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Allometric Equations for Leaf Carbon Sequestration and Leaf Area Index in Anagyris foetida L.: Implications for Conservation in Zagros Forests

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Abstract

Zagros forests play a significant role in carbon sequestration; however, the contribution of rare species such as *Anagyris foetida* L. (Ghareh Ghaj)—with unique traits such as thick leaves and summer dormancy—has been less studied. This research developed, for the first time, species-specific allometric models for this endangered tree to provide a non-destructive estimation of leaf carbon storage and LAI[1]. The study was conducted in the pure habitat of the species within the Sardasir Chaleh basin (Gilan-e-Gharb). Using systematic line sampling, 30 healthy trees were selected, and biometric parameters (height, crown diameter, and crown area) were measured. Leaf samples were collected from three crown sections and analyzed in the laboratory to determine dry biomass (gravimetric method), organic carbon percentage (combustion in a furnace), and leaf area (leaf area meter). LAI and SLA[2] were calculated and scaled up to the forest stand level using the "Mean Tree" method and a density of 253 trees per hectare. Allometric relationships were analyzed using linear, logarithmic, and power regression models. Results showed that mean LCS[3], CO_2 uptake, and leaf dry biomass per hectare were 468.13 kg of carbon, 1718.03 kg, and 975.27 kg, respectively. The average LAI at the individual-tree and per-hectare levels was 1.6 and 0.302, respectively. Statistical analyses revealed a strong and significant correlation between crown area and both leaf biomass and LCS, with the linear model based on crown area providing the best fit for predicting LCS ($R^2 = 0.719$). In contrast, LAI was only significantly correlated with leaf dry biomass. Overall, the results indicate that, despite its prolonged dormancy period, this species contributes considerably to leaf carbon storage in Zagros forests due to its relatively high density and distinct crown architecture. The simple, crown area-based models presented offer a practical and cost-effective tool for carbon monitoring, ecosystem service valuation, and the development of conservation strategies for this endangered species and similar Mediterranean ecosystems, representing a significant step toward sustainable forest management.

Keywords: Allometric models, Climate change adaptation, Carbon sequestration, Endangered species, Mediterranean ecosystems.

1. Introduction

Forests serve as Earth's primary terrestrial carbon sinks, annually sequestering approximately 2 billion tons of CO_2 (FAO, 2010). Scientific evidence demonstrates that they store 86% of aboveground and 73% of belowground carbon stocks (Vashum & Jayakumar, 2012), with distribution patterns showing 49% in tree trunks, 27% in litter and woody debris, and 24% in soil compartments (Williams & Gresham, 2006). Notably, while stem biomass dominates carbon stock assessments, leaves—though constituting a smaller biomass fraction—contribute disproportionately to photosynthetic capacity and rapid carbon turnover, making them

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[1] Leaf Area Index
[2] Specific Leaf Area
[3] Leaf Carbon Sequestration

critical for understanding ecosystem productivity. The IPCC Sixth Assessment Report (2023) emphasizes that forest conservation strategies could contribute up to 30% of global greenhouse gas emission reduction targets by 2030.

Within this context, the UN Framework Convention on Climate Change (UNFCCC, 2008) has established monitoring frameworks such as REDD+ for forest carbon stocks. However, current biomass estimation methodologies predominantly focus on stem wood, largely neglecting non-stem components (leaves, branches, roots), which may constitute up to 40% of total tree biomass (Victor et al., 2022). This research gap has been extensively documented (e.g., Hakkila, 1989; Lehtonen, 2005), emphasizing the critical need for improved quantification methods.

LAI represents a fundamental eco-physiological parameter in this regard, with reported values ranging from 0.4 in *Quercus petrea* to 14 in *Pseudotsuga menziesii* (Jonckheere et al., 2004). As a crucial parameter linking canopy architecture to carbon assimilation potential, LAI demonstrates unique patterns in drought-adapted species like *Anagyris foetida* (Valipour et al., 2015) due to: (1) thicker, longer-lived leaves exhibiting lower photosynthetic rates per unit area; (2) distinct seasonal leaf-shedding patterns that limit annual carbon uptake; and (3) non-stomatal limitations to CO_2 fixation under water stress (Chaves et al., 2009).

1.1. Global Advances in Allometric Modeling for Carbon Estimation

Extensive research has been conducted globally to develop and refine these allometric models. The accurate quantification of tree biomass and carbon stocks is fundamental to silviculture, carbon cycle modeling, and ecosystem service valuation. At the global scale, allometric modeling based on diameter at breast height (DBH) and total tree height (H) represents the standard methodological paradigm. Seminal work by Zianis et al. (2005) compiled over 600 species-specific functions for European forests, empirically validating the superiority of ecoregion-tailored equations. Chave et al. (2014), who developed a pan-tropical biomass estimation system incorporating wood density, height-diameter relationships, and eco-climatic variables, significantly advanced this foundation by achieving high accuracy across more than 400 tropical tree species. Subsequent research has further emphasized the need for specific allometric approaches when dealing with unique growth forms or non-stem components. For instance, Djomo & Chimi (2017) successfully integrated terrestrial LiDAR with traditional dendrometry to model multi-compartment biomass in complex central African rainforests. Similarly, studies in dryland ecosystems, such as those on desert shrubs, have highlighted the importance of crown and stem architecture for accurate biomass estimation (e.g., Hierro et al., 2000). This body of literature unequivocally establishes that incorporating auxiliary eco-physiological variables and growth-form-specific considerations yields superior predictive performance.

