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Carbon Pools in a 77 Year-Old Oak Forest under Conversion from Coppice to High Forest

Petros Ganatsas *, Marianthi Tsakaldimi, Theodoros Karydopoulos, Lydia-Maria Petaloudi, Alexandros Papaemmanouil, Sotirios Papadopoulos and Sofia Gerochristou

Laboratory of Silviculture, Department of Forestry and Natural Environment, Aristotle University of Thessaloniki, P.O. Box 262, 54124 Thessaloniki, Greece
* Correspondence: pgana@for.auth.gr

Abstract: Recent model projections and many research results across the world suggest that forests could be significant carbon sinks or sources in the future, contributing in a such a way to global warming mitigation. Conversion of coppice forest to high forest may play an important role towards this direction. This study deals with the estimation of biomass, carbon pool and accumulation rates in all IPCC biomass categories of a 77 year-old oak ecosystem, which has been subjected to conversion from coppice to high forest through repeated tending measures. The research includes a plethora of field tree measurements, destructive sampling of representative oak trees and a systematic sampling of dead wood (standing and fallen), litter and soil. Furthermore, for the estimation of above ground tree living biomass at the stand level, we developed and tested appropriate allometric biomass equations based on the relationships between various independent tree variables (morphological characteristics) and the different tree biomass compartments or leaf biomass. Data analysis shows that coppice conversion results in large accumulation of carbon in all ecosystem pools, with an average annual carbon rate accumulation of 1.97 Mg ha^{-1} in living above and below ground tree biomass and small amounts to dead wood and litter. The developed allometric equations indicate that above ground tree living biomass can be reliable and precisely predicted by the simple measurement of tree diameter.

Keywords: IPCC; CO_2 removal; coppice conversion; silvicultural systems; Mediterranean forests; biomass equations; forest management

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1. Introduction

Forest ecosystems play a key role in biomass production and atmospheric carbon sequestration [1–4]. It is estimated that forests store approximately 80% of the total biosphere's biomass and more than 60% of the global biomass is stored in wood tissues (trunks, branches and roots) [5,6]. Recently published work estimates that world forest ecosystems remove nearly 2 Pg of C per year from the atmosphere through the net growth process, thereby absorbing about 30% of anthropogenic CO_2 emissions [7–9]. Soil carbon plays an also important role in the earth's carbon cycling and is considered the largest terrestrial carbon pool [10–12]. Approximately 40–90% of the global soil carbon resides in forest ecosystems [13–15]. Forest aboveground and root biomass are the major sources of soil C [16]. Forest soil and litter also accumulate a large carbon amount depending on the type of ecosystems and the management system [15,17]. Thus, the evaluation of soil carbon accumulation in forests is essential and could provide basic information regarding the multiple ecosystem services and nutrient cycling, besides the soil conservation. Nevertheless, little is known about the effects of forest management on C sequestration and storage (CSS) in forest soils [9]. According to the Kyoto protocol, the implementation of Climate Change Mitigation strategies and REDD+, there is a great need for accurate and repeatable estimations of forest biomass and carbon stocks for all types of forest ecosystem.

It is widely accepted that forests could absorb more carbon quantities if an improved management system applied. Thus, the development of effective forest management strategies that could increase forest C sequestration capacity are of great priority for forest managers worldwide. Recent work reports that appropriate climate-adaptive silviculture practices (e.g., less intensive harvesting) could be among the strategies that would increase long-term CSS in forests [9]. This is true especially for those strategies that are based upon partial cuts and selective felling to increase natural forest productivity and preserve parts of the existing forest C stocks [18,19]. Additionally, moderate harvesting intensities and long rotations could result, apart from increasing C storage, in enhancing forest biodiversity as well as other economic and ecosystem services. With respect to silvicultural treatments, selective felling increases the rates of forest carbon sequestration and maintains higher carbon storage compared to clear-cuts [9].

This long-term increase in C sequestration and storage is more evidence in the case of coppice forests. Forest coppice is a management system applied to secondary forests, which focuses on continuous wood production using a short-rotation harvest and natural sprout regeneration after clear-cutting. It is estimated that the total area of coppice forests (forests originating from re-sprouts) in Europe is approx. 23 million ha or 16% of all forest formations. In the Mediterranean region, oak coppice forests are widespread, e.g., Greece 65%, Italy 63%, however, these forests are of low quality and production, resulting in low carbon pools [20]. In Turkey, where the coppice system has been widely used for wood fuel production, it has contributed to a high degradation of 70% of the coppice forests [3].

The coppicing forest management system contributes to quicker release of CO_2 back in the atmosphere and decreases the function of forest ecosystems as natural carbon sinks. This is related both to the shorter rotation period (the time between 2 consecutive fellings, which is approximately 20–25 years, even lower [21], compared to that of high forests (rotation period of 100 years or more)), and to the fact that coppice forests are mainly managed for low-quality fuel wood production, resulting in an immediately release of CO_2 back in the atmosphere. Additionally, due to the aging of tree root systems after several rotation times (harvesting cycles), the rate of tree growth decreases, a fact that also affects the amount of the produced biomass and the respective uptake of atmospheric CO_2. Coppice management may also have negative impacts on forest vegetation dynamics, species competition, litter decomposition rates, [3,22–24], species richness, forest structural diversity and forest regeneration potential, which leads to further deterioration, reduction of overall height of forest stands and gradual transformation into bush formations. The result of the above is a decreased forest stand productivity and a constrained C storage [25,26].

Due to the above reasons, most European countries have adopted plans and developed strategies for the conversion of existent coppice forests into high forests. Carbon storage in existing EU forests could continue to increase [27]; it is estimated that they can provide additional sequestration benefits of approximately up to 172 Mt CO_2/year by 2050. Measures could include, among others, enhanced thinning of stands leading to additional growth and higher quality raw material through the conversion of coppice forest to high forest. The conversion of coppice forest to high forest can be achieved either with artificial regeneration or with natural regeneration [28–30]. The latter follows a natural process as long as the seed production is abundant and frequent and the stands consist of good quality individuals of the desired species [31]. It is a more complex process that requires specific tending measures [28,32], based on the stand characteristics, species and site conditions [29,30].

