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Original Research

Evaluation of the Carbon Stock and Cork Harvesting Practices of a *Quercus Suber* Stand in Tunisia

Sghaier Tahar*, Azizi Thouraya, Ammari Youssef

National Institute for Research in Rural Engineering, Water and Forestry (INRGREF), University of Carthage, Hédi Karray, 2080, Ariana, Tunisia.

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Abstract

This study aims to evaluate the carbon sequestration potential and cork harvesting practices in a cork oak (*Quercus suber*) stand in Tunisia, where this species accounts for approximately 6% of the country's total forested area. Based on dendrometric data collected through field sampling and biomass prediction equations specifically developed for cork oak in Tunisia, the studied plot is characterized by an average density of 287 stems/ha and a basal area of approximately 30 m²/ha, and stores an estimated average of 69 t/ha of carbon. This stock is partitioned between aboveground biomass (51.6±7.7 t/ha) and belowground biomass (root biomass) (17.6±2 t/ha). The wood and cork of the main stem account for the majority of aboveground carbon (43% and 39%, respectively), while branches and foliage contribute 28%. These results highlight the crucial role of cork oak forests as carbon sinks. Analysis of debarking practices reveals significant variability in the coefficients applied (0.48 to 3.82 × CBH; CBH: Circumference at Breast Height), whereas recommended values are expected to range between 1.5 and 2.5. This heterogeneity leads to the overexploitation of small trees and the underexploitation of large ones, resulting in both economic losses and tree weakening. The estimated cork yield over an 11-year cycle shows that applying optimal coefficients could bring cork production closer to the theoretical potential of 345 tons for the plot, corresponding to a coefficient of 2.5 × CBH. Furthermore, nearly 9% of exploitable trees still retain their male cork, representing an additional loss of potential revenue. These results highlight the need to optimize and harmonize debarking practices, adapt interventions to the actual size of the trees, and strengthen silvicultural monitoring to ensure sustainable, profitable, and ecologically efficient management of cork oak forests in Tunisia.

Keywords: cork oak, carbon sequestration, debarking, cork yield, sustainable forest management, Tunisia

*e-mail: sghaier.tahar@iresa.agrinet.tn
0000-0002-4175-2351

Introduction

The cork oak (*Quercus suber* L.) is a species endemic to the Mediterranean-Atlantic region of the Mediterranean basin [1]. It belongs to the order Fagales, the family Fagaceae, the subfamily Quercineae (or Quercoideae), and the genus *Quercus* [2]. This genus comprises between 200 and 500 species [3], among which *Quercus suber* L. is the only one that produces cork of industrial use [4]. Due to its multiple ecological, socio-economic, and environmental roles, the cork oak is regarded as one of the most important forest species in Mediterranean ecosystems. The global area of cork oak forests is estimated at approximately 2,306,000 hectares, of which 37.5% are located in North Africa. More specifically, this species covers 376,000 hectares in Morocco, 400,000 hectares in Algeria [5], and 90,423 hectares in Tunisia (representing around 6% of the total forest area). In Tunisia, cork oak forests include 70,208 hectares in pure stands and 20,215 hectares in mixed stands, mainly associated with the Algerian oak (*Quercus canariensis*) [6].

The high level of carbon dioxide (CO_2) in the atmosphere is widely recognized as the main cause of global climate change [7]. To slow this phenomenon, it is essential to increase the storage capacity of terrestrial carbon reservoirs [8]. Among these reservoirs, forests play a crucial role in regulating the global carbon cycle [9]. Recognizing this importance, many European Union countries have committed to achieving carbon neutrality [10], integrating forest carbon sequestration into their climate change mitigation strategies [11]. In this regard, the cork oak stands out for its capacity to sequester atmospheric carbon, thanks to its exceptional longevity and dense foliage. Although its deciduous leaves are partially renewed throughout the year, this broadleaf tree maintains prolonged photosynthetic activity, thus promoting carbon dioxide absorption. Its thick bark, composed of cork, acts as a long-lasting carbon sink, storing large quantities of CO_2 over extended periods. Furthermore, cork oak forests, as biomass-rich ecosystems, contribute significantly to mitigating climate change by capturing carbon not only in the trees themselves, but also in the forest soils that accumulate organic matter from the decomposition of leaves and other plant debris. Furthermore, cork production, a unique property of this species, also contributes to carbon sequestration, as the harvested bark continues to store CO_2 even after extraction. Therefore, the preservation and sustainable management of cork oak stands are essential to optimizing their role in regulating atmospheric carbon and combating climate change. In this context, the precise quantification of the trees' carbon biomass is a priority, as it allows for a reliable assessment of their contribution to carbon sequestration. Although it represents only one aspect among others, this measurement is essential for estimating the productivity of forest stands, evaluating the effectiveness of environmental policies, and better understanding the processes involved in carbon dynamics. It thus plays a central role in optimizing forest management strategies to mitigate the effects of climate change [12].

To quantify tree biomass, the most accurate method is to fell trees and then weigh them after drying (destructive sampling), which is a particularly costly process in terms of time and financial resources [9]. However, slightly less accurate biomass estimates can be obtained using non-destructive dendrometric methods, such as the use of allometric equations already developed for certain forest species [1, 9, 13-15]. These equations are often developed using statistical concepts, based on small and geographically limited datasets obtained through destructive sampling. This allows for the definition of optimal conditions for model application while taking local specificities into account [9]. To this end, the assessment of carbon sequestration by trees using these equations relies on several essential parameters. Firstly, it considers dendrometric variables such as diameter at breast height (DBH), total height, and crown dimensions, which are used to estimate aboveground and belowground biomass. Secondly, it relies on species-specific biomass-to-carbon conversion coefficients, thereby enabling precise quantification of the carbon stored in the tree's living parts.

