JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2027, 28(1), 77–89
https://doi.org/10.12911/22998993/241481
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Received: 2026.09.22
Accepted: 2026.11.16
Published: 2026.12.01

Carbon stocks in tree biomass, soil and litter of *Pinus pinaster* stands in the Mâamora forest, Morocco

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ABSTRACT

Mediterranean forests are significant yet under-documented carbon reservoirs at the stand scale. This study quantifies the organic carbon stocks of maritime pine (*Pinus pinaster* Aiton) stands across their three major pools: tree biomass (above- and below-ground), soil organic carbon (0–100 cm) and litter. Twenty-three trees were destructively sampled to measure biomass, moisture and carbon content of the stem, branches, foliage and stump. In parallel, soil carbon, litter, bulk density, pH and moisture were assessed under three treatments (control, open, under-canopy) and four depth classes. Carbon content was determined by loss-on-ignition. Mean total carbon per tree reached 38.2 ± 25.0 kg C (140 kg CO_2eq), partitioned among the stem (36.4%), roots (28.6%), foliage (19.9%) and branches (15.1%). Tissue carbon content ranged from 53% to 57% of dry matter, exceeding the IPCC default of 50%. A power allometric model closely related total carbon to diameter ($C = 0.454 \cdot DBH^{1.68}$; $R^2 = 0.89$), the best model (DBH^2) reaching $R^2 = 0.94$. Soil carbon stocks ranged from 100 to 175 t C ha^{-1} over the 0–100 cm profile and tended to be higher under canopy, with no statistically significant difference among treatments (ANOVA: $F = 0.82$; $p = 0.53$). Litter, although modest, was clearly enriched beneath the pine canopy. These results provide allometric and pedological references for estimating carbon stocks of maritime pine plantations in Mediterranean settings.

Keywords: *Pinus pinaster*, carbon stocks, tree biomass, soil organic carbon, litter, allometric models.

INTRODUCTION

Forest ecosystems play a decisive role in regulating the global carbon cycle, sequestering a substantial fraction of anthropogenic CO_2 emissions: globally, forests absorb about 2.4 Pg C yr^{-1} and store the equivalent of several decades of fossil emissions (Pan et al., 2011; FAO, 2020). This service relies on pools with contrasting dynamics – living above- and below-ground biomass, necromass (litter, deadwood) and soil organic matter, the latter often being the largest and most durable pool (Lal, 2005; Jandl et al., 2007). In the Mediterranean region, coniferous plantations, particularly maritime pine (*Pinus pinaster* Aiton), cover vast areas for soil protection, timber production and, increasingly, carbon sequestration (M'hirit, 1999; Boudy, 1950).

In Morocco, maritime pine has been planted since the mid-twentieth century, notably in the Mâamora forest, the largest lowland cork oak (*Quercus suber* L.) forest of North Africa, where it accompanies cork oak in reforestation areas, stabilises sandy soils and restores vegetation cover (Boudy, 1950; Aafi et al., 2005). The species is well suited to this role: it is a fast-growing, light-demanding pioneer conifer that tolerates nutrient-poor, acidic sandy soils and summer drought, and it is used across its range for sand-dune fixation, erosion control and the production of timber, pulpwood and resin (Abad Viñas et al., 2016). Its needle litter, rich in slowly

decomposing compounds, builds a forest floor that protects the soil surface, limits evaporation and supplies organic matter to the mineral soil, so that the species influences carbon storage not only through its biomass but also through the soil (Augusto et al., 2002; Vesterdal et al., 2013). In the Mâamora, where the native cork oak stands are degraded and their natural regeneration is difficult, these plantations therefore play an important ecological role in maintaining forest cover and soil functions (Aafi et al., 2005).

Despite these functions, the contribution of maritime pine plantations to the Moroccan forest carbon balance remains poorly quantified, for several reasons. First, local quantitative references on the carbon stocks of these stands are scarce. Second, biomass is usually converted to carbon with the IPCC default carbon fraction of 50% and with allometric equations developed in other European regions, whose transferability to the sandy soils and sub-humid to semi-arid climate of north-western Morocco is uncertain (IPCC, 2006; Thomas & Martin, 2012). Third, belowground biomass, soil and litter are rarely measured together with tree biomass, although the soil is often the largest carbon pool (Lal, 2005; Jandl et al., 2007). Finally, Mediterranean forests are increasingly exposed to drought, fire and dieback, which makes baseline carbon inventories necessary to monitor future changes and to value the climate-mitigation role of reforestation programmes in national greenhouse-gas inventories (FAO, 2020; IPCC, 2006).

In parallel, the influence of tree species on soil and litter carbon depends strongly on species, stand age and edaphic conditions (Vesterdal et al., 2013; De Vos et al., 2015). This study has four objectives: (i) to quantify and partition the biomass carbon of maritime pine among compartments; (ii) to establish and compare locally applicable carbon–dimension allometric relationships; (iii) to characterise soil and litter carbon stocks by treatment and depth; and (iv) to propose an integrated carbon budget from soil to canopy. Figure 1 situates the study within the ecosystem carbon cycle.

MATERIALS AND METHODS

Study site and experimental design

The study focused on maritime pine stands of contrasting ages – an old stand and a young stand (2007 plantation) – to which, for the soil component, a stone pine (*Pinus pinea*) stand and an unforested control soil were added as references. For soil and litter, the design distinguished two positions relative to the crown: 'under canopy' (SC, from the French *sous couvert*), beneath the canopy, and 'open' (HC, from the French *hors couvert*), in the gaps between trees, to isolate the effect of cover on soil properties. This factorial structure (species/age × position × depth) allows the sources of variation in soil carbon to be decomposed.

