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A New Method for Development of a Competition Index Using Crown–Diameter Relationship of Naturally Grown *Pinus brutia* Ten. in Iraq

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Abstract

Introduction: Forests cover about 30% of the Earth's land surface, but in Iraq they are limited, mainly confined to the northern region, totaling around 1.26 million hectares, or 2.9% of the country's land area. Forests in this region include coniferous and broad-leaved types. Coniferous forests are dominated by pines, which make up approximately 80% of the stand. Calabrian pine (*Pinus brutia*), native to the Duhok governorate in northern Iraq, covers an area of approximately 50,000 ha in Zawita, Atrush, and Belkaf. This study deals with the regression of crown width on diameter at breast height to be used in the development of a competition index. Crown width is important for forest dynamics, biodiversity, carbon sequestration, and overall ecosystem health.

Materials and Methods: Field data were collected from three distinct locations within Duhok Province, Kurdistan, Iraq. In total, 480 trees were sampled from both open-grown and stand-grown trees. A total of 160 trees were selected from each location (80 open-grown trees, which were free from all competition, and 80 stand-grown trees, where there was inter-tree competition regarding resource access). Of these, 50 trees were used for calibration, while 30 trees were used for validation, resulting in a balanced and robust dataset for analysis. Using Statgraphics Centurion 19 software, separate regressions of Crown Width (CW) against Diameter at Breast Height (DBH) were developed for both tree types. Six groups of allometric regression equations were evaluated using criteria that included the coefficient of determination (R^2), bias, mean absolute error (MAE), Ohtomo's unbiased test, and additional proposed metrics.

Results: Crown width was regressed on diameter at breast height using different types of functions; among them, linear, nonlinear, and logarithmic models with different forms of dependent variables were used. Upon statistical analysis of the developed models, the linear model of the form, $Cw = b_1 + b_2$ DBH, was selected as the most appropriate one that fit the study data in both tree types across all locations. As a result, there was no major difference between the regression slopes for open-grown trees and those for trees growing within a stand. In addition, this study presented a new method for calculating the competition index.

Conclusion: From the analysis of the samples collected, certain key conclusions can be drawn. First, in all the study sites, the relationships between crown width and diameter at breast height (DBH) did not show any statistically significant differences between open-grown and stand-grown trees. This indicates a relatively low stand density, resulting in minimal competition for resources among stand-grown trees. Second, given the improvement of overall forest structure and productivity, it is advisable that replanting strategies should fill the existing canopy gaps in all sites, since this will make better use of available resources, promote the long-term health of forests, and maintain biodiversity. Lastly, the present study confirmed a strong linear relationship between crown width and DBH for Calabrian pine in Iraq.

Keywords: Allometric equations, Crown modeling, Crown competition index, Calabrian pine, Regression models.

1. Introduction

Forests are very important for the global ecosystem. They cover about 3.9 billion hectares, which is nearly 30% of the Earth's land surface (Nix, 2019). However, in Iraq, forest areas are very limited and are mostly found in the mountainous regions of the Kurdistan area (Chapman, 1950). The total

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forest area in Iraq is estimated to be about 1.26 million hectares, which is only 2.9% of the country's total land area (Assessment, 2010). In this region, there are generally two main types of forests: coniferous forests, which are mainly made up of pine species (*Pinus* sp.), and broad-leaved forests, which mostly consist of oak species (*Quercus* sp.). The forest composition varies between open and mixed forests. Broad-leaved species constitute 80% of the forest, and coniferous (softwood) species make up the remaining 20%, of which 80% are pine trees and 20% are other softwood species (Mosa, 2016; Shahbaz, 2010; Nasser, 1984; Chapman, 1948).

Calabrian pine (*Pinus brutia*), also known as Turkish pine, originates from the eastern Mediterranean, including a range from Turkey to the part of Kurdistan stretching over Iraq. In Iraq, it is distributed mainly in the Duhok governorate, covering approximately 50,000 hectares at an altitude ranging from 600 to 1,200 m (Chapman, 1948; Nasser, 1984; Shahbaz, 2010; Mosa, 2016). This medium-sized tree may reach a maximum height of 20–35 m with a stem diameter of 1 m (Muhamed, 2019). It is fast-growing in height and resistant to drought and poor soil conditions. Furthermore, it promotes biodiversity, timber production, pollution mitigation, hydrological cycle regulation, soil erosion prevention, and habitat creation for wildlife. It is the most widely planted species in plantations, reforestation, and as a roadside tree (Shahbaz, 2010; Salih, 2020).

The width of the crown is considered a very important characteristic in forestry, as it affects light interception, photosynthesis, and the growth processes of a tree. Larger crowns provide a larger area for effective light collection and growth. The shape and size of the crown also influence the canopy structure and light penetration into the forest understory. Direct measurements of crown width are rarely made; therefore, regression equations are applied to estimate crown size for any tree based on diameter at breast height (DBH). The relationship between DBH and crown measurements has important implications, especially in forest management, silviculture, and ecology. As DBH usually relates to crown width, several factors may potentially affect this relationship, such as site conditions, stand density, and tree age (Husch et al., 2003). In cases of high density, competition for resources may limit crown expansion, even though DBH is increasing. The DBH-crown width relationship is often modeled using a power law (Husch et al., 2003).

$$CW = b_1 DBH^{b_2} \quad (1)$$

CW is the crown width; DBH refers to diameter measured at breast height; and b_1 and b_2 are model coefficients. Models are thus able to estimate crown parameters from easily measurable tree parameters in both natural and managed forests. Methods such as logarithmic, linear, or allometric equations were developed to account for interspecies variation due to growth characteristics while considering environmental effects (Dykstra, 2010). These mathematical modeling approaches are also useful for gaining insight into crown architecture and tree growth, which is valuable for forest management.

Many studies have modeled the crown width-DBH relationships allometrically, predominantly in nonlinear form using the power function model. According to Jucker et al. (2015), these relationships hold true for specific allometric patterns globally. Similar findings for conifers were reported by Sharma et al. (2017) for Scots pine in Central Europe, Raptis et al. (2018) for black pine in even-aged forests, and Ma et al. (2022) for *Larix olgensis*, incorporating nonlinear mixed-effects and quantile regression. This gives further credence to the conclusion that nonlinear models are indeed effective in estimating crown dimensions across species and regions. On the other hand, some simple linear relationships may provide more basic and practical models:

$$CW = b_0 + b_1 DBH \quad (2)$$

where: b_0 and b_1 are intercept and slope of regression equations, respectively. DBH is breast height diameter, and CW is crown width of the tree.

Clear empirical evidence exists in the literature favoring the use of linear models for relating crown width and diameter at breast height (DBH) among several species and forest types. Lockhart et al. (2005) found a strong linear relationship between DBH and crown radius for certain hardwood species (adjusted R^2 values of 0.57 to 0.86). Ibrahim et al. (2014) also showed that linear regression models successfully predicted crown width from DBH in naturally grown *Terminalia* species. Similarly, Tong et al. (2022) advanced a linear mixed-effect quantile model for crown width in planted Korean pine stands, demonstrating its utility for managing even-aged plantations. These results are consistent with urban tree studies by Peper et al. (2001), whereby high predictive accuracy (adjusted $R^2 > 0.70$) was reported when using linear equations to estimate crown diameter. Taken together, these studies corroborate the soundness and practical relevance of linear models in forestry research and management.

The relationship between diameter at breast height (DBH) and crown width is significant in forest management and ecological models. It helps predict tree growth patterns and forest structure. Crown width is an important parameter in estimating forest biomass and carbon sequestration. It is one of the most important parameters for ecosystem service evaluation as well as climate change mitigation strategies (Nyirambangutse, 2016; Ekasari & Kurnia, 2023). In addition, crown width indicates tree competition in obtaining essential resources, namely water, light, and nutrients. If crowns become wider, it means that the tree dominates by having better access to light; therefore, it affects the growth performance of understory species and the overall species composition. It is an important indicator for predicting light availability in forest canopies and estimating canopy cover, which is indispensable in biodiversity conservation and habitat quality assessment (Zeng & Zou, 2024). Within forest inventory practices, crown width, in combination with DBH, is frequently employed to estimate individual tree volume and biomass. Further, these estimates aid in decisions about sustainable timber harvesting, forest productivity, and long-term resource planning, where the DBH-crown width relationship constitutes an indispensable component of modern forest assessment techniques.