In the context of quantifying carbon sequestration, the coppice management system provides a trade-off between the substitution effect of wood as an energy source and forest C storage [3]. The changes in carbon storage capacity and forest stand dynamics due to coppice systems are of particular interest, especially under climate change conditions. Much of the research so far has focused on the estimation of biomass production, carbon pool and stand growth under the coppice management system [3,20,33,34]. Some studies tried to develop a holistic approach in order to evaluate coppice management scenarios including all carbon pools [3,35] using a modeling approach for a quantitative assessment of carbon sequestration potential by coppice management. However, studies on biomass estimation of mature trees of large dimensions are scarce. Additionally, data on the gain from the coppice stand conversion into high forest are greatly scarce, even though these data could be very useful for national country reports under the Kyoto Protocol and all the relevant international conventions and agreements and could help in planning appropriate forest policy and management as well.

According to IPCC, five carbon pools are recognized in forest ecosystems [36,37]: above ground living biomass, below-ground biomass, dead wood, litter and soil. In most cases, among the various available methods, the aboveground tree biomass in forest ecosystems is determined by various biomass equations based on basic tree morphological data. This is due to the extremely high labor cost of field works. Accordingly, allometric equations have been proven to be one of the most common and reliable methods for estimating tree biomass, carbon storage and CO_2 flux, and therefore, many allometric biomass equations have been developed for many forest tree species around the world [4,38]. Unbiased biomass models are essential in evaluating a forest's productivity, structure and sequestered carbon content, while accurate biomass equations can contribute through detailed biomass potential maps for a smarter land use policy. The choice of an appropriate allometric model for biomass estimation has been demonstrated to be a critical step [39]. Unfortunately, for oak forests there is a low number of, or completely lack of, available equations for live tree biomass estimation [40], both in Europe [41] and internationally [20,42]. For oak coppice stands which are under conversion to high forests, there were no published equations until the very recently.

The aim of the present study was to evaluate the effect of conversion from a coppice system to high forest through repeated tending measures according to the forest management strategy, which is based on partial tree cuts and selective cutting to increase forest productivity and preserve parts of the existing forest C stocks [18,19] combined with elongation of rotation length, with a long-term goal to convert a coppice forest to high [9]. The study concerns a 77 year-old oak forest which has been under conversion for the last 50 years, and investigates the biomass, carbon pool, annual amount of atmospheric CO_2 removal and carbon accumulation rates, in all forest ecosystem biomass categories (above ground and below ground biomass, standing and fallen dead wood, litter and soil). More specifically, based on numerous field samplings, tree measurements and destructive sampling of representative *Quercus frainetto* Ten. trees, all the above data were obtained. Finally, at the forest stand level, the above-ground live tree biomass calculation was made by developing allometric equations that express the relationship between the tree morphological characteristics (independent variables) and the different tree biomass sections.

2. Materials and Methods

2.1. Study Area

The study was carried out in oak forests of Cholomon mountain, Chalkidiki, northern Greece (Lat: 39°56′41.4″ Long: 21°18′39.5″) (Figure 1). The forest consists of a 77 year-old oak stand (Figure 2), which has been subjected to conversion from coppice system to high forest through repeated tending measures. The forest is dominated by the species *Quercus frainetto*, a deciduous oak species that is spreading in southern Italy, the Balkan peninsula, southern Hungary and Turkey. In Greece, it appears throughout the country, from the Peloponnese to northern Greece [43], and plays an important role in forestry.

Figure 1. The area of the studied oak forest (40°23″–40°28″ N, and 23°28″–23°34″ E) in Cholomon mountain, Halkidiki, northern Greece.

Figure 2. Procedure of field destructive sampling for biomass measurements.

The study area has an altitude that ranges from 400 to 1100 m asl., consisting of slopes of all aspects and medium inclination. The vegetation of the area belongs to the sub-Mediterranean vegetation zone of *Quercetalia pubescentis*, and the sub-zone of *Quercion confertae*. This sub-zone occupies a significant part of Greek forests. The climate of the area, according to the nearest meteorological station of Taxiarchis University Forest, belongs to Mediterranean type, characterized by a dry and hot summer period, and moist and cool winters, with an average mean annual temperature 11.0 °C, mean annual precipitation of 769 mm and two or three months of dry season. The driest month is August, with an average monthly precipitation of 42 mm. Geologically, the area belongs to the Rodopi zone, and, in particular, to the part of the Serb-Macedonian mass and the Vertiskos range. The main rock formations include silicate materials and silicate sandstones, marbles, calcareous schists, micaceous gneiss, granites and various sedimentary rocks in small areas. The soil of the study area belongs to the category of acid brown forest soils [43].

The management of the forests has been carried out by the Forest Service of Taxiarchis since 1934, which is under the supervision of the Department of Forestry and Natural Environment of the Aristotle University of Thessaloniki. *Quercus frainetto* stands are of coppice origin; however, they have been under conversion to high forests through periodical (approximately every ten years) application of low intensity positive selective cuttings, aiming at favoring the best and most promising individuals of the dominant tree story. The forest conversion started in 1973.

2.2. Sampling Design and Experimental Section

2.2.1. Field Data Collection for the Estimation of Aboveground Live Tree Biomass

According to the international literature, among the several forest tree variables (height, diameter at breast height, basal diameter, wood specific gravity) used for live tree biomass (above-ground biomass AGB) estimation, the diameter and the height are the most commonly used, due to their easy availability and measurement. However, diameter at breast height (DBH) can be measured more precisely and thus, is more reliable, especially when using a single independent variable to develop biomass equations, although other tree variables are also used, such as tree height, basal diameter (in the case of small trees) or even wood specific gravity [4]. Concerning the live tree below-ground biomass (BGB), this is extremely hard to measure for large trees, and only few studies focused on determination BGB by developing equations based on easily measurable tree variables [44–49]. The root to shoot ratio (R:S) is commonly used to estimate BGB from AGB [50] in forest biomass studies [51].

