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REVIEW

Description of a new procedure to estimate the carbon stocks of all forest pools and impact assessment of methodological choices on the estimates

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Abstract Forest ecosystems play a major role in atmospheric carbon sequestration and emission. Comparable organic carbon stock estimates at temporal and spatial scales for all forest pools are needed for scientific investigations and political purposes. Therefore, we developed a new carbon stock (CS) estimation procedure that combines forest inventory and soil and litter geodatabases at a regional scale (southern Belgium). This procedure can be implemented in other regions and countries on condition that available external carbon soil and litter data can be linked to forest inventory plots. The presented procedure includes a specific CS estimation method for each of the following forest pools and subpools (in brackets): living biomass (aboveground and belowground), deadwood (dead trees and snags, coarse woody debris and stumps), litter, and soil. The total CS of the forest was estimated at 86 Tg (185 Mg ha^{-1}). Soil up to 0.2 m depth, living biomass, litter, and deadwood CSs account, respectively, for 48, 47, 4, and 1 % of the total CS. The analysis of the CS variation within the pools across ecoregions and forest types revealed in particular that: (1) the living biomass CS of broadleaved forests exceeds that of coniferous forests, (2) the soil and litter CSs of coniferous forest exceed those of broadleaved forests, and (3) beech stands come at the top in carbon stocking capacity. Because our estimates differ sometimes significantly from the previous studies, we compared different methods and their impacts on the estimates. We demonstrated that estimates may vary highly, from −16 to +12 %, depending on the selected methods. Methodological choices are thus essential especially for estimating CO_2 fluxes by the stock change approach. The sources of error and the accuracy of the estimates were discussed extensively.

Keywords Temperate forest · Forest inventory · Soil map · Biomass equation · Biomass factor · Wood basic density

Abbreviations

BF	Biomass factor
CLC	CORINE Land Cover
CS	Carbon stock
C130	Circumference at 1.3 m height
DBH	Diameter at breast height
DSMW	Digital Soil Map of Wallonia
IPCC	Intergovernmental panel on climate change
MSU	Main soil unit
NFI	National forest inventory
RFIW	Regional forest inventory of Wallonia
TH	Tree height
WD	Wood basic density

Introduction

Forest ecosystems play an important role in climate change mitigation. They act as sources or sinks of greenhouse gases through changes in the carbon stocks of forests and soils and through the delivery of biomass that can substitute fossil fuel

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and energy-intensive material (Eriksson and Berg 2007; Houghton 2005; IPCC 2006).

National evaluation of the carbon sink or source of a forest may be estimated from two different methods (IPCC 2006): the gain and loss method and the stock change method. The gain and loss method requires that the biomass carbon loss be subtracted from the biomass carbon increment for the reporting year. The stock change method requires carbon stock inventories for a given forest area at two points in time. The stock change method is considered as a Tier 3 estimation of land use carbon fluxes (IPCC 2006). A tier represents a level of methodological complexity. The IPCC guideline proposed three tiers, and the higher is the tier, more reliable are the estimates.

According to the IPCC, forest carbon stocks may be divided into three main pools and five subpools (in brackets): biomass (aboveground biomass and belowground biomass), dead organic matter (deadwood and litter), and soils (soil organic matter).

For biomass and deadwood, data of National Forest Inventories (NFIs) are suited for the stock change method and for large-scale carbon assessments (Mäkipää et al. 2008), but litter and soil data are generally lacking. NFIs have been primarily designed to measure traditional forest variables, such as diameter, height, and age, in order to estimate growing stocks and volume increments. Direct biomass measurements are generally not included in sampling procedures. Therefore, alternative and indirect methods have been developed to estimate the carbon stocks of woody vegetation based on measurement data. These methods can be divided into two groups: biomass factors and biomass equations (Somogyi et al. 2007). The first method aims at converting (or expanding) a wood parameter, such as tree stem merchantable volume, into biomass using expansion factors. The second method focuses directly on estimating tree biomass using general, site-, or species-specific allometric equations. These equations relate the biomass of individual trees to explanatory variables such as DBH, total height, age, stand basal area, and wood density. The expansion factor method could be qualified as Tier 2 and the allometric equation method as Tier 3 (Henry et al. 2011). As for biomass, dead wood when measured in NFIs can be estimated from indirect method.

For litter and soil, NFI protocols generally do not include carbon measurement. External databases are thus needed for estimating the total carbon stock of the forest and the carbon stocks of all pools separately. Soil pool can be equal to or even greater than tree biomass (Lettens et al. 2008; Liski et al. 2006; Nabuurs et al. 2003).

This last decade numerous studies estimated actual and future carbon stocks and fluxes in temperate European forests using methodologies from Tier 1 to Tier 3 or a mix of tiers depending on the pool (Baritz et al. 2010; Karjalainen et al. 2003; Liski et al. 2002; Nabuurs et al. 2003).

This study aims to present a new carbon stock estimation procedure that includes all forest pools, integrates recent technical advances, and combines forest inventory, soil and litter geodatabases at a regional scale (Wallonia, southern Belgium). In addition, we analyze the carbon stock distribution within the pools in the five ecoregions and in broadleaved and coniferous forests encountered in Wallonia. Results and methods are compared with the previous studies to underline the importance of methodological choices in carbon stock estimation. Intra- and intermethod errors and data uncertainties are discussed.

Material

Study area

Wallonia (southern Belgium) covers an area of 16,844 km^2 (55 % of Belgium's area). The climate is temperate and maritime with moderate temperature variability, prevailing westerly winds and regular rain. Wallonia has been divided into five ecoregions stretching from NW to SE according to the climatic gradient and geologic parent rocks: Loess region, Condroz, Fagne-Famenne, Ardenne, and Jurassic region (Table 1).