Both crown width and DBH are important forestry metrics. Whatever function is adopted—linear or power—it conveys valuable information on tree growth, competition, and forest structure. The power function model corroborates biological scaling laws; however, the linear model is simple and practical for interpretation. Both are incorporated into forest assessment studies to increase accuracy in biomass estimation, ecological modeling, and management decision-making.

A new crown ratio-based competition index, which is distance-independent, has been developed in this study, and it is effectively assessed through comparisons of crown widths of trees with similar DBH under two growing conditions characterized by competition intensity: stand-grown trees, where crown growth is constrained by competition, and open-grown trees, in which there is no competition from nearby trees during crown growth. Crown widths for both conditions have been estimated using regression models developed earlier in this study.

Many studies concerning differences in crown development between open-grown and stand-grown trees serve as grounds for developing crown-based competition indices. Salih et al. (2019) conducted research on competition across *Pinus brutia* stands in the Mediterranean by comparing open-grown trees and stand-grown trees. A ratio-based competition factor was developed to quantify the way stand density reduces growth and pointed out the successful comparison of open and stand conditions to assess competition. According to Bailey (1964), more than 90% of the variation in crown width in open-grown lodgepole pine trees could be explained by DBH, but this was only slightly more than half that (57%) for forest-grown ones, indicating that stronger competition effects were at work. Similarly, in research on ash and sycamore, Hein & Spiecker (2008) showed that trees grown in open spaces have significantly larger crowns than their counterparts grown in forests. According to Hasenauer (1997), crown width models for open-grown trees could provide a good benchmark for maximum crown expansion. In contrast, Minckler & Gingrich (1970) postulated that crown width-DBH relationships in dense hardwood stands would differ from the open-grown pattern due to crown overlap. This pattern was further corroborated by Vezina (1962), who recorded expanded crown dimensions in open-grown balsam fir and white spruce.

Crown competition provides a measure of tree competition through the interdigitation of their crowns and, therefore, implies competition for light, water, and nutrients. Crown competition measures are very useful in assessing stand dynamics and guiding management strategies. Under both open-grown and stand-grown environments, trees with larger crowns will always be in competition with respect to light capture; this will affect their growth behavior. Assessing crown competition helps optimize planting densities and thinning regimes for healthy and productive forests (Avery & Burkhart, 2015). Primarily, this study seeks to accomplish four main objectives: 1) establish a clear and measurable relationship between crown width and diameter at breast height in Calabrian pine (*Pinus brutia*) as an important parameter for understanding tree architecture and forest structure; 2) evaluate the effect of tree competition on crown development; 3) provide a guide for management practices on planting densities and thinning; and 4) establish and introduce a new competition index that adequately assesses competition-induced stress among trees.

2. Materials and Methods

2.1. Study Area

This study focused on naturally occurring Calabrian pine trees from three different locations in Duhok Governorate, which is in the Kurdistan Region of Iraq (Figure 1). Their detailed geographical characteristics are given in Table 1. The study area is characterized by hot, dry summers and cold, rainy winters, which corresponds to a Mediterranean climate. Summer temperatures can reach as high as 43°C, while winter temperatures fall below freezing (Hasan et al., 2022). The annual rainfall in this region is between 500 and 1000 mm, most of which falls between November and April (Directorate of Meteorological Station at Duhok). The area also has a significant annual evapotranspiration rate, which has a great influence on vegetation patterns and the dynamics of forest growth (Peel et al., 2007; Youssef et al., 2019). The soils are relatively shallow, rocky, and well-drained, and are mostly classified as Mollisols (Barwari, 2013).

Table 1. Geographical information of study sites

Locations	Longitude	Latitude	Altitude (m)
Atrush	43.35780556	36.85172222	940 – 1050
Belkef	43.35205556	36.85294444	790 – 990
Zawita	43.15002778	36.90169444	900 – 1010

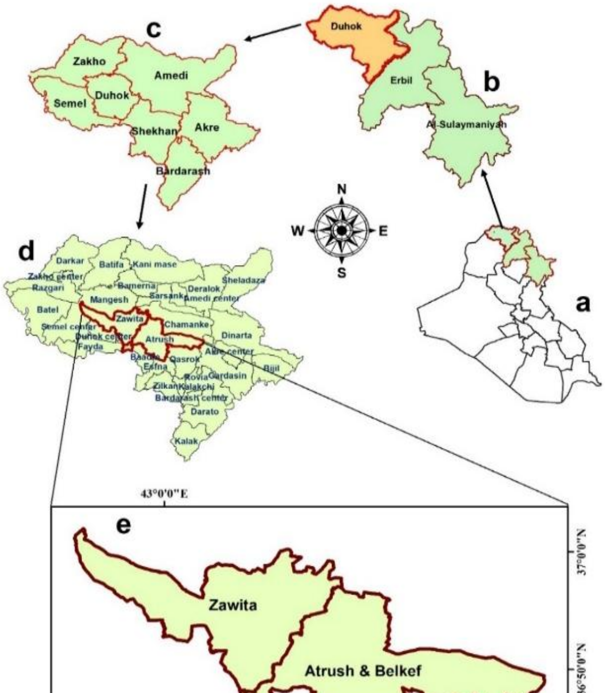

Figure 1. Map of the study area showing the three sampling locations (Atrush, Zawita, and Belkef) within Duhok Province, Kurdistan Region of Iraq

2.2. Data collection

In 2024, field data were measured from three distinct locations within Duhok Province, Kurdistan, Iraq. In total, data were collected from 480 trees, including both open-grown and stand-grown trees. A total of 160 trees were selected from each location (80 open-grown trees, which were free from all competition, and 80 stand-grown trees, which were subject to inter-tree competition for resource access). Of these, 50 trees were used for calibration, while 30 trees were used for validation (split-sample method), resulting in a balanced and robust dataset for analysis (Hinkle et al., 2003; Draper & Smith, 1998).

Crown radius and diameter at breast height were the two most important tree parameters. DBH was measured using a diameter tape at 1.3 m above ground level, while crown radii were measured with a standard tape measure. Due to the naturally irregular shape of tree crowns, radii were measured from the center of the stem to the farthest edge of the canopy in several directions at ground level according to the guidelines published by Van Laar & Akça (2007). This method ensured that crown asymmetries were captured more accurately. The various crown radius measurements were geometrically averaged to obtain a representative and consistent estimate of crown size, which was then used in the subsequent analysis.

$$\text{Geometric mean}, \left(\bar{R}\right) = \sqrt[n]{R_1 * R_2 * \ldots\ldots\ldots * R_n} \quad (3)$$

The crown width was calculated by first determining the geometric mean of the measured crown radii and then multiplying it by two. The radial measurements for each tree were described as R_1, R_2, …, R_n, where these radial measurements were taken in various directions from the stem to the edge of the canopy. A summary of the statistics of the collected open-grown and stand-grown trees is given in Tables 2 and 3.

Table 2. Descriptive statistics of open-grown trees across all study sites

	Atrush Location			**Belkef Location**			**Zawita Location**		
	Cw (m)	D (cm)	N. of tree/ ha.	Cw (m)	D (cm)	N. of tree/ ha.	Cw (m)	D (cm)	N. of tree/ ha.
Average	8.81	31.15	159	8.96	32.95	150	8.62	32.75	155
Standard deviation	2.66	12.69	44.5	1.51	10.49	48	2.62	12.70	47
Coeff. of variation	30.25%	40.75%	28%	16.93%	31.83%	32%	30.43%	38.77%	30%
Minimum	3.55	10.1	95	6.3	12.7	74	3.2	10.0	80
Maximum	14.8	55.8	223	11.85	53.5	226	13.35	57.5	230

Table 3. Descriptive statistics of stand-grown trees across all sites

	Atrush Location			**Belkef Location**			**Zawita Location**		
	Cw (m)	D (cm)	N. of tree/ ha.	Cw (m)	D (cm)	N. of tree/ ha.	Cw (m)	D (cm)	N. of tree/ ha.
Average	7.67	26.50	187	8.79	32.39	156	7.13	28.58	173
Standard deviation	2.17	9.55	37	2.96	15.06	52.78	2.05	10.52	55
Coeff. of variation	28.36%	36.02%	19.7%	33.69%	46.49%	34%	28.87%	36.80%	31%
Minimum	3.6	10.0	93	3.25	7.5	81	3.0	10.4	88
Maximum	11.5	42.3	204	13.8	61.5	201	11.25	50.3	258

The data were described using the following tools (box plots and scatter plots):

2.3. Box plot

It is a tool used for graphically representing data distribution using the most basic summary statistics: minimum and maximum values, median, quartiles, and possible outliers. It is a very useful exploratory data analysis tool that quickly allows the recognition of data patterns and irregularities (Tukey, 1977). In regression analysis, for example, outliers can be detrimental, as their presence may inflate or deflate coefficient estimates and violate fundamental assumptions such as homoscedasticity and linearity (Chatterjee & Hadi, 2015).

