forest inventories, species-specific wood densities, biomass expansion factors s.s. and carbon content values were critically selected from the literature. Based on these conversion and expansion factors, and on data from the forest inventories, the total C-stock in the living biomass of productive Belgian forests was assessed at 60.9 Mt C in the year 2000. The overall mean C-stock amounted to 101.0 t C ha^{-1}. This value was in the higher range of values reported for the neighbouring countries, mainly due to a high mean growing stock in the Belgian forests (261.9 m^3 ha^{-1}). The conversion from wood volume to wood biomass based on wood density values reported in the literature appeared to introduce the largest variability in the assessment of the carbon stocks. Additional measurements of wood densities in Belgian forests could help to reduce the uncertainty related to this factor. Because of the time-consuming and destructive character of the determination of biomass expansion factors s.s. (BEFs), the establishment of new BEFs does not have the highest priority in the framework of improving the assessment of the biomass carbon stock in the Belgian forests. As the median C-content value for all species except beech was equal to the default IPCC-value of 50% carbon in dry matter, it seems appropriate to use this value for future calculations.

forest inventory / carbon stock / biomass expansion factor / wood density / aboveground and belowground biomass / carbon content

Résumé – Estimation des stocks de carbone dans la biomasse des forêts en Belgique. La forêt belge couvrait 693 181 ha en 2000, ce qui représente 22,7 % de la surface totale du pays. Les inventaires forestiers flamands et wallons n'incluent pas de mesures directes de biomasse ou de stock de carbone. Pour calculer les stocks de carbone dans les arbres forestiers à partir des volumes de bois fort, les infradensités du bois, les facteurs d'expansion de la biomasse et les teneurs en carbone ont été sélectionnés dans la littérature. En 2000, les stocks de carbone dans la biomasse des forêts belges productives étaient de 60,9 Mt C, soit 101,0 t C ha^{-1}. Cette dernière valeur est relativement haute comparée avec celles observées dans les forêts des pays avoisinants, à cause d'un grand volume de bois fort dans les forêts belges (261,9 m^3 ha^{-1}). L'infradensité du bois semble être le facteur qui introduit la plus importante variabilité dans le calcul des stocks de carbone dans la biomasse. Des mesures complémentaires des infradensités du bois des essences les plus communes en Belgique pourraient aider à réduire significativement les incertitudes sur les mesures des stocks de carbone dans les forêts. La détermination expérimentale des facteurs d'expansion est coûteuse en temps et se base sur des analyses destructives. Ainsi, l'obtention de facteurs d'expansion propre à la situation belge n'est pas prioritaire. La valeur par défaut de la teneur en carbone dans la matière sèche proposée par l'IPCC (50 %) semble appropriée dans le calcul des stocks de carbone dans la biomasse forestière.

inventaire forestier / stock de carbone / facteur d'expansion de la biomasse / infradensité du bois / biomasse aérienne et souterraine / teneur en carbone

Abbreviations: AG: aboveground; BEF: biomass expansion factor s.s. (t DM t^{-1} DM); BEF s.l.: biomass expansion factor s.l. (collective expression for WD, BEF and CC); BG: belowground; C: carbon; CC: carbon content (t C t^{-1} DM); DM: dry mass; IM: impact factor; ResX: result of scenario X; TSW: total solid wood; WD: wood density (t DM m^{-3}).

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Table I. Distribution of forests over the three Belgian regions: Flanders, Brussels-Capital and Wallonia; forest cover gives the ratio of the regional forest area to the total regional area.

Region	Total area (km^2)	Forest area (km^2)	Forest cover (%)	% of the total Belgian forest area
Flanders	13 521	1 463	10.8	21.1
Brussels Capital	162	20	12.3	0.3
Wallonia	16 845	5 448	32.3	78.6
Belgium	30 528	6 931	22.7	100.0

1. INTRODUCTION

All over the world, countries try to fulfil their commitments under the United Nations Framework Convention on Climate Change (UNFCCC), and they seek to achieve the national engagements of the Kyoto Protocol (KP). Countries are allowed to offset their emission reduction targets by increasing biological carbon (C) sequestration in terrestrial ecosystems, as indicated in Art. 3.3 (Afforestation, Reforestation and Deforestation) and Art. 3.4 (Additional human-induced activities) of the KP [49]. Consequently, an increasing interest exists in the accurate measurement of forest carbon stocks [8, 9, 26]. Globally, forests represent important carbon stocks: while only occupying 27% of the world's area covered by terrestrial ecosystems, they contain 77% of the carbon stored in the biomass and 46% of all soil-C [8, 24].

The Intergovernmental Panel on Climate Change (IPCC) foresees through the so-called "bottom-up approach" for the calculation of the stock changes over the first commitment period (2008–2012). This approach is based on the use of data available in national or regional forest inventories. Most forest inventories are firstly meant for sound forest management practices and are intended to monitor the wood volumes of economical interest. Biomass measurements are usually not included in the sampling procedure [12]. An exhaustive review of the various forest inventories conducted by the member states in the European Union and an analysis of their potentials to meet the requirements under the KP were developed in 2000, as represented in a synoptic table by Laitat et al. [31]. However, if the inventory-based carbon budgeting method has to be applied, then calculation techniques are needed to convert and expand stemwood volume into total aboveground and belowground carbon stocks [48]. If tree-wise data are available, biomass equations can be applied [26, 51]. Otherwise, the use of a conversion procedure based on so-called biomass expansion factors s.l. (BEFs s.l.) is proposed by the IPCC guidelines for the cases where no biomass information is readily available [21]. Within this context, the question remains which of the conversion and expansion factors reported in literature represent the most suitable values to apply for a specific region or country.