Most of the Belgian forest, around 80 %, is located in Wallonia where the woodland cover is of one-third

Table 1 Description of the five ecoregions of Wallonia

Ecoregion	Productive forest area (ha)	Woodland cover (%)	Elevation (m) (mean)	Soil parent material
Loess region	37,001	7	20–200 (100)	Thick loess
Condroz	65,358	18	100–350 (250)	Limestone, micaceous sandstone, sometimes shales
Fagne-Famenne	57,287	36	120–250 (200)	Shale, limestone
Ardenne	276,434	49	200–694 (400)	Siliceous rocks
Jurassic region	29,215	35	195–465 (300)	Marl, shale, sandstone, limestone

(556,440 ha in 2003). Wallonia's forest is characterized by very scattered ownership and a great diversity of stand types, species composition, and soil growing conditions (nutrient supply and water availability). This study focuses on productive forests (84 % of the total forest area). Non-productive forest areas are clear-cuts (2 %) and forests roads, colonizing vegetations, fens, and firebreaks (14 %).

For the purpose of this study, two forest types were distinguished: broadleaves (basal area of broadleaves $\geq$50 %) and coniferous (basal area of coniferous >50 %). Broadleaved forests comprise mostly oaks (*Quercus robur* and *petraea*) and beech (*Fagus sylvatica*) stands, but other species such as birch (*Betula pubescens* and *pendula*), ash (*Fraxinus excelsior*), maple (*Acer pseudoplatanus*), and hornbeam (*Carpinus betulus*) are also well represented, mostly in mixture. Coniferous forests are essentially constituted of spruce (*Picea abies*) in pure even-aged stands on approximately 70 % of the coniferous area, and the rest is covered with stands of Douglas fir (*Pseudotsuga menziesii*), larches (*Larix sp.*), and pines (*Pinus sylvestris* and *nigra*).

Regional forest inventory of Wallonia

The Regional Forest Inventory of Wallonia (RFIW; Rondeux et al. 2010) is a permanent non-stratified inventory based on a systematic sampling design with plots located at the intersections of a 1,000 m (east–west) × 500 m (north–south) grid. The RFIW has one of the highest sampling rates (one plot per 50 ha) in Europe. The definition of forest is based on minimum requirements, which are an area of 0.1 ha, a wooded area width of 9 m, and a canopy cover of 10 %. The first inventory cycle was achieved between 1994 and 2008, and the second cycle is currently in progress.

For the purpose of this study, we used data of living and dead woods collected on 6,514 plots measured from 1998 to 2008 (as before 1998 there was no measurement of dead woods). In that case, a plot accounts for an area of 71.43 ha (instead of 50 ha if all plots would have been used). The productive forest area considered for the reference year 2003 equals 465,295 ha.

In the inventoried plots, all standing trees, coppices and snags with a circumference of at least 20 cm at 1.5 m height, and lying deadwoods with a circumference of at least 20 cm on minimum 1 m length were measured. Under 3-year old stumps were also inventoried. The deadwood decomposition of entire trees, snags, and coarse woody debris belongs to one of the following three stages of decay: (1) no decomposition, (2) decomposition in progress, and (3) highly decomposed. Additional data concerning litter and soil were available for a subset of forest inventory plots. These plots were selected throughout Wallonia following a subgrid of the RFIW.

Litter samplings were collected on 120 plots in 2009–2010 (reference year 2010). For each plot, three 25 × 25 cm-squares samples were randomly located near the plot center. Samplings include all organic horizons, also called ectorganic horizons, containing more than 17 % of organic carbon by weight and 30 % by volume. Horizons OL and OF were systematically mixed. Horizon OH was sampled separately when thickness was greater than 1 cm as was done in the RENECOFOR network (Ponette et al. 1997). Colinet et al. (2010) measured the carbon densities (g m^{-2}) according to the modified Springer and Klee's (1954) method: hot oxidation with $K_2Cr_2O_7$ and titration of oxidant excess with $(NH_4)_2Fe(SO_4)_2.6H2O$.

Soil samplings up to 20 cm depth were collected on 566 RFIW plots from 2001 to 2010 (reference year 2005). For each plot, 21 soil cores regularly distributed on the plot were sampled and put together before analysis. Colinet et al. (2010) measured the carbon concentrations (g g^{-1}) according to the modified Springer and Klee's (1954) method.

Aardewerk database

The Aardewerk soil database (De Leenheer et al. 1968; Van Orshoven et al. 1988, 1993) is the digital version of the Belgian National Soil Survey performed from 1947 to 1961 (reference year 1960 as most of plots were measured in the last years). The revised version of this database (Legrain 2005) contains, for Wallonia, descriptive and analytical data of 6,262 profiles, representing 32,228 horizons, including soil series, map coordinates, and land use class. For the purpose of this study, we selected 2,274 forest profiles and 9,746 hemiorganic horizons (up to 1 m depth). For each soil horizon, the following variables are available: depth, thickness, mineral fractions (De Leenheer et al. 1954), stoniness, and organic carbon concentration. Horizon carbon concentrations (g g^{-1}) were measured according to Walkley and Black's (1934) method. The Aardewerk database does not contain direct measurement of bulk density.

Digital Soil Map of Wallonia

The Digital Soil Map of Wallonia (DSMW; Veron and Bah 2007) is a spatial database resulting from the digitalization of 270 soil maps (1:20,000). Edaphic observations (soil boreholes) were realized from 1947 to 1991 following a systematic grid of 75 × 75 m that covers the whole area of Wallonia. Unique in Europe, this very dense sampling enables precise and reliable soil estimates.

Methods

Based on the IPCC guidelines and a literature review dealing with forest carbon stock estimation, we developed a global procedure estimating the more precisely possible carbon stocks of four pools and five subpools (in brackets) of the Wallonia's productive forest: living biomass (aboveground and belowground biomasses of trees and coppices), deadwood (biomasses of dead standing trees, snags, coarse woody debris, and stumps), litter, and soil. These pools and subpools were defined/organized from the methodological point of view and can be easily converted into IPCC's ones: biomass (aboveground and belowground parts), dead organic matter (deadwood and litter), and soils (soil organic matter).