1.2. Allometric Studies in Iranian Forests, with a Focus on the Zagros Region

Parallel to these global advances, significant efforts have been made within Iran, particularly in the Zagros region. Research has progressed from foundational equations for dominant species like Persian oak (*Quercus brantii*) and wild pistachio (*Pistacia atlantica*) based on crown metrics (Adl, 2007) to more refined models incorporating additional predictors (Panahi et al., 2011; Pilehvar et al., 2015). Parallel studies have expanded this knowledge to other ecologically important species, establishing allometric relationships for leaf biomass and carbon in hawthorn (*Crataegus* spp.) (Akbari, 2021; Mahdavi et al., 2023) and Judas tree (*Cercis siliquastrum*) (Mahdavi & Mirzaei, 2020). In the Hyrcanian forests, similar approaches have been applied to species such as oriental beech (*Fagus orientalis*) (Kahyani et al., 2016). A consistent and critical finding across these Iranian studies is the demonstrated effectiveness of crown diameter and crown area as robust predictors of leaf traits in various species, especially for those with shrub-like or multi-stemmed growth forms where DBH is less representative.

1.3. Identified Research Gap and Imperative for the Present Study

Despite the well-developed context of allometric modeling both globally and within Iran, a critical knowledge gap persists concerning rare and endangered species with unique ecophysiological adaptations. *Anagyris foetida* L. (Ghareh Ghaj), a rare and endangered shrub endemic to the Zagros forests (IUCN Red List, 2023), exemplifies this gap. While its ecological distribution and habitat characteristics have been documented (e.g., Hosseinzadeh et al., 2015; Sabzi et al., 2018; Gholami, 2017), its functional role in carbon dynamics remains entirely unquantified. This species possesses distinct xerophytic traits—such as thick sclerophyllous leaves, a deep taproot system, and a pronounced summer deciduous period (Valipour et al., 2015)—that likely result in unique allometric relationships differing from those of co-occurring tree species. The current lack of species-specific models for *A. foetida* hinders accurate assessment of its contribution to the carbon budget of the Zagros ecosystem and limits the development of targeted conservation strategies.

Therefore, this study aims to address this explicit gap by developing the first comprehensive allometric framework for *A. foetida*. Our specific objectives are to: (1) quantify leaf biomass production, LCS capacity, and LAI dynamics; (2) analyze the allometric relationships between these leaf traits and easily measurable, non-destructive biometric variables (crown diameter, crown area, and height); and (3) provide reliable species-specific equations that can serve as essential tools for carbon monitoring, ecosystem service valuation, and informed conservation planning for this endangered species within vulnerable Mediterranean woodland ecosystems.

2. Materials and Methods

2.1. Study Area

The study area is located in a sub-basin of the Gilan-e-Gharb River, covering 21,403 hectares in the eastern part of Gilan-e-Gharb County, Kermanshah Province, Iran. It lies between latitudes 34° 8’ 42" to 34° 10’ 7" north and longitudes 45° 9’ 8" to 46° 2’ 17" east (Figure 1). The *A. foetida* L. stand is distributed in the Sardasir Chaleh district, extending from the village of Kaseh Karan to the Taq Tuq area (Gholami et al., 2017).

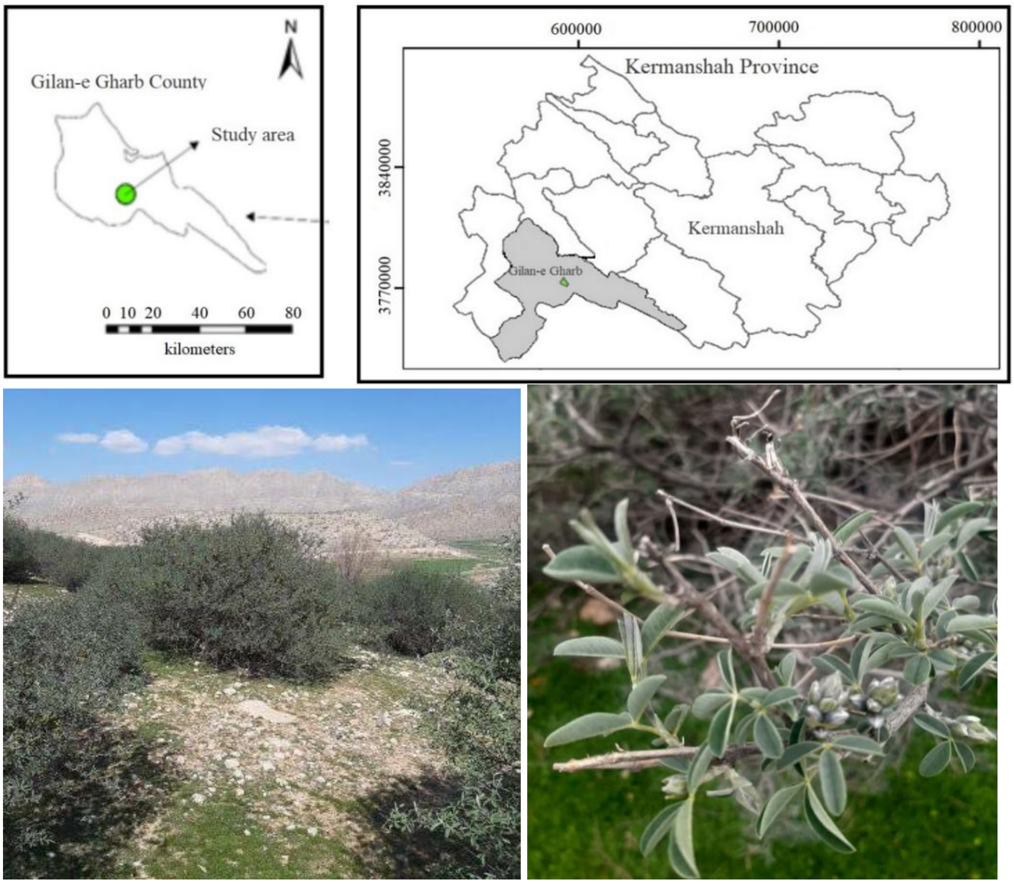

Figure 1. The location of the study area in Gilan-e Gharb County, Kermanshah Province, and a view of the pure stand and leaves of *A. foetida* L. in the region