Tree biomass sampling

Sample trees were selected by stratified sampling across diameter classes. Rather than being chosen in proportion to their frequency in the stands, trees were distributed over the whole range of diameters and heights present (DBH 6.4–25.5 cm; height 3.6–8.3 m), which improves the precision of the regression parameters at the extremes of the size range (Picard et al., 2012). Only healthy, single-stemmed trees without visible damage or broken crowns were retained. The sample size (n = 23) was constrained by the destructive nature of the measurements – felling, compartment separation and excavation of the stump and roots – in a state-managed forest, and is within the range commonly used to fit site-specific equations with one or two predictors (Picard et al., 2012).

The 23 selected trees were felled and sampled. For each tree, circumference at 1.30 m (C1.30) and total height were measured; diameter (DBH) was derived from circumference using Equation (1). Each tree was separated into four compartments – stem, branches, foliage and twigs, stump and roots – each weighed fresh. Representative subsamples were taken for moisture and carbon determination, following Picard et al. (2012).

$$DBH = C_{1.30} / \pi \quad (1)$$

where: DBH – diameter at breast height (cm), $C_{1.30}$ – circumference at 1.30 m (cm).

Soil and litter sampling

Litter (forest floor: needles, twigs, cones and fragmented organic material lying on the mineral soil) was collected exhaustively within quadrats of known area in each treatment and position, oven-dried and weighed, following standard forest carbon inventory protocols (IPCC, 2006; Pearson et al., 2007). Soil was sampled in four depth

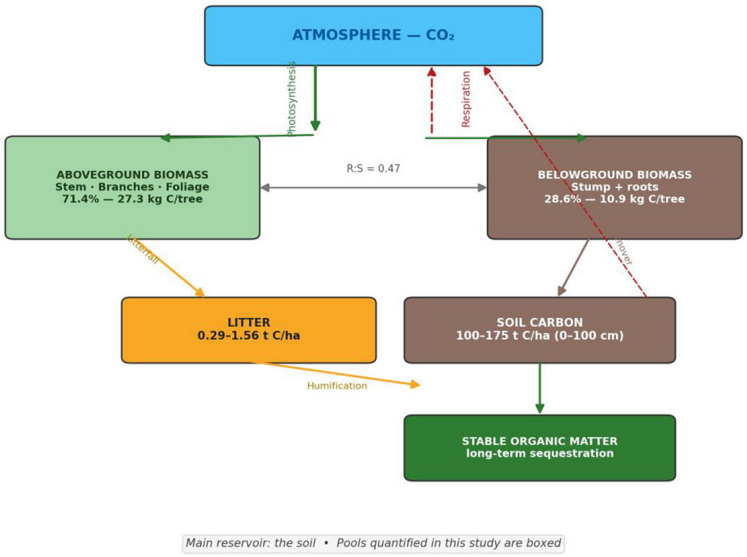

Figure 1. Conceptual diagram of the main carbon pools and fluxes of a maritime pine stand
Boxed pools and the indicated values are quantified in the present study; R:S = root-to-shoot ratio.

classes (0–20, 20–40, 40–60 and 60–100 cm), the profile being extended to 1 m to account for subsoil carbon. Bulk density was determined by the core method, using a cylinder of known volume and oven drying at 105 °C (Blake & Hartge, 1986). Soil pH was measured in water (International Organization for Standardization, 2005) and corrected to 25 °C, and gravimetric moisture was computed from the mass difference before and after oven drying at 105 °C (International Organization for Standardization, 1993).

Laboratory analyses

Subsamples were oven-dried to constant mass (dry weight, moisture content). Carbon content was estimated by loss-on-ignition (calcination); ash content was used to derive the carbon percentage of plant tissues and soil organic matter (principle related to Walkley & Black, 1934; Nelson & Sommers, 1996). Compartment carbon was obtained by multiplying dry biomass by its carbon content; soil carbon stock (t C ha^{-1}) was computed per layer from carbon percentage, bulk density and layer thickness, following IPCC (2006) guidelines.

Compartment carbon, soil carbon stock per layer and CO_2 equivalent were calculated with Equations (2) to (4):

$$C_c = DM_c \cdot CC_c / 100 \quad (2)$$

$$SOC_i = CC_i \cdot BD_i \cdot e_i \quad (3)$$

$$CO_2eq = C \cdot 44/12 \quad (4)$$

where: C_c – carbon stock of compartment c (kg C), DM_c – dry mass of compartment c (kg), CC_c – carbon content of compartment c (% of dry matter), SOC_i – soil organic carbon stock of layer i (t C ha^{-1}), CC_i – carbon content of layer i (%), BD_i – bulk density of layer i (g cm^{-3}), e_i – thickness of layer i (cm), C – carbon stock, 44/12 – ratio of the molecular mass of CO_2 to the atomic mass of carbon.

Allometric approach and carbon fraction

Biomass carbon was estimated with allometric equations, the standard approach linking easily measured variables – diameter at breast height (DBH) and height – to biomass (Chave et al., 2014; Picard et al., 2012). These equations have a theoretical basis in biological scaling laws (West et al., 1997; Niklas, 1994). Equations have been developed for maritime pine in France (Porté et al., 2002) and across contrasting environments (Shaiek et al., 2011). Spanish models are also available (Montero et al., 2005; Ruiz-Peinado et al., 2011), but their transferability to Moroccan conditions is not guaranteed; site-specific equations were therefore calibrated in this study. Moreover, because the actual tissue carbon content frequently departs from the conventional 50% value (Thomas & Martin, 2012; Bert & Danjon, 2006), carbon content was measured for each compartment rather than assumed.

Statistical analyses

Descriptive statistics were computed for each variable. Carbon–dimension allometric relationships were fitted by linear regression on log-transformed data (power model $C = a \cdot DBH^b$), with a logarithmic bias correction factor ($CF = \exp(MSE/2)$) applied after Baskerville (1972) and Sprugel (1983). Four predictors (DBH, H, DBH^2, $DBH^2 \cdot H$) were compared by R^2, Akaike Information Criterion (AIC) and root-mean-square error (RMSE). Correlations between variables were quantified by Pearson's coefficient (r), and differences in soil carbon among treatments tested by one-way ANOVA ($\alpha = 0.05$). Figure 2 details the processing chain.

