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Modeling the Phenotypic Characteristics of *Pinus Brutia* Trees in Northern Iraq

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Annotation: The morphological characteristics of forest trees are fundamental factors influencing their growth dynamics and overall development. These traits play a crucial role in evaluating biological productivity and understanding growth patterns within forest ecosystems. Mathematical modeling serves as an essential tool for analyzing changes in tree volume and biomass. In this study, 26 circular sample plots, each with a radius of 17.9 meters, were established in naturally growing Pinus brutia stands located in the Dohuk region of northern Iraq. Field data were collected from each plot, including diameter at breast height (DBH), total tree height, crown height, crown length, and crown center height. Additional calculations included basal area, crown coverage area, volume, and annual increments in diameter, height, and volume. Using these data, a variety of regression models were employed to develop equations estimating the annual growth in diameter, height, and volume. Model selection was based on several statistical criteria, including the coefficient of determination (R^2), standard error of the parameters, the Durbin-Watson statistic, and residual analysis. These indicators confirmed the accuracy and reliability of the developed models. Based on the results, growth tables were constructed to illustrate changes in diameter and height across two consecutive periods relative to tree height.

Keywords: pine trees, annual growth

functions, mathematical models, phenotypic characteristics of trees.

Introduction

Growth modeling plays a vital role in promoting forest sustainability by enabling the analysis and understanding of how forest trees develop based on their phenotypic characteristics. These models allow forest managers to estimate both current and future growth and productivity, thereby supporting informed administrative and developmental decision-making. Moreover, such models can be used to evaluate silvicultural interventions, such as thinning and selective harvesting, and their effects on ecosystem dynamics. They also contribute to enhancing forest vitality, conserving biodiversity, and maintaining growing stock, all of which are essential for long-term sustainability (Peng, 2000). Tree species exhibit distinct morphological characteristics that reflect their adaptation strategies and interactions with biotic and abiotic environmental factors. Variability among individual trees leads to significant differences in phenotypic traits, which in turn influence growth processes. The distribution of diameter and height plays a key role in determining growth stages and is closely linked to tree volume. Additionally, crown-related phenotypic traits—such as crown coverage area, width, and length—are crucial indicators of tree activity, vigor, and longevity. A well-developed crown structure enhances a tree's ability to intercept sunlight, which improves photosynthetic efficiency and ultimately supports the formation of a robust root system for optimal nutrient uptake. The crown area is directly associated with photosynthesis, and well-distributed branches increase light capture while minimizing internal competition. These traits are particularly beneficial for tree survival in semi-arid environments. Furthermore, the structural integrity and balance of a tree contribute to creating habitats favorable to wildlife (Kelley & Harris, 2020). Tree composition and form vary with developmental stages and environmental conditions. In low- to medium-density stands, reduced competition allows for increased lateral branch growth and improved crown expansion, leading to a broader crown coverage area (Smith & Lee, 2020). Tree density, expressed as the number of trees per unit area, serves as an indicator of both stand structure and biomass. While higher densities may increase total biomass, they often reduce the growth of individual trees due to intra- and interspecific competition. In contrast, moderate densities tend to optimize the balance between tree number and volume, enhancing individual tree growth. Therefore, tree density is a key parameter in production modeling and in estimating forest carbon stocks. It provides essential information for making sound decisions regarding stand structure, growth dynamics, and developmental stages. This study aims to develop models for estimating current growth based on phenotypic characteristics, structural features, biological functions, and chemical components of *Pinus brutia* and oak trees growing in the Dohuk region of northern Iraq.