The area's Mediterranean-like climate supports rare plant ecosystems and unique animal habitats. *A. foetida* L. grows in this ecotone between tropical and cold ecosystems, exhibiting a dry, deciduous state during summer and persisting in this state for up to four months annually.

The species occupies approximately 520 hectares, with elevations ranging from 970 meters in *riparian* zones to 1,420 meters at the Sarkash peaks. The topography of the habitat is characterized by an average slope of 14%, with some areas exceeding 50%. The slopes are predominantly north-facing. *A. foetida* L. forms pure stands on low slopes and in valleys. However, at elevations above 1,100 meters, it is found as an understory component of oak forests, where its size typically decreases with increasing elevation (Hosseinzadeh et al., 2015). In these forests, it is associated with species such as *Quercus persica*, *Amygdalus lycioides*, *Prunus serotina*, and *Pistacia atlantica*.

2.2. Sampling Method

All field sampling and leaf collection were conducted in late winter (March). This timing was critically chosen because *A. foetida* L. is a summer-deciduous species. Sampling at this time captured the full, mature leaf biomass on the trees immediately before the onset of leaf shedding due to summer dormancy, thereby allowing for an accurate measurement of the maximum annual leaf carbon storage potential. In collaboration with the Gilan-e-Gharb Natural Resources Department, we conducted a systematic survey of *A. foetida* populations within a homogeneous area of the Chaleh watershed. The study employed three parallel north-south transects spaced 500 m apart. Ten representative trees were selected per transect (total n = 30) based on the following strict criteria: (1) healthy crown morphology without visible pest damage or dieback, and (2) a minimum of 50 m inter-tree spacing to ensure spatial independence. For each selected tree, we measured key biometric parameters including tree height (using a laser hypsometer), crown diameter (two perpendicular measurements), and derived crown area (elliptical approximation). Leaf sampling followed a stratified protocol with proportional collection from three vertical crown layers: upper sun-exposed (30%), middle partially shaded (50%), and lower shaded (20%) positions. We collected approximately 1/8 to 1/16 of total crown leaf mass through systematic visual division of the crown into volumetric sectors. All samples were immediately placed in labeled, airtight plastic bags and transported to the laboratory under controlled conditions for subsequent analysis.

2.3. Measurement of Specific Leaf Area (SLA) and LAI

We quantified specific leaf area (SLA) and leaf area index (LAI) through an integrated gravimetric protocol involving 300 leaves collected from 30 trees (10 leaves/tree) using stratified random sampling across all crown positions. Fresh leaves were weighed (Sartorius BL 210S, ±0.0001 g), scanned for area measurement (CI-203 Laser Leaf Area Meter, 1 mm² resolution), then oven-dried (65°C, 48 hr) and reweighed after desiccation.

SLA was calculated for subsamples (SLAs $= \frac{AS}{ms}$) where As= Leaf area of the sub-sample, ms= dry weight of the sub-sample) and scaled to tree level (Ai = SLAs×mi where Ai= total leaf area, mi= total dry weight of the leaves), while LAI was derived from stand-level aggregation LAI = $\frac{(N \times \sum Ai)}{n \times 10000}$ where N = 253 trees/ha, Ai = individual tree leaf area (m²), and n = 30 samples.

2.4. Laboratory analysis

Leaf fresh weight was measured, and samples were dried at 65°C for 48 hours to determine dry weight. Total leaf dry weight per tree was calculated by scaling up the sampled proportion. (Mahdavi & Mirzaei, 2020; Yaghoubi, 2023; Mahdavi et al., 2024).

The organic carbon content (percentage) in *A. foetida* L. leaves was determined using the dry combustion method. Dried leaf samples (four one-gram samples per tree) were combusted at 450°C for 2 hours, and the resulting ash was weighed. Weight loss during combustion represented organic matter, with 50% typically considered carbon (species-specific variations may apply). In this study, the carbon sequestration coefficient in the leaves was calculated using the following formulas (Allen et al., 1986; Adl, 2007; Panahi et al., 2011; Mahdavi et al., 2023).

$$\text{Ash\%} = (W_3\text{-}W_1/ (W_2\text{-}W_1) \times 100 \quad (1)$$

$$\text{C\%} = (100\text{-Ash \%}) \times 0.58 \quad (2)$$

Ash%**:** The percentage of ash obtained after complete combustion of the leaves,

W_1: The weight of the crucible (porcelain container),

W_2: The dry weight of the sample,

W_3**:** The total weight of the ash and the porcelain container used,

C%: The calculated carbon coefficient.

The mean carbon concentration (C%) across all samples was calculated to be 48% of the leaf dry biomass. The carbon sequestration results from sampled leaves were scaled up to estimate values for the entire tree. To generalize these findings to the forest, the Mean Tree Method was applied. This involved calculating the average dimensions and characteristics of a "mean tree" based on sampled data. By multiplying the mean tree's values by the total number of trees per unit area, forest-level estimates for leaf carbon sequestration and other parameters were obtained (Adl, 2007; Akbari, 2021; Yaghoubi, 2023).