The power model was fitted in logarithmic form (Eq. 5) and back-transformed to the arithmetic scale with the correction factor *CF* (Eqs. 6 and 7):

$$\ln(C) = \ln(a) + b \cdot \ln(DBH) \quad (5)$$

$$C = CF \cdot a \cdot DBH^{\,b} \quad (6)$$

$$CF = \exp(MSE / 2) \quad (7)$$

where: *C* – total or compartment carbon (kg C), *DBH* – diameter at breast height (cm), *a* and *b* – fitted coefficients, *MSE* – mean square error of the log-log regression.

RESULTS

Dendrometric characteristics and carbon by compartment

The sampled trees spanned a wide range: DBH from 6.4 to 25.5 cm (13.3 ± 4.9 cm) and height from 3.6 to 8.3 m (5.3 ± 1.3 m). Total carbon per tree averaged 38.2 ± 25.0 kg C, with high inter-individual variability (CV = 66%) reflecting structural heterogeneity (Table 1). Aboveground biomass accounted for 71.4% of tree carbon, and the total-to-stem carbon expansion factor reached 2.75.

Carbon is concentrated in the stem (36.4%), followed by roots/stump (28.6%), foliage (19.9%) and branches (15.1%) (Figure 3). The root-to-shoot ratio (R:S) reached 0.47 ± 0.19. The compartment distribution (Figure 4a) shows increasing dispersion from stem to total carbon, and the diameter–height–carbon relationship (Figure 4b) shows a clear joint increase.

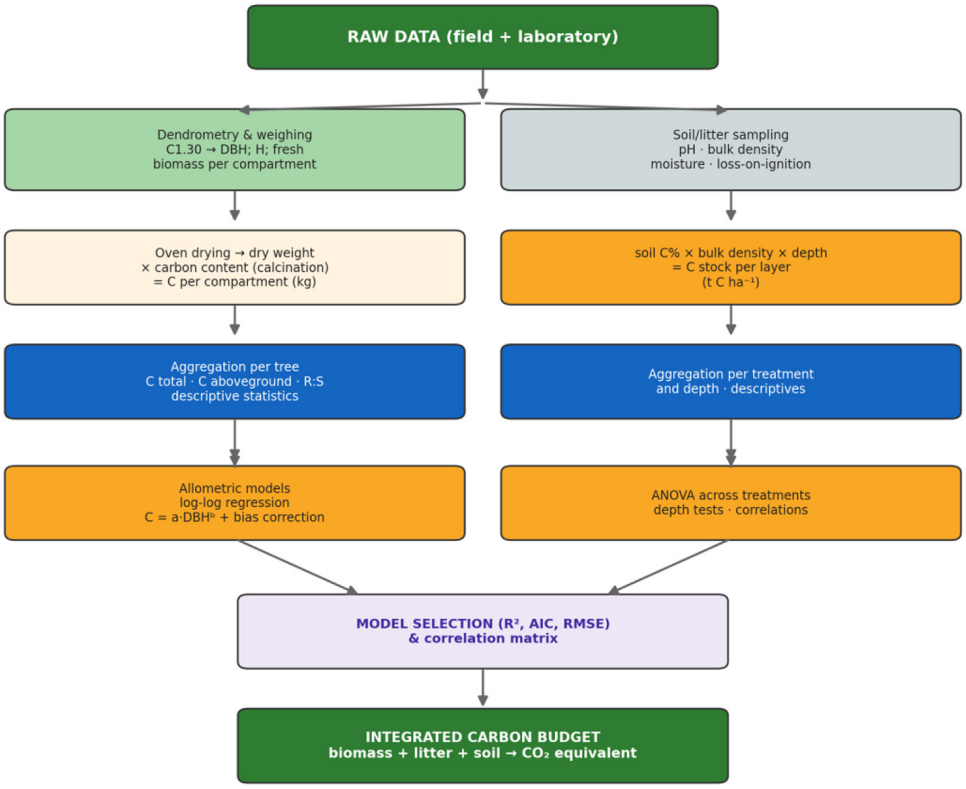

Figure 2. Analytical workflow: from raw field and laboratory data to the integrated carbon budget, via compartment carbon computation, aggregation, allometric modelling and statistical testing.

Table 1. Descriptive statistics of dendrometric variables and carbon stocks by compartment (n = 23).

Variable	Mean	SD	CV (%)	Range
DBH (cm)	13.26	4.88	36.8	6.37 – 25.46
Height (m)	5.26	1.33	25.3	3.60 – 8.25
Stem C (kg)	13.89	10.84	78.1	2.45 – 44.89
Branch C (kg)	5.77	8.69	150.6	0.00 – 39.25
Foliage C (kg)	7.61	5.14	67.6	0.89 – 20.17
Root/stump C (kg)	10.92	6.17	56.5	3.44 – 23.02
Aboveground C (kg)	27.26	19.68	72.2	4.01 – 88.62
Total C (kg)	**38.18**	**25.03**	**65.6**	**7.89 – 111.63**

Note: CV – coefficient of variation.