The objective of this study is to assess the carbon sequestration potential and cork harvesting practices in a cork oak stand located in the Tbeynia forest, in northwestern Tunisia. This assessment, which also includes estimating the cork production potential, aims to better understand the role of this type of stand in mitigating climate change, while contributing to sustainable and optimized forest management. This estimate is based on the analysis of dendrometric data collected through field sampling, as well as the application of prediction equations for the various biomass components developed specifically for cork oak in Tunisia.

Materials and Methods

Description of the Experimental Site and Data Collected

The Tbeynia forest, located in the Ain Draham region, also known as Kroumirie, in northwestern Tunisia (Fig. 1), lies at an altitude above 500 m. It is characterized by a humid upper bioclimatic zone with a mild winter variant. Average annual rainfall varies between 800 and 1200 mm, concentrated mainly during the winter season [16], while the average annual temperature is around 15ºC [17]. The dominant soils are leached brown soils and forest brown soils, characteristic of humid forest areas [1, 18]. Floristically, the climax community of *Quercus suber* and *Cytisus triflorus* Lam. is well represented, reflecting vegetation characteristic of humid Mediterranean ecosystems.

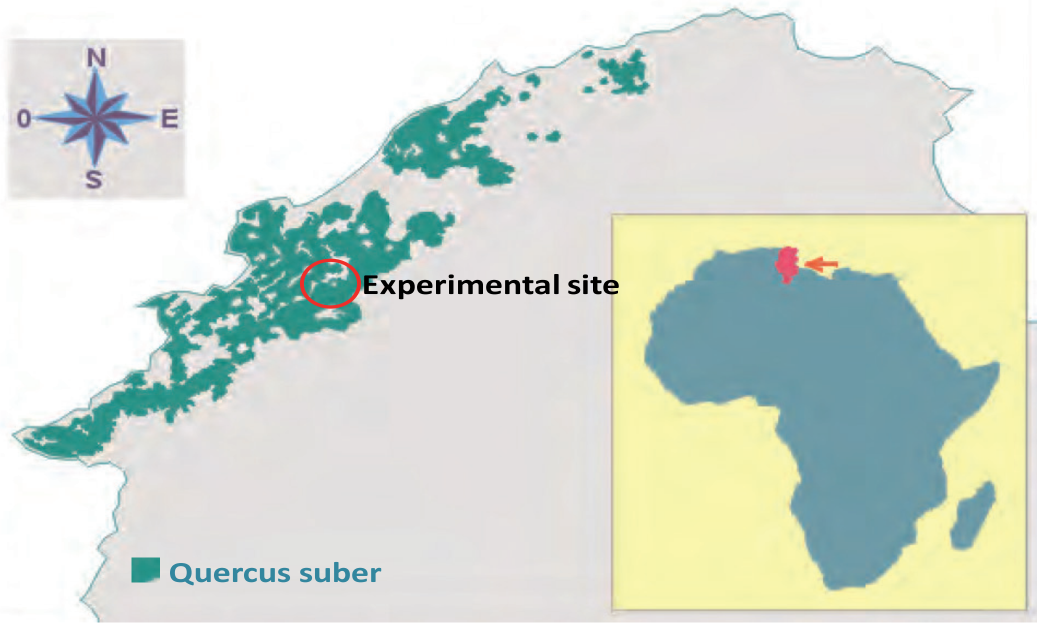

Fig. 1. Experimental site (Tbeynia *Quercus suber* forest).

The data analyzed in this study were collected in plot 4 of the Tbeynia series area, located in the Ain Draham cork oak forest. This plot covers a total area of 45.4 ha, of which 41.4 ha is forested [19]. This area is primarily composed of a dense, old-growth cork oak stand, extending over 38.7 ha, or 85.2% of the total plot area. A total of seven circular measurement plots, ranging in size from 660 to 2790 m², were established, with one plot approximately every 5 hectares. These plots, each containing 40 stems, were positioned to encompass the full range of variations in density, topography, and soil fertility observed within the studied cork oak plot. In addition to the detailed characterization of each plot (GPS coordinates, altitude, aspect, position on the slope, gradient, soil, and vegetation), the following dendrometric measurements (Fig. 2) were taken on each tree within the plot: diameter at breast height (DBH), total height (H), life crown length (LCL), crown diameter (CD), which corresponds to the average of the two perpendicular diameters measured on the crown, standing cork age (t), cork thickness at DBH (CT), and debarking height (DH). The standing cork was 11 years old at the time of measurements (March 2025).

Fig. 2. Debarked cork oak trees and field measurements.

Equations Used for Predicting Cork Production and Aboveground and Belowground Biomass of Cork Oak Trees

To estimate the cork production potential, aboveground and belowground biomass, and carbon sequestration capacity of cork oak trees in the studied plot, various allometric equations developed for this species in Tunisia were used [1, 15]. Table 1 presents the corresponding equations with their residual root mean square error (RMSE) and the coefficient of determination (R^2), indicators of the model fit.

Equations Eq. (1) to Eq. (8) are derived from in-depth work by [15], based on destructive measurements conducted on cork oak trees in Tunisia. It should be noted that in these equations, all biomass values refer to dry biomass. Eq. (9) and Eq. (10) were developed by Sghaier et al. [1] using data collected during long-term, multi-site cork debarking trials, supplemented by inventories conducted at various cork harvesting sites during two successive harvesting seasons in 2016 and 2017.

