Original article

Above- and belowground phytomass and carbon storage in a Belgian Scots pine stand

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Abstract – We investigated the storage of carbon (C) in the soil, litter and various phytomass compartments in a 69-year-old Scots pine (*Pinus sylvestris* L.) stand in the Belgian Campine region, Brasschaat, Belgium. The total amount of C stored in the stand was 248.9 t·ha^{-1}, 47 % of which was in soil organic matter, 11 % in surface litter and 42 % in phytomass. More than 60 % of total C was stored belowground. Total phytomass C in the stand was 104 t·ha^{-1}; most phytomass C was found in the stems (70 %). The root system was very shallow and contained only 14 % of the phytomass C, most of it in the coarse roots. Although total live fine root (< 1 mm) length was high (3.3 km·m^{-2}), fine roots contributed only 2 % to total phytomass. (© Inra/Elsevier, Paris.)

carbon storage / phytomass / *Pinus sylvestris* / roots / Scots pine

Résumé – Phytomasse aérienne et souterraine et stock de carbone dans un peuplement de pin sylvestre en Belgique. Nous avons étudié le stockage du carbone dans le sol, dans la litière et dans différents compartiments de la phytomasse d'une plantation de pins sylvestres (*Pinus sylvestris* L.), âgés de 69 ans, localisée à Brasschaat, région de la Campine, Belgique. La quantité totale de carbone stockée au niveau de cette plantation était de 248,9 t ha^{-1}. 47 % étaient localisés dans la matière organique du sol, 11 % dans la litière, et 42 % dans la phytomasse. Plus de 60 % de la quantité totale de carbone se trouvait dans le sous-sol. La quantité de carbone contenue dans la phytomasse était de 212 t ha^{-1}. La plus grande partie de ce dernier a été trouvé dans les tiges (70 %). Le système racinaire était très superficiel et ne contenait que 14 % du carbone de la phytomasse, principalement localisé dans les grosses racines. Bien que la longueur des racines fines et vivantes ait été importante (3,3 km m^{-2}), elles ne représentaient que 2 % de la phytomasse totale. (© Inra/Elsevier, Paris.)

stock de carbone / phytomasse / *Pinus sylvestris* / racines / pin sylvestre

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1. INTRODUCTION

European forest productivity has increased by 18 % over the last 30 years [39]. Much of the increased production can be explained by an expansion of the total forested area (+10 %) as well as improved management techniques [39]; however individual tree growth rates also appear to have been enhanced over this period [38]. Increased growth rates of trees in the last three decades may be due to the increase in atmospheric CO_2 concentration and nitrogen (N) deposition [4], but also to the lengthening of the growing season [24]. Forest ecosystems will continue to be exposed to steadily increasing atmospheric CO_2 concentrations and, arguably, changing climate. Therefore, it is likely that the observed enhanced tree growth rates will be sustained over the next few decades [39].

It has become increasingly clear, as the conferences of Helsinki (1993) and Kyoto (1997) have established, that detailed inventories of the carbon (C) storage and sequestration in forest ecosystems are needed. Although forests cover only 20–30 % of the land surface [1, 13], they contain over 60 % of the C stored in the terrestrial biosphere [35]. Minor alterations in the C input/output balance of forests, especially in relation to supposed changes in climate [14], have the potential to strongly affect atmospheric CO_2 concentrations and thus the global carbon cycle [16, 37, 41]. Therefore, the role of forests in the terrestrial C cycle needs further examination.

More than half of the C accumulated in forests resides in the soil as organic matter [39]. Globally, soil organic matter content increases with decreasing temperature, increasing precipitation and increasing clay content [36]. At the stand level, soil C storage depends on the quantity, quality and decomposition of the litter inputs into the forest floor and soil. Litter quality is strongly influenced by site quality, vegetation type and age. These key factors also influence C sequestration and biomass partitioning. Most of the current available data on C storage in forests address only aboveground phytomass; important information on belowground phytomass is still largely lacking [47].