Four large sample plots of 3000 m^2 each were selected in the study forest. Within each plot, all the trees were measured (n = 1692 trees in all four plots) for their total height, diameter at breast height, i.e., 1.3 m above ground (DBH), height till the base of the live crown (CBH) and crown length. The carbon content in AGB and the amount of sequestrated CO_2 were investigated through the combination of destructive tree harvesting and stand structural analysis. Within each plot, three representative trees, according to the number of individuals per diameter class, were selected for destructive sampling (n = 12 felled trees), in order to precisely measure their biomass, and then to construct allometric equations for the estimation of stand total biomass. The presentative trees were felled as close to terrain as feasible in late June 2020, their dimensions were measured and the following destructive procedure was followed.

For the measurement of total tree AGB, each sampled felled tree was divided into stem, branches and foliage (Figure 2) [23,44,46–49]. Fresh weight of all three categories was measured in situ in the forest [52] immediately after felling with a portable digital balance scale (acc. 5 g) (Figure 3). Due to the large dimensions and the weight of the tree components, the measurements were made after dividing each component to pieces of 20–50 kg. Afterwards, in order to calculate the dry weight and moisture content of the sampled felled trees, small pieces of the pole (approximately 5 cm thick), were cut per sample tree in regular intervals [41,52] at stem base (0.0 m), and after that, in every 2 m until the end of the stem [53]. These discs, as well as a sample of branches and foliage (approx. 10%) from different parts of each tree, were weighed directly in the field, with a second portable digital balance (acc. 1 g). Then, all samples (stem, foliage and branches) were sealed in labeled bags and transported to the laboratory for further analysis (Figure 2). Additionally, stem discs, each approximately 1 cm thick, were cut per sample tree at breast height, and transferred to the laboratory for tree annual ring measurements and tree age determination.

Figure 3. Procedure of sampling for biomass measurements.

The belowground tree biomass (BGB) was not directly measured in this study, even though relevant data for similar oak coppice forests under conversion are greatly lacking, due to the high labor cost and practical difficulties. For this reason, we used the coefficient value 0.26, suggested by [54]. This selection was based on: (i) the estimated value by [55] for *Quercus robur*, (ii) the coefficient value suggested by [1], (iii) the median value given by [56] for temperate oaks, (iv) the values developed by [3] for oak forests in Turkey and (v) the latest analysis of [57], and taking into consideration that mean shoot biomass of the studied forest was over 150 Mg/ha.

2.2.2. Dead Wood Sampling

For the estimation of C pools in dead standing wood, all the dead standing individuals were recorded throughout the plot area, within the four sampled plots and measured for their height and diameter at breast height. Then, their volume was computed based on the following standard biometric equation [58]:

$$y = \frac{\pi}{4} \times Dx\ FSx\ h \tag{1}$$

which includes a standard stem form factor (FS) of 0.44.

Volume was converted to biomass using the factor 0.7 [59], since almost all the dead standing trees had recently died and belonged to 1st decay class.

For the estimation of carbon pools in dead fallen wood, 12 transects of 50 m length and 3 m width, were established within the four plots. Within the transects all the dead snags were recorded for their length (using a tape) and width (using a caliper) at the maximum and minimum point. Afterwards, their volume was computed using the flowing formula [58]:

$$y = \frac{\pi}{4} \times\ Dx\ h \tag{2}$$

where and

$$D = \frac{Dmin + Dmax}{2}$$

Then, the dead fallen wood volume was converted to biomass using the factor 0.42 [60]. The selected value is slightly lower than those generally suggested in the literature for oak fallen dead wood [61], which depends on the decay class. However, this value was selected based on: (i) the dimensions of the fallen dead wood (usually having an average diameter 5–7.5 cm) and (ii) the observed decay class of the fallen dead wood (usually belonging to 2 or 3 class).

2.2.3. Litter and Soil Sampling

For the estimation of C pools in litter and soil, a number of samples were collected and analyzed for C within the four sampled plots [3,52]. The accumulation of soil organic carbon (SOC) is generally a process that takes place in the upper soil layer and [12,15] decreases with the soil depth. In the studied forest, the average soil depth is approximately 50 cm, ranging between 40–70 cm [43]. We systematically selected 5 points in each plot where sampling for litter and soil were carried out. These points were: one in approximately in the center of each plot and the remaining four on the diagonals and in equal distance between the corners and the center of the plot.

The size of the sampling plots for the litter was 0.5 m × 0.5 m, and the sampling was carried out for each humus horizon (L, F and H), according to the literature [15]. All of the litter materials were collected per horizon in each sample point (4 plots × 5 points × 3 horizons; n = 60) and were transferred in separate plastic bags (non-homogenized samples) for laboratory analyses.

In each selected point, a 0.25 m^2 soil pit was dug to a depth of 50 cm, from which a disturbed soil sample (approximately 500–1000 g each) was extracted from two different depths of 0–20 cm and 20–50 cm. Mineral soil was removed after successive sieving. Additionally, just near the previous points, undisturbed soil samples were taken using a metallic corer (radius 5.0 cm, height 7.0 cm, total volume 549.8 cm^3) in order to measure bulk density (BD) [17]. Both mineral soil samples (4 plots × 5 points × 2 depths; n = 40) and undisturbed soil samples (n = 40) were transferred (non-homogenized) to the laboratory for C determination.

2.3. Laboratory Analyses

The sampled tree components: stem sections (including bark), branches and foliage were oven dried to 72 °C for about 3 days [46] until constant weight in order to specify their moisture content. Based on the moisture content values of the sub-samples, the dry biomass of whole samples per tree component, and finally, for each tree component/part were determined.

Moisture content (*MC*) was estimated on the dry basis and expressed as percentage from the following equation [62]:

$$MC(\%) = \left(\frac{m - m0}{m0}\right) * 100$$

where m is the mass of wet wood and $m0$ is the oven-dry mass. Dry mass was then converted to carbon by the standard conversion factor 0.47 [1]. Accordingly, the estimated values of stand carbon accumulation were transformed to CO_2, based on the commonly used conversion factor of carbon to CO_2, 3.67.