Conversion Rate of Biomass into Sequestered Carbon

The conversion of the dry biomass of the different components of the cork oak tree into the amount of sequestered carbon was carried out by applying the rates proposed by [15]. Table 2 presents the mean, minimum, and maximum values, as well as the standard errors, of the carbon rates to be applied to the biomass of each compartment of the cork oak tree.

Results and Discussion

Fig. 3 illustrates the distribution according to DBH and total height (H) classes of the 280 cork oak trees sampled in the different measurement plots. Table 3 presents the descriptive statistics of the measured dendrometric variables, as well as the estimated values of dry biomass at the tree level and of the fresh biomass of 11-year-old cork, harvestable by using the debarking

Table 1. Equations for predicting the biomass of different components of the cork oak tree, the biomass and thickness growth of harvestable cork, developed in Tunisia.

Variables	Equations	RMSE	R^2	Name	Authors
Leaf biomass (LB, kg)	$LB = e^{(-3,8257)} \times \left(DBH^2 CR\right)^{0,9651}$	3.0165	0.7257	Eq. (1)	[15]
Stem wood biomass (SWB, kg)	$SWB = e^{(-4,1886)} \times DBH^{1,6962} \times H^{1,3323}$	16.3393	0.9550	Eq. (2)	
Stem cork biomass (SCB, kg)	$SCB = e^{(-4,5075)} \times DBH^{1,4698} \times H^{1,3296}$	8.4275	0.8743	Eq. (3)	
Branch wood biomass (BWB, kg)	$BWB = e^{(-8,3637)} \times \left(DBH^2 LCL\right)^{1,4059}$	29.3477	0.8202	Eq. (4)	
Branch cork biomass (BCB, kg)	$BCB = e^{(-3,5835)} \times \left(DBH^2 CR\right)^{1,0458}$	5.1144	0.8285	Eq. (5)	
Aboveground biomass (AGB, kg)	$AGB = LB + SWB + SCB + BWB + BCB$	-	-	Eq. (6)	
Belowground (roots) biomass (BGB, kg)	$BGB = e^{(-1,2074)} \times DBH^{1,4976} \times LCL^{0,4420}$	16.3462	0.8915	Eq. (7)	
Total biomass (TB, kg)	$TB = AGB + BGB$	-		Eq. (8)	
					[1]
Harvestable cork biomass (HCB, kg)	$HCB = 1,408 \times 10^{-2} DBH^{1,192} DH^{0,688} CT^{0,682}$	4.495	0.9320	Eq. (9)	
Cork thickness growth (CTG, mm)	$CTG = \left(42,283 + 0,703 \times DBH\right) \times \exp\left(-\exp\left(-\frac{t-7,495}{7,915}\right)\right)$	2.529	0.9570	Eq. (10)	

DBH: Diameter at Breast Height (cm); H: Total Tree Height (m); LCL: Life Crown Length (m); CR: Crown Ratio (LCL/H); DH: debarking height (m); t: Age of cork (years).

Table 2. Quantity of carbon (%) in the dry biomass of the different components of the cork oak tree.

Component	Average	Min	Max	SE
Leaves	47.97	44.26	52.39	1.37
Wood	46.08	43.62	48.93	0.98
Cork	56.20	51.28	60.50	1.64
Roots	44.07	43.24	45.82	0.48

SE: Standard error.

height actually practiced during the previous cork harvesting period. The estimates of the dry biomass of the different compartments of the cork oak trees, as well as the fresh harvestable biomass of standing cork, were made using the equations presented in Table 1. Fig. 3 shows that the most represented diameter and height classes in the studied stand are 25-39 cm (48%) and 8-11 m (35%), respectively.

Table 3, which presents the descriptive statistics of the different variables measured at the individual (tree) level, highlights significant variability, particularly in the estimated biomasses, which exceed 100% for some compartments. This high variability can be explained by the fact that none of the equations (Eq. (1), Eq. (4), and Eq. (5)) predicting the biomass of the different compartments of the crown (leaves, branch wood, and branch cork) incorporates the diameter of the crown as an explanatory variable. Only the crown length (LH) and the ratio (RH) between its length and the total height of the tree were considered. However, in cork oak stands with varying densities, the correlation between crown height and diameter generally remains weak (0.57 in our study), which limits the accuracy of estimates relating to the different compartments of the crown.

The cork thickness measured at the DBH, for the cork assumed to be 11 years old, varies between 12 and 60 mm. The maximum value of 60 mm indicates the presence of cork oak trees that were not stripped of their bark during the previous rotation, suggesting a cork age of at least 23 years, given that the cork harvest rotation period in Tunisia is set at 12 years. Indeed, under the best soil and climate conditions, cork produced on a fertile site can reach 40 to 45 mm after a 12-year rotation.

The second important point to highlight from Table 3 concerns the extreme values (minimum and maximum) of the cork stripping coefficient observed during the last cork harvest campaign. This coefficient is expected to range between 1.5 and 2.5, depending on site fertility and the vigor of the cork oak trees. However, in the studied stand, it shows values ranging from approximately 0.5 to 3.8.