Materials and Methods

This study was conducted in Dohuk Governorate, located in northern Iraq, within the geographical boundaries of latitudes 18°36′12.64″ to 20°37′33.55″ N and longitudes 42°20′25.36″ to 44°17′40.50″ E, at elevations ranging from 430 to 2500 meters above sea level. The region experiences a Mediterranean-type climate, characterized by cool winters with relatively high humidity and moderate annual rainfall ranging from 600 to 800 mm. Summers are typically hot and dry, with significantly elevated temperatures (Mzuri et al., 2012). The area's soil exhibits considerable variation in both chemical and physical properties. Sampling was conducted at four randomly selected sites—Zawita, Al-Sheikhan, Sierra-Tica, and Achaua—following initial field surveys. A total of 26 circular sample plots, each with a radius of 17.9 meters, were established. The central point of each plot was marked by a dominant tree, which served as the focal tree for measurement. Geographic coordinates of the plot centers were recorded using the GPS Test application. For each focal tree, the following measurements were collected: total height (m), crown center height (m), diameter at breast height (cm), crown diameter (m), and the number of branches. In addition, the basal area (m²), crown coverage area (m²), crown length (m), and percentage of crown length were calculated. Annual diameter growth was also assessed for each tree. To analyze the collected data, a range of statistical techniques were employed. These included traditional methods such as correlation and regression analysis, along with the coefficient of determination (R^2) and residual analysis, ensuring a comprehensive interpretation of the relationships among the measured variables and the development of robust predictive models.

Results and Discussion

Pinus brutia trees exhibit distinct morphological characteristics that not only support their adaptability but also confer both economic and ecological value. To understand the dynamics of their development, it is essential to explore the relationships between continuous annual growth functions—specifically diameter, height, and volume—and various morphological traits, including age, total height, diameter at breast height (DBH), tree density, volume, crown diameter, crown length, and crown coverage area. One effective method to visualize and interpret these relationships is through the use of a correlation matrix displayed as a heatmap. This graphical representation illustrates the correlation coefficients (r) between each pair of variables, with values ranging from -1 to 1. These values indicate both the strength and direction of the relationships: values approaching 1 (displayed in dark red) represent strong positive correlations, while values nearing -1 (shown in dark blue) indicate strong negative correlations. By analyzing the intensity and direction of these correlations, key morphological variables that significantly influence annual growth functions can be identified. This insight is instrumental in developing reliable predictive models for estimating tree growth. To this end, data were collected from naturally growing *Pinus brutia* trees across selected forest sites in the Dohuk region. Correlation analysis was performed between growth functions and morphological characteristics using the Statgraphics Centurion 18 software. The resulting correlation heatmap is presented in Figure 1, providing a comprehensive overview of the interrelationships among the studied variables.

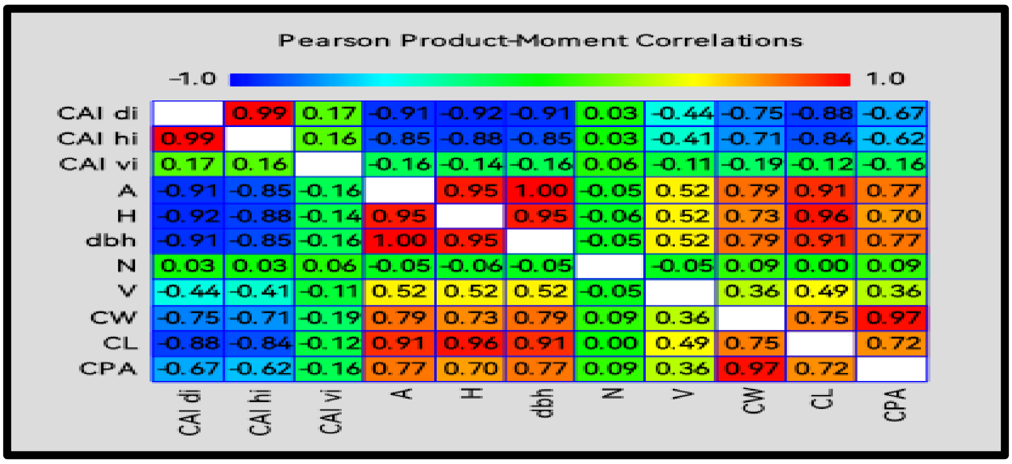

Figure (1) Thermal correlation matrix of growth functions with morphological variables of *Pinus brutia* trees