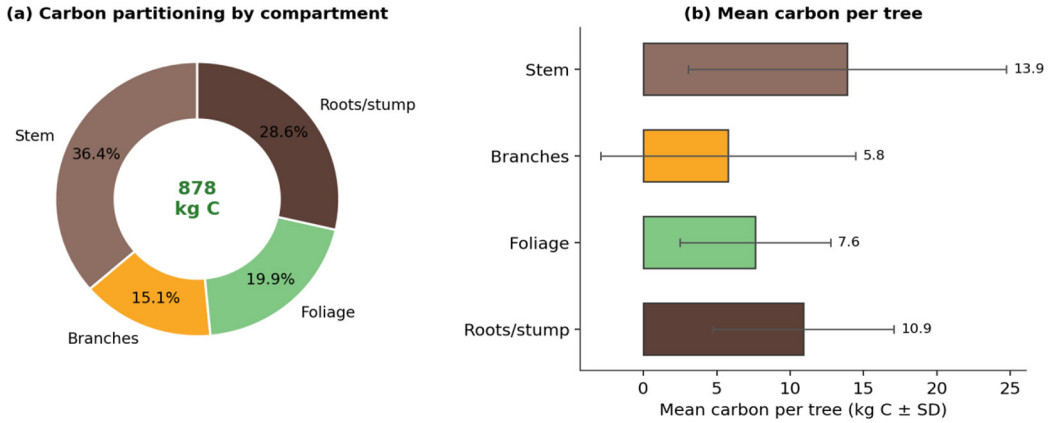

Figure 3. Partitioning of tree biomass carbon: (a) relative share of each compartment; (b) mean carbon per tree and compartment (error bars: SD)

Tissue carbon and moisture content

Tissue carbon content varied significantly among compartments: 57.1 ± 0.7% for branches, 56.5 ± 0.3% for foliage, 55.3 ± 3.5% for the stem and 53.1 ± 3.5% for the stump and roots (Figure 5a). All values exceeded the IPCC default of 50%, with a mean of 55.5%. Moisture content, key to fresh/dry biomass conversion, was highest in foliage (51.9%) and lowest in roots (39.8%) (Figure 5b).

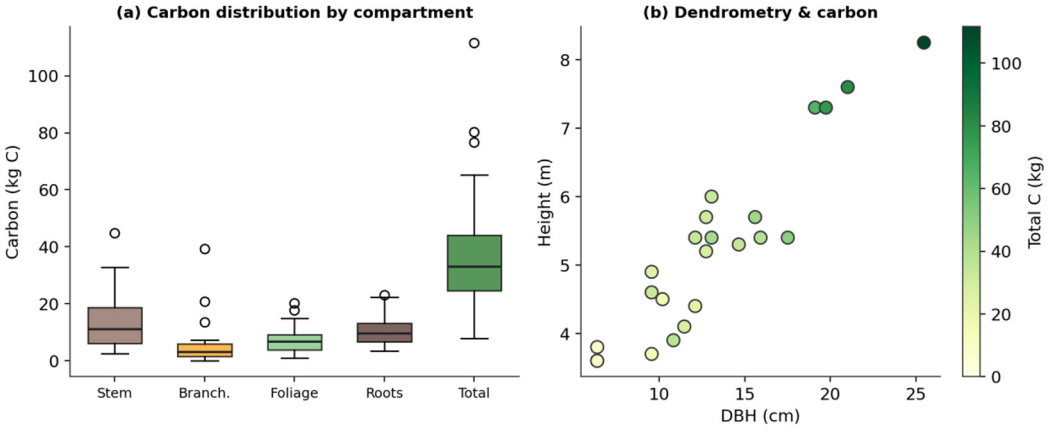

Figure 4. (a) Carbon distribution by compartment (boxplots, n = 23); (b) relationship between diameter, height and total carbon (colour gradient).

Table 2. Carbon content (% of dry matter) and moisture content (%) by compartment (mean ± SD)

Compartment	Carbon content (%)	Moisture content (%)	n
Stem	55.3 ± 3.5	45.5 ± 2.8	23
Branches	57.1 ± 0.7	47.0 ± 3.9	20
Foliage	56.5 ± 0.3	51.9 ± 6.0	23
Stump/roots	53.1 ± 3.5	39.8 ± 2.7	23
Weighted mean	**55.5 ± 2.9**	—	—

Allometric relationships and model selection

Total carbon was strongly correlated with diameter ($r = 0.95$; $p < 0.001$) and height ($r = 0.92$) (Figure 6). The power model $C = 0.454 \cdot DBH^{1.68}$ explained 89% of the variance (Figure 7). Comparison of four models (Table 3) identified DBH^2 as the best predictor ($R^2 = 0.94$; AIC = 86.0; RMSE = 5.95 kg), ahead of $DBH^2 \cdot H$ ($R^2 = 0.94$) and diameter alone ($R^2 = 0.90$), height alone being the least accurate ($R^2 = 0.84$).

Compartment-level models (Table 4, Figure 8) revealed contrasting behaviour: the stem ($R^2 = 0.97$; $b = 2.15$) and roots ($R^2 = 0.90$) were very well predicted by diameter, branches reasonably so ($R^2 = 0.84$) with a high exponent ($b = 3.21$) indicating more-than-proportional growth, whereas foliage was decoupled from diameter ($R^2 = 0.03$; $p = 0.46$), its mass depending more on crown dynamics than on tree size. The correlation matrix (Figure 9) confirms the overall consistency, with foliage standing out through weaker associations.

Soil and litter carbon

Over the 0–100 cm profile, soil carbon stocks ranged from 100 t C ha^{-1} (young maritime pine, open) to 175 t C ha^{-1} (old maritime pine, under canopy), the control being 135 t C ha^{-1} (Table 5).