2.4. Scatter plots

A scatter plot visually shows the relationship between an explanatory variable and a response variable (Kutner et al., 2005; Newbold et al., 2013). In this study, scatter plots were created to analyze the relationship between diameter at breast height and crown width for open-grown and stand-grown trees across three locations.

2.6. Construction Technique and Statistical Analysis

Regression equation development and statistical analysis were conducted systematically and in a structured manner to ensure high accuracy and reliability. At the beginning, a scatter plot was drawn to visualize the relationship between crown width (the dependent variable) and diameter at breast height (DBH, the independent variable). This initial graphical analysis was essential for identifying underlying trends and selecting appropriate modeling strategies (Picard et al., 2012). According to the patterns observed, separate regression models were developed for open-grown and stand-grown Calabrian pine trees using Statgraphics Centurion 19 and Microsoft Office 2024. The data were first divided into subsets and carefully screened to ensure that the explanatory variable was statistically significant. Different regression models were then tested using each subset of the data. To improve model performance, several mathematical transformation techniques were applied, including square root, squared, logarithmic, and reciprocal functions. Based on these analyses, multiple candidate models were developed, and the best regression equation was selected. Models were grouped based on consistent transformations of the response variable and were evaluated using precision-based criteria for model comparability and quality. The model that showed the best statistical performance and predictive accuracy within each group was taken forward for further analysis.

2.6.1. Selection Procedure for Homogeneous Regression Models

Homogeneous regression models use the same transformation of the dependent variable. The following criterion was applied to evaluate how well these models predict the dependent variable.

2.6.1.1. The Coefficient of Determination (R^2)

The value of this criterion varies between 0 and 1 and is a measure of the extent of variance in the response variable explained by the explanatory variables (Neter et al., 1996).

$$R^2 = \left(1 - \frac{\text{Residual sum of squares}}{\text{Total sum of squares}}\right) \quad (4)$$

The regression equation with the highest coefficient of determination (R^2) will be chosen as the best representative model for each group. Several authors have utilized this criterion in their studies, among them Bjarnadóttir et al. (2007), Younis & Hassan (2019), and Koirala et al. (2021).

2.6.2. Selection Procedure for Heterogeneous Regression Models

When comparing regression models based on varying transformations of the response variable, using R^2 as a selection criterion is inappropriate unless all competing models use the same transformation (Furnival, 1961; Neter et al., 1996; Studenmund & Johnson, 2006). Therefore, alternative evaluation methods are necessary, among them the following:

2.6.2.1. Ohtomo's Unbiased Test

Ohtomo introduced this method in 1956 to assess regression model accuracy for volume estimation by performing a simple linear regression between the original forms of the estimated and actual dependent values. The equation is:

$$\hat{y} = k + m * y \quad (5)$$

In the equation, k represents the y-intercept, while m represents the corresponding slope. In an optimum case, the intercept (k) must be very close to zero, while the slope (m) should be very close to one, indicating that the fitted value is highly correlated with, or very close to, the actual value (y).

Salih outlined in 2020 a new index that proposes improvements to Ohtomo's test in the following ways:

$$\text{Salih Index} = |k - 0| + |1 - m| + |1 - R^2| + |MAE|, \quad (6)$$

The first and last components serve as measures of how far k and MAE deviate from zero, while m and R^2 measure how far they deviate from one. The lower the index value, the greater the accuracy indicated. This criterion has been used by researchers such as Salih et al. (2021), Salih et al. (2023), Saeed (2023), and Salih & Abdulaziz (2023).

2.6.2.2. Mean Absolute Error (MAE)

It evaluates the average absolute deviation between the observed and predicted results, thus serving as a very good indicator of accuracy across various regression models (Willmott, 2005).

$$\text{MAE} = \frac{\sum \left| Y_i - \hat{Y}_i \right|}{n} \quad (7)$$

Where: n is the number of observations Y_i and $\hat{Y}_i$ are actual and estimated value of i^{th} observation, respectively.

According to Salih's study in 2020, there is an inverse relationship between the value of this criterion and predictive accuracy. However, researchers have noted flaws in equations selected using MAE (Obeyed, 2015; Salih et al., 2023; Bahtiar & Iswanto, 2023).

2.6.2.3. Bias Percentage Test

This statistic, used by many researchers, among them Hanberry et al. (2012) and Abdulqader & Obeyed (2023), is calculated as follows:

$$\text{Bias\%} = \frac{\sum \left(Y_i - \hat{Y}_i \right)^2}{\sum Y_i} * 100 \quad (8)$$

Bias% is a measure of the accuracy of a model, and the closer the value is to zero, the greater the likelihood that the model is unbiased in its prediction.

2.6.2.4. Homogeneity Test of Residuals

The reliability of regression models requires constant predictive accuracy across the entire dataset, which means that the residuals are expected to conform to certain statistical assumptions. In particular, the residuals should be normally and independently distributed (NID), with a zero mean and constant standard deviation (σ) (Residuals ~ $\text{NID}(0, \sigma)$) (Neter et al., 1996; Melesse & Zewotir, 2015; Salih et al., 2020; Seo et al., 2023).

These conditions ensure that the model does not have systematic biases and that its errors are randomly scattered, indicating that the model is appropriately specified and performs adequately across the values of the explanatory variable. Satisfying these assumptions is crucial for any generalization deemed admissible from statistical inference resulting from the regression analysis, whether based on confidence intervals or hypothesis testing.

2.7.Validation of the Selected Regression Equation

Predictions can only be made from a regression equation after validating it. Validation checks the model's accuracy and, subsequently, its generalizability (Todoroki & Lowell, 2016). Validation is typically performed using an independent dataset that has not been used in calibration. Model validation follows the classical approach of deriving a version of the equation from the validation dataset, provided that the functional form is the same as that established from the calibration data (Froese & Robinson, 2007; Sun & Sun, 2015; Forrester et al., 2021). This produces two models for performance comparison and evaluation of the consistency between them. For this validation dataset, DBH and crown width measurements were collected from 30 trees representing various locations and growth conditions, including both open-grown and stand-grown trees. Statistical comparison was performed through a t-test to determine the presence or absence of significant differences between the slopes of the regression equations derived from the calibration and validation datasets. The results of this analysis are presented in Table 7.

2.8. Crown Competition Index

Competition indices are parameters used in forestry to measure how much individual trees compete for limited resources such as light, water, and nutrients in the soil. Such indices measure the effect of stand density and spatial arrangement on tree growth and forest dynamics. A new crown ratio-based competition index is introduced in this study, as it measures competition in terms of the crown widths of trees of similar diameter at breast height (DBH) under different conditions: stand-grown versus open-grown. In both cases, crown widths were modeled using regression models previously developed in this study. The competition index indicates the extent to which competition restricts crown development, thus becoming an applied and quantitative measure of that stress. The calculation of the crown competition index has the following stages:

1. DBH Range Identification: The range of DBH measurements reflected in the dataset was considered, spanning from 5 cm to 65 cm.
2. Model Application: In accordance with the established regression equations, crown widths were predicted at 5 cm intervals across the DBH range for both open-grown and stand-grown trees.

3. Index Calculation: The competition index was then computed through a formula that compares the estimated crown widths under competition and non-competition conditions. This index expresses the intensity of competition continuously across different tree sizes and enables better decision-making in forest management and stand structure analysis.

$$CI = \frac{\sum C\hat{w}_{Stand}}{\sum C\hat{w}_{Open}} \quad (9)$$

where CI represents the competition index, $\sum \widehat{Cw}_{Stand}$ is the sum of all crown widths estimated using the regression equation for stand-grown trees, and $\sum \widehat{Cw}_{Open}$ is the sum of all crown widths estimated using the regression equation for open-grown trees. The CI value shows how much competition affects trees growing in a stand. The value of one indicates no competition, because the competition index of stand-grown trees is equal to that of open-grown trees ($\sum \widehat{Cw}_{Stand} = \sum \widehat{Cw}_{Open}$). In contrast, a low CI value means that stand-grown trees are experiencing strong competition for growth resources.