The estimation procedure combines data from the Regional Forest Inventory of Wallonia (RFIW), the Aardewerk database, and the Digital Soil Map of Wallonia (DSMW). A specific carbon stock estimation method has been assigned to each pool and subpool of the procedure (global synthesis in Table 2). Carbon stock estimates of each pool and subpool have been set on the common scale of RFIW plots and refer thus to the same reference area so that consistent comparisons are possible.

Living biomass and deadwood

The carbon stock (CS) of living biomass and deadwood was computed using the following three equations:

$$\text{AG CS} = V \times \text{WD} \times \text{CC} \tag{1}$$

$$\text{BG CS} = V \times \text{WD} \times \text{BF} \times \text{CC} \tag{2}$$

$$\text{T CS} = V \times \text{WD} \times (1 + \text{BF}) \times \text{CC} \tag{3}$$

where AG CS (g), BG CS (g), and T CS (g) are, respectively, aboveground, belowground, and total carbon stocks, V (m^3) is the total aboveground wood volume, WD (g m^{-3}) is the species-specific wood basic density of Wagenführ and Schreiber (1985), BF is the 'BEF2' biomass factor in Vande Walle et al. (2005) corresponding to the ratio of belowground biomass to aboveground biomass, and CC is the carbon content (=0.5).

Equation (1) was used for estimating the CSs of aboveground biomass, coarse woody debris, and stem part of snags, Eq. (2) for belowground biomass, stumps, and root part of snags, and Eq. (3) for dead standing trees and total living biomass.

The wood volume of living and dead standing trees, coppices, and corresponding trees of snags and stumps was calculated using the seven species-specific French equations (Vallet et al. 2006) that include entire stems, branches, and twigs. Vallet's equation number (1–5) corresponds, respectively, to *Quercus petrea, Fagus sylvatica, Picea abies, Pseudotsuga menziesii*, and *Pinus sylvestris* (Table 3). These five species are very common in Wallonia (>80 % of the merchantable volume).

Vallet's equations have circumference at 1.3 m height (C130) and tree height (TH) as explanatory variables. Because TH is sometime missing in the RFIW database, we developed, based on 34,429 RFIW trees, species-specific C130-TH equations for each ecoregion in the case of the main species (*Acer pseudoplatanus*, *Betula spp.*, *Fagus sylvatica*, *Fraxinus excelsior*, *Picea abies*, and *Quercus spp.*) and for the whole region of Wallonia when dealing with secondary species. These equations were built following the Johnson–Schumacher's growth model:

$$\text{TH} = m \times e^{\frac{-b}{\text{C130} - a}} \tag{4}$$

where TH (cm) is the total tree height, C130 (cm) is the circumference at 1.3 m height, and a, b, and m are curve shape coefficients.

The wood volume of coarse woody debris and stem part of snags was calculated using Huber's formula (cylinder volume from length and circumference at halfway). Thus, the CS of snags had to be calculated at two levels: (1) stem part from Huber's volume (Eq. 1) and (2) root part of the corresponding entire tree from Vallet's volume (Eq. 2).

Wood basic density, ratio between oven-dry mass and green volume of wood, was used to convert wood volume into dry wood mass (Eqs. 1, 2, and 3). Wood density varies with tree species, growth conditions, and the part of the tree measured. This explains why for most species the literature gives a range of values for wood density associated with volume shrinkage and water content. Wood basic density was calculated for each species identified by the RFIW on the basis of Wagenführ and Schreiber (1985) average values at 12 or 15 % of moisture as follows:

$$\text{WD} = \frac{\text{WD}_M}{1 + M} \times \frac{1 + \frac{M}{0.3} \times \text{VC}}{1 + \text{VC}} \tag{5}$$

where WD (g m^{-3}) is the wood basic density, M (%) is the moisture content, WD_M (g m^{-3}) is the average wood density at M % of moisture, and VC (%) is the total wood volume shrinkage.

The biomass was converted into carbon mass (Eqs. 1, 2, and 3) using a carbon content of 50 % as suggested by Vande Walle et al. (2005).

In the case of coarse woody debris, dead standing trees, and snags, deadwood decomposition was taken into account by applying to the CS a reducing factor (based on Yatskov et al. (2003) and Sandström et al. (2007)) corresponding to the decomposition degree among the three classes observed on the field: 1, if no decomposition occurred; 0.75, if decomposition was in progress; and 0.5, when the wood was highly decomposed.

Table 2 Synthesis of the carbon stock estimation procedure

Data source	Regional Forest Inventory of Wallonia (RFIW)						
Pool	Living biomass		Deadwood				
Reference year	2003						
Subpool	Trees and coppices		Stumps	Snags	Dead standing trees	Snags	Coarse woody debris
	Aboveground biomass	Belowground biomass		Root part		Stem part	
Carbon stock estimation method	Equation 1:	Equation 2:			Equation 3:	Equation 1:	
	$V \times WD \times CC$	$V \times WD \times BF \times CC$			$V \times WD \times (1 + BF) \times CC$	$V \times WD \times CC$	
	CC: carbon content (=0.5)						
	WD: Wagenführ and Scheiber's wood basic density ($g\ m^{-3}$, Equation 5)						
	V:Vallet's wood volume equation (m^3)					V: Huber's volume (m^3)	
	BF: Vande Walle's 'BEF2' biomass factor						

Data source	RFIW	RFIW, Aardewerk and Digital Soil Map of Wallonia (DSMW)	
Pool	Litter	Soil	
Reference year	2010	1960	2005
Working by	Humus type	Aardewerk horizon (several per soil profile)	RFIW horizon (1 per soil profile)
Carbon stock estimation method	LCD: litter carbon density ($g\ m^{-2}$)	Equation 6:	
		$HCD = HCC \times HT \times BD \times (1 - HS)$	
		HCD: horizon carbon density ($g\ m^{-2}$)	
		HCC: horizon carbon concentration ($g\ g^{-1}$)	
		HT: horizon thickness (m)	
		HS: horizon stoniness	
		BD: Rawls' bulk density ($g\ m^{-3}$, Equation 7)	$HT = 0.2$ m
			$BD = MSUD$: main soil unit bulk density ($g\ m^{-3}$, Equation 8)

