

Article

Diameter Increment Estimations of Open-Grown Stone Pine (*Pinus pinea* L.) Trees in Urban Parks in Istanbul, Türkiye

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Abstract: Open-grown trees in cities can improve environmental conditions by providing sustainable ecosystem services. Reliable data are necessary for assessing the functions of urban trees. The diameter at breast height (DBH), diameter increment, and annual ring measurements are the main parameters in the development of reliable models. To model periodic mean diameter increments calculated for different time periods (5, 10, 15, 20, and 25 years), a total of 43 open-grown stone pines (*Pinus pinea* L.) of different diameter classes were sampled in several urban parks in Istanbul, Türkiye. The DBH was measured, and increment cores were extracted from each tree at 1.30 m stem height using an increment borer. Tree age at breast height was determined by counting annual rings, and periodic mean diameter increments were calculated for different periods based on the measured tree-ring widths. The periodic mean increments of different periods were related to the inside-bark diameter at breast height and tree age. Since there was no significant relationship between tree age and periodic mean increments for each period's length, as shown in the correlation analysis, models used to estimate the periodic mean increments of inside-bark DBH were developed using the least squares regression and quantile regression (QR) techniques. As the period length increased, the estimation success of the diameter increment models increased while the mean absolute percentage error (MAE) values decreased from 40 to 32%. The best model was the one used for the last 25-year period with the quantile value $q = 0.50$ which estimated the diameter increment with an RMSE = 1.391 mm/year and MAE = 32.27%.

Keywords: DBH; MAE; quantile regression; urban tree; year ring



Citation: Uçan, H.A.; Özdemir, E.; Sağlam, S.; Özdemir, G.A.; Makineci, E. Diameter Increment Estimations of Open-Grown Stone Pine (*Pinus pinea* L.) Trees in Urban Parks in Istanbul, Türkiye. *Sustainability* **2024**, *16*, 9793. <https://doi.org/10.3390/su16229793>

Academic Editor: Dario Donno

Received: 2 August 2024

Revised: 30 October 2024

Accepted: 6 November 2024

Published: 10 November 2024



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1. Introduction

The increase in urbanization and the urban population as well as the significant effect of sustainable land use on the land surface have a major impact on the local environment and climate. Anthropogenic pollution and disruption brought about by urbanization raises urban temperatures and increases the emission of pollutants and particulate matter, especially carbon dioxide, making cities hotter and more polluted. The common use of impermeable dark materials that store enormous amounts of heat in urban areas contributes to further warming. Urban materials also prevent rainfall from infiltrating the soil, increase runoff, and pick up pollutants deposited on urban surfaces, degrading the overall water quality. Furthermore, the soils in which urban trees grow are often compacted and of inferior quality [1–3].

These environmental changes significantly alter the growth environment for trees in urban areas compared to rural areas. Global processes of urban growth lead to serious

environmental impacts, such as a temperature increase through the intensification of the urban heat island effect and hydrological changes, with far-reaching consequences for plant growth, human health, and well-being. In addition, over the last decade, the frequency of heat waves and drought events has increased in central Europe, exposing urban trees to even more stress under already challenging urban growth conditions [1–3].

Even while struggling to survive under such adverse urban conditions, urban trees offer many important sustainable ecosystem services [4]. The ecosystem services of urban trees can only be sustained if the trees survive and maintain their reproductive and growth potential, i.e., if they are healthy [5,6]. We emphasize that reliable tree variable data for these open-grown trees are needed to determine their value to the ecosystem, which is an increasingly critical issue. Furthermore, destructive sampling, one of the most effective sampling methods, is rarely applicable in urban inventory projects as an acceptable solution. Therefore, alternative ways to obtain the best urban free-growing tree-specific reference data are sought [6,7]. Several species-specific models have been proposed to evaluate various parameter relationships of individual trees [8,9]. These models often use readily available measurements such as the diameter at breast height (DBH) and tree height. The main limitation of model-based assessments is the requirement for species-specific population characteristics, like those used to model target populations. This depends on growing conditions, among other factors, and is problematic when assessing urban tree populations as their environments may differ from those of the models [10–12].