To analyze in more detail the significant variability observed in the applied stripping coefficient, Fig. 4 illustrates the evolution of the average values of the stripped height and the corresponding stripping coefficient according to the DBH classes. This figure shows that the stripping coefficient tends to decrease with increasing DBH, while the stripped height increases slightly for small trees, and then stabilizes for trees with a DBH of approximately 40 cm and above. These results, which can be explained by the relatively uniform stripping height applied by the cork harvesting workers, regardless of the dimensions of the trees, perfectly agree with those reported by [1] in a previous study conducted during two stripping campaigns carried out in 2016 and 2017. Indeed, to verify the actual debarking coefficient practiced during cork harvesting in Tunisia, the DBH and the height of the debarked part of 752 cork oak trees were measured during monitoring of 14 debarking sites carried out during two successive debarking campaigns (2016 and 2017). The obtained results showed that the debarking coefficient applied varied from 0.57 to 3.55 times the trunk circumference measured at the DBH (diameter at breast height). The maximum values of this coefficient observed for each DBH class were 3.55 for the 25 cm class; 3.47 for the 35 cm class; 2.70 for the 45 cm class; 2.31 for the 55 cm class; and 1.57 for the 65 cm and above class. The minimum values ranged

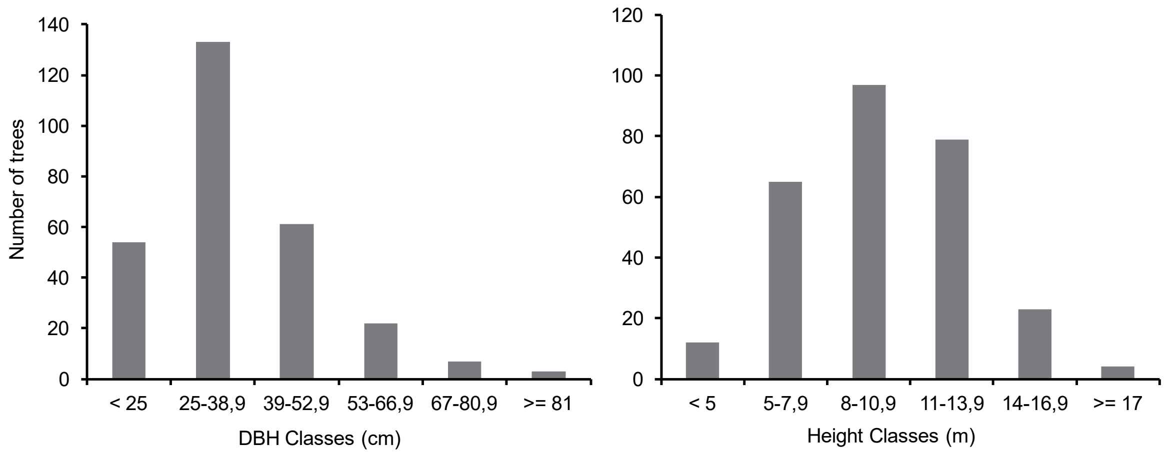

Fig. 3. Distribution of the 280 sampled trees according to diameter at breast height (DBH) and total height (H) classes.

Table 3. Descriptive statistics of measured dendrometric variables and estimated biomasses from the 280 sampled cork oak trees.

Characteristic	Size	Average	Min.	Max.	STD	CV%
Dendrometric variables:						
D30 (cm)	280	41.46	14.50	102.00	14.215	34.29
DBH (cm)	280	35.28	11.00	96.00	13.507	38.29
Total tree height (H; m)	280	9.90	2.80	18.50	3.025	30.56
Debarking height (DH; m)	232	1.97	0.86	3.00	0.483	24.52
Stripping coefficient	232	1.77	0.48	3.82	0.564	31.86
Life Crown Length (LCL; m)	280	5.56	0.65	13.10	2.431	43.72
Crown diameter (CD; m)	280	6.08	1.00	17.70	2.569	42.25
Cork thickness (CT; mm)	230	31.30	12.00	60.00	8.104	25.89
Dry biomass (kg/tree):						
Aboveground	280	407.423	11.009	5028.950	527.324	129.43
Leaves	280	14.356	0.660	112.045	13.774	95.95
Stem wood	280	179.249	5.279	1396.390	184.407	102.88
Branch wood	280	127.283	0.336	2875.160	258.746	203.28
Stem cork	280	54.195	2.097	354.564	49.787	91.87
Branch cork	280	32.340	1.115	290.786	34.474	106.60
Belowground	280	147.657	14.854	834.220	112.302	76.06
Total	280	555.079	25.863	5863.170	636.385	114.65
Harvestable cork biomass (kg/tree)	230	19.01	3.58	90.30	11.779	61.96

