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Aboveground Carbon Content and Storage in Mature Scots Pine Stands of Different Densities

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Abstract: *Background and Objectives*: The continuous increase in the amount of atmospheric CO_2 is a factor that significantly contributes to global warming. Forests can be used to mitigate climate change by absorbing carbon and storing it. Scots pine (*Pinus sylvestris* L.) is the most abundant tree species in Polish forests and can substantially aid carbon accumulation. The aim of the study was to determine the carbon content in the dry mass of various parts of Scots pine trees and to evaluate the relationship between the accumulation of carbon in aboveground tree biomass and some stand parameters. *Materials and Methods*: The research was carried out in 20 even-aged (81–90 years old) Scots pine stands in northwestern Poland (Drawno Forest District). The densities of these stands ranged from 476 to 836 trees per hectare. The aboveground biomass was calculated as the sum of the following tree compartments: stem (wood and bark), dead branches, thick branches, thin branches and needles. The carbon content and storage in these compartments was determined. *Results*: The mean carbon content was lowest in stem wood (47.0%) and highest in needles (50.3%). No correlation between the stand density and the level of carbon stored in the aboveground biomass of Scots pines was found.

Keywords: aboveground biomass; carbon sequestration; stand density; forest management

1. Introduction

Carbon dioxide is one of the most important greenhouse gases contributing to global warming. The concentration of CO_2 in the air depends on natural and anthropogenic emissions and on the accumulation of CO_2 by living organisms, particularly forests. Human activities to limit the emissions of greenhouse gases, especially carbon dioxide, have been undertaken worldwide. Over 190 countries signed the Kyoto Protocol, which obliges the signatories to reduce atmospheric emissions of greenhouse gasses. Furthermore, the signatories are committed to estimating and reporting both the level of a country's emissions and changes in forest and agricultural land cover that can influence CO_2 sequestration. The Kyoto Protocol allows for balancing anthropogenic emissions with carbon sequestration by land ecosystems [1].

Forests, as the most important carbon sink in terms of carbon sequestration, are suitable measures for controlling the carbon content in the atmosphere. Forest ecosystems store more than 80% of all terrestrial aboveground C and more than 70% of all soil organic C [2–4]. For this reason, a precise estimation of the amount of carbon stored in various types of forests should be a baseline for further actions [5,6]. These actions could involve increasing carbon sequestration in forests by expanding forest areas and improving the accumulation capabilities of existing forests [7].

Carbon is stored in various parts of the forest ecosystem, mostly in wood. Based on many studies, an overall carbon concentration of 50% of tree biomass has been assumed and widely accepted [8–10]. However, research has shown that carbon content may vary, depending on tree species, tree compartment and some environmental issues [5,11–15].

Scots pine (*Pinus sylvestris* L.) is one of the most important tree species in carbon accumulation. It has the broadest geographical range of all pines and is probably the most widespread coniferous species in the world [16]. Scots pine covers 24% of the forest area in Europe [17] and over 52% in Poland [18]. Pine is therefore a species of substantial economic and environmental significance [19–21]. Thus, many scientific studies on carbon accumulation in Scots pine stands have been carried out in multiple European countries, e.g., Belgium [17], Estonia [22], Finland [11,23], Lithuania [24], Poland [25,26] and Turkey [27–30]. Among the factors influencing carbon sequestration in pine forests, the most investigated factors are the site preparation method [31], thinning intensity [32,33] and management methods [34–38].

The goal of this study was to determine the carbon content in the dry mass of needles, branches and stems of mature Scots pine stands and to assess the relationship between the carbon storage in aboveground biomass and stand density, along with some parameters of stands (mean diameter at breast height (DBH), mean height, stand density, volume, basal area and biomass).

2. Materials and Methods

The study was carried out on 20 0.5-hectare rectangular sample plots in semi-natural, planted, mature stands of Scots pine (*Pinus sylvestris* L.) (Table 1). All sample plots were located in one forest complex in the Drawno Forest District (Figure 1), northwestern Poland (E 15°50′–16°0′, N 53°10′–53°13′). The same stands have already been used in a study on the value of timber assortments [39].

Table 1. Main characteristics of sampled Scots pine stands.