Scots pine (*Pinus sylvestris* L.) forests are the commonest forest type in Europe [39], covering 24 % of the total forested area (about 75 million km²). High tolerance to a wide range in soil nutrient and soil moisture conditions probably explains this finding [21]. In the Belgian Campine region, Scots pine is typically planted on strongly leached, nutrient-poor podzol soils that developed under heather ecosystems. Humus formed under these conditions exhibits labile, water-soluble acids that have a podzolising (leaching of humus and nutrients) and acidifying effect on the soil. As such, soil

microbial and faunal activity are low, leading to slow decomposition, absence of bioturbation and, subsequently, to an accumulation of a mor holorganic horizon [22, 23]. Immobilisation of large amounts of nutrients in the holorganic litter layer reduces even further the already poor site fertility [12, 32, 49], thereby decreasing the potential growth and C sequestration in phytomass of the forest. However, because of the typically large organic C pools and the vast surface area covered, Scots pine forests represent a potentially important reservoir for long-term C storage.

The objectives of this study were to compile and synthesise phytomass and C storage in a 69-year-old Scots pine plantation in the Belgian Campine region. Previously gathered data on site quality and aboveground phytomass, as well as new onformation on belowground phytomass, litter and soil organic matter are presented.

2. MATERIALS AND METHODS

2.1. Site description

This study was conducted in an even-aged, 69-year-old Scots pine plantation, part of a 150 ha mixed coniferous/deciduous forest (De Inslag) in Brasschaat (51°18'33" N, 4°31'14" E), in the Belgian Campine region. The stand is part of the European Ecocraft and Euroflux networks, and is a level II observation plot of the European programme for intensive monitoring of forest ecosystems (EC regulation n° 3528/86), managed by the Institute for Forestry and Game Management (Flanders, Belgium). Mean annual temperature at the site is 9.8 °C, with, respectively, 3 °C and 18 °C as mean temperatures of the coldest and warmest months. Mean annual precipitation is 767 mm. The study site has an almost flat topography, very gently sloping (0.3 %), and is at an elevation of 16 m. An overview of the main stand inventory data (1995) is presented in *table I* and *figure 1*.

The forest canopy is rather sparse, with a projected surface area of 65 % [44] and a projected leaf area index (LAI) between 2.1 and 2.4 [11]. The vigorous undergrowth of *Prunus serotina* Ehrh. and *Rhododendron ponticum* L. was completely removed in 1993, giving way to a moss layer dominated by *Hypnum cupressiforme* Hedw. There are only two needle classes (current and last year's needles). Needle analysis (*table II*) has shown the stand to be poor in magnesium (Mg) and phosphorus (P) [34, 44]. Needle nitrogen concentrations were optimal, probably because the site is located in an

Table I. Summary of stand inventory data.

Stand characteristic	Value	Units	Reference
Mean DBH	0.27	m	[8]
Mean tree height	20.6	m	[8]
Mean canopy depth	3.7	m	[8]
LAI	2.1-2.4		[11]
Density	556	trees·ha^{-1}	
Basal area	31.2	m^2·ha^{-1}	[8]
Standing wood volume	298.5	m^3·ha^{-1}	[8]
Wood volume increment			
1988–1995	8.1	m^3·ha^{-1}·year^{-1}	[27]
1995–1998	6-7	m^3·ha^{-1}·year^{-1}	(Meiresonne, unpublished)
Mean height growth	0.12	m·year^{-1}	[27]
C/N young needles	23.4		[34]
N/P young needles	16.8		[34]

All data from [8] were collected in 1995; leaf area index (LAI) was measured in 1996–1997 with a LCA-2000 (Licor, USA). DBH: diameter at breast height.

area with high NO_x and ammonia deposition (30–40 kg· ha^{-1}·year^{-1})[26].