In Belgium, climate policy is formulated at the federal level, requiring co-operation between regional and federal administrations. Belgian forests covered 693 181 ha in 2000 [2, 42]. This represented 22.7% of the total land surface. The Flemish and the Walloon region used a similar sampling strategy for their forest inventory [1, 33]. As is the case for other countries, the Belgian forest inventories are not considering tree biomass or carbon stocks. Therefore, values were selected from the literature for: (i) the wood density per tree species, (ii) the species-specific expansion factors to calculate the total aboveground and belowground biomass starting from the stem biomass, and (iii) the carbon content value for conversion of biomass into carbon stock.

The objectives of this work were: (i) to critically select biomass expansion factors s.l. applicable for the most important tree species in the Belgian forests, (ii) to calculate the total carbon stock in the living biomass of the Belgian forests for the year 2000 and (iii) to identify the biomass expansion factors s.l. which introduce the largest variability in the carbon stock calculations.

2. MATERIALS AND METHODS

Belgium has a temperate maritime climate, with moderate temperature variability, prevailing westerly winds, heavy cloud cover and regular rain. The definitions of "forest" in the Belgian inventories are based on minimum requirements: an area of 0.5 ha and 0.3 ha, a width of 25 m and 9 m and a canopy closure of 20% and 10% in Flanders and the Walloon provinces (= Wallonia) respectively [1, 33]. These slight differences are due to specific aspects of the two regional policies on land use management. The consequences on the total wood volume however are negligible. The distribution of forests in Belgium is shown in Table I. The total forest area in Flanders amounted to 146 381 ha in 2000, based on the regional forest mapping [2], while Walloon forests covered 544 800 ha [42]. The data presented hereafter do not include the forests in the Brussels-Capital Region. Moreover, the study was focussed on productive forests only, and as such, data on non-productive or so-called "Forests not available for wood supply" or FNAWS [16] were excluded from the analysis.

2.1. The regional forest inventories of Belgium

The sampling points of the regional forest inventories were selected according to a 1.0 km × 0.5 km grid oriented from the east to the west on the National Geographic Institute (NGI) maps at a scale of 1/25 000. The rectangular grid had the advantage of going against the orientation of the relief elements oriented along a southwest-northeast axis and against ecological and geological gradients predominant in the N-S orientation. Each grid intersection, located in a forest, represented the centre of a sampling plot. For plots at edges or borders, the plot centre was moved towards the inside of the forest [1, 33].

Table II. Area and total solid wood volume for different tree species in Flanders and Wallonia, for the year 2000; information deduced from the Flemish and Walloon forest inventories [1, 3] (Hugues Lecomte, personal communication).

Species	Flanders			Wallonia		
	Area (ha)	Volume (1 000 m^3)	% of total volume	Area (ha)	Volume (1 000 m^3)	% of total volume
Pine	63 550	12 867.2	39.9	14 800	3 743.4	3.0
Douglas fir	1 280	371.0	1.2	10 800	2 387.2	1.9
Larch	3 060	782.3	2.4	8 200	2 081.2	1.7
Spruce	2 860	527.1	1.6	171 700	52 502.8	41.8
Other coniferous	910	174.0	0.5	19 600	4 955.4	3.9
Total coniferous	***71 660***	***14 721.5***	***45.7***	***225 100***	***65 669.9***	***52.2***
Beech	7 790	2 500.5	7.8	42 200	12 278.0	9.8
Oak	14 320	3 696.4	11.5	81 600	20 372.4	16.2
Mixed noble	10 250	2 357.0	7.3	57 100	15 041.4	12.0
Poplar	19 060	5 217.2	16.2	9 500	2 703.9	2.2
Other deciduous	21 650	3 753.1	11.6	43 200	9 661.7	7.7
Total deciduous	***73 070***	***17 524.1***	***54.3***	***233 600***	***60 057.3***	***47.8***
TOTAL	**144 730**	**32 245.5**	**100.0**	**458 700**	**125 727.1**	**100.0**

Sampling plots are circular and of 1000 m^2 each. The following information was collected: category of property (private or public: state, region or province), municipality, forest type, stand structure and development stage, commercial quality for broadleaf species with a section exceeding 22 cm circumference, evidence of damage caused by game and the health and condition for harvest (these two last categories are only available for the Walloon forests). Topography (exposition and slope), soil texture and drainage class, age (class), canopy closure, tree species, circumference at 1.5 m and total and dominant heights were also collected. Basic information in the Flemish and the Walloon inventories was therefore very similar. Moreover, the same volume tables were applied to calculate the total solid wood (TSW) volume from tree circumference and tree height. The terminology "total solid wood" refers to the combination of stem and branches with a circumference exceeding 22 cm [14].

In Flanders, 2 665 plots were sampled in the framework of the first forest inventory, which was constituted in the period 1997–1999 [1]. This regional inventory is intended to be repeated every 10 years, to allow e.g. the calculation of growth rates in the Flemish forests. The first Walloon forest inventory was completed in 1984. For this study, the current permanent systematic sampling was used. This second inventory started in 1994 and covers each year 10% of the approximately 11 000 sampling points [33]. In 2000 (reference year for this study), 50% of the sample points of the second inventory were measured.

With more than 13 000 plots over a territory of 30 528 km^2, forest inventories in Belgium have one of the highest sampling rates in Europe. Compared to other countries or regions, the Belgian sampling grid, with each sampling point representing 50 ha of forest, is very dense [15, 31]. In comparison, one plot represents 2 400 ha of forest land in the USA [9].

Based on the information of the regional forest inventories, the total area (ha) and the total solid wood volumes (m^3) of different species were calculated for the Flemish and Walloon productive forests, or so-called forests available for wood supply (FAWS) [16]. Summation of these values, given in Table II, gives the total area and volume for Belgium. Flanders represented 24.0% of the Belgian productive forest area, and Wallonia 76.0%. In total, 75.9% of the coniferous forest area and 76.2% of the deciduous forest area were found in Wallonia, compared to 24.1% and 23.8% respectively for Flanders.