Stand Number	Age (Years)	Stand Density (tree·ha^{-1})	Mean DBH ± SD (cm)	Mean Height ± SD (m)	Basal Area (m^2·ha^{-1})	Volume (m^3·ha^{-1})
1 *	82	476	28.2 ± 4.5	22.9 ± 1.7	30.5	325
2	87	518	27.5 ± 4.9	23.6 ± 2.0	31.8	350
3	82	534	25.9 ± 4.3	22.4 ± 1.5	28.4	298
4	82	564	28.0 ± 4.5	24.5 ± 1.4	35.5	401
5 *	82	594	25.7 ± 4.7	20.8 ± 1.4	31.5	306
6	82	596	27.1 ± 5.2	21.6 ± 1.4	35.7	358
7	82	618	24.6 ± 4.0	20.4 ± 1.5	30.2	288
8	82	632	24.0 ± 4.7	21.1 ± 1.4	29.6	293
9	82	632	25.6 ± 4.7	22.0 ± 1.4	33.6	347
10	82	634	24.6 ± 4.6	21.4 ± 1.6	31.0	311
11	82	640	26.0 ± 4.7	23.4 ± 1.7	35.1	385
12	82	644	26.4 ± 4.4	23.0 ± 1.4	35.9	384
13	82	648	25.9 ± 5.2	22.3 ± 1.7	35.4	373
14 *	82	674	23.6 ± 4.3	19.6 ± 1.5	30.1	280
15	82	682	24.7 ± 4.9	22.8 ± 1.7	34.0	363
16	82	708	21.8 ± 4.2	19.5 ± 2.2	27.3	250
17	82	720	22.3 ± 4.3	24.7 ± 3.8	29.1	345
18	82	756	21.7 ± 4.4	20.5 ± 2.0	28.9	281
19 *	82	758	23.9 ± 5.3	20.1 ± 2.0	35.7	340
20 *	82	836	21.8 ± 4.0	19.3 ± 1.7	31.5	291

*—stands in which model trees for biomass determination were selected. DBH—diameter at breast height, SD—standard deviation. The data presented in the table are after [39].

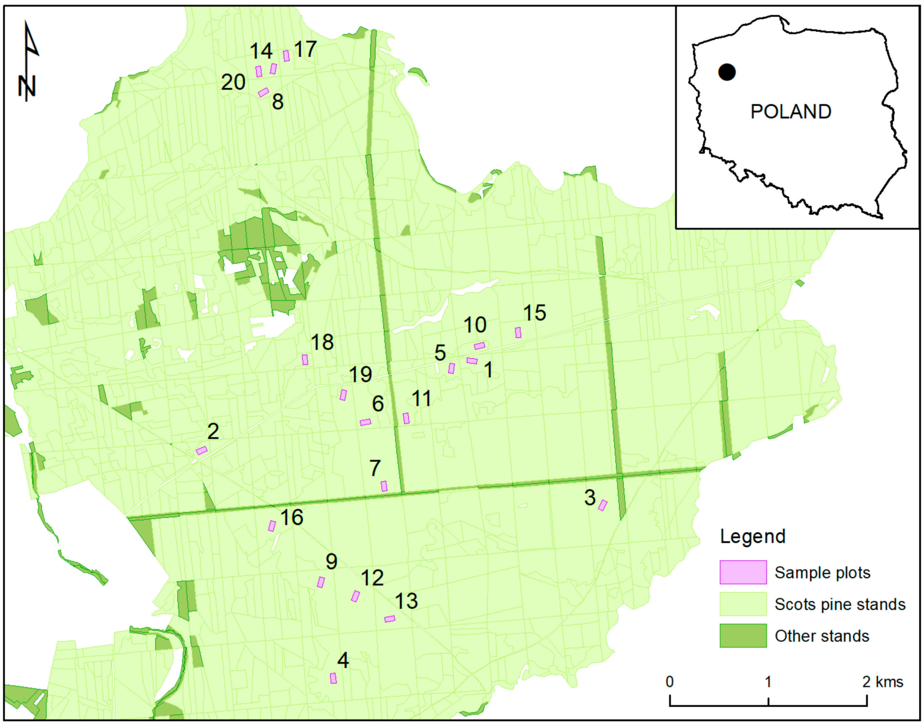

Figure 1. Distribution of sample plots in the south-eastern part of the Drawno Forest District. The same map was used in a previous paper concerning the value of timber assortments, which concerned the same stands: after [39].

All stands were characterized by shared attributes: single-layer, single-species, even-aged 81–90-year-old stands, flat terrain (without hills or pits), same soil type (Carbic Podzol), not damaged or deformed, without any gaps or undergrowth, and with forest floor plants typical to this habitat type (not grass-covered). In these stands, no thinning had been performed in the past 5 years. The differentiating factor was the stand density, expressed as the number of trees in a given area, ranging from 476 to 836 trees per hectare (Table 1).