The carbon stored in living biomass (*Cbt*) at the stand level was expressed as the sum of the biomasses of each fraction (stem, branches, foliage):

$$Cbt = \Sigma Cbt,$$

where *Cbt* is the carbon stored in the living biomass of fraction (i) at time (t) per ha (Mg C ha^{-1}) [63].

All litter samples were oven-dried to a constant weight at 72 °C, weighed and finally they were ground in a Willey mill to pass through a 40 mesh stainless steel sieve. The organic matter of each sample was determined by the loss on ignition method (LOI) at 540 °C for 5 h [64]. The percentages of organic matter in each litter horizon were converted to kg ha^{-1} using the dry weight of each sample and multiplying to aggregate to ha.

The soil samples were air-dried and sieved through 2 mm mesh screens. Soil organic carbon was determined by means of wet oxidation. Multiplying the soil organic carbon by 1.72 resulted in the soil organic matter. Bulk density was determined with the undisturbed soil samples by the core method. Then, the percentages of organic matter in each soil sample were converted to kg ha^{-1}, using the bulk density values [17].

2.4. Statistical Analysis

Several linear and non-linear regression models were tested in order to determine any correlation between dry weight (biomass) of aboveground tree components and tree morphological characteristics. Independent variables tested were: tree diameter at breast height (DBH), total height (H), crown base height (CBH) and crown length (CL). Dependent variables considered in the analysis were: total tree aboveground biomass (AGB), stem biomass (STB), branches biomass (BRB) and foliage biomass (FB). At the final stage, statistical analysis proceeded using non-linear mathematical models as they were proved more accurate, improving tree biomass prediction. According to the worldwide literature review, as in a large part of biomass equations [4,23,40,42,44,47,55,65,66], the simple power form Y = a × b or its linear transformation, is widely suggested for biomass prediction [67]. The most common independent variable used in this equation is DBH, which means the form Y = a (DBH) b is expected to predict in more accuracy the tree aboveground biomass from diameter at breast height if a and b parameters could be accurately estimated. Furthermore, several regression models were tested with least-square techniques in order to detect the specific tree characteristics, which predict, in the best possible way, biomass quantities of the corresponding tree parts. Predicted values and residuals were analyzed graphically checking principles of normality, constant variance and independence combined with Durbin–Watson tests, non-parametric Kolmogorov–Smirnov tests [68]. The criteria used for the final model selection was the (corrected) coefficient of determination (r2), the significance value of F test and the significance level of each coefficient (*p*-value). Additionally, the average relative error (%) of the predicted values was estimated. Several independent variables were tested, as well as combinations of them, without overloading the models and finally, we selected those that gave the best fitting results and prediction for each tree compartment according to statistical criteria. Statistical analysis was performed with the software IBM® SPSS® Statistics, Version 25.0, © 2019 IBM, Armonk, NY, USA Corp.

For the assessment of the average total biomass (Mg dry matter) and carbon stock at the stand level, we applied the selected aboveground biomass equations developed from the tree destructive sampling' procedure to all the trees measured in the four plots of 3000 m^2 (1692 trees in total), as we had already inventoried their diameter at breast height during the field works.

3. Results

3.1. Stand Structural Characteristics of the Studied Forest

According to the field measurements and the analysis of the tree annual rings of the sampled trees, the studied forest is even-aged, 77 years old and probably coming from the resprouting of the previous mature trees. The forest is a pure, one-story oak forest, with a sporadic presence of other tree species (e.g., *Fagus sylvatica*, *Sorbus domestica*, *Ilex aquifolium*), in a total density less than 1%. The forest consists of trees of a mean height 12.97 m (range 1.5–23.5 m) and mean diameter of 15.49 cm (range 4–44.5 cm) (Table 1). However, the dominant stand height is approximately 19 m, while there are a relatively small percentage of oak individuals of small dimensions belonging to middle or substory, which lower the mean tree height and diameter values. The mean crown base height is 6.21 m, and the mean crown length 6.83 m. The stand density reaches a mean value of 1463.3 trees/ha, the mean basal area is 34.85 m^2 and the stand volume 252.89 m^3.

Table 1. Average values of the stand structural characteristics in the studied forest (tree morphological characteristics and basic biometric data of the sampled forest stands).

	Tree Level				Forest Stand Level		
	DBH	**H**	**CBH**	**CL**	**Density**	**Basal Area**	**Stand Volume**
	(cm)	(m)	(m)	(m)	(Trees/ha)	(m^2)	(m^3 ha^{-1})
Max.	44.50	23.50	16.50	12.70	1936.7	35.85	270.93
Mean.	15.49	12.97	6.21	6.83	1463.3	34.85	252.89
Min.	4.00	1.50	0.50	0.50	1080.0	34.02	237.99
St error	0.19	0.11	0.09	0.05	185.6	0.48	13.10

DBH = Tree Diameter at Breast Height, H = Height, CBH =Tree Crown Base Height, CL = Tree Crown Length.

3.2. Biomass and Carbon Pools in the Aboveground Living Part of the Forest Ecosystem

The estimation of biomass and carbon pools in the living above ground part of the forest ecosystem was based on: (i) the data of the destructive sampling of the twelve representative trees and (ii) on the measurements of the dimensions of all trees in the sampling plots. The average values of the morphological characteristics of the sampled trees are shown in the Table 2. The average age of the destructive trees was 77 years.

Table 2. Morphological characteristics of the 12 sampled oak trees subjected to the destructive sampling.

	DBH (cm)	**H (m)**	**CBH (m)**	**CL (m)**	**Age (Years)**
Max.	31.00	23.50	9.30	14.00	83
Mean.	20.52	18.79	8.05	10.83	77
Min.	12.00	14.08	5.80	6.28	66
St error	1.85	0.86	0.45	0.62	2.4

DBH = Tree Diameter at Breast Height, H = Height, CBH = Tree Crown Base Height, CL = Tree Crown Length.