The upper soil layer is ca. 1.8 m thick and consists of aeolian northern Campine cover sand (Dryas III). Beneath this sand layer, at a depth of 1.5 to 2 m, lies a clay layer (Tiglian) and deeper down another sand layer (sands of Brasschaat, Pretiglian) [3]. The stand has been described as a moderately wet sandy soil with a distinct humus and/or iron B horizon. The soil type is a psammentic haplumbrept (United States Department of Agriculture classification) or a haplic podzol (Food and Agriculture Organisation classification) [3]. A more detailed description of the topsoil profile with texture analysis and pH for all horizons is given in *table III*. The site has poor drainage due to the clay layer. The soil is moist but rarely saturated, and has a high hydraulic conductivity in the upper layers (sand). Groundwater normally is at 1.2 to 1.5 m [3]. The low pH values (*table III*) indicate that the soil is in the aluminium buffer region [42]. In this buffer region, base cation absorption is reduced and base cations are subject to leaching [40]. This could in part explain the low Mg content of the needles (*table II*). In these acid conditions, polymeric Al-hydroxy cations are being produced that block the free exchange sites on the clay minerals and organic matter particles. This further reduces the already poor cation exchange capacity (*table IV*). Another feature of the aluminium buffer region is the precipitation of Al and Fe phosphates [20], which strongly reduces P availability and may be responsible for the low P concentrations in the needles (*table II*).
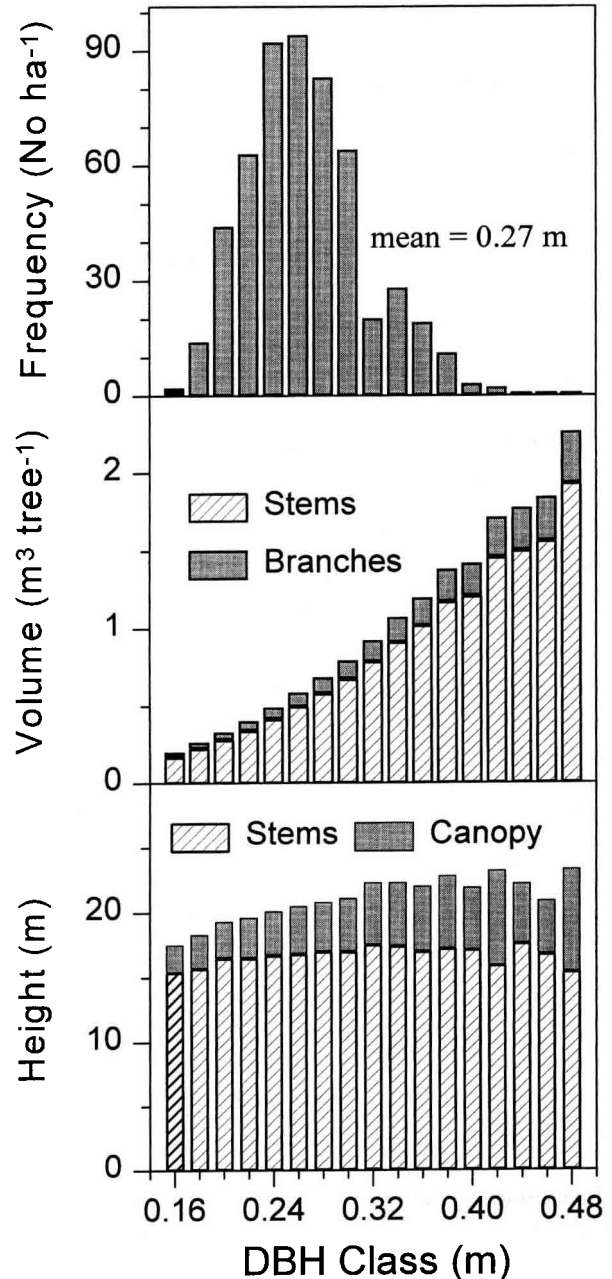

Figure 1. Top: Frequency distribution of diameter at breast height (DBH) classes (measured at 1.3 m). Middle: Mean stem and branch volume for the different DBH classes. Bottom: Mean stem and canopy height for the different DBH classes (modified after [8]).