From the analysis of Figure 1, a clear variation is observed in the correlation values between the continuous annual growth functions and the morphological characteristics of *Pinus brutia* trees. Regarding continuous annual increment in diameter (CAI_di), there was a strong negative correlation with tree age, total height, diameter at breast height (DBH), crown length, and crown width, with respective correlation coefficients of -0.91, -0.92, -0.91, -0.75, and -0.88. CAI_di also exhibited moderately strong negative correlations with tree volume and crown coverage area, with correlation values of -0.44 and -0.67, respectively. Similarly, the continuous annual increment in height (CAI_hi) demonstrated strong negative correlations with age, height, DBH, crown length, and crown width, with correlation coefficients of -0.85, -0.88, -0.85, -0.71, and -0.84, respectively. Moderate negative correlations were also observed with volume and crown coverage area, with values of -0.41 and -0.62, respectively. These negative correlations between CAI_di and CAI_hi and tree age can be attributed to the natural growth dynamics of forest trees. During the early stages of growth, trees exhibit vigorous increases in diameter and height. However, as trees mature, their growth rate declines due to physiological aging and increased competition for limited resources. The negative relationships between annual growth increments and both DBH and tree height similarly reflect the impact of size and age on growth performance; as trees become larger, their resource demands increase, intensifying competition and subsequently reducing growth rates. The observed negative correlations between growth increments and volume are consistent with the fact that volume is a composite outcome of increased diameter and height. As these dimensions grow, tree age and structural mass increase, which again intensifies competition, particularly for light, water, and nutrients, thereby reducing the rate of new growth. Furthermore, the negative correlation between growth increments (diameter and height) and crown dimensions (length, width, and coverage area) suggests intra-crown competition. The expansion of crown volume—encompassing branches, twigs, and foliage—demands greater nutrient allocation, especially those produced through photosynthesis. This internal competition may hinder further growth in stem diameter and height. Based on this analysis, multiple regression models were developed to describe the continuous annual growth functions (diameter, height, volume) and individual tree volume in relation to morphological characteristics. These models are summarized in Table 1.

Table (1) Equations for estimating continuous annual growth in (diameter, height, volume) and single tree volume for *Pinus brutia* trees.

No.	Model	R^2	S.E.	DW
1	$CAI\ d = 0.345763 * H^{-0.0544546}$	96.86	0.00143	1.72
2	$CAI\ h = 0.663204 * H^{-0.516073}$	98.12	0.00921	1.69
3	$CAI\ v = 0.0458534 * H^{-0.630927}$	94.26	0.00118	1.80

The continuous annual growth in diameter (CAI_d) represents the yearly increase in a tree's stem diameter and is typically estimated through periodic field measurements or predictive modeling using associated variables. This metric serves as a critical biological indicator, where robust annual diameter growth reflects favorable environmental conditions and supports species-specific growth assessments. Consequently, forest productivity can be evaluated based on diameter increment trends, as they are directly tied to timber yield and stand development. Estimating CAI_d at the regional level also facilitates the projection of future tree volume, which in turn informs the development of forest management strategies aimed at promoting long-term sustainability (Williams & Johnson, 2018). Furthermore, this indicator is instrumental in monitoring ecological and climatic changes and assessing the degree of inter-tree competition for essential resources. It also plays a role in determining appropriate harvesting cycles within forest stands. Thus, CAI_d functions as a key tool in forest planning and management, helping to strike a balance between resource utilization and ecosystem conservation. Based on the regression analysis shown in Table 1, the CAI_d of *Pinus brutia* trees was modeled as a function of total tree height, as expressed in Equation (1). This non-linear model yielded a high coefficient of determination (R^2 = 96.86%), a low standard error (0.00143), and a Durbin-Watson (DW) statistic of 1.72. These values confirm the model's robustness and accuracy in estimating growth. Additionally, residual analysis revealed no evidence of autocorrelation and a random distribution of residuals, supporting the validity and reliability of the model. Accordingly, Equation (1) from Table (4-3) can be confidently applied to estimate the continuous annual diameter growth of *Pinus brutia* trees of uneven-aged stands in the forests of Dohuk. Utilizing this equation, a reference table (Table 2) was developed, presenting CAI_d values corresponding to total tree height, thereby facilitating practical application for forest growth prediction and management planning.