The amount of CO_2 absorbed by *A. foetida* L. trees was calculated by applying a coefficient of 3.67 to the carbon stored in their leaves. The Mean Tree Method was used to generalize results from sampled trees to the entire forest. Tree density in the study area was estimated based on prior studies: Hosseinzadeh et al. (2015) reported 223–284 trees per hectare, while Sabzi et al. (2018) estimated 539 trees per hectare. For this study, an average density of 253 trees per hectare (from Hosseinzadeh et al., 2015) was used to estimate LAI, leaf biomass, and LCS. It is important to note that the per-hectare estimates are linearly sensitive to the assumed tree density. Based on the reported range of 223–284 trees ha^{-1} (Hosseinzadeh et al., 2015), our estimates in Table 3 would scale proportionally. The use of significantly different densities, such as 539 trees ha^{-1} (Sabzi et al., 2018), would approximately double the per-hectare values.

2.5. Data Analysis

The Kolmogorov-Smirnov test was used to assess data normality. Pearson correlations were used to test relationships between leaf biomass, LCS, and LAI (dependent variables) and crown area, crown diameter, and tree height (independent variables). Allometric relationships between biomass, LCS, LAI, and tree variables were analyzed using linear, logarithmic, and power regression models. Three models were fitted:

$$Y_i = b_0 + b_1 X_i \quad (1)$$

$$Y_i = b_0 + b_1 Ln(X_i) \quad (2)$$

$$Y_i = b_0 \times X_i^{b_1} \quad (3)$$

Where:

Yi**:** Dependent variables (leaf biomass, LAI, LCS),

Xi**:** Independent variable (average crown diameter),

b_0: Constant term,

b_1: Model coefficient.

The power model was linearized by taking the logarithm of both sides for easier fitting. The best model was selected based on the coefficient of determination (R^2). The null hypothesis (no effect of the independent variable) was rejected if the p-value was $<$ 0.05. Statistical analyses were performed using SPSS 22, and graphs were created in Excel 2016.

3. Results

The Kolmogorov-Smirnov test confirmed that the data followed a normal distribution (Table 1). The p-values for all indices exceeded 0.05, confirming that the data for each index followed a normal distribution.

Descriptive statistics for key variables, including tree height, average crown diameter, crown area, specific leaf area, leaf biomass, LCS, and CO_2 absorption, are presented in Table 2. These values represent the average tree dimensions. The carbon coefficient in *A. foetida* L. leaves was determined to be 48% of the dry leaf biomass, calculated using Equations (1) and (2).

Using the average tree dimensions and tree density (253 trees per hectare), leaf dry biomass, LCS, and CO_2 absorption were estimated per hectare. These values, along with the LAI (0.302), are summarized in Table 3.

Table 1. Results of the normality test for measured variables

variables	Kolmogorov Smirnov	P-value
Height (m)	0.909	0.381
Mean diameter of crown (m)	0.539	0.934
Crown area (m^2)	0.630	0.822
Mean weight of single leaf (gr)	0.761	0.608
Mean area of a single leaf (cm^2)	0.750	0.585
Total leaf biomass of tree (kg)	0.870	0.435
Average specific area of tree leaves(cm^2/gr)	0.860	0.451
Atmosphere CO_2 absorption (kg)	0.751	0.460
LCS (kg)	0.854	0.459
LAI	0.990	0.281

Table 2. Mean values of the investigated variables for the average tree in the study area

Variable	Minimum	Maximum	Average	St. d	Coefficient of variation (%)
Height (m)	1.5	4.2	2.85	0.67	23.3
Mean crown diameter (m)	2	4.5	3.65	0.51	13.82
Crown area (m^2)	6.15	15.9	10.67	2.93	27.46
Mean weight of a single leaf (gr)	0.05	0.097	0.065	0.01	19.62
Mean area of a single leaf (cm^2)	2.37	5.5	2.94	0.73	24.77
Mean total number of leaves per tree	36000	162000	58464	10409	28.90
Mean dry weight of all leaves per tree	2195	12116	3854	90220	38.34
Mean total leaf area of a tree (cm^2)	88152	642254	179130	48809.69	45.16
Average SLA (cm^2/gr)	33.77	60.82	45.68	6.88	15.05
LAI	1.12	4.04	1.6	0.26	26.42
LCS (kg)	1.05	5.82	1.85	0.43	38.34
Atmosphere CO_2 absorption (kg)	3.84	21.34	6.79	1.59	38.34

Table 3. Leaf Biomass, Carbon Sequestration, and CO_2 Absorption per Hectare

Parameter	Value ($kg \cdot ha^{-1}$)
CO_2 absorption from atmosphere	1718.03
LCS	468.13
Leaf biomass	975.27
LAI (LAI)	0.302
Average Number of trees per hectare	253

3.1. Correlation Analysis Results

The correlations between dependent variables (leaf biomass, LCS, LAI) and independent variables (tree height, mean crown diameter, and crown area) are presented in Table 4. Key findings of this analysis include the following: biomass and LCS showed significant correlations with crown diameter and crown area ($p < 0.01$). LAI correlated significantly only with tree height ($p < 0.01$), but not with crown diameter or crown area ($p > 0.05$).