Table II. Nutrient concentrations in the soil, litter layer and needles in the forest stand [34].

	Na	K	Ca	Mg	Fe	Al	N	P	S
Needles									
Optimal		> 7 000	> 2 000	> 1 000			> 18 000	> 1 700	
1st year	155	7 256	1 841	723	84	153	20 593	1 226	5 044
2nd year	467	5 269	3 042	688	131	175	21 751	1 084	5 240
Litter									
$O^F + O^H$	90	420	1 860	310	3 140	1 030	13 010	446	1 535
Soil									
A1	40	204	92	124	2 669	1 527	1 021	76	30
Ap	23	164	52	111	2 355	1 586	457	41	30
A/E/Cg	23	239	57	131	5 288	1 826	164	15	33
Cg	32	954	33	440	6 918	4 527	167	21	67

All units are mg·kg^{-1} dry matter. Optimal values are taken from [45, 46] and are valid only for current year (1st year) needles.

Table III. Depth, pH, texture analysis, bulk density, C concentration and C storage to a depth of 1 m in all soil horizons at the forest stand [3, 10, 23].

Horizon	Depth (cm)	pH (H_2O)	pH ($CaCl_2$)	Clay (%)	Loam (%)	Sand (%)	Bulk Density (g·cm^{-3})	% C (wt. %)	Total C (t·ha^{-1})
Litter	–6–0	3.9	3.3						
A1	0–2		3.0	6.2	13.0	80.8	1.21	8.99	21.8
Ap	2–34	3.8	3.3	4.2	6.9	88.9	1.363	1.12	48.9
A/E/Cg	34–50	4.1	3.7	2.1	9.2	88.8	1.543	0.75	18.5
Cg	50–90	4.1	3.8	1.1	0.8	98.1	1.549	0.33	20.7
2CBhg	90–100	4.1	3.8				1.555	0.31	4.8
								Total	*114.7*

Table IV. Effective cation exchange capacity (CEC eff), total cation exchange capacity (CEC tot), CEC eff/CEC tot ratio, effective base saturation (BS eff) and total base saturation (BS tot) at three depths in the soil [44].

Depth (cm)	CEC eff	CEC tot	CEC eff/tot	BS eff	BS tot
10	0.9	3.1	0.28	17.5	5.0
30	1.0	2.0	0.50	31.3	15.7
50	1.0	1.2	0.85	20.9	17.8
Mean	*1.0*	*2.1*	*0.55*	*23.2*	*12.8*

CEC is in meq 100 g^{-1} and BS in %; effective values were measured at the prevalent soil pH and total values were measured at pH = 7.

2.2. Standing phytomass

2.2.1. Stems

Total stemwood volume (7 cm diameter height) was calculated from the 1995 stand inventory data [8]. We measured wood density ($n = 13$) and C concentration (see later) ($n = 53$) to convert volume estimates to C equivalents.

2.2.2. Needles

Six trees (representative for the site) were selected according to the technique by Cermak and Kucera [7]. An allometric estimate of needle biomass was obtained from a destructive harvest of these six trees, using the equation:

$$Y = -0.4908 + 0.0433\,X - 0.0003\,X^2$$

[8] where Y = needle biomass (kg) and X = diameter at breast height (DBH; cm) ($R^2 = 0.965$). This equation was applied to each tree in the stand to obtain total stand needle biomass. Needle C storage at stand level was calculated by multiplying needle biomass with the mean needle C concentration ($n = 12$).

2.2.3. Branches

No statistically significant correlation between branch biomass and stem biomass of the six harvested trees was found, which was probably related to the small sample size. We therefore used the mean ratio of branch weight to stem weight (= 0.175) to scale up branch biomass to the stand level. C storage in the branches was calculated from the C concentration of the branches ($n = 12$).