2.2. Biomass expansion factors s.l.

The calculation of the amount of carbon stored in the biomass of trees is usually based on biomass expansion factors s.l. [7, 9, 18, 41]. Conversion factors are used to calculate amounts of dry mass (t DM) from information on the volume (m^3), or to convert dry mass (t DM) into carbon stock (t C). Expansion factors on the other hand give the possibility to scale up information from a smaller to a higher level, e.g. from stem volume to total aboveground and belowground volume. In this study, "biomass expansion factors s.l." (BEFs s.l.) is used as the collective name for both conversion factors and expansion factors. Three categories of BEFs s.l. were distinguished here. In the first place, this concerned the wood density (WD), in order to convert fresh wood volume to wood dry mass. Secondly, biomass expansion factors s.s. (BEFs) were used to calculate (i) aboveground (AG) dry mass from solid wood dry mass, (ii) belowground (BG) dry mass from aboveground dry mass, or (iii) total aboveground and belowground dry mass from solid wood dry mass. Finally, the carbon content (CC) enabled the conversion from total dry mass to total carbon stock.

As the aim of our study was to improve the methodology for the calculation of the total carbon stock in the living biomass of Belgian forests, some explicit conditions were applied for the selection of biomass expansion factors s.l. from the literature. For the expansion factors s.s., foliage had to be included, in accordance with the IPCC-methodology [25]. The analysis was limited to data reported for Belgium, Denmark, France, Germany, Great Britain, Ireland and the Netherlands. These countries all belong to the Central-Western European or North-Western European group of countries as indicated in the TBFRA report of the FAO [16]. Values were selected for ten (groups of) species occurring in the Belgian forests: pines (*Pinus* sp.), Douglas fir (*Pseudotsuga* *menziesii* (Mirb.) Franco), larches (*Larix* sp.), Norway spruce (*Picea abies* (L.) Karst.), beech (*Fagus sylvatica* L.), oaks (*Quercus robur* L. and *Q. petraea* L.), mixed "noble" species (including maple (*Acer pseudoplatanus* L.), elms (*Ulmus* sp.), ash (*Fraxinus excelsior* L.) and red oak (*Quercus rubra* L.)) and poplars (*Populus* sp.). Other species were grouped in the "other coniferous" or "other deciduous" species class. The intention was to select BEFs s.l. for three age classes: 1–20 years, 21–40 years and more than 40 years, and to define a minimum, a maximum and a median value for each category of BEF s.l.

2.3. Total carbon stock in Belgian forests

The total aboveground and belowground carbon stock for a specific species can be calculated by formula (1) or (2):

$$\text{total (AG + BG) C} = \text{TSW-volume} \times \text{WD} \times \text{BEF1} \times (1 + \text{BEF2}) \times \text{CC} \quad (1)$$

or

$$\text{total (AG + BG) C} = \text{TSW-volume} \times \text{WD} \times \text{BEF3} \times \text{CC} \quad (2)$$

with:

total (AG + BG) C: total C-stock in the aboveground and belowground biomass (t C),

TSW-volume: total volume of the solid wood (m^3),

WD: wood density (t DM m^{-3}),

BEF1: ratio aboveground dry mass to total solid wood dry mass (t AG DM t^{-1} TSW DM),

BEF2: ratio belowground dry mass to aboveground dry mass (t BG DM t^{-1} AG DM),

BEF3: ratio aboveground and belowground dry mass to total solid wood dry mass (t (AG + BG) DM t^{-1} TSW DM),

and CC: carbon content (t C t^{-1} DM).

For all species, species-specific BEF3 values were found in the literature. Therefore, the total carbon stock in the Belgian forest biomass was calculated by applying formula (2). Carbon stocks were calculated by species, for Flanders and for Wallonia, and were then summed to give the total C-stock for Belgium. To acknowledge the uncertainty linked with the use of biomass expansion factors s.l., C-stocks were calculated based on minimum, median and maximum values of the expansion factors s.l. found in the literature.

2.4. Predominant expansion factor category

In a first test, the difference between formula (1) and (2) was assessed. For pine, Douglas fir, "other coniferous", beech and "other deciduous", species-specific values for BEF1, BEF2 and BEF3 were available (see Tab. III). For these five (groups of) species, the total carbon stock was calculated by using both formula (1) (with BEF1 and BEF2) and formula (2) (with BEF3), and this for the minimum, median and maximum BEFs s.l. The ratio of the result of formula (1) to the result of formula (2), expressed in terms of percentage, represented the difference between both formulas.

In a second analysis, eight scenarios were established, to analyse all possible combinations of the minimum and maximum values of WD, BEF and CC (see Tab. IV). For each scenario, the total carbon stock was calculated for each species. The resulting carbon stocks are indicated as Res1, Res2, Res3, etc., with the number referring to the scenario applied. As for all species species-specific values for BEF3 were found in the literature, formula (2) was used for this second test. The impact factors of the wood density (IM-WD), the biomass expansion factor s.s. (IM-BEF) and the carbon content (IM-CC) on the total carbon stock for Belgium as a whole, for all conifers and all deciduous species, and for a specific species were calculated as follows:

$$\text{IM} - \text{WD} = \left[\frac{\frac{\text{Res5}}{\text{Res1}} + \frac{\text{Res6}}{\text{Res2}} + \frac{\text{Res7}}{\text{Res3}} + \frac{\text{Res8}}{\text{Res4}}}{4} \times 100\right] - 100 \quad (3)$$

$$\text{IM} - \text{BEF} = \left[\frac{\frac{\text{Res3}}{\text{Res1}} + \frac{\text{Res4}}{\text{Res2}} + \frac{\text{Res7}}{\text{Res5}} + \frac{\text{Res8}}{\text{Res6}}}{4} \times 100\right] - 100 \quad (4)$$

$$\text{IM} - \text{CC} = \left[\frac{\frac{\text{Res2}}{\text{Res1}} + \frac{\text{Res4}}{\text{Res3}} + \frac{\text{Res6}}{\text{Res5}} + \frac{\text{Res8}}{\text{Res7}}}{4} \times 100\right] - 100. \quad (5)$$

The impact factors calculated with formula (3), (4) and (5) gave the mean ratio between the results obtained with the maximum and minimum values of the expansion factor category under consideration, expressed in terms of percentage. These impact factors were then used to find the expansion factor category introducing the largest variability in the calculation of the total C-stock.