Predicting allometric relationships of individual, urban, or open-grown trees with models developed for forests can lead to significant errors. The results from previous studies are conflicting in terms of the applicability of common forest-derived models to urban trees. Nowak [13] reported that when forest-derived models were applied to urban and open-grown trees, some variables related to tree size, tree age, etc., especially those of the above-ground tree components, were estimated to have had error rates of up to 25%. However, Jo and McPherson [14] reported that these error rates can actually be higher, with underestimates of up to 50% for some tree species and overestimates of up to 45% for others.

It is important to determine the tree parameters of open-grown trees reliably and consistently because trees growing freely in the open develop different architectural and structural characteristics than trees growing in plantations or forest canopies in terms of competition for light, water, nutrients, and temporal processes. An accurate estimation of these parameters is essential for achieving high-accuracy measurements of sustainable ecosystem functions, even on an individual tree basis [2,4,6,7,15]. In addition, Canetti et al. [16] state that urban trees improve the quality of life in urban centers by providing social and environmental benefits. Understanding the growth of urban trees exposed to air pollution will support the sustainable planning, management, and expansion of urban areas.

The most used method is the revealing of the relationships between the diameter and the diameter increment variables of open-grown trees and making reliable estimates of the increment and growth potential of individual trees with the help of the DBH, which is easily measurable. Rohner et al. [17] emphasize that such reliable estimates are essential in many contexts, from nature conservation to forest science and management. Current methods for estimating the relationship between the tree diameter and the diameter increment are often inaccurate as they do not utilize the full potential of the available data and information on tree growth. Nature conservation also utilizes tree increment and growth information, which is a clear indicator of a tree's ecological value because of the structural diversity of protected trees and, in turn, biodiversity often increases with tree growth [18]. The aim of this approach is to identify the increment and growth patterns of urban trees to support future sustainable urban planning. For these reasons, modeling the increment and annual ring information of individual open-grown urban trees is of foremost importance for sustainable conservation and utilization purposes [19,20].

Stone pine (*Pinus pinea* L.) is an important urban tree species planted in parks and gardens with suitable ecological conditions in Istanbul and around Türkiye [21–23]. Based on this information, the main aim of this study is to develop models for the periodic mean diameter increments of inner bark diameter at breast height (DBH) using the least squares and quantile regression (QR) techniques for open-grown stone pine (*Pinus pinea* L.) trees in several urban parks in Istanbul and Türkiye. Different time periods (5, 10, 15, 20, and 25 years) were calculated for a total of 43 trees by measuring the DBH and extracting the increment cores from each tree at 1.30 m height using an increment borer.

Despite the importance of open-grown trees in urban sites, there are insufficient differentiations between them in previous researches. For this reason, this novel study aims to fill gaps in the paucity of research on the growth of open-grown stone pine trees as their sustainable development serves continuous ecological services.

2. Materials and Methods

2.1. Study Area

The study area in Istanbul consists of two peninsulas. The province of Istanbul, where the study was conducted, is a bridge between Asia and Europe and has high strategic value. Throughout history, it has been the home of many civilizations and is now an important commercial, cultural, and administrative center. Green areas and urban trees are of immense value for the people of Istanbul, which is among the world's major metropolitan cities with a population of approximately 15 million. It features a transitional climate between the Black Sea and Mediterranean climates [21]. Annual precipitation is approximately 1000 mm [23], and the highest temperature is +40 °C while the lowest is −11 °C [21].