2.2.4. Coarse roots

We excavated the root systems of four recently deceased trees in 1997 to establish a site-specific allometric relation between DBH and coarse root (> 5 mm) biomass. A linear regression between coarse root biomass and DBH^3 was used to scale up to the stand level. Root C concentration (four pooled samples) was used to estimate stand level coarse root C content.

2.2.5. Fine and medium roots

Fine (< 1 mm) and medium (1–5 mm) root biomass was estimated by core sampling [30, 33] in January ($n = 15$) and May ($n = 15$) 1997. Intact litter columns (down to the mineral layer) were excavated using a sharp-edged metal cylinder (inner diameter of 12 cm).

One half was used to assess fine root biomass and the other half to determine total litter mass. Fine root biomass in the soil underlying the removed litter columns was estimated using a soil corer (inner diameter of 8 cm; Eijkelkamp, The Netherlands). Intact 15-cm increments were removed to a depth of 90 cm. Samples from different depths were assessed separately (0–5, 5–15, 15–30, 30–45, 45–60 and 60–90 cm). Root fragments were removed from the samples, washed and sorted into three diameter classes: 0–1, 1–2 and 2–5 mm. Live and dead root fragments were subsequently separated by visual inspection as described by Persson [31] and Vogt and Persson [48]: the xylem of dead roots looks darker and deteriorated, the degree of cohesion between the cortex and periderm decreases and root tips become brittle and less resilient. Total root length of each sample was measured using a portable laser area meter modified for root lengths (CI-203RL, Cid Inc., Vancouver USA). Dry mass (24 h at 80 °C) and ash content (5 h at 550 °C) of each sample was determined. Ash-free fine root biomass was used to avoid contamination by mineral soil particles [2]. Fine root C content for each diameter class was estimated from standing biomass and C concentration ($n = 4$).

2.3. Surface litter

2.3.1. Holorganic horizon

The total mass of organic matter in the holorganic horizon was estimated from the 30 subsamples taken from the litter columns (see earlier). We assumed an equal fine root biomass in each half of the litter column. This amount was subtracted from the total litter dry mass (24 h at 80 °C) to obtain an estimate of the total organic matter in the litter layer. The O^L horizon (fresh litter) of each sample was separately assessed from the $O^F + O^H$ layers (decomposing litter). C concentrations of each litter sample ($n = 2$) were used to convert total dry mass to C content.

2.3.2. Coarse woody debris

The amount of dead wood (> 5 mm in diameter) at the soil surface was assessed in 1997 in five randomly selected subplots of varying area. We used 1-, 25- and 100-m^2 plots to sample branches with diameters of respectively 0.5–2.5, 2.5–5 and > 5 cm. All branches were taken to the laboratory, dried (2 weeks at 80 °C), weighed and analysed for C. For the logs, eight 400 m^2 plots were sampled. The volume of all logs was calculated, and density and C concentration were determined on two to three subsamples per log.

2.4. Mineral soil

2.4.1. Soil organic matter

Fifteen, 1-m deep soil cores were taken to estimate the organic matter content of each horizon in the soil profile. All samples were dried, sieved (mesh = 2 mm), ground and analysed for C. Total C content in each horizon ($t \cdot ha^{-1}$) was calculated from the layer thickness, bulk density and C concentration (*table III*).

2.4.2. Belowground litter

The amount of dead roots in the soil, obtained while sampling fine root biomass, was used as an estimate for belowground litter. C content was determined for the different diameter classes from their C concentrations ($n = 3$).

2.5. Chemical analysis

Estimating C storage in phytomass compartments requires information on both total phytomass and C concentration in the different tissues. Although data from the literature were available on the C concentrations in the phytomass compartments, these data cover quite a wide range (e.g. 45–54 % in Scots pine needles in Belgium [44]) and could lead to serious over- or underestimations of total C content. We therefore chose to perform chemical analysis on each of the C pools at the site.