Statistical Analysis of Crown Width Differences: To determine whether there is a significant difference between the slopes of the model selected for calibration and the validated equation across all sites, the following formula was used to conduct such a test (Montgomery et al., 2021).

$$t-Test = \frac{b_{1(validition)} - b_{1(calibration)}}{S_p\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}}, \quad S_p = \sqrt{\frac{(n_1-1)S_1^2+(n_2-1)S_2^2}{n_1+n_2-2}} \quad (10)$$

where b_1 (validation) is the slope of validation model, b_2 (calibration) is the slope of calibration model. n_1 and n_2 are the corresponding sample sizes. S_p is the pooled standard deviation.

3. Results

The results focus on developing a new crown competition index based on the crown–diameter relationships of open-grown and stand-grown Calabrian pines across the three study locations. Site-specific regression equations were derived for each location to evaluate differences in tree structure, growth patterns, and competitive status. Box plots for open-grown and stand-grown trees from each site are presented in Figure 2 to illustrate differences in the extent and distribution of crown width and DBH. Scatter plots for all locations are shown in Figure 3 and illustrate the various relationships between the measured tree parameters.

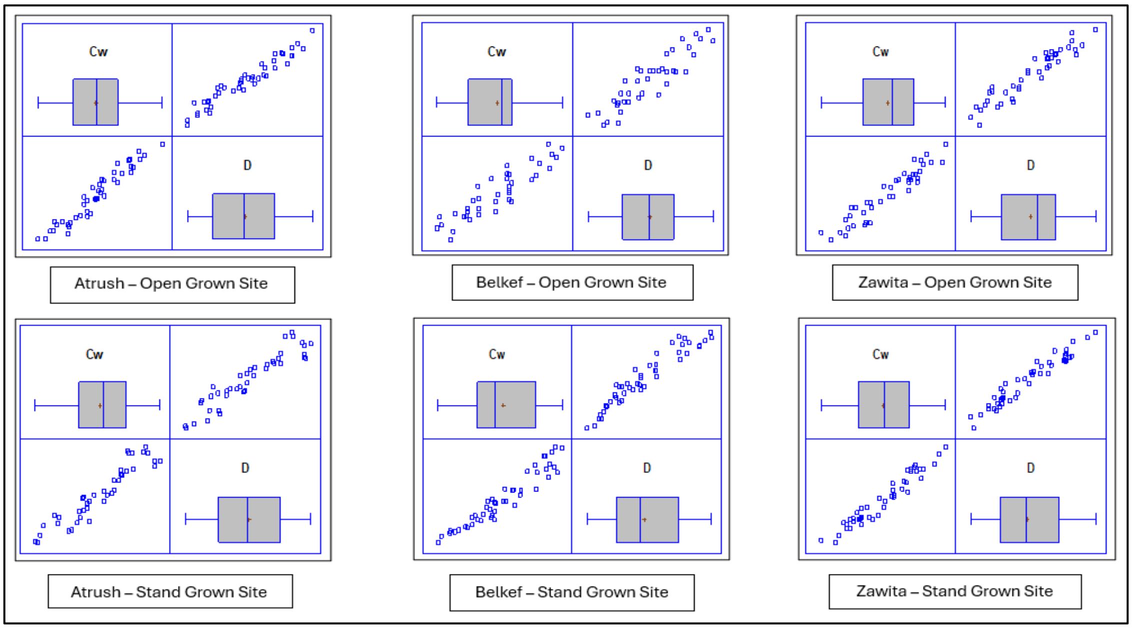

Figure 2. Box plots of crown width (Cw) and diameter at breast height (DBH) for open-grown and stand-grown Calabrian pines across the three study locations (Atrush, Belkef, and Zawita).

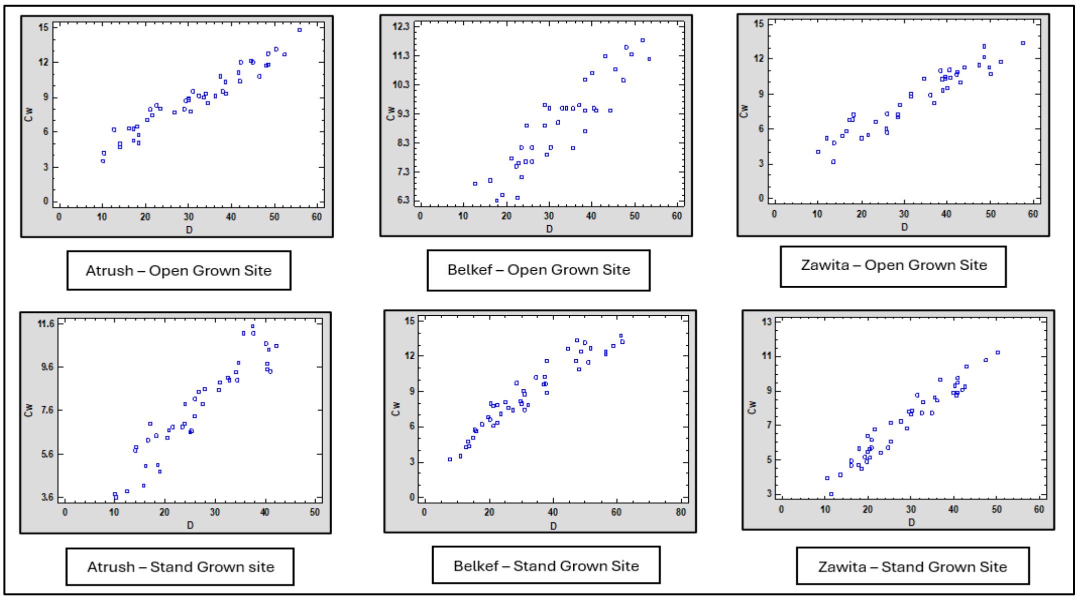

Figure 3. Scatter plots illustrate the relationship between variables for open-grown and stand-grown trees across the three study locations

These visualizations form a basic step in understanding the underlying relationships between CW and DBH along a certain gradient of growing conditions that will assist further statistical analysis and model development.

3.1. Developed Regression Equations for Atrush Location

3.1.1. Areas with Open-Grown Trees (Cw vs. D)

The same technique and procedure were applied to develop and screen equations for both open-grown and stand-grown trees across all study locations. To simplify the presentation and avoid repetition, a detailed discussion is provided for the open-grown tree dataset from the Atrush location. This site is used as a representative example to illustrate the methodology, model development process, and results, which are similar for the other locations.

Fifteen allometric regression equations were derived for the open-grown trees of Atrush using Statgraphics Centurion software. These models used various functional forms to describe the relationship between crown width and DBH appropriately. The equations were sorted into four main categories based on the mathematical form of the dependent variable (crown width) to provide a systematic comparison and evaluation. The grouping and specific forms of these equations are presented in Table 4, giving an overview of the modeling framework adopted in this study.

Table 4. Regression models were formulated for trees growing in open conditions at the Atrush site

Eq.	Equations	R^2
	Linear Regression Eq. Models	
1	Cw = 2.495 + 0.2028*D	0.932
2	Cw = -3 + 2.1645*sqrt(D)	0.926
3	Cw = 5.319 + 0.00309*D^2	0.901
	Linear Regression Eq. Models (Fixed Y-intercept)	
4	Cw = 2 + 0.2164*D	0.990
5	Cw = 2 + 1.2886*sqrt(D)	0.969
6	Cw = 2 + 2.1002*ln(D)	0.941
	Square Root Regression Eq. Models	
7	$\sqrt{Cw}$ = (1.845 + 0.0349*D)	0.919
8	$\sqrt{Cw}$ = (0.881 + 0.3759*sqrt(D))	0.929
9	$\sqrt{Cw}$ = (-0.270 + 0.9581*ln(D))	0.920
	Squared Regression Eq. Models	
10	Cw^2 = (-27.913 + 3.6113*D)	0.909
11	Cw^2 = (-122.265 + 37.9057*sqrt(D))	0.873
12	Cw^2 = (20.484 + 0.0568*D^2)	0.933
	Logarithm Regression Eq. Models	
13	Ln (Cw) = (1.362 + 0.0245*D)	0.887
14	Ln (Cw) = (0.671 + 0.2665*sqrt(D))	0.914
15	Ln (Cw) = (-0.168 + 0.6862*ln(D))	0.924

3.1.1.1. Screening of Equations

In the developed regression equations, the dependent variable (crown width) was expressed in four different mathematical forms, including both original and transformed formats. Because the coefficient of determination (R^2) serves as a measure of precision only when comparing models with the same dependent variable form, it was used to rank equations within each respective group. The selected equations 1, 4, 8, 12, and 15, according to this criterion, showed the maximum values of R^2 within their respective equation groups. All except equations 1 and 4, which are in the original form of crown width without any transformation, represent different forms of the dependent variable. To further investigate the performance and predictive accuracy of the selected models, a heterogeneous set of evaluation criteria was employed that is applicable across different forms. A summary of the results pertaining to this broader evaluation is given in Table 5.