3. RESULTS

3.1. Biomass expansion factors s.l.

Table III gives an overview of the selected minimum, maximum and median biomass expansion factors s.l. for each species (group). In addition, the number of available values for each species and each expansion factor category are indicated. These BEFs s.l. fulfilled the conditions stated above, and were reported by (at least one of) the following authors: Baritz and Strich [4], Bartelink [5, 6], COST-E21 [13], Dieter and Elsasser [15], Grote [19], Guilley et al. [20], Houghton et al. [21], IPCC [25], Janssens et al. [27], Joosten and Schulte [28], Joosten et al. [29], Lebaube et al. [32], Lefèvre et al. [34], Levy et al. [36], Löwe et al. [37], Milne and Brown [38], Mund et al. [39], Nabuurs et al. [41], Pignard et al. [43], Ponette et al. [44], Pontailler et al. [45], Schalck et al. [47], Vande Walle and Lemeur [52], Vande Walle et al. [53]. BEFs s.l. from other studies that were inconsistent with (one of) the above-mentioned selection conditions (e.g. [9, 35]), were not taken into consideration. As can be seen from Table III, no age classes were distinguished in the end, although it is widely known (e.g. [26, 35, 39, 46]) that BEFs s.l. are age-dependent. However, we couldn't find enough species-specific BEF s.l. values with a clear indication of tree age to make the distinction of three age classes meaningful in the framework of this study.

From Figure 1, it can be seen that wood density (WD) values were in general significantly lower for coniferous than for deciduous tree species, except for poplar. minimum values ranged from 0.34 t DM m^{-3} for spruce and poplar to 0.55 t DM m^{-3} for beech (Tab. III). The range of the maximum values spanned from 0.45 t DM m^{-3} for spruce to 0.77 t DM m^{-3} for "other deciduous" species. Median values varied between 0.38 t DM m^{-3} for spruce and 0.60 t DM m^{-3} for oak.

For all species except poplar, species-specific values were found for the first biomass expansion factor *s.s.*, the ratio of the aboveground biomass to total solid wood biomass (BEF1). Box plots of the BEF1 values are shown in Figure 2 for those species for which at least 5 values were available. Minimum values ranged from 1.14 t DM t^{-1} DM for pine, larch, spruce and other

Table III. Minimum (min.), maximum (max.) and median (med.) values of biomass expansion factors (BEFs) s.l. of different tree species; DM = dry matter; TSW = total solid wood biomass (stems and branches with a diameter > 7 cm); AG = aboveground biomass, foliage included; BG = belowground biomass; "noble species" = maple, ash, elm and red oak; # gives the number of values found for a particular tree species and expansion factor category; see text for references.

Species	Wood density ($t\ DM\ m^{-3}$)				Carbon content ($t\ C\ t^{-1}\ DM$)				AG / TSW or BEF1 ($t\ DM\ t^{-1}\ DM$)				BG / AG or BEF2 ($t\ DM\ t^{-1}\ DM$)				AG + BG / TSW or BEF3 ($t\ DM\ t^{-1}\ DM$)			
	min.	max.	med.	#	min.	max.	med.	#	min.	max.	med.	#	min.	max.	med.	#	min.	max.	med.	#
Pine	0.39	0.60	0.48	13	0.40	0.55	0.50	9	1.14	1.40	1.32	5	0.16	0.16	0.16	1	1.43	2.00	1.50	7
Douglas fir	0.37	0.54	0.45	7	0.50	0.50	0.50	1	1.18	2.24	1.28	10	0.17	0.17	0.17	1	1.50	2.00	1.71	3
Larch	0.41	0.55	0.47	8	0.40	0.50	0.50	3	1.14	1.36	1.30	3					1.50	2.00	1.75	4
Spruce	0.34	0.45	0.38	15	0.40	0.51	0.50	5	1.14	1.71	1.29	9					1.50	2.00	1.75	2
Other coniferous	0.35	0.50	0.40	20	0.40	0.50	0.50	7	1.14	1.71	1.33	5	0.18	0.25	0.20	3	1.50	2.00	1.75	4
Beech	0.55	0.72	0.56	11	0.44	0.51	0.49	10	1.16	2.04	1.34	9	0.23	0.25	0.24	2	1.50	1.75	1.67	3
Oak	0.50	0.72	0.60	9	0.45	0.50	0.50	3	1.24	1.39	1.32	2					1.50	1.50	1.50	1
Mixed noble	0.52	0.69	0.59	9	0.50	0.50	0.50	1	1.29	1.29	1.29	1					1.50	1.50	1.50	3
Poplar	0.34	0.55	0.41	48	0.50	0.50	0.50	1									1.50	1.50	1.50	1
Other deciduous	0.38	0.77	0.55	34	0.45	0.50	0.50	6	1.24	1.40	1.32	2	0.20	0.22	0.21	2	1.50	1.50	1.50	1

Table IV. Eight scenarios applied for the impact study of three categories of biomass expansion factors s.l.: wood density (WD), biomass expansion factor s.s. (BEF) and carbon content (CC).

Scenario	WD ($t\ DM\ m^{-3}$)	BEF ($t\ DM\ t^{-1}\ DM$)	CC ($t\ C\ t^{-1}\ DM$)
1	Min.	Min.	Min.
2	Min.	Min.	Max.
3	Min.	Max.	Min.
4	Min.	Max.	Max.
5	Max.	Min.	Min.
6	Max.	Min.	Max.
7	Max.	Max.	Min.
8	Max.	Max.	Max.