All C analyses used in the budgets were made using the dry combustion technique, except for the soil analyses, which were determined by wet oxidation (dichromate) of organic matter followed by colorimetric determination of the chromic produced [28]. All soil, litter and needle mineral analyses in *table I* were performed following the procedures of Cottenie et al. [9].

3. RESULTS

3.1. Standing phytomass

Total stemwood volume was 298.5 $m^3 \cdot ha^{-1}$ [8], with an average density of 0.502 $g \cdot cm^{-3}$. Stem biomass totalled 149.9 $t \cdot ha^{-1}$, with a total C content of 73.3 $t \cdot ha^{-1}$ (*table V*). Branch mass was 26.2 $t \cdot ha^{-1}$, representing a C pool of 13.5 $t \cdot ha^{-1}$ (*table V*). Needle biomass was 6.3 $t \cdot ha^{-1}$ [8]; total C storage in the needles was 3.0 $t \cdot ha^{-1}$.

All harvested Scots pines had surprisingly shallow rooting depths, and none exhibited a tap root. These data are consistent with results from the same stand presented by Cermak et al. [8]. In their study (seven wind-toppled trees), the mean depth of the coarse root system was 1.04 m and the projected root area was 29.9 m^2. The allometric relation between DBH and coarse root (> 5 mm) biomass obtained in this study was:

$$Y = 22.47 + 1020.2\, X$$

where Y = coarse root biomass (kg) and X = DBH^3 (m) ($R^2 = 0.69$). Total coarse (> 5 mm) root biomass was 23.9 $t \cdot ha^{-1}$, with a total C storage of 11.8 $t \cdot ha^{-1}$ (*table V*). Fine root biomass did not differ between January and May. The majority of the live fine (< 1 mm) roots was found in, and just below, the holorganic horizon, and maximum root density shifted downwards from fine to medium roots (*figure 2*). Biomass of both live and dead fine (< 1 mm) roots over the total investigated rooted soil was much higher than that of medium size roots (1–2 and 2–5 mm) (*figure 3*). This difference was completely situated in the upper 15 cm of the soil (*figure 2*). Few fine roots were found below 60 cm. For the smallest size class (< 1 mm), specific root length was 10.2 $m \cdot g^{-1}$, and total root length was 3.3 $km \cdot m^{-2}$. No correlation with the distance from the nearest tree (or trees) was detected. C storage was 1.8 $t \cdot ha^{-1}$ in the fine roots and 1.0 $t \cdot ha^{-1}$ in the medium roots (*table V*).

Total phytomass contained only 42 % of the total amount of C stored in the ecosystem (*figure 4*). Most of the phytomass C was stored in the stems (70 %), and no more than 14 % was stored in the belowground biomass (*figure 4*).

3.2. Surface litter

The amount of organic matter in the holorganic horizon (not including live roots) was 73.1 $t \cdot ha^{-1}$. Most of this dry matter (85 %) was stored in the $O^F + O^H$ layer, representing a C pool of 20.6 $t \cdot ha^{-1}$ (*table V*). The upper layer of the holorganic horizon, the O^L layer, had a carbon content of 4.9 $t \cdot ha^{-1}$ (*table V*).

As could be expected for a managed plantation, the amount of coarse woody debris (in various stages of fragmentation or decomposition) was rather small. Total dry matter was 2.8 $t \cdot ha^{-1}$, 40 % of which was found in logs, and another 40 % was found in twigs and small branches (< 2.5 cm). C storage in dead wood was 1.3 $t \cdot ha^{-1}$ (*table V*). The total surface litter C pool contained 26.8 $t \cdot ha^{-1}$, representing 11 % of the C accumulated in the stand (*figure 4*).