2.2. Data

A total of 43 open-grown stone pine (*Pinus pinea* L.) trees of different diameter classes were sampled in various urban parks in Istanbul in order to model the periodic mean diameter increments calculated for different time periods. First, the breast-height and over-bark diameters of the sample trees were measured by a caliper in two perpendicular directions with a precision of 0.1 mm. To determine the diameter increments of the trees, two increment cores were extracted at 1.30 m height from two directions perpendicular to each other using an increment borer. In the laboratory, the cores were glued onto corrugated cardboard and sanded until the annual rings were clearly visible [24]. The annual rings were counted to determine tree age at breast height, and their widths were measured with a precision of 1/1000 mm using the TSAP-WinTM-4.81 program [25] on a LINTAB-6 (Frank Rinn S.A, Heidelberg, Germany) device [26]. LINTAB, used for measuring annual ring width, is a measuring system with a linear guide with a 560 mm measurement length, a feed rate of 5 mm/dev, a resolution of 10 µm (1/100 mm), a Leica M50 stereo microscope, an LED spot light source and TSAP-Win™ 4.81 Scientific software for recording measured values, graphical display, and analysis of temporal sequences [27]. Based on the last 5-, 10-, 15-, 20-, and 25-year ring widths on the increment cores, periodic mean diameter increments were calculated for different period lengths using Equation (1).

$$ID_n = \frac{\Delta d_n}{n} \quad (1)$$

The formula ID_n gives us the periodic mean diameter increment at period length n , while the formula Δd_n gives us the ring width at n years, with n being the period length. Additionally, the bark thicknesses of the trees were measured on the increment cores, and the inside-bark diameters at breast height were calculated using Equation (2).

$$DBH_{ib} = DBH_{ob} - b \quad (2)$$

The formula DBH_{ib} gives the inside-bark diameter at breast height, and the over-bark diameter at breast height is given by DBH_{ob} , where b is bark thickness.

2.3. Data Analysis

Pearson correlation analysis was used to determine explanatory variables in the developing models to estimate the periodic mean increments of inside-bark diameter at breast height for different period lengths. In this context, periodic mean increments of inside-bark diameter in different period lengths were related to the inside-bark diameter at breast height and tree age variables. Since there was no significant relationship between tree age and periodic mean increments for each period length, as shown by the correlation analysis using (Equations (3)–(7)), the following models in which only inside-bark diameter at breast height was an explanatory variable were tested to estimate periodic mean increments of inside-bark diameter at breast height for different period lengths.

$$M1 \rightarrow ID_n = \beta_0 + \beta_1 x DBH_{ib} + \epsilon \quad (3)$$

$$M2 \rightarrow ID_n = \beta_0 x DBH_{ib}^{\beta_1} + \epsilon \quad (4)$$

$$M3 \rightarrow ID_n = \exp(\beta_0 + \beta_1 x DBH_{ib}) + \epsilon \quad (5)$$

$$M4 \rightarrow ID_n = \exp(\beta_0 + \beta_1 x DBH_{ib} + \beta_2 x DBH_{ib}^2) + \epsilon \quad (6)$$

$$M5 \rightarrow ID_n = \beta_0 + \beta_1 x DBH_{ib} + \beta_2 x DBH_{ib}^2 + \epsilon \quad (7)$$

The ordinary linear regression (OLS) method, a classical regression technique, was used to fit M1 and M5 and to estimate their coefficients, while the ordinary nonlinear least squares (ONLS) method was used for the other models. The least squares regression technique is a mean-regression technique that may not be reliable when random and independent observations are included [28,29]. Quantile regression (QR), first introduced by Koenker and Bassett [30], is a regression technique that estimates the complete conditional distribution of dependent variables or quantile functions. This technique is very advantageous in revealing a non-normal distribution of the relationship between dependent and independent variables [29,31]. Also, by accepting the basic assumptions of traditional models such as independence, normality, and equal variance, consistent estimates that are not substantially affected by extreme values or tailed distributions [32,33] are provided. The general representation of the quantile regression equation at a given quantile level is shown in Equation (8). Quantile regression parameters and the q th quantile are estimated by minimizing Equation (9) [34].