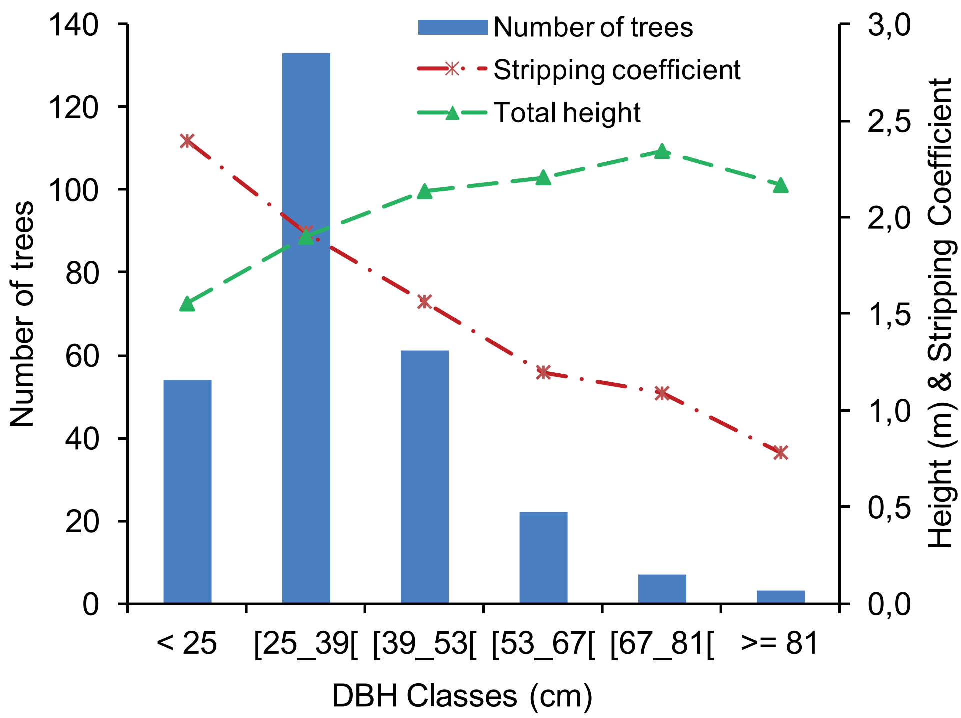

Fig. 4. Distribution of the 280 cork oak trees sampled by DBH classes and evolution of the average stripped height and average debarking coefficient practiced in Tunisia, according to the size of the stems.

from 0.6 to 0.9 for all DBH classes. By comparing the yield estimated with the debarking coefficient actually applied and that obtained with a uniform coefficient equivalent to 2.5 times the circumference measured at the DBH, the yield loss was estimated at 32%. This decrease is mainly attributed to the under-harvesting of large-diameter trees (DBH ≥ 50 cm).

Table 4 presents the descriptive statistics of the average and total values of dendrometric variables and biomass by compartment of cork oak trees, calculated from the measurement plots and then extrapolated to the hectare.

Table 5 presents, in tonnes per hectare (t/ha), the predicted biomass produced by cork oak trees as well as the corresponding quantities of carbon stored in the studied stand.

To ensure the sustainable management of Mediterranean forests threatened by climate change, determining their carbon sequestration potential is now a key element. Indeed, to assess the contribution of forest ecosystems to climate change mitigation, it is necessary to know the amount of carbon stored in the biomass, soils, and leaf litter of these ecosystems. The prior availability of such information allows forest managers to adjust silvicultural practices by adopting management methods that promote both the conservation and increase of carbon stocks, while preserving the productivity and biodiversity of forest stands. This information also

Table 4. Descriptive statistics of the main stand characteristics and biomass by compartment of cork oak trees calculated from the measurement plots and then extrapolated to the hectare.

Characteristic	Average	Min.	Max.	STD	CV%
Density (trees/ha)	287	159	462	102	35.54
Mean total height (m)	9.90	7.23	12.19	1.695	17.12
Mean quadratic diameter (cm)	37.54	31.65	48.33	6.404	17.06
Basal area (m^2/ha)	30.42	18.93	41.47	8.233	27.06
Aboveground biomass (t/ha)	106.788	49.412	173.760	42.281	39.59
Biom. Leaves (t/ha)	3.837	2.351	4.998	1.077	28.07
Biom. Stem wood (t/ha)	47.769	21.425	73.186	18.389	38.50
Biom. Stem cork (t/ha)	14.586	6.703	21.416	5.485	37.60
Biom. Branch wood (t/ha)	32.012	13.577	62.571	17.001	53.11
Biom. Branch cork (t/ha)	8.585	5.117	11.588	2.490	29.00
Belowground (roots) biom (t/ha)	40.067	23.653	54.979	12.060	30.10
Total Biomass (t/ha)	146.855	73.065	225.090	53.173	36.21
Harvestable cork biom (t/ha)	4.286	2.420	7.444	1.649	38.47

Biom.: Biomass; CV%: Coefficient of variation in percent.

Table 5. Dry biomass and quantity of carbon stored per hectare according to the different compartments of the cork oak trees in the studied stand.

Tree compartment	Dry biomass (t/ha) (mean±SE)	Carbon stock (t/ha) (mean±SE)
Aboveground biomass	106.788±7.991	51.625±3.830
Leaves	3.837±0.204	1.840±0.098
Stem wood	47.769±3.475	22.012±1.602
Branch wood	14.586±1.037	8.197±0.583
Stem cork	32.012±3.213	14.751±1.481
Branch cork	8.585±0.471	4.825±0.265
Belowground (roots)	40.067±2.279	17.649±1.004
Total biomass	146.855±10.049	69.274±4.739

SE: Standard error.

forms an essential basis for defining relevant indicators for the implementation of climate policies, the valuation of ecosystem services, and the integration of forests into carbon offset schemes.

The obtained results of this study allowed for a precise evaluation of the carbon sequestration potential of a cork oak stand in Tunisia. With an average density of 287 stems per hectare and a basal area of approximately 30 m²/ha, the total amount of carbon stored by the trees is estimated at 69 t/ha, with a confidence interval of approximately ±9.5 t/ha. This carbon biomass is distributed between the aboveground and belowground parts of the tree. Aboveground biomass represents 51.6±7.7 t/ha, while root biomass contributes 17.6±2 t/ha. Within the aboveground parts, the wood and cork of the main stem constitute the main carbon reservoirs, totaling 43% and 39% of the aboveground stock, respectively. The other components, notably branches and foliage, contribute approximately 28% of the total stored carbon. These results confirm the major ecological role of cork oak stands as carbon sinks, highlighting the importance of their preservation and sustainable management in national climate change mitigation strategies.