Table V. Biomass, C concentration (wt %) and C storage (t ha^{-1}) in the phytomass, surface litter and soil compartment of the pine ecosystem.

	Pool size (t·ha^{-1})	C concentration (wt. %)	C storage (t·ha^{-1})
Soil			
Organic matter			114.7
Root litter	6.4		3.0
Subtotal soil			117.7
Surface litter			
O^L layer	10.8	45.9	4.9
O^F + O^H layers	62.3	33.0	20.6
Woody debris	2.8		1.3
Subtotal litter	75.9		26.8
Phytomass			
Stems	149.9	48.9	73.3
Branches	26.2	51.6	13.5
Needles	6.3	48.2	3.0
Coarse roots (> 5 mm)	23.9	49.4	11.8
Medium roots (1– 5 mm)	2.0	52.6	1.0
Fine roots (< 1 mm)	3.2	55.4	1.8
Subtotal phytomass	211.5		104.4
Total			*248.9*
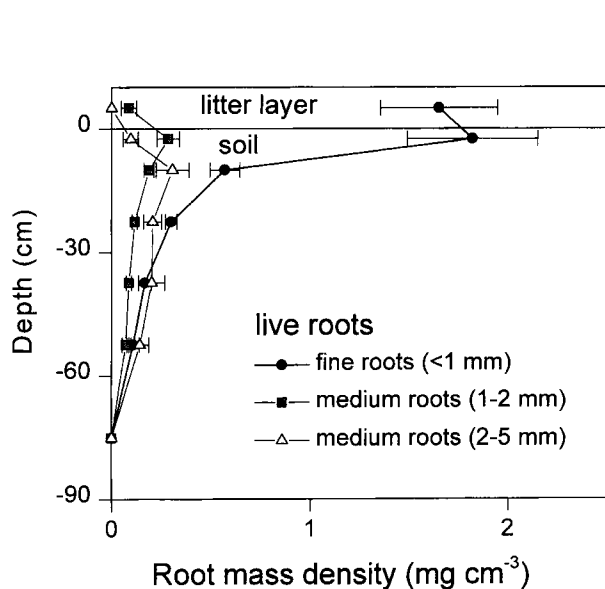
Figure 2. Root mass density of live fine and medium roots as a function of depth in the Brasschaat forest stand. Error bars indicate 1 standard error of the mean (n = 30).
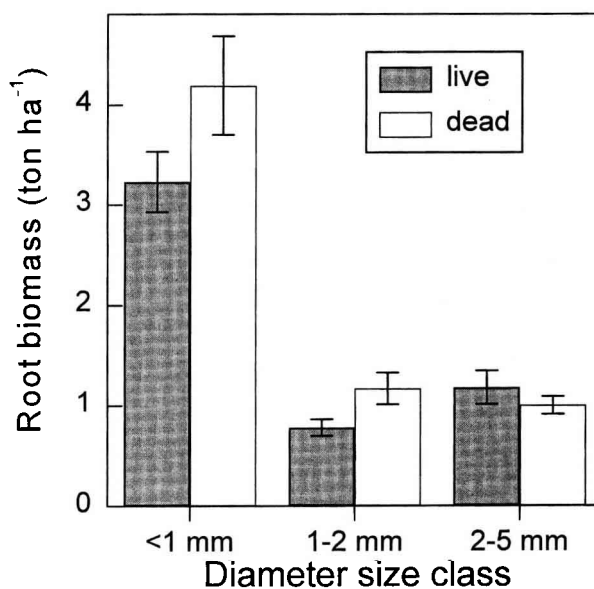
Figure 3. Biomass of both live and dead fine and medium roots in the Brasschaat forest stand. Error bars indicate 1 standard error of the mean (n = 30).
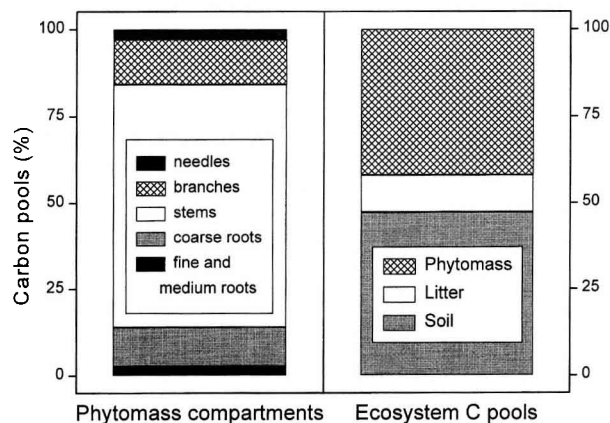
Figure 4. Left: Carbon (C) storage in the phytomass compartments as a percentage of the total amount of C in the phytomass. Right: C storage in the phytomass, surface litter and soil as a percentage of the total amount of C in the forest stand.