Based on the criteria discussed above for evaluation, Equation 4 was finally chosen as the best model. It produced balanced and reasonable values across several performance metrics, including Ohtomo's coefficients, the Salih index, MAE, and bias, thus ensuring the overall reliability and predictive accuracy of the model.

3.1.1.2. Homogeneity Test of Residuals for the Selected Equation

A significant feature of the selected regression model is the homogeneity of the residuals defined as the differences between observed and predicted crown width value of the form $(\mathrm{Cw} - \widehat{\mathrm{Cw}})$. When such residuals are plotted against the independent variable (Figure 4), they should not show a trend or pattern of any kind. Such randomness would imply that the residuals are normally and independently distributed with a mean of zero and a constant standard deviation (σ). Such distributions confirm the fulfillment of some basic assumptions of linear regression and hence confirm that the model is statistically valid and reliable for prediction.

$$\text{Residuals} \sim \mathrm{NID}(0, \sigma)$$

Table 5. Comparison of candidate equations for open-grown trees of Atrush location using goodness-of-fit criteria to identify the best-fit model

Eq.	Ohtomo's Test	Salih Index	MAE	Bias %
1	$\widehat{Cw}$ = 0.589 + 0.933*Cw	1.277	0.597	0.0529
4	$\widehat{Cw}$ = -0.032 + 0.995*Cw	0.693	0.592	0.056
8	$\widehat{Cw}$ = 0.566 + 0.934*Cw	1.249	0.586	0.0528
12	$\widehat{Cw}$ = 0.850 + 0.908*Cw	1.577	0.623	0.058
15	$\widehat{Cw}$ = 0.630 + 0.925*Cw	1.327	0.580	0.054

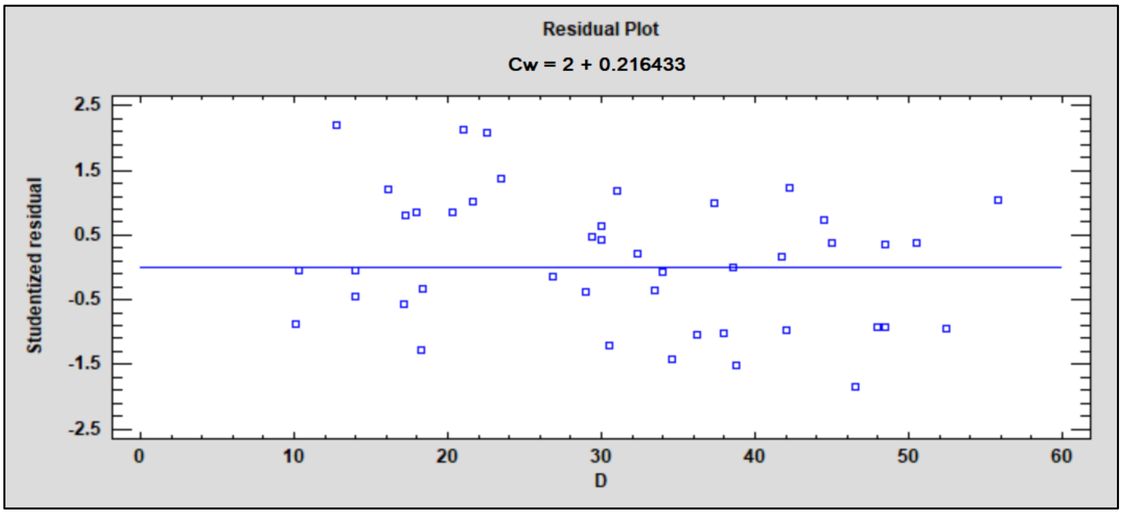

Figure 4. Distribution of residuals for the selected model applied to open-grown trees in the Atrush site

3.1.2. Stand-Grown Trees (Cw vs. D)

Fifteen regression models were developed and evaluated using the same methodology to determine the best-fitting model for stand-grown trees at the Atrush location. The model selected based on this analysis is as follows:

$$Cw = 1.5 + 0.2309 * D$$

The selected regression model demonstrated strong statistical performance, with an R^2 value of 0.986, a Salih index of 1.087, a mean absolute error (MAE) of 0.600, and a bias value of 0.071. The residuals were tested for homoscedasticity by plotting them versus the independent variable $(Cw - \widehat{Cw})$. Figure 5 shows the random distribution of the residuals without any visible trend, indicating that the residuals are normally and independently distributed around a mean of zero with constant variance (σ). This supports *Residuals ~ NID* (0, σ), implying that the model satisfies important assumptions applicable for drawing valid conclusions from regression analyses.

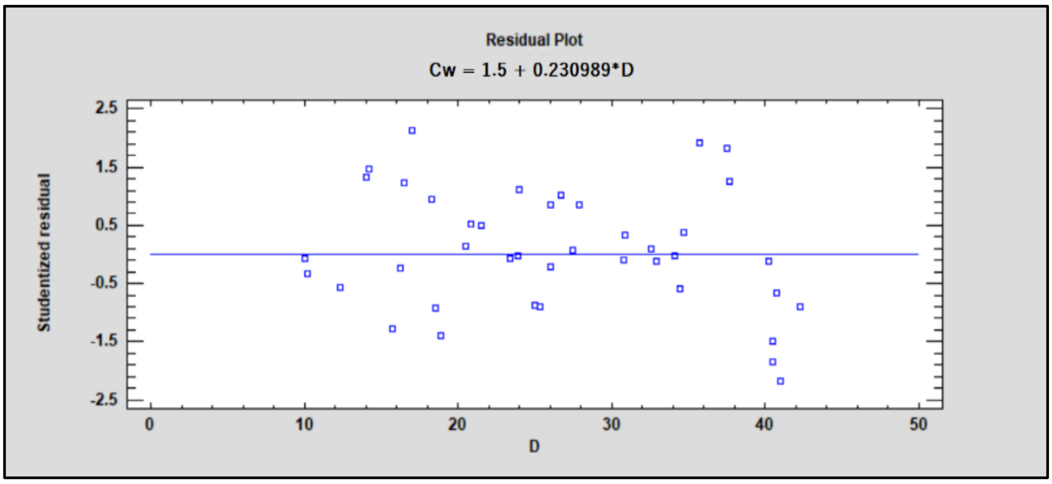

Figure 5. Distribution of residuals for the selected model applied to stand-grown trees at the Atrush site

3.2. Developed Regression Equations for the Belkef Location

3.2.1. Open-Grown Trees (Cw vs. D)

Fifteen regression models were developed to examine the relationship between crown width and diameter at breast height (DBH). Among these, the most suitable equation was selected based on a set of screening criteria, reflecting a high degree of model accuracy, supported by an R^2 value of 0.983, a Salih index of 0.579, a mean absolute error (MAE) of 0.555, and a bias value of 0.0483. The selected model is expressed as:

$$Cw = 4 + 0.1489 * D$$

To evaluate the assumption of residual homogeneity, the residuals were analyzed. A plot of the residuals against DBH was prepared (Figure 6), and the resulting scatter showed randomness without any observable trend. Such a scattering pattern reaffirms the normality and independence of the residuals.