Table (2) The relationship between tree height and continuous annual growth in diameter for *Pinus brutia* trees growing in mixed trees of unequal age in Dohuk forests.

CAI d / cm	H / m	CAI d / cm	H / m
0.332954	2	0.308746	8
0.325683	3	0.306772	9
0.320621	4	0.305017	10
0.316749	5	0.303439	11
0.31362	6	0.302004	12
0.310999	7	0.300691	13

From Table (2), it is evident that the thickness of the annual rings—representing the tree's radial growth (CAI_d)—gradually declines with increasing tree height. This increase in height is generally associated with tree age, and is a direct result of cumulative radial growth, expressed as the annual addition of xylem and phloem tissues, contributing to the tree's circumference expansion. The progressive decline in annual diameter growth with age is largely attributed to the physiological aging of vascular cambium cells, whose activity diminishes over time, reducing their capacity to produce wood and bark tissues. This decline leads to a corresponding reduction in the radial growth rate of *Pinus brutia* (Miller & Thompson, 2020). Furthermore, these trees grow in dry to semi-arid environments, which negatively impact photosynthetic efficiency. Reduced photosynthesis limits the formation of carbohydrates necessary for tree growth, further contributing to the decline in annual diameter increment. Therefore, the narrowing of annual growth rings serves as a biological indicator of the tree's developmental stage, continuing through various phases of maturity until the tree reaches physiological senescence. Regarding continuous annual height growth (CAI_h), this metric reflects the yearly vertical increment in tree height, typically measured through field observations or modeled using related variables. Height growth is a crucial indicator of tree vitality and site quality, reflecting the availability of essential resources such as soil nutrients, moisture, and favorable climatic conditions. It also plays a central role in determining the **site index**, which evaluates a site's productivity potential and helps match species to suitable environments—especially important for evaluating the performance of introduced species. As such, CAI_h serves as a guiding parameter in forest management decision-making, helping formulate administrative plans aimed at achieving sustainability goals. Understanding the height growth trajectory across different life stages allows for optimized planning of silvicultural interventions, such as thinning operations. Thinning reduces intra-stand competition and selectively removes less vigorous trees, thus favoring the growth of dominant individuals. This is particularly beneficial in uneven-aged forests, where proper thinning promotes continuous height increment, ultimately enhancing productivity and stand structure (Martin & Roberts, 2021). Referring again to Table (2), Equation (2) models CAI_h as a function of total tree height. The statistical parameters of the model are strong, with a coefficient of determination (R^2) of 98.12%, a low standard error (0.00921), and a Durbin-Watson (DW) statistic of 1.29. These metrics suggest that total tree height is a reliable predictor of annual height growth. To verify the model's robustness, a residual analysis was conducted, showing randomly distributed residuals around the zero line—indicating the absence of autocorrelation and supporting the model's validity. Thus, Equation (2) can be confidently used to estimate the continuous annual height growth of *Pinus brutia* in uneven-aged stands. Based on this equation, a reference table was generated (Table 3), showing corresponding values of CAI_h for varying total tree heights, thereby offering a practical tool for forest management and growth forecasting.

Table (3) The relationship between tree height and continuous annual growth in height of *Pinus brutia* trees growing in mixed trees of unequal age in Dohuk forests.