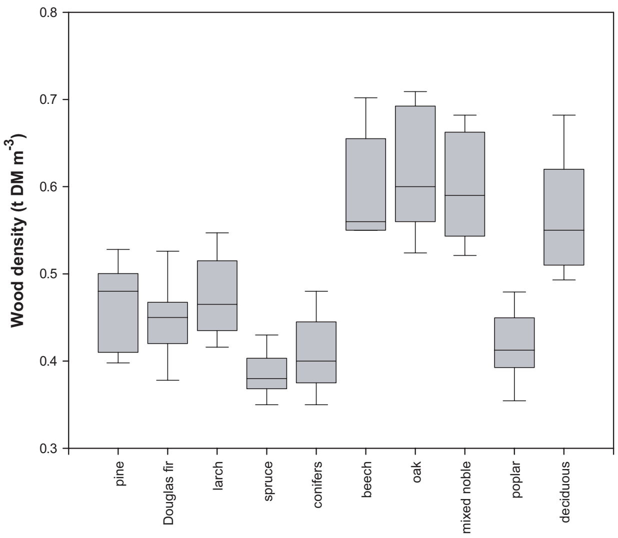

Figure 1. Box plots of wood density values for different tree species (groups); the horizontal line within each box represents the median value for each species (group). Each box contains 50% of the observed values within the limits of the first and the third quartile. Error bars indicate 10 and 90% quartiles.

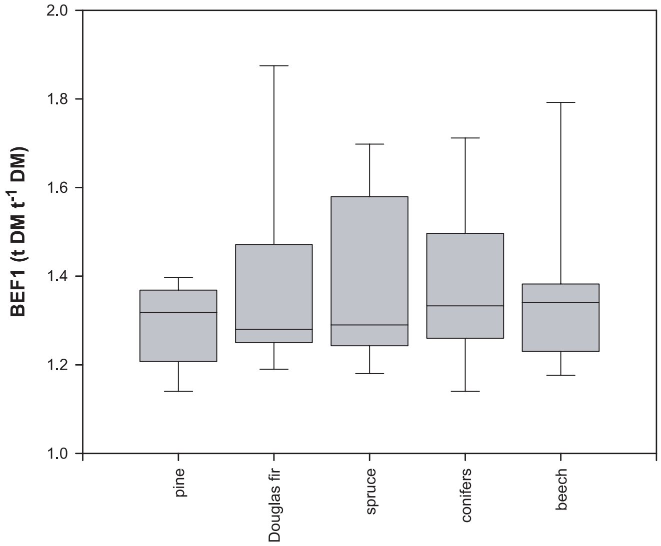

Figure 2. Box plots (see Fig. 1 for detailed description) of BEF1 values for different tree species (groups); only species for which more than 5 BEF1 values were available are presented.

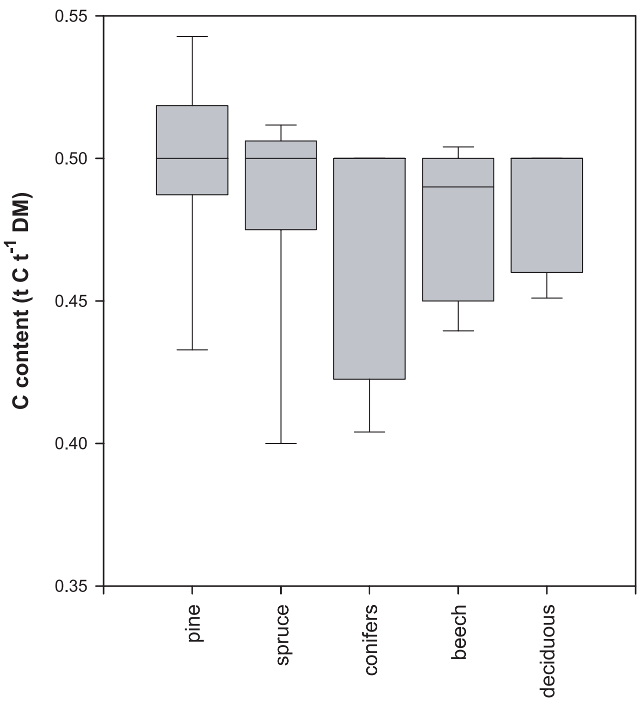

Figure 3. Box plots (see Fig. 1 for detailed description) of carbon content values for different tree species (groups); only species for which more than 5 CC values were available are presented.

conifers, to 1.29 t DM t^{-1} DM for noble species (Tab. III). While the range of the maximum BEF1 values was rather large, from 1.29 t DM t^{-1} DM for mixed noble species to 2.24 t DM t^{-1} DM for Douglas fir, the median values for all species ranged only from 1.28 t DM t^{-1} DM for Douglas fir to 1.34 t DM t^{-1} DM for beech. For the ratio belowground biomass to aboveground biomass (BEF2), values were found only for 5 of the 10 species categories considered. A review study for all major biomes [11] showed that most values for BEF2 are found to be between 0.20 and 0.30. Values found here fitted the lower half of this range, or were lower. For each of the selected species, values were found for the ratio total (aboveground and belowground) biomass to solid wood biomass (BEF3). Median values for BEF3 were in general higher for coniferous than for deciduous species (Tab. III), except for pine and beech.

The median values for carbon content, graphically presented in Figure 3, were 0.50 t C t^{-1} DM for all species, except for beech, which had a median value of 0.49 t C t^{-1} DM. Remarkable is the high range of CC values reported for coniferous tree species (Tab. III).

Table V. Total carbon stock (Mt C) in the living biomass of Belgian productive forests in the year 2000; calculations based on minimum (min.), median (med.) and maximum (max.) biomass expansion factors s.l.