$$\hat{y}_q = f(x, \beta) + \epsilon \quad (8)$$

$$S = \sum_{y_q \geq \hat{y}_q} q(y_q - \hat{y}_q) + \sum_{y_q < \hat{y}_q} 1 - q(y_q - \hat{y}_q), \quad (9)$$

In Formulas (8) and (9), $\hat{y}_q$ denotes the dependent variable estimated at the q th quantile value, q is the quantile value, β is the regression parameter, x is an independent variable, ϵ is the error term, y_q is the variable value observed at the q th quantile, and S is the sum of the weighted absolute residuals at the q th quantile. Recently, the quantile regression technique has been widely used in various modeling studies in forestry. In the present study, the quantile values of $q = 0.25, 0.50$, and 0.75 were taken as the basis for all the model structures (M1–M5). As in the classical regression approach (OLS, ONLS), linear quantile regression (LQR) was used for adjusting M1 and M5 and for calculating their coefficients, and nonlinear quantile regression (NQR) was used for the other model structures. As a result, 20 models were developed for each period length to estimate the periodic mean diameter increment: 5 different model structures $\times$ 4 different regression techniques (1 classical + Q25, Q50, Q75). Since diameter increments were calculated and modeled for five different period lengths, a total of 100 (20×5) diameter increment models were developed within the scope of the study. In adjusting the models and calculating the coefficients, the following functions in R software version 4.3.1 were used: `lm` for OLS, `nls` for ONLS, and `qr` and `nqr` for quantile regression (in the “quantreg” package) [35].

The descriptive statistics of the sample trees' diameter values and periodic mean diameter increment values as calculated for different period lengths (5, 10, 15, 20, and 25 years) are given in Table 1.

Table 1. Descriptive statistics of sampled trees (n = 43).

Variables	Mean	Std. Dev	Min.	Max.
DBH _{ib} ¹ (cm)	49.52	19.4	13.4	91.26
Tree age ² (year)	103	42.4	44	211
ID ³ _5 (mm/year)	3.31	2.25	0.78	9.83
ID_10 (mm/year)	3.24	2.04	0.83	6.73
ID_15 (mm/year)	3.16	1.84	0.89	6.69
ID_20 (mm/year)	3.16	1.84	0.90	7.54
ID_25 (mm/year)	3.19	1.87	1.00	7.51

¹ DBH_{ib}: Diameter at breast height inside bark. ² Tree age at breast height. ³ ID: Periodic mean diameter increment based on different period lengths.

2.4. Model Evaluation

It is necessary to calculate the goodness-of-fit statistics of the developed models to determine their success and compare them with each other. Therefore, we calculated the values of the mean error (BIAS), root mean square error (RMSE), mean absolute error percentage (MAE (%)), and Akaike information criterion (AIC). The formulas for these goodness-of-fit statistics are given below (Equations (10)–(13)).

$$BIAS = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)}{n} \quad (10)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n - p}} \quad (11)$$

$$MAE(\%) = \frac{\sum_{i=1}^n |y_i - \hat{y}_i|}{\sum_{i=1}^n y_i} 100 \quad (12)$$

$$AIC = n + n \log 2\pi + n \log \left(\sum_{i=1}^n (y_i - \hat{y}_i)^2 / n \right) + 2(p + 1) \quad (13)$$

In the formulas, n is the number of data points used in the model, y_i is the measured value, $\hat{y}_i$ is the estimated value, and p is the number of parameters in the model.

The model with the smallest value in terms of BIAS, RMSE, MAE (%), and AIC, which represent model errors, was selected as the most successful model. The relative rank method proposed by Poudel and Cao [36], which collectively assesses the four goodness-of-fit statistics calculated (BIAS, RMSE, MAE (%) and AIC), was used to evaluate and compare the success of the obtained diameter increment models and thus to select the most successful model Equation (14).

$$R_i = 1 + \frac{(m - 1)(S_i - S_{min})}{S_{max} - S_{min}} \quad (14)$$

In the equation, R_i is the relative rank of the i th model, m is the number of models compared, S_i is the goodness-of-fit statistic of the i th model, S_{min} is the smallest S_i value among the models, and S_{max} is the largest S_i value among the models. In accordance with this method, after the relative ranks of the models were calculated, these rank values were summed to determine the total relative rank values. Among the models predicting the periodic mean diameter increment for each period length, the one with the lowest total relative rank value was selected as the best model.