3.2. Regression Analysis of Leaf Traits in Anagyris foetida

Our comprehensive regression analysis revealed distinct patterns in the relationships between crown architecture, leaf biomass, and carbon sequestration metrics. Three key findings emerged from the modeling approaches:

First, examination of LAI through linear, logarithmic, and power regression models showed that crown diameter and crown area were not significant predictors (Table 5).

In contrast, leaf dry biomass demonstrated a strong, consistent relationship with LAI across all model forms. The linear model provided the best fit (see Table 5), explaining approximately 34-41% of LAI variation through biomass alone (Figure 2).

Table 4. Correlation coefficients and p-values

Dependent Variable	Tree height	Mean crown diameter	Crown area
Leaf biomass	0.520 (p=0.019*)	0.835 (p=0.000**)	0.849 (p=0.000**)
LCS	0.518 (p=0.018*)	0.834 (p=0.000**)	0.848 (p=0.000**)
LAI	0.564 (p=0.010**)	0.247 (p=0.294)	0.265 (p=0.259)

*Significant at $p < 0.05$; **Significant at $p < 0.01$.

Table 5. Summary and comparison of allometric models for predicting LAI per tree in *Anagyris foetida* L. (n = 30)

Independent Variable	**Model Form**	**Equation**	**b_0 (Intercept)**	**b_1 (Slope/Coeff.)**	**R^2**	**Adj. R^2**	**p-value**
Leaf Dry Biomass (DB)	Linear	LAI = 0.557 + 0.186 × DB	0.557	0.186	0.409	0.376	0.002
Leaf Dry Biomass (DB)	Logarithmic	LAI = 0.662 + 0.420 × ln(DB)	0.662	0.420	0.340	0.303	0.007
Leaf Dry Biomass (DB)	Power*	LAI = 10^(-0.327) × DB^(0.373)	-0.327	0.373	0.356	0.320	0.005
Crown Diameter (CD)	Linear	LAI = 0.526 + 0.128 × CD	0.526	0.128	0.061	0.027	0.294
Crown Area (CA)	Linear	LAI = 0.742 + 0.024 × CA	0.742	0.024	0.070	0.036	0.259

Notes: DB: Leaf Dry Biomass per tree (kg); CA: Crown Area (m^2); CD: Mean Crown Diameter (m). R^2: Coefficient of determination; Adj. R^2: Adjusted R^2. The only significant predictor for LAI was Leaf Dry Biomass. Models based on crown metrics were not significant ($p > 0.05$). (*) Parameters for the power model are reported after linearization. The actual power equation is of the form LAI = a × (Variable)^b.

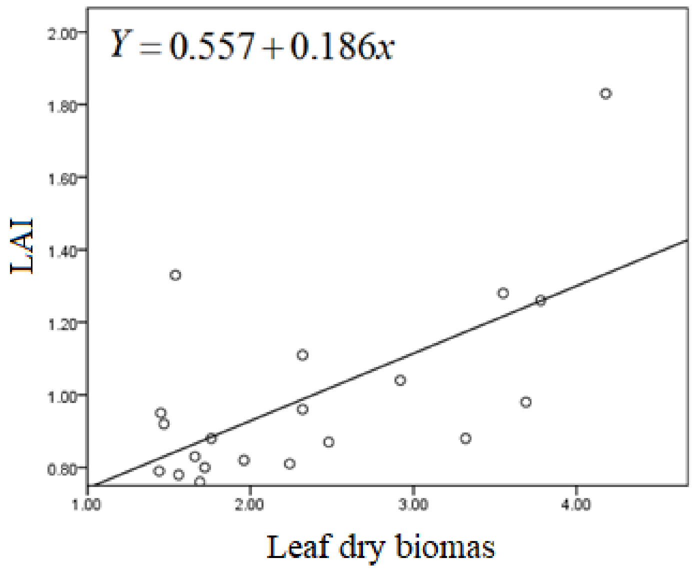

Figure 2. Allometric-linear relationship between dry biomass and LAI

Second, analysis of LCS yielded robust predictions from crown metrics. A comprehensive comparison of linear, logarithmic, and power models for both crown diameter and crown area is presented in Table 6. The linear model using crown area (LCS = -0.207 + 0.125 × CA) provided the strongest prediction ($R^2 = 0.719$), slightly outperforming the model based on crown diameter. These relationships are visually summarized in Figures 3, and 4.

Third, bootstrap validation (1000 iterations) confirmed model stability, with narrow 95% confidence intervals for R^2 values (e.g., 0.69-0.73 for crown area vs. LCS). This robustness persists despite our moderate sample size (n=30), suggesting the allometric relationships are consistent within the studied population.

Table 6. Summary and comparison of allometric models for predicting LCS in *Anagyris foetida* L. (n = 30).

Independent Variable	**Model Form**	**Equation**	**b_0 (Intercept)**	**b_1 (Slope/Coeff.)**	**R^2**	**Adj. R^2**	**p-value**
Crown Area (CA)	Linear	LCS = -0.207 + 0.125 × CA	-0.207	0.125	0.719	0.704	< 0.001
Crown Area (CA)	Logarithmic	LCS = -1.836 + 1.272 × ln(CA)	-1.836	1.272	0.666	0.647	< 0.001
Crown Area (CA)	Power*	LCS = 10^(-2.478) × CA^(1.087)	-2.478	1.087	0.692	0.675	< 0.001
Crown Diameter (CD)	Linear	LCS = -1.485 + 0.715 × CD	-1.485	0.715	0.696	0.679	< 0.001
Crown Diameter (CD)	Logarithmic	LCS = -2.144 + 2.544 × ln(CD)	-2.144	2.544	0.666	0.647	< 0.001
Crown Diameter (CD)	Power*	LCS = 10^(-2.741) × CD^(2.174)	-2.741	2.174	0.692	0.674	< 0.001

CA: Crown Area (m^2); CD: Mean Crown Diameter (m). R^2: Coefficient of determination; Adj. R^2: Adjusted R^2. The best-performing model for each independent variable is indicated in bold. (*) Parameters for the power model are reported after linearization (log-transformation of both sides). The actual power equation is of the form LCS = a × (Variable)^b, where a = 10^(b_0).