	Min.	Med.	Max.
Flanders			
Coniferous	3.3	5.3	9.5
Deciduous	5.3	6.9	9.0
Coppice	0.06	0.09	0.13
Total Flanders	**8.7**	**12.3**	**18.6**
Wallonia			
Coniferous	13.8	22.3	31.5
Deciduous	18.5	23.9	30.4
Coppice	1.8	2.4	3.0
Total Wallonia	**34.1**	**48.6**	**64.9**
Belgium			
Coniferous	17.1	27.6	41.0
Deciduous	23.9	30.8	39.4
Coppice	1.9	2.5	3.1
Total Belgium	**42.8**	**60.9**	**83.5**

3.2. Total carbon stocks in the Belgian forest biomass

The total carbon stocks in the living biomass of the Flemish and the Walloon productive forests are given in Table V. Summation of the Flemish and Walloon stocks gave the total carbon stock in the productive forests of Belgium for the year 2000, also presented in Table V. Based on the use of median expansion factors for all species, the total carbon stock in Belgian forests amounted to 60.9 Mt C. In total, 20.2% of the Belgian living forest biomass carbon stock was located in the Flemish forests, while the Walloon forests contained 79.8% of the forest carbon of Belgium. The minimum BEF s.l. scenario resulted in a value of 42.8 Mt C for the total carbon stock in Belgium, while the maximum scenario result amounted to 83.5 Mt C.

Based on the total carbon stocks resulting from the median expansion factor scenario on the one hand (Tab. V), and the total forest area in both Flanders and Wallonia on the other hand (Tab. II), the mean carbon stock per area unit was calculated. In Flanders, productive forests contained 85.2 t C ha^{-1} on average. The mean value for the Walloon forests amounted to 105.9 t C ha^{-1}. When all Belgian productive forests were considered together, a mean carbon stock of 101.0 t C ha^{-1} was found.

3.3. Predominant expansion factor category

The results of the first test, comparing the application of formula (1) and formula (2) for five (groups of) species, are given in Table VI. The ratios were lower than 100% for the minimum BEF s.l. scenario and higher than 100% for the maximum scenario (except for pine). When the median BEF s.l. values were used, both ratios lower (Douglas fir, other coniferous species and beech) and higher (pine and other deciduous species) than 100% were found.

Table VI. Comparison of the carbon stock calculated by formula (1) (using BEF1 and BEF2) and formula (2) (based on BEF3); ratios in %, giving the outcome of (result formula (1) / result formula (2)) × 100.

	Min.	Med.	Max.
Pine	92.5	101.9	81.0
Douglas fir	92.0	87.6	131.0
Other coniferous	89.7	91.4	107.0
Beech	95.1	99.5	145.7
Other deciduous	99.2	106.5	113.9

Table VII. Impact factor (IM) of wood density (WD), biomass expansion factor s.s. (BEF) and carbon content (CC) on the total carbon stock of Belgian forests.

	IM-WD	IM-BEF	IM-CC
Belgium	42.9	17.1	17.4
Coniferous	38.6	34.9	28.6
Deciduous	46.9	3.7	8.5
Spruce	32.5	33.3	27.7
Douglas fir	46.0	33.3	0.0[1]
Larch	34.2	33.3	25.0
Pine	53.9	40.0	38.0
Other coniferous	42.9	33.3	25.0
Beech	30.9	16.7	15.9
Oak	44.0	0.0[1]	11.1
"Noble" species	32.7	0.0	0.0[1]
Poplar	61.8	0.0[1]	0.0[1]
Other deciduous	102.6	0.0[1]	11.1

[1] Indicates that only one value was available for this BEF s.l. category.

The impact factors for wood density, biomass expansion factor s.s. and carbon content calculated with formula (3), (4) and (5) are given in Table VII. Wood density had the highest impact factor regarding the calculation of the total C-stock in Belgium (42.9%), while the impact factors of the carbon content (17.4%) and the biomass expansion factors s.s. (17.1%) were comparable. When coniferous and deciduous trees were considered separately, it became clear that for both species types, WD had the highest IM: 38.5% for coniferous trees, and 46.8% for deciduous species. The IM of BEF3 was almost ten times higher for conifers than for deciduous species (34.9% and 3.7% respectively). Moreover, the IM of the carbon content for coniferous species (28.6%) was more than threefold the IM found for deciduous species (8.5%).

Table VIII. Total solid wood volume (TSW) and mean carbon stock per ha forest area in Belgium and neighbouring countries.

	TSW (m^3 ha^{-1})	C-stock (t C ha^{-1})	Reference
Great Britain (G.B.)		36.8	Milne and Brown [38]
conifers		21.1	Milne and Brown [38]
deciduous		61.9	Milne and Brown [38]
Ireland	152.4	38.3	Gallagher et al. [17]
Denmark	132.4	56.6	Vesterdal [54]
France	151.0	59.0	IFN [22] and Pignard et al. [43]
The Netherlands	170.0	59.0	Nabuurs and Mohren [40]
Belgium	261.9	101.0	This study
Flanders	*222.8*	*85.2*	This study
Wallonia	*274.1*	*105.9*	This study
Germany	276.0	105.7	Baritz and Strich [4]

The impact factors of wood density, biomass expansion factors s.s. and carbon content were also calculated for the tree species separately (Tab. VII). In some cases, the minimum and maximum values of the parameters were the same (see Tab. III), which resulted in an impact factor equal to zero. Wood density had the highest impact factor regarding the C-stock assessment of all species except spruce. For spruce, the IM of BEF3 was slightly higher (33.3%) than the IM of wood density (32.4%). From Table VII, it can also be seen that the impact factor of BEF3 was higher for the coniferous species than for the deciduous species. However, for three of the five groups of deciduous species, only one species-specific BEF3 value was found.