Considering biomass, our results (Table 3) are lower than those reported by Saana et al. [20] in Morocco, who used two methods (field data collection and ALS–UAV–TLS data acquisition). They obtained 619.9 kg/tree and 586.80 kg/tree of AGB, respectively. These values are close to those reported by Oubrahim et al. [21] for the Maamora forest, with an average biomass of 379 kg/tree, and by Makhloufi et al. [22] for another Moroccan cork-oak stand, where values ranged from 11 to 1,255 kg/tree. Our findings are also comparable to those of Ruiz-Peinado et al. [23] for a Spanish cork-oak forest, which reported a mean value of 512 kg/tree. However, when compared with other species reported in previous studies, our estimated AGB is lower than those for *Quercus ilex* L., which reached an average of 920 kg/tree, but higher than those for *Quercus pyrenaica* Willd. and *Quercus faginea* Lam., which recorded mean values of 100 kg/tree and 212 kg/tree, respectively. This difference may be attributed to variations in tree architecture. In the study by Saana et al. [20], the trees had a DBH of 94.16 cm and a total height of 10.55 m, whereas in our case, the average DBH and total height were 35.28 cm and 9.90 m, respectively. The values obtained in our study indicate that BGB (147.657 kg/tree) is higher than the average reported by Saana et al. [20], which was 81.75 kg/tree. In contrast, total biomass (555.079 kg/tree) is lower than their estimate of 701.7 kg/tree. According to Ruiz-Peinado et al. [24], biomass allocation varies among species; hardwoods generally allocate more biomass than softwoods, and Mediterranean species such as *Q. suber*, *Q. ilex*, and *Q. canariensis* Lam. may allocate more than 35% of their total biomass to the crown.

The carbon stock estimated in the total biomass of our study site is 69.274 t/ha, which falls within the range reported by Zaher et al. [25], who found values between 49.19 and 231.37 t C ha^{-1}. These results are also consistent with those of Cao and Chen [26], who assessed the total biomass carbon stock of cork-oak forests on the southern slope of the Qinling Mountains in China. Our results indicate that cork represents 39% of the carbon stored in above-ground biomass (AGB), a proportion higher than that reported for cork oaks older than 80 years in the Maâmora agro-forest, located on the Atlantic coast of northwestern Morocco, where this share ranges from 11% to 14%. The lowest carbon stock values were observed in the leaves (Table 5), consistent with the findings of Zaher et al. [25] in the study cited above. In other words, the carbon stock contained in cork at our study site, estimated at 19.576 t/ha, is higher than the values (10,1 t/ha) reported by Oubrahimi et al. [21] for flat lowland areas in Morocco.

The quantification of aboveground and total carbon stock per tree yielded values that are lower than those reported for the Maâmora forest in Morocco [25]. The aboveground biomass (AGB) carbon stock was 179.878 kg/tree, while the total carbon stock reached 241.373 kg/tree. In contrast, the belowground carbon stock was 61.495 kg/tree, exceeding the 44.14 kg/tree reported in the same study.

In addition to quantifying the carbon stored by this cork oak stand in Tunisia, the study also assessed the cork harvesting practices currently implemented in the country. The results show that the height of the stripped section of the trunk (that is, the height up to which cork is harvested) should be determined in principle by applying a coefficient dependent on the trunk's circumference. This coefficient, generally fixed between 1.5 and 2.5, varies according to site fertility and stand characteristics. However, analysis of the collected data in our study reveals that this stripping height is, in practice, almost constant, regardless of variations in circumference or site fertility. Indeed, in this study, the observed values of the stripping coefficient showed significant variability, ranging from 0.48 to 3.82 times CBH. This range, significantly wider than the expected theoretical values (1.5 to 2.5), confirms the existence of considerable heterogeneity in cork harvesting practices. It highlights that the height at which cork is extracted does not systematically follow recommended dendrometric or ecological criteria, but rather appears to result from local habits or practices. Consequently, small trees are overexploited because the stripping height applied often exceeds what their circumference would sustainably allow. Conversely, larger-diameter trees are underexploited, since their cork production potential is not fully utilized. This situation results in both lost economic opportunities due to the underutilization of large trees and a physiological weakening of younger or smaller trees, which are exposed to excessive harvesting that can compromise their growth, vitality, and future production capacity. Therefore, better adaptation of cork stripping practices to the actual size of the trees is essential to reconcile profitability, sustainability, and responsible management of cork oak stands.

Table 6. Observed yield and potential cork per hectare estimated according to different debarking coefficients (1.5 to 3 × CBH) for a stand of 38.7 hectares.

Predicted cork biomass (Cork age = 11 years)	Stripping coefficient				
	Actual debarked height	1.5 × CBH	2 × CBH	2.5 × CBH	3 × CBH
Average (t/ha)	4.29	4.25	5.18	6.04	6.85
Min (t/ha)	2.42	2.32	2.83	3.30	3.74
Max (t/ha)	7.44	6.42	7.82	9.12	10.34
Total stand	165.88	164.50	200.50	233.77	265.01
Min (T)	93.66	89.87	109.54	127.71	144.78
Max (T)	288.10	248.32	302.67	352.89	400.05

To concretely illustrate the potential lost revenue in the studied stand, Table 6 presents the estimated cork yield per hectare, calculated from data actually observed in the field for 11-year-old cork. This table highlights the quantity of cork currently harvested based on current debarking practices. It also allows for comparison with the potential yield that could have been obtained if the harvesting heights had been adjusted to the actual dimensions of the trees, by applying coefficients of 1.5, 2, 2.5, and 3 times CBH. This estimate thus provides a quantified overview of the economic impact linked to the under-exploitation of large-diameter trees and the over-exploitation of smaller ones.