3. Results

The inside-bark diameters at breast height of the sample trees ranged between 13.4 and 91.3 cm, while the periodic mean diameter increments calculated for different period lengths ranged between 0.78 and 9.83 mm/year. This shows that the sample trees had a wide range of diameter variation and different diameter increment potentials. Moreover, the fact that the ages of the trees at breast height range from 44 to 211 years indicates that they were sampled from various development stages (Table 1). Periodic mean increments in different period lengths were related to the inside-bark diameter at breast height and tree age at breast height variables using Pearson correlation analysis. While there was a significant relationship between periodic mean diameter increments and inside-bark diameter at breast height at the $p = 0.05$ significance level, there was no significant relationship with tree age as result of the Pearson correlation analysis (Table 2).

Table 2. Results of Pearson correlation analysis.

Variables	ID_5	ID_10	ID_15	ID_20	ID_25
DBH _{ib}	0.457 *	0.590 ***	0.639 ***	0.637 ***	0.674 ***
Tree Age	−0.046 NS	−0.085 NS	−0.109 NS	−0.118 NS	−0.108 NS

* 0.05 significance level, *** 0.001 significance level, NS: Non-significant.

The relationship between diameter increments and tree age is given in Figure 1. As can be seen in the figure, there is no significant relationship between diameter increments and tree age, supporting the analysis results. Therefore, diameter increment models were developed based on diameter only.