Tree measurements and sample collections were performed from July to September 2012. On each 0.5-hectare sample plot, the DBH of each tree and the height of 20% of the trees (every fifth tree) were measured. The DBH was measured (in two directions N-S and E-W) using calipers (accurate to 1 mm) and the height of the trees was recorded with a Haglof Vertex Laser hypsometer (accurate to 0.1 m). Based on these data, Näslund's height curves were developed for each plot to assign a height to each tree. Out of 20 sample plots, five plots with different densities were selected. In each selected plot, 10 model trees, representing the range of diameters (from 16.5 cm to 37.5 cm), were designated (50 trees in total) for detailed measurements. Model trees were felled and divided into fractions (compartments): stem, branches and needles. Stem volume was established by a sectional volume measurement and the fresh mass of each compartment was obtained. From the stem, samples were taken as 10-cm cross sections that were cut every meter along the stem. The fresh mass of each compartment was measured immediately on site. The crowns of the model trees were divided into two parts: the living branches and the dead branches. The tips with needles (thin branches about 4 mm in diameter) were then cut off from the living branches. Finally, the needles were separated from the thin branches by hand. From each compartment, samples were taken randomly. These samples were weighed fresh, dried to a constant mass at 65 °C and weighed again. For each sample, a conversion factor was calculated for estimating the dry mass of each compartment of every model tree. Based on the data obtained from these 50 model trees, allometric equations were developed [40]. The best fitting equations to determine the dry mass of each compartment were selected based on: Akaike's Information Criterion (AIC), the coefficient of determination (R^2) and the residual standard error (RSE). These equations allowed for calculating the dry mass of its aboveground biomass divided into the following compartments: stem, dead branches, thick branches, thin branches and needles, using DBH and tree height for each tree as the input variables (Table 2). The stand volume was calculated based on empirical equations developed by Bruchwald [41].

Table 2. Allometric equations used to determine the dry mass of different parts of Scots pine trees.

Tree Part	Equation	Equation Coefficients			R^2	RSE
		a	b	c		
Stem (wood + bark)	$a \cdot (D^2 \cdot H^2)^b$	0.012996	0.761234		0.9357	22.187
Thick branches	$a \cdot D^b \cdot H^c$	0.048094	3.333163	−1.53455	0.7281	8.9224
Thin branches	$a \cdot (D^2 \cdot H^2)^b$	0.001054	0.879284		0.6744	1.5290
Dead branches	$a \cdot D^b \cdot H^c$	0.023518	3.569452	1.87147	0.7457	3.3543
Needles	$a \cdot (D)^b$	0.011092	2.012406		0.7499	1.9823

D—diameter at breast height (cm); H—tree height (m); a, b, c—equation coefficients; R^2—coefficient of determination; RSE—residual standard error.

To estimate the carbon content, out of the 10 model trees for each plot, 3 trees were selected. There were 15 trees in total for all sample plots. These model trees were divided into three equal groups (5 trees each) according to their diameter: small (DBH: 16.8–21.9 cm), medium (DBH: 23.8–26.1) and large (DBH: 28.2–34.0). From a list of model trees for a sample plot, ordered by diminishing diameter, a second, fifth and ninth tree were considered. For the carbon content estimation, samples previously used for determining dry weight were used. Sections cut from stems were used to calculate the proportion between the masses of bark and wood, as previously these fractions were not differentiated. Samples from each compartment were ground, labeled and sent to the laboratory. Carbon content was determined using LECO TruMac CNS (Leco Corporation, St. Joseph, MO, USA).

A statistical analysis was performed using the “Multivariate Platform” tool in the statistical software JMP 10.0 (SAS Institute Inc., Cary, NC, USA). The correlations between the carbon content and various tree and stand characteristics were calculated. Pearson’s correlation coefficients and the corresponding significance levels were calculated. Data normality was assessed using a Shapiro–Wilk normality test.

3. Results

Stems accounted for most of the biomass (average 116.0 $Mg \cdot ha^{-1}$), followed by branches (average 21.3 $Mg \cdot ha^{-1}$), stem bark (average 10.1 $Mg \cdot ha^{-1}$) and needles (average 4.7 $Mg \cdot ha^{-1}$) (Table 3).

Table 3. Aboveground dry biomass of stands (N = 20) and content of carbon in model trees (N = 15) in different parts of Scots pine trees.