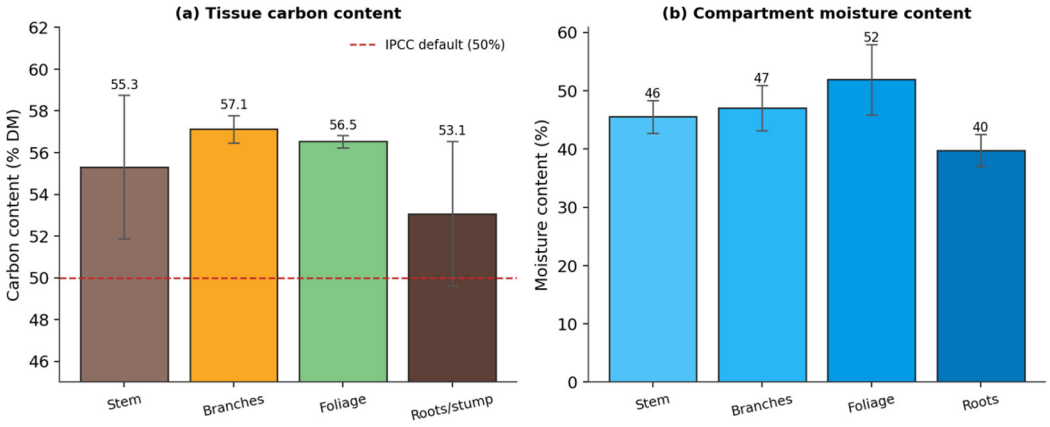

Figure 5. (a) Tissue carbon content by compartment, compared with the IPCC default (50%); (b) compartment moisture content. Error bars: SD

Table 3. Comparison of models for estimating total tree carbon. Best model in bold

Model	R^2	AIC	RMSE (kg C)
$C = a + b \cdot DBH$	0.902	97.6	7.64
$C = a + b \cdot H$	0.844	108.3	9.66
$C = a + b \cdot DBH^2$	**0.941**	**86.0**	**5.95**
$C = a + b \cdot DBH^2 \cdot H$	0.936	87.8	6.18
$C = a \cdot DBH^b$ (power)	0.890	—	—

Note: AIC – Akaike information criterion (lower = better); RMSE – root-mean-square error.

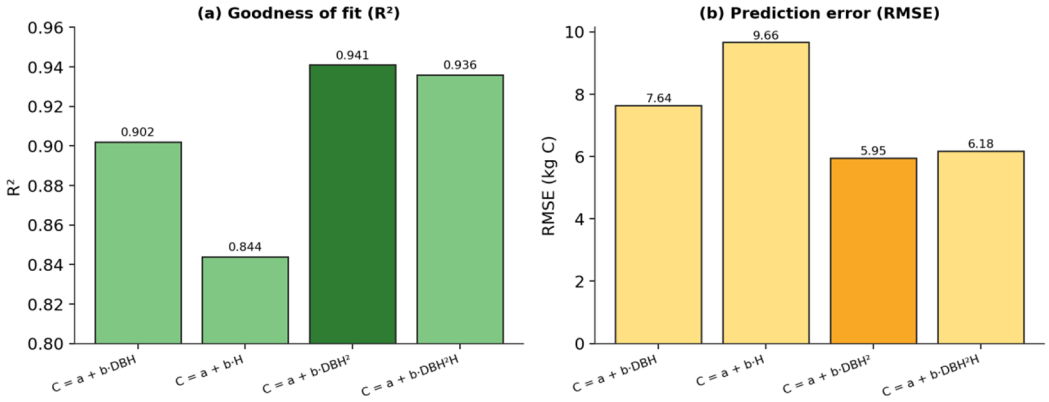

Figure 6. Model comparison: (a) goodness of fit (R^2); (b) prediction error (RMSE) The DBH^2 model minimises error.

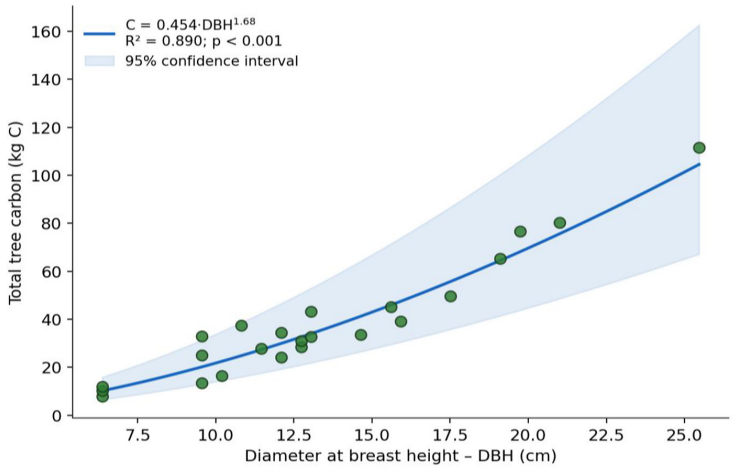

Figure 7. Power allometric relationship between DBH and total carbon Curve: fitted model; band: 95% confidence interval.

Table 4. Compartment-level allometric models ($C = a \cdot DBH^b$, n = 20–23)

Compartment	a	b	R^2	CF
Stem	0.0457	2.152	0.968	1.011
Branches	0.0009	3.213	0.835	1.091
Foliage	2.5383	0.336	0.026	1.367
Roots/stump	0.2438	1.449	0.896	1.018
Aboveground C	0.2322	1.796	0.820	1.053
Total C	**0.4538**	**1.680**	**0.890**	**1.026**

Note: CF – logarithmic bias correction factor (Baskerville, 1972).

The vertical distribution was non-monotonic: high at the surface (0–20 cm: 38.1 ± 6.4 t C ha^{-1}), decreasing in intermediate horizons then rising at depth (60–100 cm: 48.2 ± 25.1 t C ha^{-1}), with increasing variability (Figures 10 and 11).

For both maritime pine stands, soil and litter carbon under canopy exceeded that in open positions (Figure 12), illustrating a canopy enrichment effect. ANOVA, however, found no significant difference in soil carbon among treatments (F = 0.82; p = 0.53), owing to high spatial heterogeneity and low replication. Litter carbon, an order of magnitude lower than soil carbon, clearly followed the cover gradient: from 0.29 t C ha^{-1} on the control to 0.6–1.6 t C ha^{-1} under the pines, and systematically higher under canopy.