It should be noted that, according to the management plan developed by the Directorate General of Forests [19] for the period 2019-2042, the production potential of this same 38.7 ha stand, in the case of optimal application of the debarking coefficient, was estimated at 345 tonnes for 12-year-old cork. This result likely corresponds to that obtained in our simulation for a coefficient of 2.5 times the CBH, which confirms the consistency between the estimates from the management plan and those derived from our projection model.

Finally, another particularly significant finding of this study concerns the high proportion of potentially exploitable trees that have not yet been stripped of their bark. Indeed, nearly 9% of the trees have already reached the minimum size required for stripping (21 cm DBH), but still retain their male cork. This situation represents a significant loss for the industry, as a portion of the cork production potential remains untapped. It also highlights the existence of dysfunctions in the implementation of forestry practices, linked either to a delay in operations or to a lack of adequate monitoring of stands. This observation should encourage the forestry administration to strengthen monitoring mechanisms, optimize the planning of debarking operations, and put in place measures to ensure more efficient, sustainable, and economically profitable management of cork oak forests in Tunisia.

Conclusions

This study assessed both the carbon storage potential and cork harvesting practices in a cork oak stand in Tunisia. The results show that this stand stores an average of 69 t/ha of carbon, distributed between aboveground and root biomass, highlighting the major ecological role of cork oak forests as carbon sinks.

However, as with any study based on estimates, some limitations remain that should be considered when interpreting the results. First, the findings are specific to the studied stand, which may limit their extrapolation to all Tunisian cork oak forests, given the ecological, structural, and site variability that characterizes these ecosystems. In addition, the use of allometric models relies on relationships developed from specific datasets covering a defined range of cork oak tree dimensions. Therefore, their application is only appropriate for trees whose dendrometric characteristics fall within the validity range of the data used to build these models (DBH: 20-90 cm; H: 8-17 m). Outside these ranges, any extrapolation should be made with caution to avoid potential bias in the estimation of forest variables.

It should be noted that, in this study, some of the sampled trees have dimensions slightly outside the validity limits of the models used (DBH<20 cm: 7%; DBH>90 cm: 1%; H<8 m: 13%; H>17 m: 3%). However, given the heterogeneity of forest environments and the limited availability of models for cork oak in Tunisia, these deviations are considered acceptable, and their impact on the estimates is expected to remain limited.

Furthermore, the analysis of cork harvesting practices revealed significant variability in the application of harvesting coefficients, leading to the overexploitation of small trees and the underexploitation of large-diameter trees, with significant economic and ecological consequences. The assessment of cork yield also highlighted notable discrepancies between actual production and theoretical potential, particularly for trees where the male cork is still present even though the tree has reached harvestable size.

These findings highlight the need to revise and harmonize cork harvesting practices, adapt interventions to the actual size of the trees, and strengthen monitoring and forestry planning. Such an approach would optimize cork production, ensure the sustainability of stands, and improve economic profitability while preserving the essential ecological functions of cork oak forests in Tunisia.

Ultimately, this study provides quantitative and practical elements that can guide forest management decisions and contribute to the sustainable development of this strategic resource.

Author Contributions

Conceptualization: S.T.; formal analysis: S.T.; data curation: S.T.; writing-original draft preparation: S.T. and A.T.; writing-review and editing: S.T., A.T., and A.Y.; supervision: S.T., A.Y., and A.T.; funding acquisition: A.Y., S.T., and A.T. All authors have read and agreed to the published version of the manuscript.