According to the data analyses, the mean fresh weight per tree was 436.95 kg, ranging between 99.42 and 1153.6 kg depending on tree size (Table 3). There were great (significantly) differences of moisture content between the three tree parts (stem, branches and foliage); the foliage presented almost two-fold higher moisture (107.39% of the dry weight) compared to that of stem (58.61%), while the moisture content of branches was found to be 70.98%.

Table 3. Above-ground biomass (at tree level), carbon stored/content and amount of CO_2 of the sampled oak trees per each tree component. Values are the mean and the standard error of mean (n = 12).

Tree Parts	**Fresh Weight kg (%)**		**Moisture Content (%)**	**Dry Weight (Biomass) kg (%)**		**Carbon Content kg (DwX0.47)**	**CO_2 Amount kg (CX3.67)**
Stem	324.438 ± 52.7	74.25	58.61 ± 1.4	203.24 ± 31.9	76.47	95.53	350.57
Branches	72.936 ± 21.1	16.69	70.98 ± 3.2	43.255 ± 12.0	16.28	20.33	74.61
Foliage	39.572 ± 6.9	9.06	107.39 ± 3.3	19.273 ± 3.4	7.25	9.06	33.24
Total	436.946 ± 70.5	100	64.41 ± 1.6	265.768 ± 48.5	100	124.91	458.42

The average total above-ground biomass produced and accumulated by each tree at the age of 77 years is 265.77 kg (dry mass) (Table 3). In each tree, the carbon stored in the above-ground biomass was 124.91 kg, of which 76.5% was stored in stems (95.5 kg), 16.3% in branches (20.3 kg) and 7.25% in foliage (9.06 kg). The 124.91 kg of stored carbon corresponds to an equivalent of 458.42 kg of CO_2 and to an annual accumulation of 1.62 kg of carbon on each tree tissue, or 5.95 kg of CO_2.

3.2.1. Biomass Prediction Allometric Equations

Based on the statistical analysis, the coefficients of the selected allometric biomass equations for aboveground tree living biomass on DBH was significant for all biomass components ($p < 0.01$). The models developed for predicting the living biomass of the studied species, *Q. frainetto*, explained more than 95% of the total variations for total aboveground biomass ($R^2 = 0.97$), stem biomass ($R^2 = 0.96$) and branch biomass ($R^2 = 0.97$), except for foliage biomass, where R^2 was 0.87 (Table 4). The best fitting model was the power function, based on the tree DBH. The analytical statistical data and the estimation parameters for the selected biomass equations are presented in Table 4.

Table 4. Final biomass equations in order to predict dry biomass (kg) from different tree compartments in the studied oak forest, mountain Cholomon, Halkidiki, northern Greece.

Model	a	b	R^2	Sig.	SEE a	SEE b	R_D (%)
AGB = a (DBH) ^{b}	0.1279	2.4852	0.97	***	0.052	0.185	6.59
STB = a (DBH) ^{b}	0.229	2.214	0.96	***	0.140	0.189	8.00
BRB = a (DBH) ^{b}	0.000046	4.400	0.98	***	0.0000	0.272	16.31
FB = a (DBH) ^{b}	0.013	2.374	0.87	***	0.016	0.380	21.53

Notes: Equations (models) follow the power function form $Y = a \times X^b$, where a, and b are parameters of the selected equations. AGB: aboveground biomass; STB: stem biomass; BRB: branches biomass; FB: foliage biomass; DBH: diameter at breast height SEE: standard error of estimated parameters; R^2: coefficient of determination; Sig.: significance level where *** $p < 0.001$; R_D (%): mean percent relative difference.

However, using tree height as a single independent variable resulted in lower values of the coefficient of determination (Equation (2); 87% vs. 97%), while testing the addition of tree height in the model very slightly improved the model in all cases (e.g., from $R^2 = 0.97$ to $R^2 = 0.98$ for the total aboveground biomass and from $R^2 = 0.96$ to $R^2 = 0.98$ for stem biomass), while adding other parameters, such as tree crown base height and crown length, does not further help in model performance. In any case, taking into consideration the high cost for the field tree height measurements or crown length measurements, we suggest the use of models based on tree DBH, as many other researchers do for many forest tree species. Diameter measurement is an easily and low-cost field work, compared to any other tree measurements in the field.

Furthermore, in order to check the prediction accuracy of the selected biomass models, we computed the mean percent relative differences (R_D%) between the real measured data and the models' predictions as follows [20,67]:

$$R_D(\%) = \left(\frac{|Vr - Vp|}{Vp} \right) \times 100$$

where: R_D is the average of absolute differences between observed (Vr) and predicted values (Vp). The data of the check are shown in Table 4 (last column). According to the check, the prediction accuracy of the selected biomass models is high (over 92%) for total aboveground biomass and stem biomass.

3.2.2. Estimation of Aboveground Living Biomass at Forest Stand Level per Hectare

At stand level, the average values for above-ground biomass, carbon stored and amount of CO_2 of the sampled oak trees per each tree compartment are shown in Table 5. A total amount of 255.73 t ha^{-1} biomass was found to accumulate in the studied oak forest in its above-ground living tree parts during the stand life of 77 years, which corresponds to a mean annual rate of biomass accumulation of 3.32 t ha^{-1}. This amount is mainly deposited in the tree poles (76.47%), and less in branches (16.28%) and foliage (7.25%). Based on the conversion factor 0.47 suggested by IPCC (2010), the correspondence values of carbon accumulation at stand level are 1.56 Mg y^{-1} ha^{-1} and totally 120.19 Mg ha^{-1} during the time of stand life (77 years). If the last values of stand carbon accumulation were transformed to CO_2, based on the commonly used conversion factor of carbon to CO_2, 3.67, it is estimated that the studied stand removes 5.73 Mg CO_2 ha^{-1} every year, and during the stand life of 77 years, 441.11 Mg CO_2 ha^{-1}.

Table 5. Above-ground biomass, carbon stored and amount of CO_2 of the studied forest per each tree compartment at forest stand level.