Table 3 Listing of Vallet's wood volume equations, Wagenführ and Scheiber's wood basic densities, and Vande Walle's 'BEF2' biomass factors used to compute living biomass and deadwood carbon stocks

Vallet's volume equation		Wagenführ and Scheiber's wood basic density	Vande Walle's 'BEF2' biomass factor	Associated species of the Regional Forest Inventory of Wallonia
Number	Species			
1	*Quercus petrea*	0.295	0.21	*Salix caprea, Salix* spp.
1		0.568	0.21	*Quercus robur, Quercus petraea*
1		0.578	0.21	*Quercus rubra*
2	*Fagus sylvatica*	0.372	0.21	*Populus alba, Populus x canescens, Populus hybrids*
2		0.453	0.21	*Alnus incana, Alnus glutinosa*
2		0.515	0.21	*Castanea sativa*
2		0.518	0.21	*Prunus avium, Prunus* spp.
2		0.523	0.21	*Acer pseudoplatanus, Acer platanoides, Acer campestre*
2		0.534	0.21	*Betula pendula, Betula pubescens*
2		0.569	0.21	*Fraxinus excelsior*
2		0.586	0.24	*Fagus sylvatica*
2		0.61	0.21	*Sorbus* spp.
2		0.668	0.21	*Carpinus betulus*
3	*Picea abies*	0.39	0.2	*Picea abies, Picea stitchensis*
4	*Pseudotsuga menziesii*	0.423	0.17	*Pseudotsuga menziesii*
5	*Pinus sylvestris*	0.423	0.16	*Pinus sylvestris*
6	*Pinus pinaster*	0.423	0.16	*Pinus nigra subsp. Nigra, Pinus nigra* subsp. *Laricio*
6		0.487	0.2	*Larix kaempferi, Larix decidua, Larix hybrid*
7	*Abies alba*	0.375	0.2	*Abies alba, Abies grandis, Abies* spp.

Species with less than 150 trees measured are not listed in this table

Litter

The litter CS was calculated based on the litter carbon data of 120 RFIW plots. Measured litter carbon densities (g m^{-2}) were averaged over the six humus types identified by the RFIW: calcic mull, mull, moder–mull, moder, dysmoder, and mor (Delecour 1980; Jabiol et al. 2007). The CS (g) of each humus type was obtained by multiplying mean carbon density and representative area (=numbers of plots × 71.43 ha).

Soil

The soil organic CSs were calculated with the data from: (1) the Aardewerk database, (2) the soil data of 566 RFIW plots, and (3) the Digital Soil Map of Wallonia (DSMW). The main soil units (MSUs) that derived from the DSMW linked the Aardewerk and RFIW databases. MSUs combine information on soil texture, drainage, and stoniness (Table 4). These three variables were available for almost all RFIW plots (soil auger). When it was not the case (3 %), the intersect between RFIW grid and DSMW was geoprocessed. As for humus areas in litter CS, MSU areas correspond to RFIW plot counting (with 1 plot = 71.43 ha).

Soil CSs were computed for 1960 and 2005 in order to compare methods and associated estimates of other studies. Horizon carbon densities (g m^{-2}) were computed for both reference years as follows:

$$\mathrm{HCD} = \mathrm{HCC} \times \mathrm{HT} \times \mathrm{BD} \times (1 - \mathrm{HS}) \qquad (6)$$

where HCD (g m^{-2}) is the horizon carbon density, HCC is the horizon carbon concentration (g g^{-1}), HT (m) is the horizon thickness, BD (g m^{-3}) is the horizon bulk density, and HS is the horizon stoniness.

Table 4 Description of the main soil units (MSUs) combining information on soil texture, drainage, and stoniness of the Digital Soil Map of Wallonia

MSU	Main soil unit description		Area (ha)
	Texture/stone charge	Drainage	
1,000	Peat soils and mors		4,286
2,010	Sand or loamy-sand	Slightly excessive to excessive	16,929
2,020		Moderate to imperfect	3,714
3,010	Sandy-loam	Good	5,072
3,020		Moderate to imperfect	6,572
4,010	Loam	Good	15,072
4,020		Moderate to imperfect	19,643
4,030		Poor to very poor	11,215
5,010	Clay	Good to imperfect	9,643
5,020		Poor to very poor	4,143
6,010	Loam with less than 15 % of stone charge	Good	34,858
6,020		Moderate to poor	26,358
7,110	>15 % of shale and slate	Good	95,216
7,210	>15 % of shale and sandstone	Good	83,073
7,220		Moderate to poor	36,501
7,310	>15 % of shale	Good	45,715
7,410	>15 % of micaceous sandstone	Good	18,215
7,510	>15 % of limestone	Good	18,643
7,610	>15 % of flintstone and quartz pebble	Good	5,500
7,710	>15 % of calcareous clayey sandstone	Good	714
7,810	>15 % of chalk	Good	214
10,000	Soil complexes, steep slopes, alluvial soils		714
30,000	Artificial or unmapped soils		3,286
Total	/		465,295

The source of data differs between 1960 and 2005: For 1960, carbon concentrations (g g^{-1}) of Aardewerk database were used, while for 2005, carbon concentrations of RFIW soil samplings were used. The measurement method of carbon concentration differs also between the two reference years: for 1960, carbon extraction method of Walkley and Black (1934) was used, while for 2005, carbon extraction method of Springer and Klee (1954) was used. Moreover, bulk densities of 1960 are required for 2005 estimates (Eq. 9).