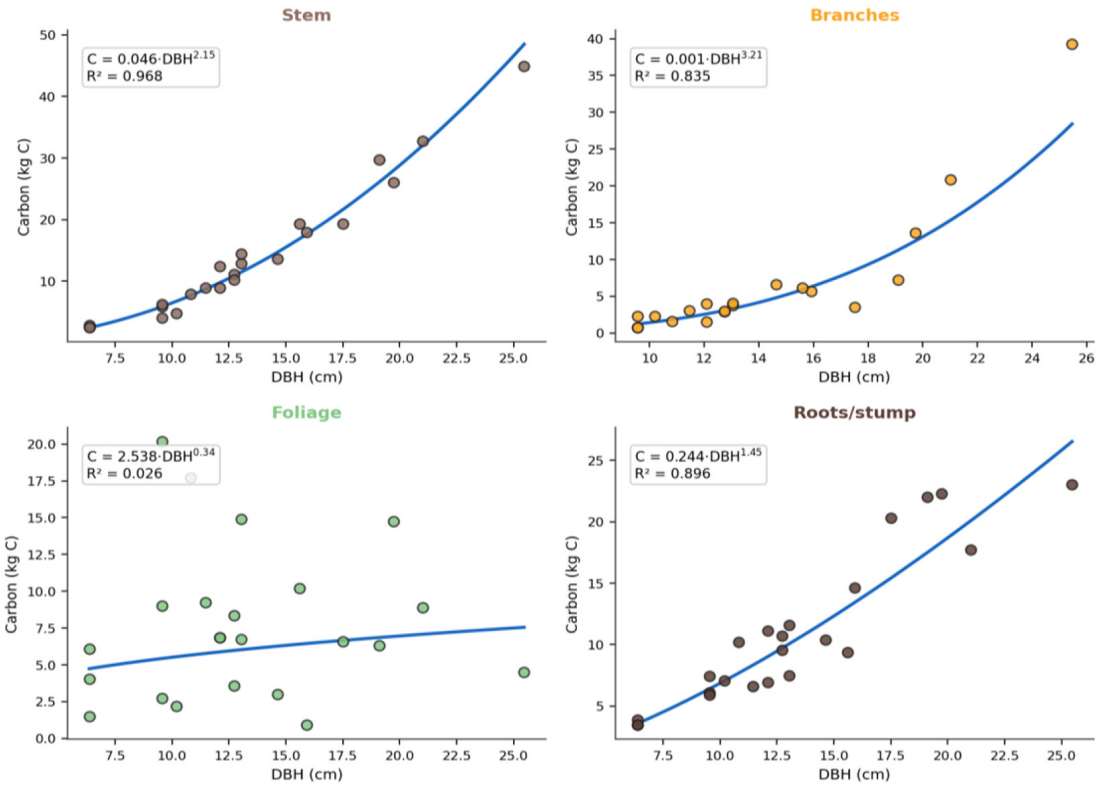

Figure 8. Compartment-level allometric models. Stem and roots track diameter closely; foliage is decoupled from it



Figure 9. Pearson correlation matrix among dendrometric variables and compartment carbon stocks (n = 23)

Complementary edaphic variables remained within narrow ranges: water pH from 5.0 to 5.9 (moderately acidic soils), bulk density from 1.40 to 1.52 g cm^{-3}. pH increased slightly with depth (5.72 to 5.81; Figure 10a) while bulk density varied little. Gravimetric moisture was markedly higher in the stone pine reference stand (9–11%) than under maritime pine or on the control (2–3%), suggesting enhanced water retention linked to litter and the canopy microclimate.

Table 5. Soil carbon stocks (0–100 cm profile), litter carbon and edaphic properties by treatment and position

Treatment	Position	Soil C (t C ha^{-1})	Litter C (t C ha^{-1})	pH (25 °C)
Control soil	—	135.4	0.29	5.56
Old maritime pine	HC	101.8	0.59	5.85
Old maritime pine	SC	174.7	1.03	5.34
Young maritime pine	HC	100.1	0.17	5.40
Young maritime pine	SC	152.7	1.17	5.32
Stone pine	mean	≈ 144	0.93	5.14

Note: HC – open (hors couvert); SC – under canopy (sous couvert).

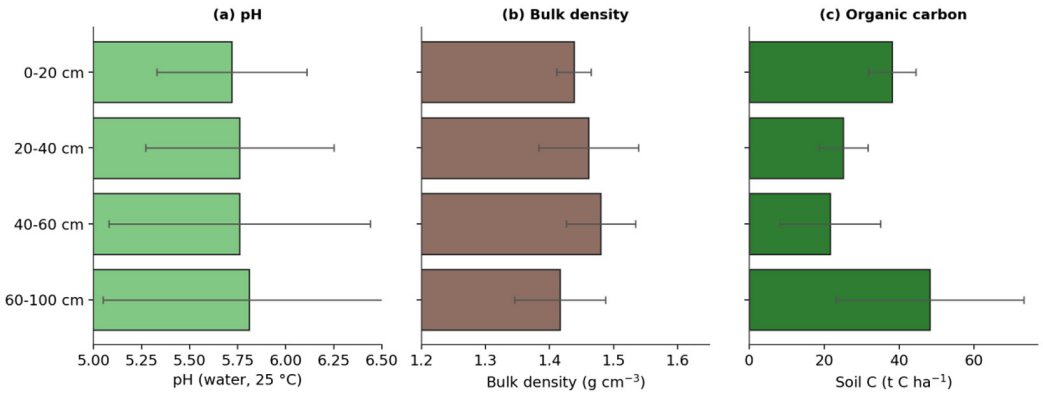

Figure 10. Mean vertical profiles (all series): (a) water pH; (b) bulk density; (c) soil organic carbon, by depth class. Error bars: SD

Carbon budget and CO_2 equivalent

At the tree scale, the mean total carbon of 38.2 kg C is equivalent to 140 kg of CO_2, i.e. for the 23 sampled trees a total of 878 kg C (3.2 t CO_2eq) immobilised in biomass. At the stand scale, the soil remains by far the main reservoir (100–175 t C ha^{-1}), followed by tree biomass then litter, whose share of the total stock remains marginal (< 1%) but plays a key role in the continuous supply of the soil pool (Table 6).