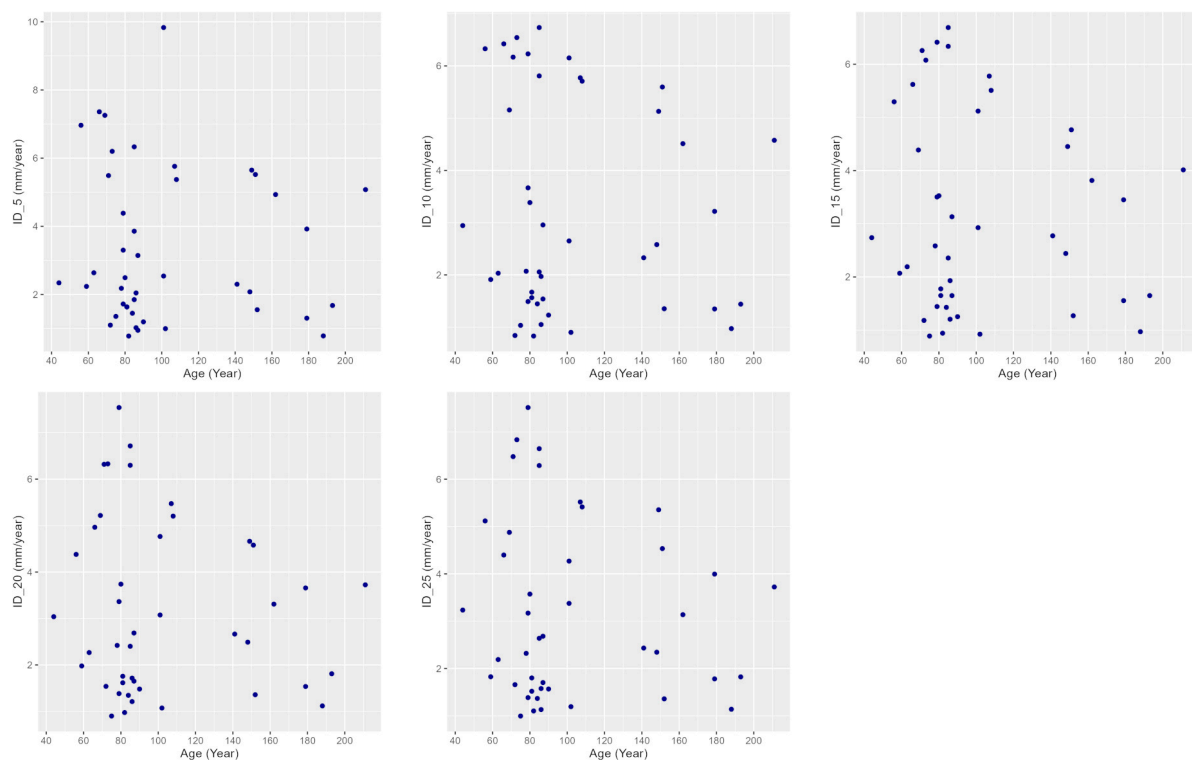


Figure 1. The relationship between diameter increments and tree age.

The RMSE values of the models created to estimate the periodic mean increment calculated for the last five-year period ranged between 2.03 and 2.58 mm/year, while the mean absolute error (MAE) percentage ranged between 39.8 and 55.8%. According to the relative rank method, the most successful model was M2, which was fitted using the quantile regression technique with $q = 0.50$ (Table 3).

Table 3. Regression coefficients, goodness-of-fit statistics, and relative ranking values of the models developed to predict the periodic mean diameter increment calculated based on the last five-year period.

MODEL	RT	β_0	β_1	β_2	BIAS	RMSE	MAE (%)	AIC	ΣR	Overall Rank
M1	OLS	0.6798	0.0530		1.55×10^{-17}	2.028	44.27	187	19.4	2.7
	QR25	0.006	0.0429		1.1767	2.368	45.95	168	38.6	10.6
	QR50	−0.4377	0.0667		0.4396	2.095	40.48	175	16.7	1.6
	QR75	−0.1081	0.0799		−0.5436	2.169	49.72	202	45.8	13.6
M2	ONLS	0.1686	0.7667		−0.0057	2.025	44.60	187	19.8	2.9
	QR25	0.0434	0.9977		1.1768	2.368	45.95	168	38.6	10.6
	QR50	0.0304	1.1653		0.3968	2.093	40.27	174	15.3	1.0
	QR75	0.0666	1.0385		−0.5371	2.170	49.64	202	45.7	13.5
M3	ONLS	0.4750	0.0139		−0.0155	2.052	45.46	188	22.4	3.9
	QR25	−0.3037	0.0183		1.3620	2.501	48.67	168	48.8	14.8
	QR50	−0.0510	0.0208		0.4395	2.132	40.20	174	17.1	1.7
	QR75	0.5918	0.0159		−0.8549	2.263	55.80	204	61.4	20.0
M4	ONLS	−0.5738	0.0538	−0.0003	0.0050	2.031	43.39	188	19.1	2.6
	QR25	−1.0143	0.0485	−0.0002	1.1044	2.348	44.72	170	36.5	9.7
	QR50	−0.5638	0.0388	−0.0001	0.4484	2.136	39.83	175	17.4	1.9
	QR75	−0.9947	0.0757	−0.0005	−0.602	2.165	47.71	197	41.4	11.8
M5	OLS	−0.5348	0.1076	−0.0005	$−4.65 \times 10^{-17}$	2.042	44.66	188	20.9	3.3
	QR25	1.2617	−0.0153	0.0005	1.4306	2.584	49.62	170	54.7	17.2
	QR50	1.4157	−0.0072	0.0006	0.4162	2.149	39.96	176	18.1	2.2
	QR75	−1.6378	0.1719	−0.001	−0.7535	2.217	51.56	201	51.9	16.1

The models created to estimate the periodic mean increment calculated for the last 10-year period predicted the diameter increment with mean absolute error percentages between 36.7 and 50.7%. The most successful model was M4, which was fitted using the quantile regression technique with $q = 0.50$. The best model predicted diameter increments with $RMSE = 1.68$ mm/year and $MAE = 36.7\%$ (Table 4).