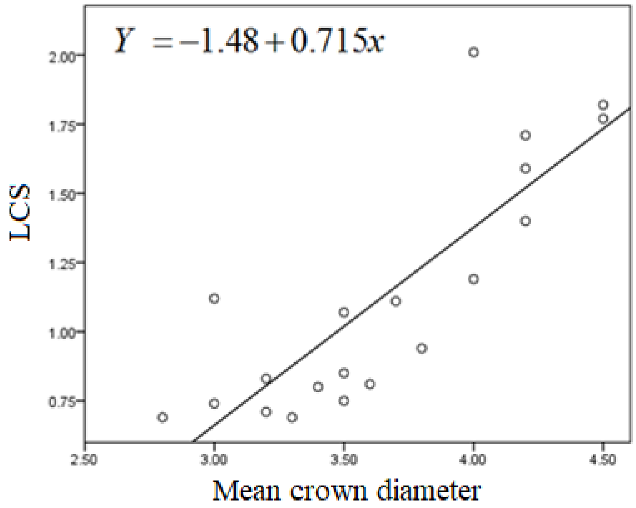

Figure 3. Allometric-Linear relationship between mean crown diameter and carbon sequestration

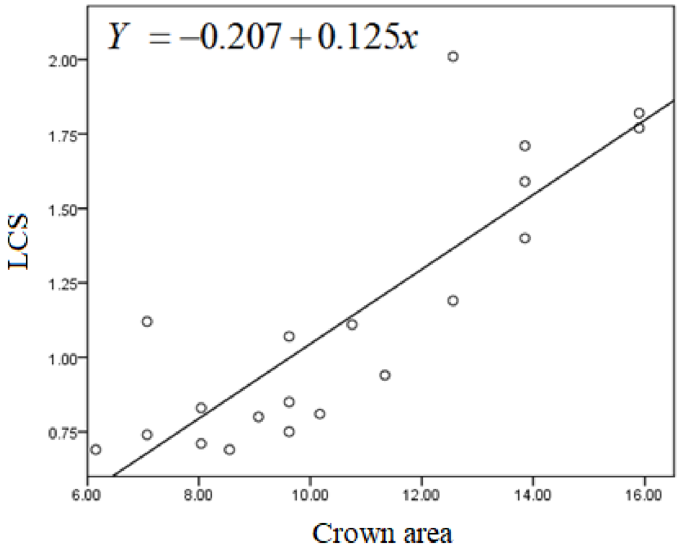

Figure 4. Allometric-Linear relationship between crown area and Leaf LCS

4. Discussion

Forest ecosystems function as pivotal carbon reservoirs through photosynthesis and biomass production, critically mitigating atmospheric CO_2 levels. Comprehensive assessment of carbon sequestration across tree organs—particularly understudied components such as leaves—remains essential for both ecological research and evidence-based forest management (Fang et al., 2007; Akbari, 2021).

While Iranian studies have quantified biomass and carbon storage in multiple species (e.g., hawthorn, oak, and wild pistachio; Naghash Zargaran, 2001; Adl, 2007; Panahi et al., 2011; Mahdavi et al., 2024), Anagyris foetida has been notably overlooked despite its endemic status in Gilan-e-Gharb County. Prior research on this species has focused exclusively on ecological distribution and habitat traits (Sabzi et al., 2018; Gholami, 2017; Hosseinzadeh et al., 2015), leaving its carbon sequestration potential and LAI dynamics unexamined. Our work addresses this gap by providing the first empirical data on these key functional traits, enabling informed conservation planning for Zagros forest ecosystems.

Leaf dry biomass and LCS in A. foetida L.

Our study reveals substantial leaf-level carbon storage in *Anagyris foetida* stands, with 975.27 kg/ha leaf biomass and 468.13 kg C/ha LCS. While these values represent foliar-specific measurements (excluding stem, branch, and root biomass), they establish critical baseline data for this endangered species (IUCN Red List, 2023) at its characteristic density of 253 trees/ha. These findings are particularly valuable for (1) conservation prioritization, (2) future whole-plant carbon studies, and (3) monitoring climate impacts on Mediterranean shrub ecosystems (IPCC, 2023).

Comparative analysis shows distinct variation from other Zagros species—from high leaf biomass in oak (1317.3 kg/ha; Adl, 2007) to low values in wild pistachio (57.2 kg/ha) and Judas tree (53.55 kg/ha; Mahdavi & Mirzaei, 2020). Globally, this spectrum extends further (*Q. douglassi*: 3100 kg/ha; poplar: 1.98 t/ha; Fang et al., 2007; Karlik & McKay, 2007). These differences reflect species-specific traits, stand densities, and developmental stages (Adl, 2007; Pourhashemi et al., 2012).

Our 0.48 carbon conversion factor aligns with regional reports (wild pistachio: 0.467; Judas tree: 0.48; maple: 0.47), although the literature shows wide variability—from 41.9% to 60.7% depending on species and organ (Thomas et al., 2007). Notably, woody tissues typically exceed leaves in carbon factors, and conifers surpass angiosperms (Rosta et al., 2011; Yaghoubi, 2023).