Tree Parts	Biomass t ha^{-1}	Carbon Content Mg ha^{-1}	CO_2 Amount Mg ha^{-1}
Stem	195.56	91.91	337.32
Branches	41.63	19.57	71.81
Foliage	18.54	8.71	31.40
Total	255.73	120.19	441.11

By considering the estimated values of stand volume, presented in Table 1, and the above ground living biomass of the above Table 5, then the biomass expansion/conversion factor BEFD, for the studied oak forest, takes the value 1.011, computed as 255.73/252.89.

3.3. Biomass and Carbon Accumulation in Standing and Fallen Dead Wood per Hectare

Based on the analysis of the field data and after the laboratory analyses, the estimation of biomass, carbon pool and CO_2 in standing and falling dead wood are shown in Table 6. Generally, a low amount of carbon was found both in standing and fallen dead wood that reaches to 1.18 Mg ha^{-1}. Especially in falling deadwood, the amount of carbon is very low (0.20 t ha^{-1}), due to the periodical removal of a percentage of standing trees by thinning application that does not allow trees to fall down.

Table 6. The carbon stored in standing and fallen dead wood. Values are the mean and standard error of mean (n = 12).

Category of Dead Wood	Volume m^3 ha^{-1}	Biomass t ha^{-1}	Carbon Content Mg ha^{-1}	CO_2 Amount Mg ha^{-1}
Standing	2.81 (0.44)	1.97 (0.37)	0.98 (0.19)	3.60 (0.72)
Fallen	0.94 (0.30)	0.40 (0.16)	0.20 (0.08)	0.73 (0.32)
Total	3.75 (0.56)	2.37 (0.48)	1.18 (0.25)	4.33 (0.93)

3.4. Biomass and Carbon Accumulation in Forest Litter and Soil Per Hectare

An amount of 31.13 t ha^{-1} biomass (dry weight) was found to be accumulated in forest litter, distributed in the three litter layers L, F and H, which corresponds to 11.51 Mgha^{-1} carbon accumulation (Table 7). In terms of atmospheric CO_2 removal, this amount corresponds to 42.27 Mgha^{-1} CO_2 during the 77 years of stand life. This means that an amount of 549.0 kg CO_2 ha^{-1} is removed from the air and is deposited to forest litter during the tree's lifecycle. The great part (46.8%) of this amount is concentrated in the F layer, which consists of the deeper and most composited organic materials, just above the soil and in contact with its upper layer.

The soil in the studied forest was found to contain a great amount of carbon (Table 8), which totally reaches to 44.0 Mg ha^{-1} up to a depth of 50 cm. The upper soil layer, up to 20 cm, is a greater carbon pool 24.2 Mg ha^{-1} (i.e., it accumulates the 55.5% of biomass), while in the deeper soil layer of 20–50 cm, the carbon pool is 24.2 Mg ha^{-1} (44.5%).

Table 7. Mean values of Carbon accumulation in the different layers of litter and soil of the studied forest (n = 40).

Layer	Biomass Accumulation		Carbon Content	CO_2 Amount
	t ha^{-1}	(%)	Mg ha^{-1}	Mg ha^{-1}
Litter layer				
P	6.78	21.78	2.51	9.207
H	9.79	31.45	3.62	13.299
F	14.56	46.77	5.38	19.766
Total in litter	31.13	100.00	11.51	42.272
Soil layer	Organic matter			
0–20 cm	41.72	55.00	24.20	88.814
20–50 cm	34.14	45.00	19.80	72.666
Total in soil	75.86	100.00	44.00	161.480

Table 8. Total stand biomass and forest ecosystem carbon content at the five tree part/component categories.

Part of the Forest Ecosystem	Biomass Accumulation	Carbon Content		CO_2 Amount Mg ha^{-1}
	t ha^{-1}	Mg ha^{-1}	%	
Above ground living biomass (AGB)	255.73	120.19	57.75	441.11
Below ground living biomass (BGB = AGB × 0.26)	66.49	31.25	15.01	114.69
Dead wood (standing and fallen)	2.37	1.18	0.57	4.33
Litter	31.13	11.51	5.53	42.27
Soil	75.86	44.00	21.14	161.48
TOTAL	431.58	208.13	100.00	763.88

3.5. Estimation of Total Stand Biomass and Ecosystem Carbon Pools per Hectare

The estimation of total stand biomass and ecosystem carbon pools is presented in Table 8. This includes the estimated above-ground living biomass, the estimated carbon pool in dead standing and fallen wood, the measured litter biomass and the soil carbon, as well an assessment of below-ground living biomass. Below-ground biomass and carbon pool were estimated based on the conversion factor 0.26 of the above ground living biomass, as described in the methods section.

According to the data analysis, the total amount of carbon in all ecosystem pools is 208.13 Mg ha^{-1} which corresponds to an estimation removal of an amount of 763.88 Mg ha^{-1} atmospheric carbon dioxide. The great part of this carbon is allocated in above ground tree living biomass (57.75%), while an important percentage (15.01%) is estimated to exist in the below ground (root system) biomass. Soil also accumulates an important percentage of carbon (21.14%), while in litter and dead wood (standing and fallen) smaller percentages are present. On the above amount, we have to add the quantity of Harvest Wood Products (HWP), which were removed during the 50 years of forest management by selective cutting. Based on the archives of Forest Service of Taxiarchis, this amount reaches 69.6 m^3 ha^{-1} woody volume, which corresponds to a biomass amount of 70.3 Mg ha^{-1} or 33.0 Mg ha^{-1} of carbon.