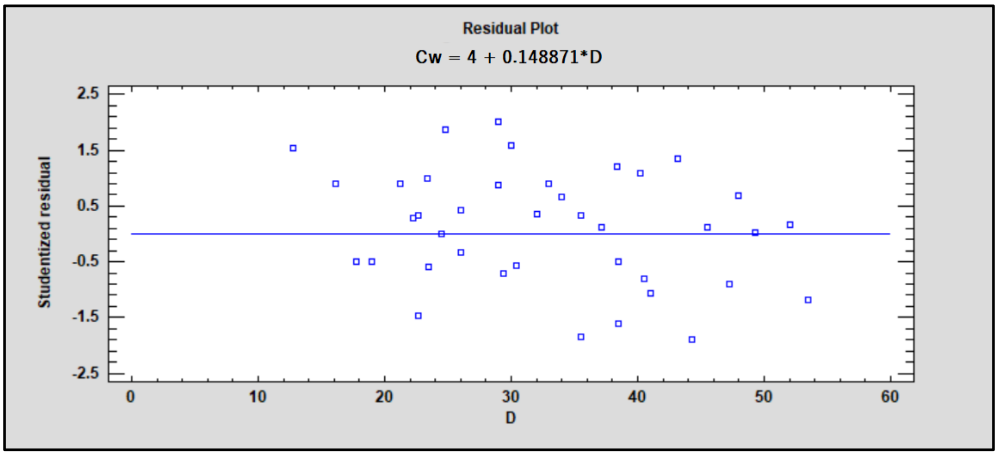

Figure 6. Residual distribution for the selected model (Belkef – open-grown trees)

3.2.2. Stand-Grown Trees (Cw vs. D)

In total, fifteen regression equations were developed using the same methodology for the relationship between crown width (Cw) and diameter at breast height (D) for stand-grown trees. Each model was subjected to thorough precision and performance evaluations to identify the most accurate and reliable representation of the observed data. Based on these assessments, the following regression equation was identified as the most suitable:

$$Cw = 2.1 + 0.2035 * D$$

The model exhibited high predictive strength, evidenced by an R^2 value of 0.985, a Salih index of 0.829, a mean absolute error (MAE) of 0.719, and a bias value of 0.088. However, this equation deals with the relationship between crown width and stem diameter in stand-grown trees, for which allometric patterns have been established and cited in similar studies. Figure 7 shows a scatter plot of the residuals plotted against DBH. This scatter plot shows a random pattern with no obvious trend. This randomness means that the residuals are independently and normally distributed, thereby validating the basic assumptions upon which the regression model was based.

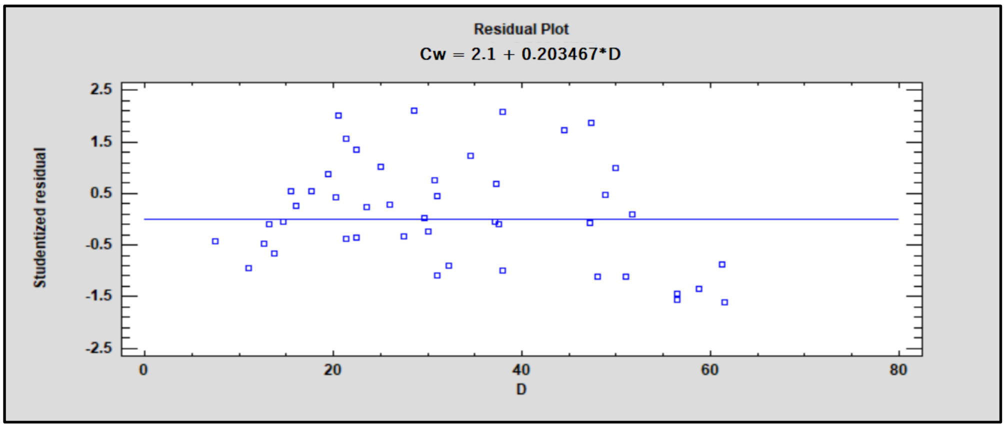

Figure 7. Residual distribution for the selected model (Belkef – stand-grown trees)

3.3. Developed Regression Equations for the Zawita Location

3.3.1. Open-Grown Trees (Cw vs. D)

In total, fifteen allometric equations were derived through various transformations of both variables to describe the relationship between crown width and diameter at breast height (DBH). To ensure consistency, the same modeling procedure as in the Atrush site was followed. The models were thoroughly analyzed, and the equation with the most favorable statistical performance was selected, with R^2 = 0.987, a Salih index of 1.215, an MAE of 0.695, and a bias value of 0.079.

$$Cw = 1.8 + 0.2069 * D$$

The residuals of the selected equation scatter randomly when plotted, without presenting systematic patterns, confirming that the assumptions of normality and independence are satisfied (Figure 8).

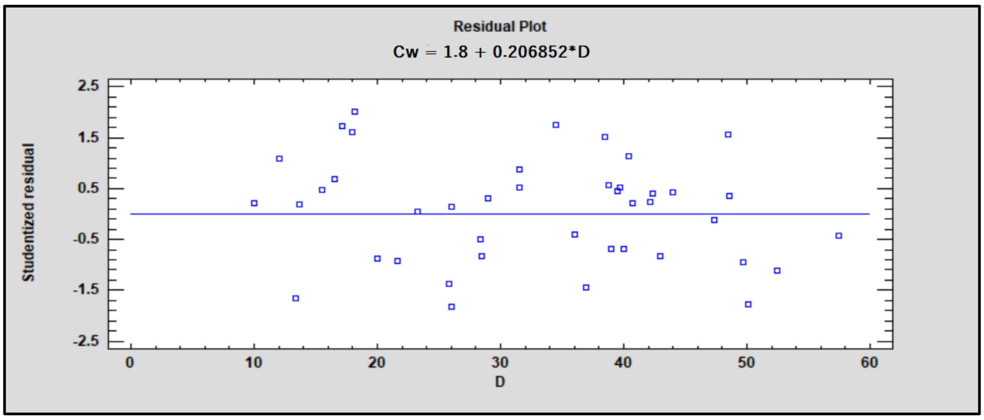

Figure 8. Residual distribution of the selected model for open-grown trees at the Zawita site

3.3.2. Stand-Grown Trees (Cw vs. D)

After the development and analysis of fifteen regression equations for precision, the following allometric equation was chosen as the most representative model for the site:

$$Cw = 1.5 + 0.1961 * D$$

The derived result showed the following statistic: R^2 = 0.992, a Salih index of 0.702, MAE = 0.422, and bias values of 0.036. The scatter plot shows a random distribution of the residuals with no apparent pattern, confirming that the residuals are normally and independently distributed. This justifies the underlying assumptions for linear regression (Figure 9).

3.4. Presentation of Selected Allometric Equations

Concise and well-organized tabulated presentations of the selected allometric equations best capture the relationship between various variables at all study sites (Table 6). Such presentations maintain clarity, allow direct comparison among models, and avoid duplication of results.

3.5. Validation

Table 7 provides R^2 values and t-test results for the comparison of calibration and validation equations for all sites. These results confirm that the calibration equations can be assumed to predict crown widths accurately.

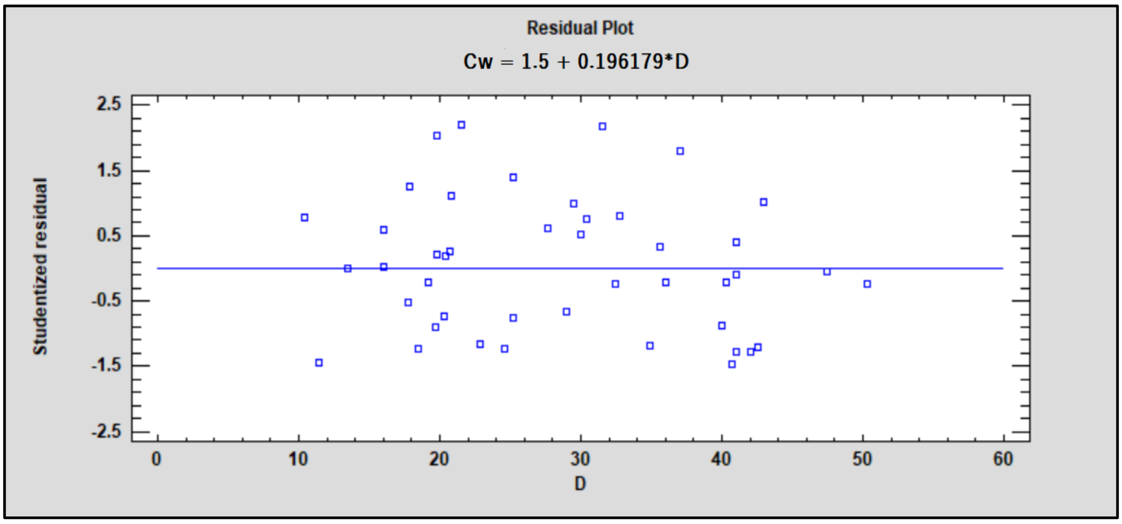

Figure 9. Residual distribution of the selected model for stand-grown trees at the Zawita site