Our quantitative analysis demonstrates that Anagyris foetida exhibits intermediate carbon sequestration capacity at the individual tree level (1.85 ± 0.43 kg C/tree), measuring 40% lower than Cercis siliquastrum (3.12 kg/tree; Mahdavi & Mirzaei, 2020) but 50% higher than Crataegus spp. (1.23 kg/tree; Akbari, 2021), while its exceptional stand density (253 trees/ha) results in substantially greater hectare-scale performance. Leaf carbon storage (468.13 kg C/ha) exceeds Pistacia atlantica (26–77.1 kg/ha; Rosta et al., 2011; Olfati et al., 2013) by 6–18× and Acer monspessulanum (97.14 kg/ha; Mahdavi et al., 2024) by 4.8×, with CO_2 absorption (1718.03 kg/ha) surpassing comparative species by 4.8–20× (Acer: 356.5 kg/ha; Pistacia: 96.3 kg/ha; Cercis: 86.02 kg/ha; Panahi et al., 2011; Mahdavi & Mirzaei, 2020; Yaghoubi, 2023), reflecting both its ecological adaptations (specific leaf area = 45.68 cm^2/g vs. 60–110 cm^2/g in mesic species) and unique stand structure characteristics.

LAI in A. foetida L.

LAI characteristics of *Anagyris foetida* (1.6 per tree; 0.302/ha; this study) must be interpreted through its unique drought-deciduous ecology (IUCN Red List, 2023). While its LAI exceeds some xerophytes such as wild pistachio (1.2; Adl, 2007) and maple (1.52; Yaghoubi, 2022), it remains substantially lower than that of mesic species (hawthorn: 9.08, Mahdavi et al., 2023; hackberry: 3.7, Panahi et al., 2011), reflecting an evolutionary compromise between (1) complete summer leaf shedding (4–5 months; Valipour et al., 2015) to prevent water loss, and (2) efficient light capture during the growth season through dense stands (253 trees/ha vs. maple's 41.3; Yaghoubi, 2023) and sclerophyllous leaves (SLA = 45.68 cm^2/g vs.

hackberry's 103.5; Panahi et al., 2011). This adaptive strategy yields LAI values lower than global observations (*Morus alba*: 0.37–4.25; *Prunus serotina*: 0.49–7.57; Peper & McPherson, 1998; French deciduous forests: 1.7–7.5; Dufrêne & Bréda, 1995) but achieves remarkable carbon sequestration (468.13 kg C/ha) through optimized leaf longevity and arrangement. Our gravimetric approach (Milla et al., 2008), combined with stratified canopy sampling (Eriksson et al., 2005), captured these dynamics, revealing how *A. foetida*'s LAI reflects both its ecological constraints and carbon capture efficiency in semi-arid zones.

Practical implication of the Biomass-LAI Model

While the allometric relationship between leaf dry biomass and LAI is indeed grounded in their definitions, the developed model (LAI = 0.557 + 0.186 × DB) serves a critical practical purpose beyond merely confirming that relationship. For A. foetida, where direct LAI measurement is labor-intensive, this equation provides a valuable secondary estimation tool. Once leaf biomass is predicted non-destructively using our primary crown-based models (e.g., from crown area), this secondary model allows indirect estimation of LAI, completing a useful predictive framework for field assessments. Its inclusion highlights that crown architecture alone is not a sufficient predictor of LAI in this species, necessitating biomass as an intermediary variable.

Allometric relationships evaluation

The shrub-like growth form of Anagyris foetida (Figure 1), which is characterized by multi-stemmed clusters without distinct trunks, necessitated the use of alternative allometric approaches instead of traditional DBH measurements. Our analysis revealed crown architecture metrics (height, diameter, and area) as superior predictors for leaf traits, with three key findings emerging:

Model Performance

The linear model demonstrated optimal performance for estimating both leaf dry biomass (R^2 = 0.721) and LCS (R^2 = 0.719) when using crown area as the predictor, outperforming power and logarithmic forms. For LAI, dry biomass emerged as the sole significant predictor (R^2 = 0.409), with crown metrics showing no meaningful relationship (Tables 4–12). These results align with regional studies of shrub-type species in which crown diameter predicted leaf biomass in Pistacia atlantica (Panahi et al., 2011), Cercis siliquastrum (Mahdavi & Mirzaei, 2020), and Crataegus spp. (Mahdavi et al., 2023), contrasting with DBH-driven models for single-trunk trees such as Quercus (Adl, 2007).

Comparative Context

The superiority of linear models in our study diverges from findings in other ecosystems—linear-logarithmic hybrids for oaks (Adl, 2007), power models for hawthorn (Mahdavi et al., 2023), and multi-model solutions (power and linear models) for Judas tree (Mahdavi & Mirzaei, 2020). This variability mirrors global patterns in which optimal predictors range from collar diameter (Acer monspessulanum; Yaghoubi, 2023) and DBH (oaks; Adl, 2007) to stem diameter (Cavanillesia erinaceae; Hierro et al., 2000), depending on growth form, supporting the need for growth-form-specific allometry.

Practical implications

The strong crown area-LCS relationship (R^2=0.719) enables rapid carbon stock assessments in A. foetida stands, although three limitations warrant consideration:

- Site specificity (calibration needed for rainfall >500mm/year or elevations beyond 900-1,400m)
- Exclusion of non-foliar carbon pools (roots, stems)
- Seasonal LAI variations unaccounted for in current models

These findings underscore that crown metrics effectively capture carbon allocation patterns in shrub-form Mediterranean species, providing a viable alternative when DBH measurement is impractical (Kumar Sarker et al., 2013). Validation in adjacent ecoregions with comparable A. foetida stands is recommended to test model transferability.