4. Discussion

Under the demands of the climate crisis for the reduction of carbon dioxide from the atmosphere, a large worldwide campaign is realizing, where the LULUCF sector can play a crucial role. Accurate and repeatable estimations of forest biomass and carbon sequestration and stocks are greatly needed for all types of forest ecosystems in order for each country increase the capacity for an effective implementation of Climate Change Mitigation strategies, and REDD+. Also, according to the European Green Deal, forest areas must be improved both qualitatively and quantitatively in order for the EU to achieve climate neutrality [69]. Sustainable forestry and restoration of degraded forests can increase CO_2 absorption while improving forest resilience and promoting the circular bioeconomy. Most European countries have adopted plans and developed strategies to increase carbon storage in EU forests, but an effective method, capable for wide use, is still wanted. Based on the last estimations, EU forests can provide additional sequestration benefits of approximately up to 172 Mt CO_2/year by 2050 [27]. Measures could include, among others, partial cuts and selective fellings and enhanced thinning approaches of forest stands to result in additional growth and higher quality raw material through the conversion of coppice forest to high forest. In order to develop an effective way of fulfilling the above scope, some investigation efforts have been made aiming at the evaluation of the effect of different options of coppice management or coppicing abandonment on the potential for carbon sequestration. Some of them concern abandoned coppice oak forests, however, they did not clarify the net effect of abandoning continuous coppicing [23,66,70,71]. Other studies used simulations to assess the effects of different coppice system options (e.g., interval and intensity) [33,35]. Lee et al. [3] tried to quantify (based on field data and a forest carbon model) the net effect of coppice management abandonment on C sequestration by assessing the forest C dynamics and by hypothesizing that the abandonment of repeated coppicing would enhance the mean annual C sequestration in forest stands [72,73]. However, in all cases, the choice of appropriate allometric models for real forest biomass estimations has been generally accepted to be a critical point [39].

Being within the above framework, the results of current study contribute towards this direction, indicating feasible ways for increasing C sequestration rates of temperate oak forest through the application of conversion of coppice forest to high. The analysis of the collected research field data indicates a clear carbon sink role of the studied oak stands being under conversion for the last 50 years. More specifically, it shows that the studied oak forest of the species *Quercus frainetto*, which is 77 years old, and has been under conversion from coppice to high forest through silvicultural treatments (periodical positive selective fellings) for the last 50 years, presents quite high rates of carbon accumulation, following the general pattern proposed by [3] for coppice forests subjected to conversion to high forests, but with much higher values. The forest acts as a sink of carbon and accumulates important quantities of carbon on an annual basis, reaching to a total pool of carbon in all ecosystem pools of 208.13 Mg ha^{-1} which corresponds to an estimation of carbon dioxide 763.88 Mg ha^{-1} removal from the atmosphere. The great part of this carbon is allocated in AGB (57.75%), while an important percentage (15.01%) is estimated to exist in the BGB. Soil also accumulates an important percentage of carbon (21.14%), while in litter and dead wood (standing and fallen) smaller percentages are present.

These values are similar to those reported by [52] for a large diameter forest (LDF) (DBH: 20–36 cm) of coppice-originated oak stands in European (north-western) Turkey, aged 83 years, who reported an amount of C pool of 192 Mg ha^{-1}, with similar allocation in stem, branches and foliage, as well in forest litter. However, they reported much higher quantities of C in soils (103 Mg ha^{-1} compared to 44 Mg ha^{-1} found in this study), but up to a soil depth of 100 cm. The reported stands were pure oak stands, like in current study, with varying dominance of three major species: Sessile oak (*Quercus petraea* (Mattuschka) Liebl.), Hungarian oak (*Quercus frainetto*) and Turkey oak (*Quercus cerris* L). It can be noted that the estimated C values of total tree living biomass (AGB+BGB) of the current study (151.3 Mg ha^{-1}) are exactly similar to those reported by [55] for mature *Quercus robur* L. stands in NW Spain (150.3 Mg ha^{-1}), with similar distribution in above-ground and below-ground parts, while the age of the most studied trees ranged from 80 to 140 years.

The estimated average annual C rate in total living biomass accumulation of the stands is 1.97 Mg ha^{-1}, values that are much higher than those suggested by [3] for abandoned coppice managed stands in Turkey, giving an increase of carbon sequestration by 0.5 Mg ha^{-1} year^{-1}. On the contrary, our values are quite similar to those found for mature oak stands in NW Spain [55], as well as in coppice-originated oak forests at a similar development stage in Turkey [52]. Taking into account that the studied forest is laying in temperate zone in northern Greece, in an area characterized by Mediterranean climate with dry and hot summer period, with an average mean annual temperature 11.0 °C, mean annual precipitation 769 mm and 2–3 months dry season, the findings can be characterized as very interesting. The forest is dominated by *Quercus frainetto*, a deciduous oak species, which is widely spreading in southern Europe, where it plays an important role in forestry; thus, an appropriate management of its forest could greatly contribute to mitigating the climate crisis. The estimated values of the annual rate of carbon accumulation should be considered as of great importance if we compare them with those reported at the European level or world level [10,74,75]. Additionally, the applied silvicultural treatments maintain more complex forest structures than the coppice forest, which promotes more efficient resource use by trees. They likewise maintain C stock stability and reduce vulnerability to natural disturbances, such as wildfires, by reducing the amount of dead wood fuels, which was found to be extremely low due to applied selective fellings [76,77].

Based on the real estimated volumetric data of the studied forest, the stand volume is 252.89 m^3 per ha, while the estimated of above-ground living biomass at stand level is 255.73 t ha^{-1}, thus, the real conversion factor BEFD value, according to the measurements, is 1.01 (255.73/252.89). This value is greater than the theoretical value used by [30] for deciduous oaks, who used the value 0.89 as the BEFD factor. If we consider this value, then the above ground biomass of the studied forest would be estimated to be equal to 252.89 × 0.89 = 225.07 t/ha, much lower than the estimated value by current study.

Statistical analysis revealed that the best fitting model was the power function, based on the tree DBH as in many other forests around the world [39]. The model equations developed for predicting AGB for the species *Q. frainetto*, as well as for each tree component, follows the common equation model, the simple power form Y = aXb or its linear transformation [39,65], and many other studies, listed in the Methods section, use tree DBH as the independent variable in the equation. That means the form Y = a (DBH) b is capable of predicting, with accuracy, the tree aboveground biomass, based on the measurements of only the tree diameter at breast height, and using the estimated values of a and b parameters of the equation. Based on the statistical criteria used, this model explained more than 95% of the total variations for all tree components. Tree stem diameter, considered a very accurate predictor variable, usually explained 94–96% of measured dry compartment biomass variation in several oak species [78]. This was confirmed in our case.