Tree Part	Aboveground Biomass ($Mg \cdot ha^{-1}$)			Carbon Content (%)			
	Mean	SD	Proportion	Mean	SD	Min	Max
Stem wood	116.0	16.2	76.3%	47.0	0.5	46.3	48.1
Stem bark	10.1	1.4	6.6%	47.1	1.0	45.8	49.1
Thick branches	13.3	1.9	8.7%	48.8	1.0	45.5	50.0
Thin branches	3.0	0.3	2.0%	50.2	0.6	49.2	51.3
Dead branches	5.0	0.8	3.3%	49.6	1.0	48.4	52.5
Needles	4.7	0.4	3.1%	50.3	0.3	49.7	50.9
Total	152.1		100%				

SD—standard deviation, min—minimum, max—maximum.

The mean carbon content in the various tree compartments ranged from 47.0% in the stem wood to 50.3% in the needles. The lowest carbon content was found in thick branches (45.5%) and the highest

(52.5%) in dead branches (Table 3). In cases of stem wood and needles, the C content was correlated with tree size (DBH) and both correlations were negative (Figure 2).

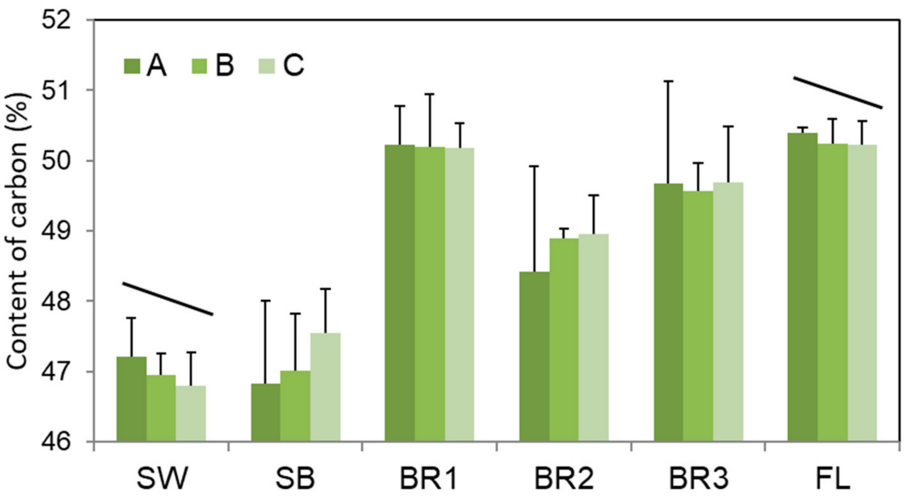

Figure 2. Average content of carbon (+SD) in tree parts (SW—stem wood, SB—stem bark, BR1—thin branches, BR2—thick branches, BR3—dead branches, and FL—foliage) of the model trees ($N = 15$) divided into small (A), medium (B), and large (C) trees (5 trees in each group according to DBH). The oblique lines show in which tree parts the content of carbon was significantly correlated ($p < 0.05$) with tree size. In both cases, correlations were negative.

The dry mass of the aboveground part of Scots pine stands ranged from 118.0 to 183.7 Mg·ha^{-1}, with an average of 152.1 Mg·ha^{-1} (Table 4). In all stands, the most carbon was stored in the stem wood and the least carbon in the needles (Table 4, Figure 3). Stand density was not correlated with the carbon content in any tree compartment or in the aboveground stand biomass. Density was also not correlated with stand volume, basal area or the dry aboveground stand biomass. On the other hand, stand density was correlated with mean DBH and with mean height. Carbon stock and percentage of carbon stock in particular tree compartments in several cases were correlated with mean DBH, mean height, stand volume, basal area and the aboveground stand biomass (Table 5).