DISCUSSION

This study set out to (i) quantify and partition tree biomass carbon, (ii) establish locally applicable allometric relationships, (iii) characterise soil and

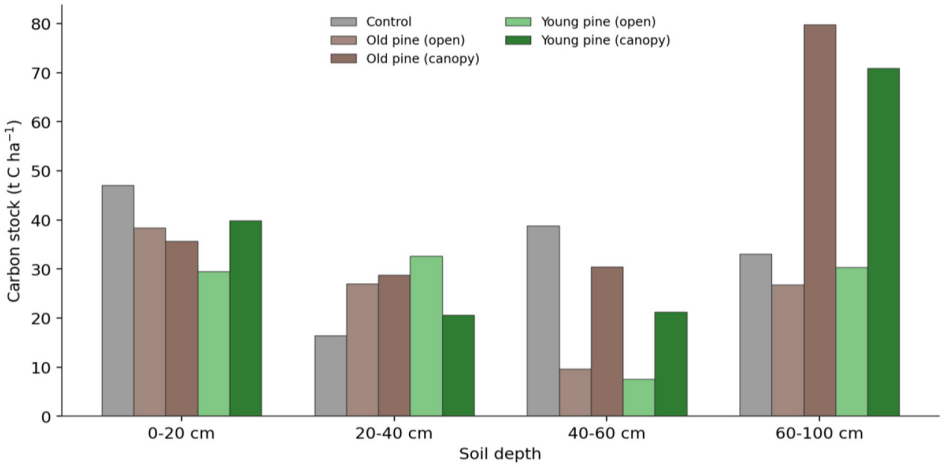

Figure 11. Soil organic carbon by depth class and treatment (HC: open; SC: under canopy)

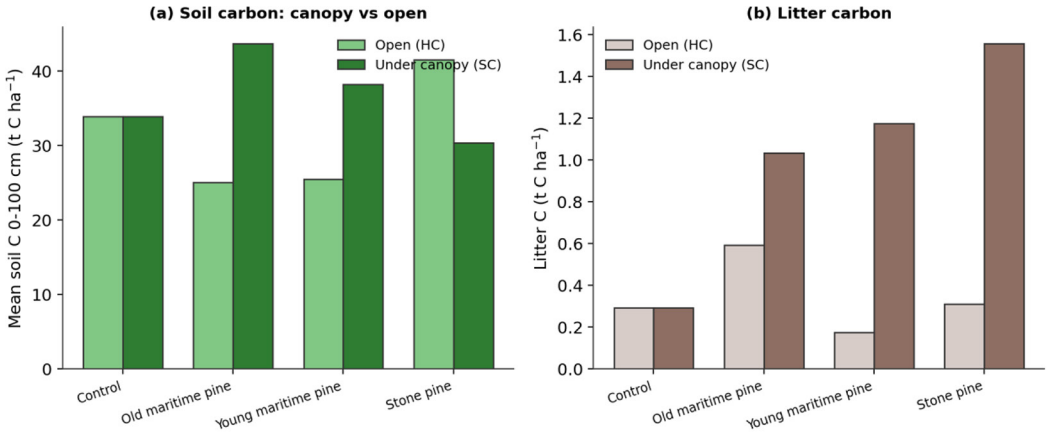

Figure 12. Under canopy (SC) vs open (HC): (a) soil carbon; (b) litter carbon, by treatment

litter carbon by treatment and depth, and (iv) build an integrated carbon budget from soil to canopy. The discussion below follows these four objectives.

Biomass allocation and carbon content (objective i)

The observed partitioning – stem-dominated (36%) then roots (29%) – is consistent with conifer architecture and the allocation patterns reported for maritime pine (Porté et al., 2002; Shaiek et al., 2011). The root-to-shoot ratio of 0.47 lies at the upper end of syntheses for temperate and boreal forests, where values of 0.20–0.30 prevail (Cairns et al., 1997; Mokany et al., 2006). This high value may reflect enhanced root investment under Mediterranean constraints (water deficit, sandy soils), where deep rooting favours water access and anchorage. The measured carbon contents (53–57%) confirm that the conventional 50% value underestimates the actual tissue carbon, as established by Thomas & Martin (2012) and Bert & Danjon (2006); neglecting this difference introduces a bias of about 6–14% in estimated stocks.

Foliage represented nearly one fifth of tree carbon (19.9%), a share that reflects the relatively young age and small size of the sampled trees (mean DBH 13.3 cm), since the proportion of foliage decreases as trees grow and stem wood accumulates (Porté et al., 2002; Balboa-Murias et al., 2006). Conversely, the very high variability of branch carbon (CV = 151%), with some trees carrying almost no live branches, is consistent with natural pruning in dense plantations. Carbon content also differed among compartments, being higher in branches and foliage (56.5–57.1%) than in the stump and roots (53.1%); this is in line with the within-tree variations reported for maritime pine (Bert & Danjon, 2006) and with the high lignin and extractive contents of conifer tissues (Thomas & Martin, 2012). Likewise, moisture contents ranged from 39.8% (roots) to 51.9% (foliage), so that a single fresh-to-dry conversion factor would bias biomass estimates; compartment-specific factors should be used when only fresh masses are measured in the field.