Reference year 1960

The correction factor of 1.58 proposed by De Vos et al. (2007) was used to convert the Aardewerk carbon concentration into total organic carbon. De Vos' correction factor compensates for the incomplete oxidation of Walkley and Black's carbon extraction method. The soil horizon carbon density (Eq. 6) was calculated from the corrected horizon carbon concentration, the Aardewerk thickness and stoniness, and the horizon bulk density estimated with Rawls' (1983) pedotransfer function:

$$\mathrm{BD} = \left(\frac{\mathrm{OMP}}{\mathrm{OMD}} + \frac{1 - \mathrm{OMP}}{\mathrm{MFD}}\right)^{-1} \tag{7}$$

where BD (g m^{-3}) is the horizon bulk density of Rawls (1983), OMP is the organic matter concentration (=Aardewerk carbon concentration × 2 × 1.58; the factor 2 allows to convert carbon mass into organic matter; 1.58 is the De Vos' correction factor), OMD (g m^{-3}) is the bulk density of the organic matter ($=0.224 \times 10^6$ g m^{-3}), and MFD (g m^{-3}) is the bulk density of the mineral fraction according to Boon (1984) (Lettens et al. 2004, 2005a, b).

Wallonia's soil CSs (g) in 1960 were estimated up to 0.2 and 1 m depth as follows:

$$\mathrm{SCS_d} = \sum_{i=1}^{m} \left(A_i \frac{\sum_{j=1}^{n} \sum_{k=1}^{p} \mathrm{HCD}_{ijk}}{n} \right) \tag{8}$$

where $\mathrm{SCS_d}$ (g) is the total amount of soil organic carbon in 1960 above depth d, A_i (m^2) is the area of the MSU i (=numbers of RFIW plots × 71.43 ha), and HCD_{ijk} (g m^{-2}) is the horizon carbon concentration up to depth d of horizon k, profile j, and MSU i.

The soil CSs of some MSUs were calculated from the carbon densities of a few profiles. However, the areas of these MSUs (1,000, 7,710, and 7,810) are small in order not to alter global estimations. When no profile was available (MSUs: 10,000 and 30,000), general means were used. The same conventions were applied for the reference year 2005.

Reference year 2005

Horizon carbon density (Eq. 6) was calculated from horizon carbon concentration and horizon stoniness of the RFIW soil sampling. No correction is necessary for carbon concentration measured with Springer and Klee's (1954) method. RFIW horizon thickness is constant and equals 0.2 m. Because Eq. (7) was not applicable (information about mineral fraction was lacking), RFIW bulk densities were estimated by averaging Aardewerk bulk densities by main soil unit (MSU) as follows:

$$\mathrm{MSUD} = \frac{\sum_{j=1}^{m} \left(\frac{\sum_{k=1}^{p} (\mathrm{HT}_{jk} \times \mathrm{BD}_{jk})}{\sum_{k=1}^{p} \mathrm{HT}_{jk}} \right)}{m} \qquad (9)$$

where MSUD ($\mathrm{g\ m^{-3}}$) is the main soil unit bulk density, HT_{jk} (m) is the Aardewerk horizon thickness of horizon k and profile j up to 0.2 m depth, BD_{jk} ($\mathrm{g\ m^{-3}}$) is Rawls' horizon bulk density of horizon k and profile j, and m is the number of profiles in the MSU considered.

Results and discussion

Regional carbon stocks

The total CS of the productive forest amounts to 86.19 Tg (185.24 Mg $\mathrm{ha^{-1}}$) (Table 5). Soil up to 0.2 m and living biomass are the most important carbon pools with, respectively, 48 and 47 % of the total CS. The remaining pools are far behind with 4 % for litter and 1 % for deadwood. The soil CS's 0.2 m/1 m ratio in 1960 equals 54 %.

Living biomass and deadwood CS estimates in Table 5 are slightly underestimated. No data were available to take into account the CS of five elements:

(1) Biomass of young stands where all dead or alive trees have circumference smaller than 20 cm at 1.5 m height (RFIW measurement threshold). That concerns 17 % of the productive forest area. Taking into account the woody vegetation in these stands would roughly increase the aboveground biomass CS by 0.7–4.2 % (+0.51 to 3.06 Mg $\mathrm{ha^{-1}}$). This range derives from an average age of woody vegetation of 6 years and an annual mean growth of 0.5–3 Mg $\mathrm{ha^{-1}}$ $\mathrm{year^{-1}}$ (Dieter and Elsasser 2002).

(2) Biomass of dead or alive trees smaller than RFIW threshold in mature stands. This element is very difficult to estimate because it may vary greatly depending on stand structure.

(3) Biomass of foliage which is not included in Vallet's wood volume equations. Based on Muukkonen's (2007) foliage equation (type 2), the foliage biomass would increase the living biomass by approximately 3.4 % (+2.96 Mg $\mathrm{ha^{-1}}$).

(4) Biomass of stumps more than 3 years old that are not inventoried by the RFIW. This element is negligible (CS of stumps less than 3 years old = 0.36 Mg $\mathrm{ha^{-1}}$).

(5) Biomass of coarse woody debris with midcircumference <20 cm. This element is also negligible (CS of coarse woody debris of at least 20 cm = 0.73 Mg $\mathrm{ha^{-1}}$).

Carbon stocks by ecoregion and forest type

The total carbon stock (Mg $\mathrm{ha^{-1}}$) and his distribution within the pools differed significantly between ecoregions and forest types (Fig. 1).

The living biomass CS of broadleaved forests always exceeds that of coniferous forests. Although the growing volume stock per hectare is greater in coniferous stands, the broadleaves' higher wood densities and Vande Walle's 'BEF2' biomass factors (Table 3) compensate for and even surpass this difference (Eqs. 1, 2, and 3). Living biomass CSs fit also well with the ecoregions' characteristics: Higher values in coniferous stands are found in Condroz and Jurassic region dominated by Douglas fir; lower values in broadleaved stands are found in Fagne-Famenne dominated by unfertile oak forests.

Litter CS is systematically higher in coniferous forests. Softwoods generate litter that degrades very slowly generating humus as moder and dysmoder; all the more so that coniferous stands are generally planted on poorer soils.

Soil CS is also systematically slightly higher in coniferous stands. Ardenne contains the highest CS for both forest types. This is due to Ardenne's typical poor soil (MSUs 7,110 and 7,210), high mean basal area (±30 $\mathrm{m^2\ ha^{-1}}$), and high percentage of coniferous (63 %).