4. DISCUSSION

For the calculation of the total carbon stock in the Belgian forest biomass, formula (2) was used. In this study, our strict selection conditions for biomass expansion factors s.l. should sustain the assumption that the carbon stock assessed by applying these BEFs s.l. is reasonable for Belgium. This means that the carbon stock in the living biomass of the Belgian forests in the year 2000 amounted to 60.9 Mt C, or was at least expected to fall within the range between 42.8 Mt C and 83.5 Mt C. Shrubs and very small trees were not included in this value. Schroeder et al. [48] reported that small trees contained as much as 75% of the biomass in trees with a diameter at breast height greater than 10 cm, in stands with a low aboveground biomass stock. However, it can be assumed that in most Belgian forests, this shrub and small tree pool represents only a very small carbon stock [1, 33]. Another pool that was neglected in this study, was the dead wood in the forests. In the Flemish and Walloon inventories, information on dimensions of standing and laying dead wood is available. However, the decomposition phase of the dead wood is not noted. This information is crucial to assess the dead wood density from literature values [9, 12]. A specific study on the determination of the C-stock in this dead wood compartment is therefore needed.

In Flanders, 49.3% of the forests are younger than 40 years, while in Wallonia, only 26.1% have an age lower than 40 years. This explains the lower mean carbon stock per area unit in Flanders (85.2 t C ha^{-1}) compared to Wallonia (105.9 t C ha^{-1}). This lower carbon stock is also linked with a lower mean standing volume in the Flemish forests (222.8 m^3 ha^{-1}), compared to the Walloon forests (274.1 m^3 ha^{-1}). Mean standing volumes and mean carbon stocks for neighbouring countries are listed in Table VIII. The mean carbon stock in the biomass of Belgian forests, 101.0 t C ha^{-1}, was considerably higher than the values reported for Great Britain (36.8 t C ha^{-1}), Ireland (38.3 t C ha^{-1}), Denmark (56.6 t C ha^{-1}), the Netherlands and France (both 59.0 t C ha^{-1}). German forests on the other hand had a carbon stock of 105.7 t C ha^{-1}, which is slightly higher than the value for Belgium. There are several explanations for the differences in mean carbon stock. The main reason is the difference in mean standing volume, which can on its turn be due to various causes. Forests in Ireland for example are mainly planted since 1950. This results in a predominance of young forests, mainly on peat soils, with a related low standing stock [10]. The lower standing stock in Dutch forests compared to Belgium can be attributed to the fact that forests in the Netherlands are mainly concentrated on poor, dry sandy soils [40], while in Belgium, forests are located on richer sandy-loam and loamy soils too. The good agreement between the standing stock in German productive forests (276.0 m^3 ha^{-1}) and in Wallonia (274.1 m^3 ha^{-1}) is reflected in an almost identical mean C-stock (105.7 t C ha^{-1} for Germany, 105.9 t C ha^{-1} for Wallonia).

Besides the difference in standing stock, the choice of the BEFs s.l. used for the carbon stock calculation explains the differences in mean carbon stock. The solid line in Figure 4 indicates the relation between standing stock and mean carbon content based on the overall Belgian BEF of 0.39 t C m^{-3} TSW. The overall BEF for the Netherlands (0.35 t C m^{-3} TSW) and Ireland (0.25 t C m^{-3} TSW) were lower than the ones used for the carbon stock assessment in Belgium, Germany and France, which were all close to 0.39 t C m^{-3} TSW. Wood density values used by Nabuurs and Mohren [40] were comparable to the minimum values used in our study. The mean carbon stock in Belgium based on the minimum BEF s.l. parameter scenario

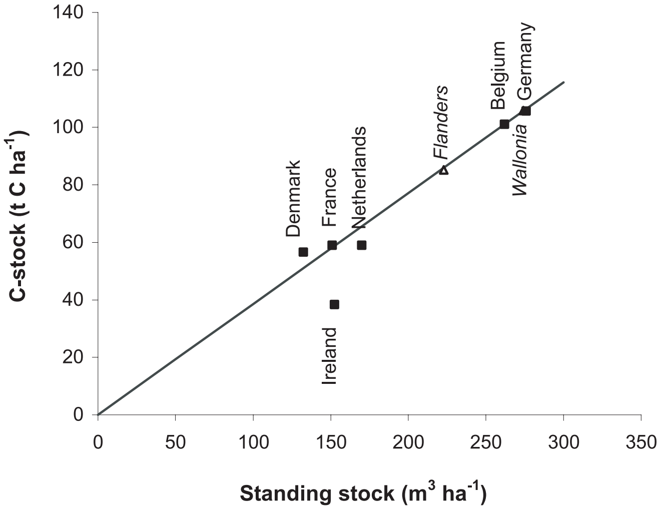

Figure 4. Relation between standing stock (m^3 ha^{-1}) and carbon stock (t C ha^{-1}) for Belgium and neighbouring countries; the solid line gives the C-stock when the overall Belgian BEF s.l. is used.

amounted to 70.9 t C ha^{-1}, which is much closer to the Dutch C-stock of 59.0 t C ha^{-1}. The overall BEF for Denmark was 0.43 t C m^{-3} TSW, which is 10% higher than the Belgian one. This high Danish BEF confirms the statement of Vesterdal [54] that Danish wood densities differ from IPCC default factors because of a lower volume to dry weight ratio.

In our study, shrubs, forest floor vegetation and dead wood are not considered. In the German study of Baritz and Strich [4] however, these carbon pools were taken into account. Nabuurs and Mohren [40] only refer to living biomass, while it is not clear if foliage and fine roots were included in the work of Milne and Brown [38]. The fact that some studies consider more compartments of the forest ecosystems than other studies, can also contribute to differences in mean carbon stocks when starting from the same basic information, being total standing solid wood volume. And even this last concept should be handled with some caution, as the definition of "total solid wood" is not always the same [14, 16].

From our study, it cannot be concluded unambiguously if using formula (1) (with BEF1 and BEF2) always gives lower or higher C-stock values than formula (2) (with only BEF3), as ratios were both higher and lower than 100% for the five (groups of) species studied (Tab. VI). As it is advised by the IPCC [25] to use species-specific BEF values, it seems appropriate to apply formula (2), as for each species, species-specific BEF3 values are available. However, if one really wants to know the division between aboveground and belowground biomass, formula (1), and as such, BEF1 and BEF2, has to be used. From Table III, it can also be seen that in total, 31 species-specific values for BEF1 were found, compared to only 18 BEF3 values. This could be a reason to prefer to use the first formula, where the "other coniferous" and the "other deciduous" species values for BEF2 can be used in these cases where no species-specific values for this parameter were found. However, one should always keep in mind that the choice of the formula influences the final result of the carbon stock assessment.