Table 6. A summary of the developed allometric equations across the three study sites

location	Open grown trees	Stand grown trees
Atrush	$Cw = 2 + 0.2164 * D$	$Cw = 1.5 + 0.2309 * D$
Belkaf	$Cw = 4 + 0.1489 * D$	$Cw = 2.1 + 0.2035 * D$
Zawita	$Cw = 1.8 + 0.2069 * D$	$Cw = 1.5 + 0.1961 * D$

Table 7. t-Test results for comparing calibration and validation equations across studied locations

Locations	Equations	b_1	R^2	P-Value	Sig.
Atrush–open	Calibration Eq.	0.2164	0.990	0.99	P > 0.01
	Validation Eq.	0.2055	0.965		
Atrush–stand	Calibration Eq.	0.2309	0.986	0.98	P > 0.01
	Validation Eq.	0.2062	0.982		
Belkef–open	Calibration Eq.	0.1489	0.983	0.99	P > 0.01
	Validation Eq.	0.1480	0.967		
Belkef–stand	Calibration Eq.	0.2035	0.985	0.98	P > 0.01
	Validation Eq.	0.1815	0.972		
Zawita–open	Calibration Eq.	0.2069	0.987	0.98	P > 0.01
	Validation Eq.	0.1840	0.980		
Zawita–stand	Calibration Eq.	0.1961	0.992	0.98	P > 0.01
	Validation Eq.	0.1744	0.966		

According to Table 7, the slopes of the calibration and validation equations for all sites and growth conditions were very similar, and all t-test comparisons were not significant ($p > 0.01$). This suggests that the calibration models reliably capture the crown–diameter relationship, and the differences between calibration and validation equations are negligible. This means that the selected sample for calibration at both growth conditions across all locations is representative of the whole population. The high R^2 values for both the calibration and validation models across all sites indicate the good predictive accuracy and consistency of the chosen equations. This implies that the developed models can be confidently used for estimating crown width in both open-grown and stand-grown trees in the areas under study.

3.6. Comparison of Developed Allometric Equations

T-test comparison analyses were performed to understand the differences in the crown–diameter relationship of open-grown trees versus stand-grown trees within each site, as well as between sites for both types of growth. Table 8 contains these summary results: P-values and significance levels ($p < 0.01$ or $p > 0.01$) for each comparison. The selected allometric equations are simple linear models as follows:

$$Cw = b_0 + b_1 * D$$

where: b_0 and b_1 represent y-intercept of the regression model and slope respectively.

A total of nine t-test comparisons were performed to evaluate differences in the crown–diameter relationship between open- and stand-grown trees within each site, as well as between locations for both growth conditions (Table 8). Within-site comparisons (Atrush: p = 0.99; Zawita: p = 0.29; Belkef: p = 0.94) showed no significant differences, indicating that growth condition did not affect the parameter. Similarly, between-site comparisons for stand-grown trees (Atrush vs. Zawita: p = 0.08; Atrush vs. Belkef: p = 0.62; Zawita vs. Belkef: p = 0.18), and open-grown trees (Atrush vs. Zawita: p = 0.43; Atrush vs. Belkef: p = 0.61; Zawita vs. Belkef: p = 0.68) were all not significant ($p > 0.01$). This indicates that any observed differences are likely due to random variation rather than true differences between growth conditions or locations. These findings prove that the crown–diameter relationship is consistent across different growth types and sites, which means that variations in tree density among the locations may not influence the parameter significantly.

3.7. Calculation of the Proposed Competition Equation

The Competition Index (CI) is the ratio of the sum of the estimated crown widths (Cw) of trees growing in competitive stand conditions to the sum of the estimated crown widths of trees growing in free-growing conditions:

$$CI = \frac{\sum C\hat{w}_{Stand}}{\sum C\hat{w}_{Open}}$$

For achieving accurate and consistent CI values, the selected allometric equations were employed within a standardized diameter at breast height (DBH). Table 9 lists the estimated crown widths of open-grown and stand-grown trees in all three study sites.

Table 8. Summary of t-test results comparing the slopes of regression models across locations

Type of comparison	P-value	Sig.
Atrush (stand vs open grown)	0.99	P > 0.01
Zawita (stand vs open grown)	0.29	P > 0.01
Belkaf (stand vs open grown)	0.94	P > 0.01
Atrush stand grown vs Zawita stand grown	0.08	P > 0.01
Atrush stand grown vs Belkaf stand grown	0.62	P > 0.01
Zawita stand grown vs Belkaf stand grown	0.18	P > 0.01
Atrush open grown vs Zawita open grown	0.43	P > 0.01
Atrush open grown vs Belkaf open grown	0.61	P > 0.01
Zawita open grown vs Belkaf open grown	0.68	P > 0.01

Table 9. Estimated crown widths for trees in open and stand-grown conditions across three study locations

Diameter (Cm)	Atrush location		Belkaf location		Zawita location	
	Open grown trees (m)	Stand grown trees (m)	Open grown trees (m)	Stand grown trees (m)	Open grown trees (m)	Stand grown trees (m)
5	3.08	2.65	4.74	3.11	2.83	2.48
10	4.16	3.80	5.48	4.13	3.86	3.46
15	5.24	4.96	6.23	5.15	4.90	4.44
20	6.32	6.11	6.97	6.17	5.93	5.42
25	7.41	7.27	7.72	7.18	6.97	6.40
30	8.49	8.42	8.46	8.20	8.00	7.38
35	9.57	9.58	9.21	9.22	9.04	8.36
40	10.65	10.73	9.95	10.24	10.07	9.34
45	11.73	11.89	10.70	11.25	11.11	10.32
50	12.82	13.04	11.44	12.27	12.14	11.30
55	13.90	14.19	12.18	13.29	13.17	12.28
60	14.98	15.35	12.93	14.31	14.21	13.26
65	16.06	16.50	13.67	15.32	15.24	14.24
Sum=	124.46	124.56	119.75	119.89	117.54	108.71

To measure the degree of influence of stand density on crown growth for each site, the Competition Index (CI) was determined:

For Zawita site: CI = 108.71 / 117.54 = 0.925,

For Atrush site: CI = 1.00,

For Belkef site: CI = 1.00

The proposed competition index provides clear evidence of the effect of stand density on crown development. In Zawita, the CI was 0.925, indicating that stand-grown trees maintained crowns about 7.5% narrower than open-grown trees, reflecting a minor competitive influence on lateral crown expansion. In Atrush and Belkef, CI values of 1.00 indicate that stand-grown trees achieved crown widths equal to those of open-grown trees, with no measurable competition effect. These results suggest that competition had only a minor impact on crown growth in Zawita, while Atrush and Belkef represented conditions where crown expansion was largely unaffected by stand density. Overall, the CI effectively quantifies site-specific competitive effects, demonstrating its usefulness for assessing the influence of stand density on crown development.

4. Discussion

This study found a clear and strong relationship between CW (crown width) and DBH (diameter at breast height) in *Pinus brutia* trees. The relationship was described by a simple linear equation with very high R^2 values ranging from 0.983 to 0.992, which supports the use of DBH for predicting CW. The results presented in this study are consistent with those reported for Mediterranean pines in previous studies. Avsar (2004) reported a strong positive relationship for *Pinus brutia* in Turkey, with an R^2 of 0.74. Condés and Sterba (2005) established allometric equations relating crown width to DBH for several Spanish pine species, using power-function models to describe crown expansion under open-grown and stand-grown conditions in Spain. Similarly, Raptis et al. (2018) reported a strong relationship between crown width and DBH in the Mediterranean pine forests of Greece, where R2R^2R2 was 0.71. On the Iberian Peninsula, Poorter et al. (2012) analyzed architectural relationships for six *Pinus* species and generally reported strong coordination between crown diameter and stem diameter across species, with fits in the moderate to high range (e.g., $R^2 \approx 0.50–0.84$). These findings support the general allometric trend in Mediterranean pines, where crown width consistently increases with diameter at breast height across species and sites.