Ratios between pools differ widely between ecoregions and forest types. For example, the ratio of biomass to soil CS of broadleaved stands equals, respectively, 1.05 and 1.36 for Ardenne and Jurassic region. This ratio for coniferous stands is much less with, respectively, 0.80 and 1.08.

Comparisons can go further. For example, differences between the three most common stands (spruce, oaks, and beech) appear clearly for living biomass, litter, soil, and

Table 5 Carbon stock estimates of Wallonia's forest; soil carbon stocks for 1960 are in brackets; Tg: teragrams (1 Tg = 10^{12}g) and Mg ha^{-1}: megagrams per hectare (1 Mg = 10^{6}g)

(Sub)Pool	Tg	Mg ha^{-1}	Percentage subpool in pool	Percentage (sub)pool in total
Living biomass	40.53	87.12	100	47 (54)
Aboveground biomass	33.52	72.03	83	39 (44)
Belowground biomass	7.02	15.08	17	8 (9)
Dead biomass	0.90	1.94	100	1 (1)
Dead standing trees and snags	0.40	0.85	44	0 (1)
Coarse woody debris	0.34	0.73	38	0 (0)
Stumps	0.17	0.36	18	0 (0)
Litter	3.85	8.26	/	4 (5)
Soil up to 0.2 m depth	40.91 (30.40)	87.93 (65.34)	/	48 (40)
Total carbon stock	86.19 (75.68)	185.24 (162.65)	/	100 (100)
Soil up to 1 m depth	(56.13)	(120.64)	/	/

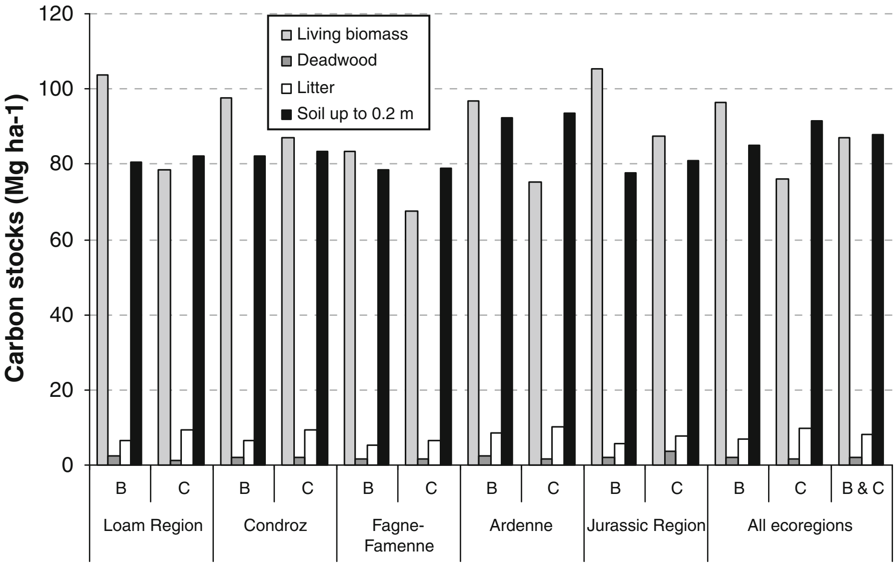

Fig. 1 Carbon stocks distributed by ecoregion and forest type. Forest type: *B* broadleaves and *C* coniferous; *Mg ha*$^{-1}$ megagrams per hectare (1 Mg = 10^{6} g)

total CSs. The highest soil (92.5 Mg ha^{-1}) and litter (10.2 Mg ha^{-1}) CSs are found in spruce stands. The lowest soil CS is found in oak stands (83.4 Mg ha^{-1}). The highest living biomass (115.2 Mg ha^{-1}) and total (214.9 Mg ha^{-1}) CSs are found in beech stands. Beech stands thus come at the top in carbon stocking capacity. This is mainly due to the fact that: (1) the growing stock of beech stands (Vallet's volume) is the highest among broadleaves; (2) the wood basic density of beech is the highest after hornbeam's (Table 3); and (3) soil CS in beech stand (89.0 Mg ha^{-1}) is close to that of spruce stands.

Comparison between carbon estimation methods

Our estimates (Table 5) differ sometimes greatly from other studies dealing with forest CS estimation in Belgium (synthesis in Table 6). We analyzed the methods used by the other authors to highlight pool by pool the elements having a significant impact on carbon stock estimates.

Living biomass

Our living biomass CS estimate of 87 Mg ha^{-1} is 8 and 18 % smaller than estimations for the year 2000 also based on RFIW data in Lettens et al. (2008) and in Vande Walle et al. (2005). The Vande Walle's estimate is derived from Belgian wood volume equations (Dagnelie et al. 1999) in combination with Vande Walle's 'BEF1' biomass factor. Dagnelie's equations estimate the total solid wood volume (stem and branches with a circumference $\geq$22 cm) for twelve groups of species encountered in Wallonia.

When replacing Vallet's volumes by Dagnelie's ones and BEF1 in Eq. (3), our living biomass CS amounts to 103 Mg ha^{-1} instead of 87 Mg ha^{-1} (+16 %, +16 Mg ha^{-1}).