CAI h / cm	H / m	CAI h / cm	H / m
0.463761	2	0.226772	8
0.3762	3	0.213398	9
0.324296	4	0.202105	10
0.289021	5	0.192405	11
0.263067	6	0.183956	12
0.24295	7	0.176512	13

From Table (3), it is evident that the continuous annual growth in height (CAI_h) gradually declines as the total height of the tree increases. This increase in height is generally associated with advancing tree age, and as trees age, the efficiency of physiological processes—including apical meristematic activity—diminishes. Reduced cell division at the shoot apex limits vertical growth, resulting in a lower annual height increment. Additionally, as tree height increases, the crown expands in volume, necessitating a redistribution of photosynthates. A significant portion of these carbohydrates is allocated to the development of branches and twigs, while another portion is directed toward reproductive structures such as cones and seeds. This allocation pattern reduces the resources available for height increment, ultimately decreasing the continuous annual growth in height of *Pinus brutia* (Parker & Peterson, 2019). Furthermore, indicators of continuous annual growth in volume (CAI_v) are also essential in assessing tree vitality and stand productivity. These indicators provide valuable insights for sustainable forest management by helping estimate timber yields, evaluate cutting cycles, and optimize productivity per unit area. Volume growth data serve as the basis for developing economically efficient harvesting strategies and predicting long-term forest outputs. Moreover, changes in annual volume growth can be used as indicators to monitor environmental stress and climatic fluctuations affecting forest ecosystems (Hernandez & Johns, 2021). Referring to Table (3), Equation No. (3) was developed to estimate the continuous annual growth in volume (CAI_v) of *Pinus brutia* as a function of total tree height. The model demonstrates a strong fit, with a coefficient of determination (R^2) of 94.26%, a low standard error (0.00118), and a Durbin-Watson (DW) statistic of 1.80. These statistical indicators confirm the model's robustness and its suitability for accurate prediction. To validate the model, a residual analysis was conducted, which showed that residuals were randomly distributed around the zero line—indicating no autocorrelation among the observations. Thus, Equation No. (3) is statistically valid and can be reliably used to estimate the continuous annual growth in volume of *Pinus brutia* trees. Based on this equation, Table (4) was prepared to present estimated CAI_v values corresponding to different total tree heights, offering a practical reference for assessing growth dynamics and supporting forest management planning.

Table (4) The relationship between tree height and continuous annual volume growth of *Pinus brutia* trees growing in mixed trees of unequal age in Dohuk forests.

CAI v / cm^3	H / m	CAI v / cm^3	H / m
0.029608	2	0.012347	8
0.022925	3	0.011463	9
0.01912	4	0.010726	10
0.016609	5	0.0101	11
0.014804	6	0.00956	12
0.013432	7	0.009089	13

From Table (4), it is evident that the continuous annual growth in volume (CAI_v) of *Pinus brutia* trees shows a gradual decline as the total height of the tree increases. This trend aligns with the results obtained from the mathematical model developed to estimate CAI_v based on total tree height. The observed decline can be attributed to the fact that volume growth is inherently dependent on both diameter and height increments. As trees grow taller—typically as a function of age—their physiological efficiency, particularly photosynthesis, begins to diminish due to aging processes. This reduction in photosynthetic activity translates into a lower availability of carbohydrates essential for secondary growth, including volumetric development of the stem. Moreover, with increasing tree height, there is a corresponding expansion in crown volume and complexity. This includes an increase in the number and size of leaves, branches, and twigs, all of which demand a significant share of the nutrients produced through photosynthesis. Consequently, a greater proportion of these resources is diverted to sustaining and developing the crown, leaving fewer resources available for stem volume growth. This nutrient competition between crown expansion and stem development contributes to the decline in volumetric growth with increasing height (Smith & White, 2019).

Conclusion

Based on the findings of this study, it can be concluded that the continuous annual growth in diameter, height, and volume of *Pinus brutia* trees is negatively influenced by increasing tree age and height. As trees mature, their physiological processes, such as photosynthesis, decline, which reduces the available nutrients for growth, particularly in diameter and volume. Additionally, as tree height increases, resources are allocated to crown development, further limiting growth in stem volume. These insights are crucial for forest management and planning, as they highlight the importance of considering tree age, height, and competition for resources when developing sustainable management practices.

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