In Mediterranean pine research, many earlier allometric studies reported only model-fit statistics without evaluating predictive accuracy. However, several recent studies have emphasized the need for validation. For example, Raptis et al. (2018) developed crown width–diameter models for *Pinus* species in Greece and evaluated their predictive performance using independent crown width observations, providing a direct methodological parallel to the present work. Similar validation practices have been applied in Türkiye: both Özçelik & Altınkaya (2019) and Özçelik & Kalkanlı (2018) used split-dataset or cross-validation techniques in studies conducted specifically on *Pinus brutia*. In addition, Sağlam & Sakici (2024) introduced an entirely independent validation dataset while developing regression models for *Pinus* species. Therefore, based on such studies, validation procedures are being increasingly adopted in Mediterranean pine research. This study follows this improved methodology by using split-sample validation, thereby increasing confidence in the derived crown width–DBH model.

The competition index findings of the present study fit well within the context of earlier work on Mediterranean *Pinus brutia*. Salih et al. (2019) developed a competition factor for *P. brutia* by comparing the performance of open-grown and stand-grown trees and therefore expressed competition as a ratio between potential (competition-free) and realized growth. Although their index was based on diameter growth rather than crown width, the logic is the same as in the present study: values close to 1 indicate little competitive influence, while lower values reflect increasing competitive pressure. This is sufficient to conclude that the newly proposed crown-width Competition Index (CI) is aligned with the previously established Mediterranean approach. Additional insights come from studies outside the region that demonstrate the same biological principle. Hein and Spiecker (2008) found that open-grown ash and sycamore trees in Germany had much wider crowns than those in denser stands, confirming the sensitivity of crown dimensions to spacing. Bailey (1964) similarly showed that competition reduces crown width and modifies crown form in lodgepole pine. Earlier work by Hasenauer (1997), Minckler & Gingrich (1970), and Vezina (1962) also reported wider crowns in open-grown trees compared with stand-grown individuals. Although these studies differ in species and location, they consistently support the idea that crown size responds directly to competition, providing a strong conceptual foundation for the CI introduced in the present study.

5. Conclusions

The study presents several key conclusions. First, there is a strong and significant relationship between crown width and diameter at breast height across all study locations. This finding supports that tree crowns increase in width proportionately with tree diameter growth, thus highlighting the close relationship between stem growth and canopy development.

Second, the relationship between CW and DBH remained almost the same regardless of site or growth condition. The slopes of the regression lines did not differ significantly, and there were no major differences between open-grown and stand-grown trees at the same site. This shows that tree density in the stands was not high enough to limit crown growth.

Third, the study introduces a new index for quantifying tree competition in terms of crown width. By comparing crown widths of stand-grown and open-grown trees, the Competition Index (CI) provides a direct measure of how competition influences canopy development. Values of CI close to 1 indicate minimal competition, while lower values reflect stronger competitive pressure. In this regard, the measure is biologically meaningful and practically useful for evaluating stand structure and guiding silvicultural decisions and forest management planning. In the present study, CI values were nearly 1 at all sites.

Fourth, the low stand density observed at the study sites indicates that present stocking levels are not making maximum use of the available growing space and site resources. This suggests that further planting is needed to fill canopy gaps and achieve a more balanced stand structure. Increasing stocking through systematic replanting would help improve resource-use efficiency, support healthier crown development, and provide long-term resilience and biodiversity benefits for forests.

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روشی نوین برای ارائۀ شاخص رقابت با استفاده از رابطۀ قطر تاج و قطر برابرسینه در درختان کاج مدیترانه‌ای (*Pinus brutia* Ten.) طبیعی در عراق

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چکیده

مقدمه: جنگل‌ها حدود ۳۰ درصد از مساحت خشکی‌های زمین را پوشش می‌دهند، اما در عراق مساحت آنها محدود بوده و اغلب در نواحی شمالی کشور متمرکز است؛ چنانکه در مجموع حدود ۱/۲۶ میلیون هکتار، معادل ۲/۹ درصد مساحت کشور را شامل می‌شود. جنگل‌های این منطقه شامل تیپ‌های سوزنی‌برگ و پهن‌برگ هستند. جنگل‌های سوزنی‌برگ اغلب تحت سلطۀ گونه‌های کاج هستند که حدود ۸۰ درصد توده‌ها را تشکیل می‌دهند. کاج مدیترانه‌ای (*Pinus brutia*) که بومی استان دهوک در شمال عراق است، مساحتی در حدود ۵۰۰۰۰ هکتار را در مناطق زاویته، اتروش و بیلکیف پوشش می‌دهد. این پژوهش به بررسی رگرسیون عرض تاج با قطر برابرسینه به‌منظور استفاده در توسعۀ یک شاخص رقابت می‌پردازد. عرض تاج برای پویایی جنگل، تنوع زیستی، ترسیب کربن و سلامت کلی اکوسیستم اهمیت دارد.

مواد و روش‌ها: داده‌های میدانی از سه مکان متمایز در استان دهوک، اقلیم کردستان عراق جمع‌آوری شد. در مجموع ۴۸۰ درخت از هر دو گروه درختان رشدیافته در فضای باز و درختان رشدیافته در توده نمونه‌برداری شدند. از هر مکان ۱۶۰ درخت انتخاب شد (۸۰ درخت رشدیافته در فضای باز که عاری از هرگونه رقابت بودند و ۸۰ درخت رشدیافته در توده که رقابت بین‌درختی برای دسترسی به منابع وجود داشت). از این تعداد، ۵۰ درخت برای کالیبراسیون و ۳۰ درخت برای اعتبارسنجی استفاده شد که به یک مجموعه دادۀ متوازن و قابل اتکا برای تحلیل انجامید. با استفاده از نرم‌افزار Statgraphics Centurion 19 ، رگرسیون‌های جداگانه‌ای بین عرض تاج (CW) و قطر برابرسینه (DBH) برای هر دو نوع درخت توسعه داده شد. شش گروه از معادلات رگرسیون آلومتریک با استفاده از معیارهایی شامل ضریب تعیین (R^2)، اریبی، میانگین قدر مطلق خطا(MAE) ، آزمون بی‌طرفی اوتومو و بقیۀ شاخص‌های پیشنهادی ارزیابی شدند.

نتایج: عرض تاج در برابر قطر برابرسینه با استفاده از انواع مختلف توابع، از جمله مدل‌های خطی، غیرخطی و لگاریتمی با اشکال گوناگون متغیر وابسته، برازش داده شد. براساس تحلیل‌های آماری مدل‌های توسعه‌یافته، مدل خطی به‌صورت $Cw = b_1 + b_2\ DBH$ به‌عنوان مناسب‌ترین مدل که داده‌های مطالعه را در همۀ مکان‌ها به‌خوبی برازش می‌دهد انتخاب شد. در نتیجه، تفاوت زیادی بین شیب‌های رگرسیون درختان رشدیافته در فضای باز و درختان رشدیافته در داخل توده مشاهده نشد. افزون‌بر این، در این پژوهش روشی نوین برای محاسبۀ شاخص رقابت ارائه شد.

نتیجه‌گیری: از تجزیه‌وتحلیل نمونه‌های جمع‌آوری‌شده، می‌توان به نتایج مهم زیر دست یافت: نخست، در همۀ سایت‌های بررسی‌شده، رابطۀ بین عرض تاج و قطر برابرسینه (DBH) تفاوت آماری معنی‌داری بین درختان انفرادی و توده‌ای نشان نداد. این امر نشان‌دهندۀ تراکم به‌نسبت کم توده است که به رقابت حداقلی برای منابع در میان درختان توده‌ای منجر می‌شود؛ دوم، با توجه به بهبود ساختار کلی و بهره‌وری جنگل، توصیه می‌شود که راهبردهای بازکاشت به پر کردن شکاف‌های موجود در تاج‌پوشش در همۀ سایت‌ها متمرکز شوند، زیرا این کار سبب استفادۀ بهتر از منابع موجود، ارتقای سلامت بلندمدت جنگل‌ها و حفظ تنوع زیستی خواهد شد. در نهایت، پژوهش حاضر رابطۀ خطی قوی بین عرض تاج و قطر برابرسینه را تأیید کرد.

واژه‌های کلیدی: شاخص رقابت تاج، کاج بروسیا، مدل‌سازی تاج، مدل‌های رگرسیون، معادلات آلومتریک.

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