Table 6 Synthesis/review of carbon stock estimates (Mg ha^{-1}) for Belgium, Flanders (northern Belgium) and Wallonia (southern Belgium)

		Soil						Litter			Living biomass			Deadwood
		0.2 m depth			1 m depth									
		B	C	TF	B	C	TF	B	C	TF	B	C	TF	TF
1960	Belgium		54^{5}	50^{2}	93^{1}	113^{1}	103^{5}	46^{1}	70^{1}					
	Flanders			46^{2}			112^{5}	$4(29)^{5}$	$7(31)^{5}$					
	Wallonia	*63^{7}*	*67^{7}*	51^{2}/*65^{7}*	*118^{7}*	*124^{7}*	101^{5}/*121^{7}*							
2000	Belgium	66^{3}	71^{3}	70^{2}	148^{3}	155^{3}	151^{5}				100^{6}	95^{6}	$93^{6}/101^{4}$	
	Flanders			59^{2}			135^{5}	10^{3}	35^{3}				85^{4}	
	Wallonia			75^{2}			158^{5}				100^{6}	104^{6}	$95^{6}/106^{4}$	
2003	Wallonia										*96^{7}*	*76^{7}*	*87^{7}*	*2^{7}*
2005		*85^{7}*	*91^{7}*	*88^{7}*										
2010								*7^{7}*	*10^{7}*	*8^{7}*				

Exponents: 1. Lettens et al. (2004), 2. Lettens et al. (2005a), 3. Lettens et al. (2005b), 4. Vande Walle et al. (2005), 5. Van Wesemael et al. (2006), 6. Lettens et al. (2008), 7. This study (in italics). Forest types: *B* broadleaves, *C* coniferous, *TF* all types of forests

To illustrate this difference, species-specific ratios (=Dagnelie's volume/Vallet's volume) were computed with RFIW data and compared with 'BEF1' biomass factor (Fig. 2). The ratio of thin branches' volume to total volume of a tree varies with tree circumference. Using BEF1 constant value tends to underestimate the biomass of small trees and overestimates it for bigger ones (from circumference >50 cm for beech, Fig. 2). This method comparison confirms that total aboveground biomass allometric equations and age-specific biomass expansion factors are clearly more adapted and accurate, especially when working on small areas or at stand type level (Brown 1997; Lehtonen et al. 2004).

It has been previously demonstrated that wood density has strong influence on biomass estimations (Vande Walle et al. 2005). For example, estimates of living biomass of Scots pine and poplar stands in Wallonia can differ by 11 % depending on the wood density reference: Vande Walle et al. (2005) or Wagenführ and Schreiber (1985). For the main stands in Wallonia (spruce, beech, and oaks), this difference varies from 2.5 to 3.5 %.

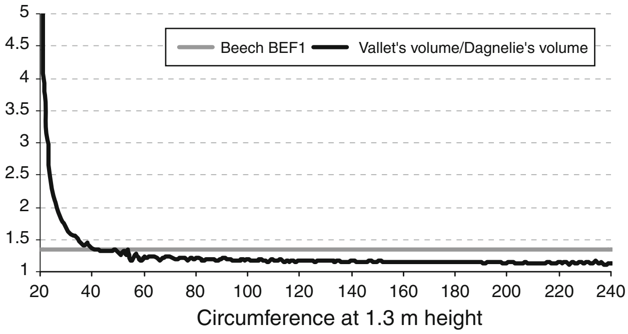

Fig. 2 Ratio Vallet's volume and Dagnelie's volume, and Vande Walle's 'BEF1' biomass expansion factor BEF1 (=1.34) according to beech tree circumference

Litter

The litter CS of Flanders (northern Belgium) was estimated by Lettens et al. (2005b) in 2000 at 10 Mg ha^{-1} for broadleaved forests to 35 Mg ha^{-1} for coniferous forests, and by Van Wesemael et al. (2006) at 4–7 Mg ha^{-1} in 1960. These estimates were obtained based on Eq. (6) with ectorganic horizon bulk density values proposed in the literature (and not deriving from Eq. 7). When using Eq. (7), Wesemael et al. obtained a litter CS varying from 29 Mg ha^{-1} (broadleaved forests) to 31 Mg ha^{-1} (coniferous forests). They concluded that Eq. (7) caused an overestimation of the ectorganic horizon bulk density (from 5 to 13 times more).

Our estimates for 2010 (7.01 Mg ha^{-1} for broadleaved forest, 9.79 Mg ha^{-1} for coniferous forests, and 8.26 Mg ha^{-1} for all forests) were directly calculated from carbon density expressed in g m^{-2} and are therefore not impacted by the error resulting from bulk density estimation.

Soil

Lettens et al. (2005a) estimated the soil CS in Wallonia's forest up to 0.2 m depth in 1960 (51 Mg ha^{-1}) and in 2000 (75 Mg ha^{-1}). Our results are much higher than these, +37 % in 1960 (65.34 Mg ha^{-1}) and +18 % in 2005 (87.93 Mg ha^{-1}). These differences may be explained by the following reasons: (1) We used data from a revised/corrected version of the Aardewerk database (Legrain 2005), (2) we considered MSU/RFIW associations and not landscape units for spatial generalization, so the forest reference area is not exactly the same, and (3) we used a correction factor of 1.58 (De Vos et al. 2007) instead of 1.32 (Walkley and Black 1934) to compensate for the incomplete oxidation of Walkey and Black's carbon extraction method.

According to De Vos et al. (2007), Walkley and Black's correction factor, often used as default for all kinds of land uses, is not adapted to soil of temperate lowland forests. De Vos et al. proposed a new correction factor of 1.58 instead of 1.32. De Vos' correction factor is reliable only for horizons with less than 8 % of carbon. This is the case for 99 % of Aardewerk hemiorganic horizons. Using the Walkley and Black's correction factor generates important decreases in carbon density (Eq. 6) and small increases in bulk densities (Eqs. 7 and 9). Therefore, when we used 1.32, we obtained smaller estimates for 1960 (57.58 Mg ha^{-1}, −12 %) and higher ones for 2005 (91.74 Mg ha^{-1}, +4 %).

Sources of error and accuracy of the estimates

Imprecision may occur at different levels (field sampling, measurement method, work assumptions, and simplifications) and be related to different phases of the estimation procedure (especially when mixing data from several sources).

Goidts et al. (2009) showed that sources of uncertainty linked to the soil CS of Wallonia's land under agriculture increased with the sampling scale. The estimation reliability is thus not directly proportional to the number of inventory plots or soil profiles.