3.3. Belowground pools

As in most podzols, the C concentration was very high in the thin uppermost soil layer, and low in all lower horizons (absence of bioturbation). Total C storage in the mineral soil, to a depth of 1 m was 114.7 t·ha^{-1} (*tables III* and *V*).

The amount of belowground litter was more or less equal to the amount of live roots (*figure 3*). A total of 3.0 t·ha–1 C was contained in the dead roots (*table V*), 74 % of which was found in the fine (< 1 mm) roots.

This soil organic C pool contains over 47 % of the total amount of C in the ecosystem, and exceeds the C storage in the phytomass.

4. DISCUSSION

Stand age and site quality clearly determine the total amount of Scots pine phytomass [43, 47], as well as the allocation and distribution of biomass among different phytomass components. However, trees growing in fertile soils exhibit faster growth rates, thereby reaching the same developmental stage (with similar patterns of allocation) earlier. Therefore, comparison of phytomass allocation requires the examination of stands of similar height and development [47]. The relative contribution of needles and fine roots (and to a lesser degree of branches and coarse roots) decreases with stand age. In addition, the ratio of needles to fine roots decreases [47].

In this study, we found a total phytomass storage of 210 t·ha^{-1} for a 20.6 m tall, 69-year-old Scots pine stand.

Over 70 % of total phytomass was stored in the stems, which represents a large potential long-term C sink. The proportion of phytomass in the aboveground woody biomass was 83 %, which was just within the range reported for various species of pine: 67–84 % [17]. Our estimate of root biomass (14 % of total phytomass) also fell just within the range reported for different pine species: 13–25 % [29]. The observed root:shoot ratio of 0.16 was indeed very low compared to the usually reported mean for coniferous forests: 0.24–0.26 [5, 6, 18]. This shallow rooting system probably developed because there was no need for the trees to invest in larger and deeper root systems: the subsoil is poor in nutrients and the clay layer prevents the soil from drying out.

Almost 60 % of the total C in the stand was found in organic matter in soil and litter, which was in agreement with similar Belgian [15] and Dutch [25] forests. Scots pine litter has an acidifying effect on the soil, leading to slow decomposition and accumulation of a thick holorganic horizon on the forest floor, in which large amounts of nutrients are stored. In this stand, 10 % of the total C was stored in the litter layer, whereas almost 50 % was in the soil. In addition to being the largest C pool, forest soils may store C in highly recalcitrant molecules, with turnover times of hundreds to thousands of years. Soils may therefore be the most important forest C pool in the perspective of long-term C storage.

European forests may sequester between 0.17 and 0.35 Gt. C (the equivalent of 10 to 40 % of the anthropogenic CO_2 emissions) [19]. As such, in light of the Kyoto protocols, planting trees to sequester C is likely to contribute to the reduction of net greenhouse gas emissions. An inventory of the terrestrial C storage in forest systems would help to define the global C budget and, therefore, aid in the understanding of the source-sink relationships among, and the potential storage capability of, forest ecosystems.

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