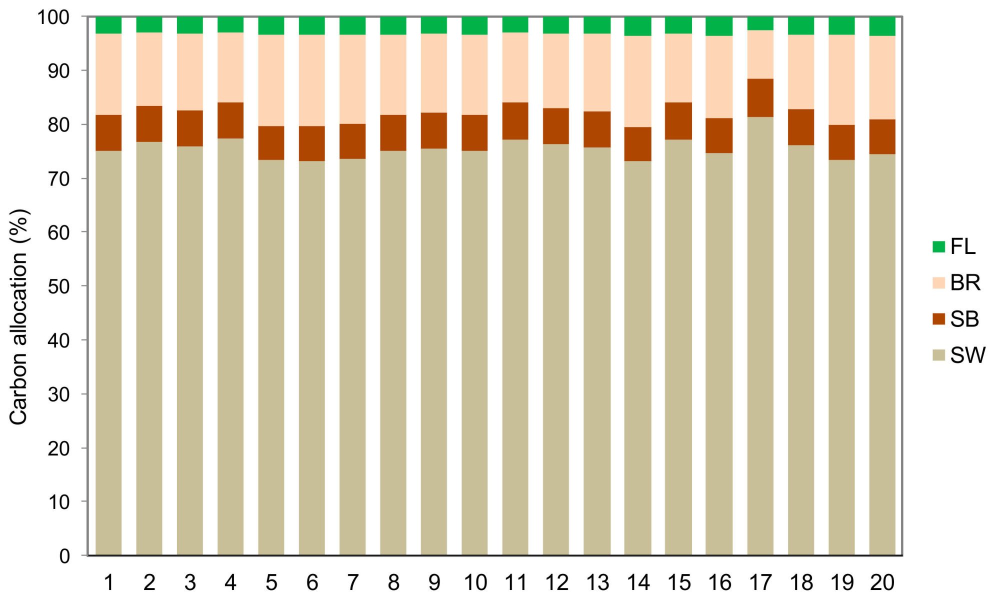

Figure 3. Carbon allocation in aboveground biomass of 20 Scots pine stands. Tree parts: FL—foliage, BR—branches, SB—stem bark, and SW—stem wood.

Table 4. Aboveground dry biomass of Scots pine stands and carbon stock in different parts of trees (SW—stem wood, SB—stem bark, BR—branches, and FL—foliage).

Stand Number	Stand Density (tree·ha^{-1})	Above Ground Biomass (Mg·ha^{-1})	Carbon Stock (Mg·ha^{-1})				
			SW	SB	BR	FL	Total
1	476	147.6	52.5	4.6	10.6	2.3	69.9
2	518	160.2	58.1	5.1	10.3	2.3	75.8
3	534	137.3	49.4	4.3	9.2	2.1	65.1
4	564	183.7	67.1	5.9	11.3	2.6	86.9
5	594	140.7	48.9	4.3	11.2	2.3	66.8
6	596	162.9	56.5	5.0	13.1	2.6	77.2
7	618	133.1	46.6	4.1	10.4	2.2	63.2
8	632	135.8	48.4	4.2	9.6	2.2	64.5
9	632	159.7	57.1	5.0	11.1	2.5	75.7
10	634	143.4	51.1	4.5	10.2	2.3	68.0
11	640	177.6	65.0	5.7	10.9	2.6	84.1
12	644	176.2	63.7	5.6	11.6	2.7	83.5
13	648	171.1	61.4	5.4	11.7	2.6	81.1
14	674	130.0	45.2	4.0	10.5	2.2	61.8
15	682	169.0	61.8	5.4	10.3	2.5	80.1
16	708	118.0	41.9	3.7	8.6	2.0	56.1
17	720	168.4	64.9	5.7	7.1	2.2	79.8
18	756	132.5	48.0	4.2	8.7	2.1	63.0
19	758	157.3	54.8	4.8	12.5	2.6	74.7
20	836	137.1	48.5	4.2	10.1	2.3	65.2

Table 5. Pearson's correlation coefficients for stand density and carbon stock and selected stand parameters on the 20 Scots pine sampled stands.

Parameter	Mean DBH	Mean Height	Basal Area	Stand Volume	Above Ground Biomass	Stand Density
C stock in stem	0.486 *	0.850 ***	0.713 ***	0.961 ***	0.986 ***	−0.160
C stock in branches	0.599 ***	−0.053	0.827 ***	0.501 *	0.413	−0.223
C stock in needles	0.534 *	0.321	0.999 ***	0.846 ***	0.809 ***	−0.045
C stock in aboveground biomass	0.011	0.789 ***	0.815 ***	0.991 ***	1.000 ***	−0.184
Percentage of C stock in stem	−0.019	0.790 ***	−0.026	0.447 *	0.534 *	0.005
Percentage of C stock in branches	0.061	−0.762 ***	0.051	−0.416	−0.505 *	−0.041
Percentage of C stock in needles	−0.334	−0.956 ***	−0.186	−0.666 ***	−0.721 ***	0.292
Stand density	−0.860 ***	−0.508 *	−0.044	−0.269	−0.190	–