In general, wood density appeared to introduce the largest variability in the calculation of the carbon stock. This result confirms the study of Bascietto and Scarascia-Mugnozza [7], who found that the major contributor to carbon increment error was the variability of the wood density measures, and not the variation in carbon content. In total, we selected 174 wood density values from the literature. The range of these values was large, which is due to the geographical dependence of this parameter [12, 23, 30, 46]. This large range could possibly also be the consequence of the fact that different methods were applied to measure the wood density. Information on the measurement method however was only rarely available.

The lower impact factors of the biomass expansion factors s.s. compared to wood density can be due to the low number of values found for this category, or to the fact that this expansion factor category is less related to the geographical location within Belgium than wood density. This last assumption is confirmed by the study of Cairns et al. [11], who found no apparent relation between BEF2 and soil texture, precipitation, temperature or latitudinal class. Species-specific values of BEF3 were found for all species, which was not the case for BEF1 and BEF2. Although some sources mention the age-related character of these BEFs (e.g. [44, 48, 56]), it was not possible to find BEF1, BEF2 or BEF3 values for the three age classes of the distinguished species, because of the explicit conditions applied in our study. Moreover, the volume and age class for which the BEFs were established were not communicated in most cases, a problem also signalled by Van Camp et al. [51].

Generally, the impact factor of the carbon content was only slightly lower than the IM of the BEFs (Tab. VII). For this carbon content category, 46 values were available, compared to only 29 values for BEF3. So, the range of carbon content seemed to be less pronounced than the range of BEFs. As it appeared (Tab. III) that the median CC value for all species except beech was equal to the default IPCC-value of 50% carbon in dry matter [21, 55], it seems appropriate to use this value for all species.

The results of the second test indicated that improving wood density assessment by additional measurements is certainly the most efficient way to improve the C-stock assessment in Belgian forests. This means that in an ideal situation, the wood density should be measured at the sampling plot level, as this would eliminate the uncertainty due to the geographical variation of this parameter. Our results also confirmed the IPCC guidelines [21], which stated clearly that average default wood density values can only be used for initial calculations, and that it is much better to use actual measured average values. However, the method used to determine the wood density (X-ray densitometry, volumetric-gravimetric method) should be well-described and harmonised, to eliminate this factor of uncertainty as well. Simpson [50] emphasised that an exact description of the procedure followed to determine wood density is indispensable for a correct application of published values. A similar nationwide study is going on in Australia, where the aim is to establish a database with wood density values for all relevant tree species [23]. In the Australian study, the geographic distribution of wood densities is taken into account. The relation between the wood density and the age of the tree is not so clear, as results from studies are sometimes contradictory to each other [23, 46].

Determination of biomass expansion factors s.s. is a time-consuming, laborious and destructive activity [19, 57]. Therefore, the establishment of new BEFs should not have the highest priority for future forest inventories in Belgium. However, more detailed investigations on biomass expansion factors s.s. can undoubtedly contribute to the improvement of the forest carbon stock assessment for Belgium, as also mentioned by Van Camp et al. [51].

5. CONCLUSION

In Belgium, data of two regional forest inventories are available. However, these inventories do not provide biomass or carbon stock information. The IPCC guidelines advise to use species-specific BEFs s.l. to convert information from forest inventories into carbon stocks. For Belgium, no country-specific biomass expansion factors s.l. are available. Therefore, we selected wood densities, biomass expansion factors s.s. and carbon content values from the literature, applying specific selection conditions. Using the selected species-specific expansion factors, the total carbon stock in the living biomass of the Belgian productive forests was calculated for the year 2000. In a final analysis, the BEF s.l. category that introduces the largest variability in the calculation of the C-stocks in the Belgian forest biomass was detected.

According to our methodology, the total carbon stock in the living biomass of the Belgian forests amounted to 60.9 Mt C in the year 2000, with a minimum value of 42.8 Mt C and a maximum value of 83.5 Mt C. Shrubs and dead wood were excluded from this calculation. The mean value of 101.1 t C ha^{-1} for the Belgian forests was only slightly lower than the value reported for Germany, and was considerably higher than values for other neighbouring countries as the Netherlands, France, Ireland and Great Britain. These differences were on the one hand due to a different standing stock volume, and on the other hand to another overall BEF s.l.

From our analysis, it was not possible to conclude if using two biomass expansion factors s.s. (BEF1 and BEF2) results systematically in a higher or lower C-stock value than when only one expansion factor s.s. (BEF3) is applied. The IPCC guidelines recommend the use of species-specific values instead of more general ones when possible. As such, it is recommended to use formula (2). When one specifically wants to know the partitioning of the carbon stock over the above- and the belowground biomass compartments in detail, two separate BEFs should of course be used.

From a second test, it became clear that wood density introduces the largest variability in the C-stock calculations. Therefore, more research is needed concerning this BEF s.l. category. Ideally, the wood density should be measured at plot level in the regional forest inventories, by a well-described and harmonised method.

The exact definition of reported biomass expansion factors s.s. was sometimes missing, or it was not clear if the foliage was included in the BEFs. These values were not selected for our calculations. A more exact and complete description of biomass expansion factors s.s. is therefore strongly recommended. The determination of biomass expansion factors s.s. is a laborious and time-consuming activity. Therefore, the establishment of new BEF values is not of the highest priority for the assessment of the C-stock in Belgian forests. Detailed studies however, could help to reduce the uncertainty related to this type of biomass expansion factor.

The impact factor of the carbon content on the C-stock assessment was higher for coniferous than for deciduous species. As the median value for all species (except beech) was equal to the IPCC default value of 50% carbon in dry mass, we propose to use this value for future carbon stock calculations.

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