Using tree height as a predictor variable in the equation model resulted in lower values of the coefficient of determination, as in many other similar studies for other forest species (Equation (2); 87% vs. 97%) [78]. Also, the addition of the model of tree height as the second independent variable in combination with DBH very slightly improved the model in all cases (e.g., R^2 = 0.97 to 0.98 for the total aboveground biomass and R^2 = 0.96 to 0.98 for stem biomass), while adding other parameters, such as tree crown base height and crown length, do not further help in model performance. In any case, taking into consideration the high cost for the field tree height measurements or crown length measurements, we suggest the use of models based on tree DBH, as many other researchers do for many forest tree species. Diameter measurement is an easy and low-cost field work, compared to any other tree measurements in the field. Similarly, Makineci, et al. [52] for a large diameter forest (LDF) (DBH: 20–36 cm) of oak in European northwestern Turkey, aged 83 years, reported that the C content of tree biomass was strongly correlated with DBH, presented a R^2 = 0.83, compared to 0.97 found in this study, as well as those reported by Balboa-Murias et al. [55] for mature *Quercus robur* stands in NW Spain. They reported a value of R^2 = 0.94, but included the factor tree height in the (stem) equation.

According to findings of our study for oak forest under conversion, which are in agreement with the finding by Manolis et al. [20] for a Greek coppice forest, diameter at breast height is an objective, very accurate and fast-measured variable in the field which is also always inventoried in the forest management plans of Greece's Forest Services. Thus, the above-ground biomass equation for oak coppice forest and coppice under conversion stands can be successfully used in forest inventory in Greece, and furthermore contributes to the literature's scant data for providing allometric equations for biomass estimation for oak species in the Mediterranean region that are notable non-existent in Mediterranean region. The findings could also help the country in covering the demands for the implementation of Climate Change Mitigation strategies and REDD+ according to the Kyoto protocol for the long-term increase of CSS in forests. Taking into account that oak coppice forests are widespread not only in Greece, but also in many European countries, the contribution can be very important; carbon storage in existing EU coppice forests could continue to increase for the next 100 years through the suggested conversion method.

They also could be applicable to other species with similar characteristics, and therefore, could potentially be applied to a wider range. Additionally, this determined prediction model can be used in the conversion of biomass to carbon, which is greatly requested for all forest stands due to climate change international conventions. Similar to total tree living biomass estimation, the performed statistical analysis for each tree component explained more than 95% of the total variations, for all tree components, total (R^2 = 0.97), stems (R^2 = 0.96), branches (R^2 = 0.97) and foliage (R^2 = 0.87). This helps in understanding the biomass allocation in tree components, which will be considered in stand tending, and specific silvicultural treatments should be applied.

The estimated values of dead wood biomass and the corresponding accumulated amount of carbon was very low (1.1 Mg ha^{-1}), similar to the values reported for other oak forests in Italy, e.g., 1.62 Mg ha^{-1} [58]. However, the carbon stored in deadwood is strongly influenced by forest management. The intensity of management interventions, as well as the applied silvicultural practices, influence the conditions of the deadwood in forest ecosystems [79]. In managed forests, the quantity of deadwood is reduced by logging [80], while in protected forests, the deadwood is much higher [81]. Thus, in our case, the application of repetitive selective thinning greatly contributed to the decrease in dead wood biomass, both standing and fallen.

The amount of accumulated C in forest litter was also found to be low (11.5 Mg ha^{-1}), e.g., comparative to that reported by Balboa-Murias et al. [55] for mature *Quercus robur* stands in NW Spain (24.75 Mg ha^{-1}). This can be attributed to the relatively young age of the forest (as oak forest), which, on the other hand, is very optimistic, since it shows the high dynamics of the stands that can store great amounts of carbon in the future. The rotation age of this type of oak forest is anticipated to be 150 years or more [28].

5. Conclusions—Application in Forest Management

The findings of the study clearly indicate that the forest conversion from a coppice management system to high forest, through specific silvicultural treatments (periodical repetitive positive selective cuttings) of the species *Quercus frainetto*, presents quite high rates of carbon accumulation for the whole period of 50 years of forest conversion. This carbon sequestration follows the general pattern proposed by Lee et al. [3] for coppice forests subjected to conversion to the high forests but gives quite higher rates of carbon accumulation. The forest acts as a sink of carbon and accumulates important quantities of carbon in annual base in all ecosystem pools, and especially in above ground tree living biomass. Taking into consideration that the conversion of the studied forest can be continued for the next 70–80 years, since the rotation age of this type of oak forest is anticipated to be 150 years or more [28], this shows the high dynamics of the forest for future carbon accumulation. This finding is very optimistic, since it provides great opportunities to forest managers to increase the contribution of the forest sector in climate crisis mitigation. Consequently, encouraging such a forest strategy for the coppice forest would likely improve the climate change mitigation benefits of forests. Silvicultural practices and systems could be effectively used to convert degraded forest stands to more suitable stand structures and compositions and increase C sequestration, as well as mitigating and adapting ecosystems to the effects of global change. The applied selective cutting with cut-to-length or tree-length harvesting systems is suggested as one of the major solutions for increasing forest biomass and C content in forest soils [9].

Additionally, the developed equations for tree biomass estimation proved that the diameter at breast height is a high quality and accurate predictor for the estimation of tree living aboveground biomass. The applied approach and the developed equations can be used in forest practice in the case of oak coppice conversion to high forest, especially when future conversion results are needed to estimate the benefits from conversion. The produced knowledge of biomass allocation in each tree part could also help in the design of appropriate silvicultural treatments effective for accelerating tree growth and carbon sequestration in trees, and thus, increasing the amount of carbon dioxide removal from the atmosphere, which, in turn, will result in mitigating the climate crisis.

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