Significance level: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

4. Discussion

The mean carbon contents in the various tree compartments of Scots pine did not differ considerably from the generally accepted level of 50% [5,27]. The largest discrepancies were found in the stem wood and bark, where the mean contents were 47.0% and 47.1%, respectively (Table 3). Other studies reported higher contents in stem wood: 49.8% [24], 51.2% [27], 49.3%–54.9% [28] and 51.1%–54.8% [30] and stem bark: 51.3% [24], 53.5% [27], 49.2%–53.9% [28] and 51.1%-54.8% [30]. The mean carbon content in the thick branches was 48.8% and in the thin branches 50.2% (Table 3). These figures were smaller than those reported by others, which ranged between 51.5% and 54.7% [24,27,28]. The carbon content of the needles (50.3%) was in the lower-middle range of the results given in the literature: 50.1%–55.2% [24,27,28,30].

Because the amount of carbon stored in plants is strongly correlated with the amount of biomass, the accumulation level in the stand depends mostly on the growth rate, especially the wood biomass increment. Biomass production in forests can be regulated, to some extent, by controlling stand density. This process is usually performed when designing the intensity and frequency of thinning operations. Thinning reduces the density, improves the resource availability for the remaining trees and increases tree growth [16,21,42]. Long-term experiments show that the higher the intensity of thinning (i.e., reduction in density), the lower the stand growth is. More intense growth was noted in non-thinned control stands [43–45]. Due to intensive thinning, the stand volume increment was smaller than in control stands [19,20,46], whereas due to low intensity management, the influence of thinning was weak or none [46,47]. Some studies show a complete lack of influence of thinning on either stand growth [21,48] or biomass production [49]. It was found that, immediately after thinning, there was a decrease in stand volume growth, typically lasting approximately 10 years, levelling off after this period [50]. In addition, the remaining trees had a greater volume increment if thinning was more intense [44,48,51].

Many studies reported that the carbon stock in aboveground biomass changes significantly with the intensity of thinning. The total C stored at the end of the rotation period was greater in Scots pine stands with a longer rotation period and a lighter thinning regime [32–34,37]. Furthermore, C storage in aboveground biomass after partial cutting decreased linearly with cutting intensity [52]. While thinning has a similar effect on the stand structure as harvesting, its range is much more limited and the effect on carbon fluxes could be indistinguishable from natural inter-annual variability or is very short-term [7]. Zhou et al. [52] reported that thinning more than doubled diameter growth, increased understory biomass 4-fold, but had no noticeable effect on the forest floor and mineral soil C pools.

Another aspect was the influence of various stand characteristics on carbon content in tree biomass. The C content in the wood and needles was negatively correlated with DBH (Figure 2). This result means that in comparison to smaller trees, larger trees had a lower content of C in the dry mass of their wood and needles. A similar pattern was found for Scots pine in Turkey by Erkan and Güner [30]. In their study, the C content in the needles was negatively correlated with DBH, but the C content in the wood was positively correlated with tree diameter. Such correlations have also been found for other pine species [12,53].

The studied stands showed a strong relationship between stand density and mean DBH, a correlation which is widely known [20,45,54]. Therefore, if stand density is correlated with tree size and tree size is correlated with carbon content, then it could be expected that there is a correlation between the stand density and the carbon content in tree biomass. However, such a correlation was not confirmed in this study. The aboveground biomass of trees, the amount of stored carbon and C allocation patterns were shown to be independent of stand density. A similar absence of a relationship was shown in the USA for *Pinus contorta* [55]. However, studies carried out in Spain for Scots pine showed that in dense stands, where no thinning (or mild thinning) was conducted, the accumulation of carbon was greater than that in other stands [33,37].

5. Conclusions

The obtained results may have some practical significance for forest management. As expected, the carbon stock in mature Scots pine stands was correlated with basal area, stand volume and aboveground biomass of the stand i.e., the amount of wood. This means that optimizing forest management for increased wood production does not impair a high carbon accumulation.

The carbon content in the dry mass of the various compartments of the Scots pine trees differed from the widely reported level of 50%. The lowest C content was in stem wood (47.0%) and stem bark (47.1%) and the highest in needles (50.3%). In pine stands, stems accumulate the most carbon (about 80%) despite the main constituents of stems (i.e., bark and wood) having the lowest carbon content. To increase the precision of estimating the amount of carbon stored in forest ecosystems, it is worth measuring the carbon content of individual species at various geographical locations.

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