Regarding living biomass and deadwood, errors of measurements in the field, wood volume, and forest area calculation can be considered as low. Error in Wallonia' forest area estimated by counting plots on grid (Bouchon 1975) equals 0.27 %. Uncertainty is mainly due to wood density introducing large variability in the CS estimates (Vande Walle et al. 2005). To minimize the risk of error, we calculated all the specific wood basic densities (Eq. 5) based on a unique reference (Wagenführ and Schreiber 1985). Concerning belowground biomass, Vande Walle's 'BEF2' biomass factor could generate important overestimations in Eqs. (2) and (3) as we have seen with BEF1. Another but small source of uncertainty concerns deadwood decomposition, which is crucial though in order to assess the deadwood CS (Coomes et al. 2002).

Estimates for litter, as demonstrated, may vary largely depending on carbon measurements and calculation methods. Because no bulk density estimation was needed, errors remain relatively small and linked to sampling and analyses, even though the number of samplings stays weak in the case of some less representative humus types (mor, dysmoder, and calcic mull).

Several errors concerning the soil may have occurred because of differences in sampling protocols and calculation procedures. The first point to mention is the difference in methods to measure carbon concentration: Walkley and Black's for 1960 and Springer and Klee's for 2005. Walkley and Blacks's carbon concentration had to be corrected to compensate for incomplete carbon extraction. As discussed previously, the factor 1.32 of Walkley and Black (1934) is not adapted for temperate forests. The use of 1.58 (De Vos et al. 2007) is highly recommended.

Another source of soil CS imprecision comes from the use of the pedotransfer function of Rawls (1983) to estimate soil bulk density based on the mineral fractions and carbon concentrations of Aardewerk database. Stevens and Van Wesemael (2008) compared bulk density measurement values and those predicted by Rawls' function. They evidenced low accuracy for the Ardenne ecoregion. Considering that no error occurred in their own estimations, they assessed a relative error on the soil CS of about 15 % when using Rawls' function instead of direct measurement. Furthermore, De Vos et al. (2005) found large differences in the accuracy of 12 published pedotransfer functions (including Rawls') for forest soils of Flanders (northern Belgium). Rawls' function appeared as one of the best, but it underestimates bulk density systematically, particularly in subsoil. As a result, the soil CS for both years (1960 and 2005) would be quite higher. It is also important to signal that although we used a revised version of the Aardewerk database (Legrain 2005), we excluded some profiles because of data uncertainty.

Working independently of land cover maps avoided the inaccuracies generated by geomatching between point and surface data, and error of land use and forest type classification. For example, CORINE Land Cover (CLC) maps have a minimum map unit of 25 ha. Therefore, a polygon classified as forest means that the dominant land use in the polygon is forest, but other small land uses may be found in this polygon. In case of fragmented landscape, as in Belgium, these classifications overestimate the dominant land use (Perdigão and Annoni 1997; Pekkarinen et al. 2009). Moreover, the polygon limits depend on the image resolution on which the map is based (30 m in the case of CLC). CLC maps were used by Lettens et al. (2004, 2005a, b, 2008), Vande Walle et al. (2005) and Van Wesemael et al. (2006).

Conclusion

The forest ecosystem is particularly complex to apprehend in comparison with other land uses, such as grasslands and croplands, for which only soil carbon stock is taken into account. This complexity may justify to consider forest ecosystem differently. In that case, forest inventories at regional or national levels cannot be ignored. Thanks to their specificity and permanency, they allow precise estimations of forest type areas and carbon stocks.

We developed a new carbon stock (CS) estimation procedure that includes all forest pools and combines forest inventory and soil and litter geodatabases available for the southern Belgium (Wallonia). This procedure turns out to be relatively simple and potentially applicable abroad on condition that available external carbon soil and litter data can be linked to forest inventory plots. This is the case for most NFIs that describe soil and litter on the field at least qualitatively (soil auger) and thus enable connections with external carbon databases. The main soil units (combination of texture, drainage, and stoniness) used to link forest inventory plots and soil profiles have proven to be efficient (good compromise between practicability and complexity).

We estimated the Wallonia's forest CSs of four pools and five subpools (in brackets): living biomass (aboveground and belowground biomasses of trees and coppices), deadwood (biomasses of dead standing trees, snags, coarse woody debris, and stumps), litter, and soil. The total forest CS is estimated at 86 Tg (185 Mg ha^{-1}). Soil up to 0.2 m depth, living biomass, litter, and deadwood CSs account, respectively, for 48, 47, 4, and 1 % of the total CS. As far as we know, we are the first to propose estimates of deadwood pool and subpools at the scale of a region such as Wallonia.

The analysis of CSs through stand types and ecoregions helped to detect some points of interest. Broadleaved stands present on average more carbon in their biomass than coniferous stands. However, this is reversed when considering litter and soil carbon stocks. On average, low biomass CS is compensated by higher soil CS. Beech stands are the stands with the highest potential CS capacity in Wallonia.

Being aware that CS's may vary significantly depending on the method used (biomass factors or equations, soil pedotransfer functions, correction factors, etc.), we compared our estimates and estimation methods with those found in the Belgian literature (but based on same data). For living biomass, using Vallet's equation instead of Dagnelie's equations in combination with Vande Walle's 'BEF1' biomass factor generates a decrease by up to 16 %. Litter CS estimates deriving from direct carbon density measurements (g m^{-2}) are at least three times less than those obtained with the Rawls' pedotransfer function. For soil, the use of a correction factor of 1.58 instead of 1.32 can explain an increase of at least 12 %. Therefore, selecting the appropriate estimation method is thus vital, especially when CS estimates are used to simulate forest CO_2 sequestrations and emissions.

Improving the CS estimation procedure would ideally mean first increasing the precision of horizon bulk density for soil and wood basic density and biomass factor (ratio belowground/aboveground) for living biomass. To estimate litter CS at regional or national level, mean carbon densities (g m^{-2}) by humus type may be sufficient. The contribution of the deadwood pool to the total carbon balance is low, so that increasing accuracy is not a priority.

In the coming years the ongoing re-inventory cycle of the regional forest inventory will provide new data useful to estimate reliable carbon stock changes based on the procedure described in this paper.

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