Performance and scope of the allometric models (objective ii)

The excellent model performance (R^2 = 0.89 for the power model, 0.94 for DBH^2) confirms that

Table 6. Summary of the carbon budget by pool and CO_2 equivalent (tree scale for biomass, hectare scale for soil and litter)

Pool	Carbon stock	CO_2 equivalent
Tree biomass (per tree)	38.2 kg C	140 kg CO_2eq
of which aboveground (71.4%)	27.3 kg C	100 kg CO_2eq
of which belowground (28.6%)	10.9 kg C	40 kg CO_2eq
Soil carbon (0–100 cm)	100–175 t C ha^{-1}	367–642 t CO_2eq ha^{-1}
Litter	0.29–1.56 t C ha^{-1}	1.1–5.7 t CO_2eq ha^{-1}

diameter remains the most efficient predictor of tree carbon (Zianis & Mencuccini, 2004; Chave et al., 2014). The superiority of the DBH^2 predictor, consistent with the dependence of biomass on cross-sectional area, aligns with European literature (Zianis et al., 2005). The exponent of 1.68 for the total model, lower than the 2.3–2.5 values often obtained for aboveground biomass alone, reflects the narrow size range and the inclusion of the root component. The decoupling of foliage from diameter ($R^2 = 0.03$) illustrates a known limitation of foliar allometry, leaf mass depending on recent crown dynamics (pruning, defoliation) rather than cumulative size (Niklas, 1994; West et al., 1997). Applying logarithmic bias correction factors (Baskerville, 1972; Sprugel, 1983) is essential to avoid systematic underestimation when back-transforming to the arithmetic scale.

Height alone was the least accurate predictor ($R^2 = 0.84$), and adding height to DBH^2 did not improve the fit ($R^2 = 0.936$ vs 0.941; AIC = 87.8 vs 86.0), indicating that, within these relatively homogeneous plantations, height carries little information independent of diameter. This is a practical advantage, since diameter is measured rapidly and with low error in routine inventories, whereas height measurements are more time-consuming and error-prone. The compartment models further show that stem ($R^2 = 0.97$) and root ($R^2 = 0.90$) carbon can be reliably estimated from DBH alone, which is valuable because belowground biomass is rarely measured. These equations should nevertheless be applied only within the calibrated range (DBH 6.4–25.5 cm) and under similar site conditions, and their validation on an independent sample remains a priority.

Soil carbon, litter and canopy effect (objective iii)

Stocks of 100–175 t C ha^{-1} over 1 m are of the same order as those reported for temperate and Mediterranean forest soils (Jandl et al., 2007; De Vos et al., 2015). The trend toward under-canopy enrichment, observed for both soil and litter, is consistent with the documented effect of tree species via litter inputs, root activity and organic-matter stabilisation (Vesterdal et al., 2013; Six et al., 2002). The absence of a statistically significant difference ($p = 0.53$) does not imply the absence of a biological effect: it stems from the high spatial heterogeneity of soil carbon and low replication, which reduce statistical power. The rise in carbon at depth (60–100 cm) warrants confirmation, possibly reflecting translocation by deep roots or heterogeneities inherited from the parent material.

The vertical distribution is also informative: although the topsoil (0–20 cm) stored 38.1 t C ha^{-1}, the 60–100 cm layer still held 48.2 t C ha^{-1} (about 24 t C ha^{-1} per 20 cm of soil). Inventories restricted to the upper 30 cm, as in the IPCC default approach (IPCC, 2006), would therefore substantially underestimate soil carbon in these sandy soils. Litter showed the clearest response to cover: litter carbon under canopy was 1.7 times (old stand) to 6.9 times (young stand) that in open positions, and all pine stands exceeded the control (0.29 t C ha^{-1}), reflecting the direct dependence of litter accumulation on needle fall beneath the crown. Edaphic variables were consistent with these patterns: the slightly lower pH under canopy (5.32–5.34) than in open positions (5.40–5.85) agrees with the acidifying effect of conifer litter (Augusto et al., 2002), and the higher gravimetric moisture under stone pine suggests that a well-developed litter layer improves water retention, which may in turn favour organic-matter accumulation.

Integrated carbon budget and implications (objective iv)

The integrated budget shows that the soil is by far the dominant pool (100–175 t C ha^{-1}, i.e. 367–642 t CO_2eq ha^{-1}), whereas litter represents less than 1% of the total stock while ensuring the continuous supply of organic matter to the soil. At the tree level, each sampled tree stored on average 38.2 kg C (140 kg CO_2eq), 28.6% of which belowground. Scaling these tree-level values to the stand with inventory data on stand density is the next step needed to compare biomass and soil pools on a common per-hectare basis. The results nevertheless have direct implications for carbon accounting: using the IPCC default carbon fraction of 50% instead of the measured 55.5% would underestimate biomass carbon by about 10%, and ignoring roots would omit more than a quarter of tree carbon. The site-specific equations, carbon fractions and root-to-shoot ratio established here can therefore replace default (Tier 1) values with country-specific (Tier 2) factors for maritime pine plantations in the national greenhouse-gas inventory (IPCC, 2006), and support the carbon valuation of reforestation programmes in the Mâamora forest.

Limitations and perspectives

Several limitations call for caution: low replication per treatment, carbon estimation by loss-on-ignition – which may overestimate organic matter relative to oxidation or elemental-analysis methods (Nelson & Sommers, 1996) – and the lack of coarse-fragment correction. Future work would benefit from increased replication, cross-validation of equations, coupling loss-on-ignition with CHN analysis, and integrating a chronosequence to capture the temporal dynamics of sequestration (Houghton, 2005; Pretzsch, 2009).

CONCLUSIONS

This study provides an integrated, soil-to-canopy carbon budget of maritime pine stands in a Mediterranean context. Tree carbon, averaging 38.2 kg C per tree (140 kg CO_2eq), is concentrated in the stem and roots, shows a tissue content above the default value (53–57%), and is faithfully predicted from diameter, the DBH^2 model being the most accurate ($R^2 = 0.94$). The soil is by far the main reservoir (100–175 t C ha^{-1}), enriched beneath the pine canopy, while litter reflects active transfer to the soil. Beyond their protective and productive functions, maritime pine plantations emerge as significant carbon sinks. The allometric references, carbon contents and pedological data established here constitute local references for estimating the carbon stocks of these stands.

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