Methodological considerations and limitations

This study employed a standard set of allometric models (linear, logarithmic, and power) to establish relationships between crown metrics and leaf traits. While these models provide robust and practical tools for estimation, we acknowledge that more complex multivariate or non-linear approaches could be explored with larger, purpose-built datasets. The primary aim here was to develop readily applicable equations using the most accessible field measurements (crown diameter/area). Future research with expanded sampling could investigate whether incorporating additional predictors (e.g., soil parameters, precise age) or using advanced non-linear fitting techniques in software such as R yields significant improvements in predictive accuracy for this species.

5. Conclusions

This study establishes the first species-specific allometric models for the endangered summer-deciduous shrub, Anagyris foetida L., in the Zagros forests. The key finding is that crown area serves as the strongest and most practical non-destructive predictor for estimating leaf biomass and leaf carbon sequestration (LCS) at the individual tree level (LCS = -0.207 + 0.125 × Crown Area, R^2 = 0.719). Despite its prolonged summer dormancy, our findings reveal that A. foetida stands possess a significant carbon storage capacity (468.13 kg C ha^{-1} in leaves alone), exceeding that of several common associated species in the region when its high stand density is considered.

The developed linear models provide forest managers and conservationists with a reliable tool for rapid carbon stock assessment and monitoring, which is crucial for valuing ecosystem services and formulating conservation strategies for this rare species under climate change scenarios. Future research should focus on: (1) validating these models across the species' full geographical and elevational range, (2) incorporating root and stem carbon pools for a whole-plant carbon budget, and (3) investigating the species' long-term response to climatic variations.

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معادلات آلومتریک برای ترسیب کربن برگ و شاخص سطح برگ در گونهٔ *Anagyris foetida* L. کاربردهایی برای حفاظت از جنگل‌های زاگرس

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چکیده

جنگل‌های زاگرس نقش مهمی در ترسیب کربن دارند، اما دربارهٔ سهم گونه‌های نادری مانند *Anagyris foetida* L. (قره‌قاج) - با ویژگی‌های منحصربه‌فردی چون برگ‌های ضخیم و خواب تابستانه - کمتر تحقیق شده است. این پژوهش برای نخستین بار مدل‌های آلومتریک برای برآورد ویژهٔ این گونهٔ درختی در معرض انقراض را توسعه داده است تا برآورد غیرمخربی از ذخیرهٔ کربن برگ‌ها و شاخص سطح برگ (LAI) آن ارائه دهد. پژوهش در رویشگاه خالص گونه در حوضهٔ سردسیر چاله (گیلانغرب) انجام گرفت. با نمونه‌برداری خطی-سیستماتیک از ۳۰ درخت سالم، پارامترهای بیومتریک (ارتفاع، قطر و مساحت تاج) اندازه‌گیری شد. نمونه‌های برگ از سه بخش تاج جمع‌آوری و در آزمایشگاه، زیست‌تودهٔ خشک (گراویمتری)، درصد کربن آلی (احتراق در کوره) و مساحت برگ (برگ‌سنج) تعیین شد. LAIو سطح ویژهٔ برگ (SLA) محاسبه و با روش «درخت میانگین» و تراکم ۲۵۳ درخت در هکتار به سطح تودهٔ جنگلی تعمیم داده شد. روابط آلومتریک با مدل‌های رگرسیون خطی، لگاریتمی و توانی تحلیل شد. یافته‌ها نشان داد که میانگین ترسیب کربن برگ (LCS)، جذب CO_2 و زیست‌تودهٔ خشک برگ در هکتار به‌ترتیب ۴۶۸/۱۳ کیلوگرم کربن، ۱۷۱۸/۰۳ کیلوگرم و ۹۷۵/۲۷ کیلوگرم و میانگین LAI در سطح درخت و هکتار ۱/۶ و ۰/۳۰۲ است. تحلیل‌های آماری رابطهٔ قوی و معناداری بین مساحت تاج با زیست‌تودهٔ برگ و LCS نشان داد، به‌طوری که مدل خطی مبتنی بر مساحت تاج بهترین برازش را برای پیش‌بینی LCS (R^2 =۰/۷۱۹) داشت. در مقابل، LAI تنها با زیست‌تودهٔ خشک برگ رابطهٔ معنادار نشان داد. نتیجه‌گیری کلی حاکی از آن است که علی‌رغم دورهٔ خواب طولانی، این گونه به‌دلیل تراکم به‌نسبت زیاد و ساختار تاجی ویژه، سهم مهمی در ذخیرهٔ کربن برگ‌ها در جنگل‌های زاگرس دارد. مدل‌های ساده و مبتنی بر مساحت تاج ارائه‌شده، ابزاری عملی و کم‌هزینه برای پایش کربن، ارزشگذاری خدمات اکوسیستمی و تدوین راهبردهای حفاظتی برای این گونهٔ در معرض انقراض و اکوسیستم‌های مشابه مدیترانه‌ای فراهم می‌کنند و عاملی مهم در مدیریت پایدار این جنگل‌ها محسوب می‌شوند.

واژه‌های کلیدی: اکوسیستم مدیترانه‌ای، ترسیب کربن، سازگاری با تغییرات آب‌وهوایی، گونهٔ در معرض انقراض، مدل‌های آلومتریک.

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