AI Usage Disclosure Statement

The authors declare that artificial intelligence (AI) tools were used exclusively for language-related purposes during the preparation of this manuscript. In particular, ChatGPT was used to assist with translation from French into English, language editing, grammatical correction, and improvement of clarity and readability. AI tools were not used to generate, analyze, interpret, or modify scientific data, results, figures, conclusions, or any other scientific content. All AI-assisted outputs were carefully reviewed, verified, and, where necessary, revised by the authors. The authors retain full responsibility for the accuracy, integrity, and originality of the manuscript and for all content presented therein.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. SGHAIER T., GARCHI S., AZIZI T. Modélisation de la croissance et de la production du liège en Tunisie. Bois et Forêts des Tropiques, **346**, 3, **2020** [In French].
2. BOUCHAFRA A., FRAVAL A. Présentation du chêne liège et de la subéraies. In Viellemant C. et Fraval A. La faune du chêne-liège. Actes éditions, Rabat, 1-26, **1991** [In French].
3. NATIVIDADE V.J. Subériculture. Ecole National des Eaux et des Forêts. Nancy, 281 p, **1956** [In French].
4. BONNET S. Le chêne-liège, un arbre généreux. The Forest Time, **2019**.
5. BENDANOUN M. La Mamora, un patrimoine national vital pour l'avenir de Salé et de la région. Journée d'étude «Sauvons la Mamora», Salé, 25 Mars 1996, ENFI-MEABR (Maroc), 31, **1996** [In French].
6. DGF. Deuxième Inventaire National Forestier et Pastoral: Résultats de l'Inventaire Forestier sur l'échelon de Jendouba (Gouvernorats de Jendouba, Béja et Bizerte). Direction Générale des Forêts (Tunisie), 129 p. **2005** [In French].
7. IPCC. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change . Pörtner H.-O., Roberts D.C., Tignor M., Poloczanska E.S., Mintenbeck K.A., Alegría A.M., Craig M.S., Langsdorf S., Löschke S., Möller V., Okem A., Rama B. Eds., Cambridge University Press, Cambridge, UK and New York, NY, USA, **2022**.
8. KEENAN T.F., WILLIAMS C.A. The Terrestrial Carbon Sink. Annual Review of Environment and Resources, **43**, 219, **2018**.
9. JORGE C., TOMÉ M., RUIZ-PEINADO R., ZRIBI L., PAULO J.A. *Quercus suber* Allometry in the West Mediterranean Basin. Forests, **14**, 649, **2023**.
10. SANTOS F.D., FERREIRA P.L., PEDERSEN J.S.T. The Climate Change Challenge: A Review of the Barriers and Solutions to Deliver a Paris Solution. Climate, **10**, 75, **2022**.
11. ANDERSEN S.P., ALLEN B., DOMINGO G.C. Biomass in the EU Green Deal: Towards Consensus on the Use of Biomass for EU Bioenergy' Policy Report. Institute for European Environmental Policy (IEEP), Brussels, Belgium, **2021**.
12. BROWN S. Measuring Carbon in Forests: Current Status and Future Challenges. Environmental Pollution, **116**, 363, **2022**.
13. SEBEI H., ALBOUCHI A., RAPP M., El AOUNI M.H. Évaluation de la biomasse arborée et arbustive dans une séquence de dégradation de la suberaie à Cytise de Kroumirie (Tunisie). Annals of Forest Sciences, **58**, 175, **2001**.
14. EL MOKNI R., MAHMOUDI M.R., SEBEI H., EL AOUNI M.H. Évaluation de la biomasse épigée des peuplements naturels de chêne zéen (Quercus canariensis Willd.) dans les forêts de Kroumirie (Nord-Ouest de la Tunisie). Integrated Protection in Oak Forests IOBC/wprs Bulletin, **76**, 47, **2012** [In French].
15. ZRIBI L., CHAAR H., KHALDI A., HANCHI B., MOUILLOT F., GHARBI F. Estimate of biomass

and carbon pools in disturbed and undisturbed oak forests in Tunisia. Forest Systems, **25** (2), e060, **2016**.
16. NCIRI R., REJEB H. Essai méthodologique pour le maintien et la valorisation d'une ressource naturelle sise en Kroumirie. Conference: Alternatives éco paysagères dans les régions méditerranéennes at UR «HPE» ISA-IRESA-Univ Sousse, **2015** [In French].
17. HAMDI M., LEMPÉRIÈRE G., PETIT-BERGHEM Y. Les montagnes de Kroumirie (Tunisie): entre patrimoine naturel et patrimoine paysager. Actes du 135e Congrès National des Sociétés Historiques et Scientifiques, «Paysages», Neuchâtel, 231, **2014** [In French].
18. MATA F., DOS-SANTOS M. Modeling Cork Yield, Thickness, Price, and Gross Income in the Portuguese Cork Oak Montado. Forests, **15**, 2163, **2024**.
19. DGF. Aménagement intégré et participatif de la VIIIème série forestière d'Ain Draham (1968,7 ha). Rapport de la deuxième phase de planification. PV d'aménagement (version définitive). Période de la validité du PV d'aménagement 2019/2042. Publication Ministère de l'Agriculture, des Ressources Hydrauliques et de la Pêche, Tunisie, 32 p, **2019** [In French].
20. SANAA F., IMANE S., MOHAMED B., KENZA A.E.K., SOUHAIL K., LFALAH H., KHADIJA M. Biomass and Carbon Stock Quantification in Cork Oak Forest of Maamora Using a New Approach Based on the Combination of Aerial Laser Scanning Carried by Unmanned Aerial Vehicle and Terrestrial Laser Scanning Data. Forests, **13**, 1211, **2022**.
21. OUBRAHIM H., BOULMANE M.,BAKKER M., AUGUSTO L., HALIM M. Carbon Storage in Degraded Cork Oak (*Quercus Suber*) Forests on Flat Lowlands in Morocco. IForest, **9**, 125, **2016**.
22. MAKHLOUFI M., ABOUROUH M., EL HARCHAOUI H. Structure Du Peuplement, Tarifs de Cubage et Essai de Traitements Sylvicoles Dans La Subéraie de Chefchaouen. In Annales de la Recherche Forestière au Maroc; National Center of Forestery Research: Rabat, Morocco, **39**, 175, **2008** [In French].
23. RUIZ-PEINADO GERTRUDIX R., MONTERO G., DEL RIO M. Biomass Models to Estimate Carbon Stocks for Hardwood Tree Species. Forest System, **21** (1), 42, **2012**.
24. RUIZ-PEINADO R., RÍO M., MONTERO G. New models for estimating the carbon sink capacity of Spanish soft wood species. Forest Systems, **20 (**1), 176, **2011**.
25. ZAHER H., RHOUFACHA M., DAHMANI H. Carbon stock dynamics along a cork oak stand chronosequence: implications for climate-smart forest management. Journal of the Saudi Society of Agricultural Sciences, **24**, 45, **2025**.
26. CAO Y., CHEN Y. Biomass, carbon and nutrient storage in a 30-year-old Chinese cork oak (*Quercus variabilis*) forest on the south slope of the Qinling Mountains, China. Forests, **6** (4), 1239, **2015**.