Table 4. Regression coefficients, goodness-of-fit statistics, and relative ranking values of the models developed to predict the periodic mean diameter increment calculated based on the last 10-year period.

MODEL	RT	β_0	β_1	β_2	BIAS	RMSE	MAE (%)	AIC	ΣR	Overall Rank
M1	OLS	0.1690	0.0620		3.87×10^{-17}	1.664	40.69	170	14.6	3.5
	QR25	0.2270	0.0328		1.3906	2.265	49.03	165	55.2	17.7
	QR50	−0.8586	0.0781		0.2295	1.711	38.77	169	15.3	3.7
	QR75	−0.2448	0.0831		−0.6303	1.833	43.69	183	42.4	13.2
M2	ONLS	0.0912	0.9172		−0.0102	1.663	40.97	170	15.1	3.6
	QR25	0.0644	0.8666		1.3632	2.243	48.61	165	53.7	17.1
	QR50	0.0176	1.3048		0.2955	1.725	38.63	169	16.4	4.1
	QR75	0.0527	1.1003		−0.6568	1.859	44.12	183	44.1	13.8
M3	ONLS	0.3393	0.0161		−0.0263	1.712	42.89	172	20.9	5.7
	QR25	−0.2451	0.0155		1.4772	2.359	50.69	166	61.9	20.0
	QR50	−0.131	0.0222		0.3514	1.782	39.77	171	21.8	6.0
	QR75	0.3941	0.0190		−0.8174	1.963	48.22	187	57.8	18.6

Table 4. Cont.

MODEL	RT	β_0	β_1	β_2	BIAS	RMSE	MAE (%)	AIC	ΣR	Overall Rank
M4	ONLS	−1.3139	0.0763	−0.0005	0.0228	1.629	38.29	169	9.9	1.8
	QR25	−0.7563	0.0361	−0.0002	1.3555	2.257	48.29	166	54.4	17.4
	QR50	−1.6925	0.0823	−0.0005	0.0425	1.678	36.71	167	7.5	1.0
	QR75	−1.1939	0.0830	−0.0006	−0.9171	1.938	45.16	177	45.7	14.3
M5	OLS	−1.0938	0.1188	−0.0005	$−1.19 \times 10^{-16}$	1.669	40.87	171	15.9	3.9
	QR25	0.1391	0.0373	−0.00004	1.3643	2.272	48.60	167	56.2	18.0
	QR50	−0.4458	0.0591	0.0002	0.2877	1.746	38.69	171	18.6	4.9
	QR75	−1.5744	0.1618	−0.0008	−0.9126	1.948	47.52	183	54.3	17.3

The RMSE values of the models created to estimate the periodic mean increment as calculated for the last 15-year period ranged between 1.4 and 2 mm/year and the mean absolute error (MAE) percentage between 34.4 and 46.8%. According to the relative rank method, the most successful model was M4, fitted with the nonlinear least squares method. This model estimated diameter increments with a mean error of 1.4 mm/year (Table 5).

Table 5. Regression coefficients, goodness-of fit-statistics, and relative ranking values of the models developed to predict the periodic mean diameter increment calculated based on the last 15-year period.

MODEL	RT	β_0	β_1	β_2	BIAS	RMSE	MAE (%)	AIC	ΣR	Overall Rank
M1	OLS	0.1516	0.0608		7.75×10^{-17}	1.435	36.14	157	9.6	1.7
	QR25	0.0716	0.0370		1.2560	1.983	45.00	155	56.7	16.0
	QR50	−0.5152	0.0704		0.1891	1.461	35.55	160	15.7	3.6
	QR75	−0.1766	0.0839		−0.8187	1.723	42.62	169	54.1	15.3
M2	ONLS	0.0819	0.9376		−0.0038	1.435	36.20	157	9.8	1.8
	QR25	0.0479	0.9489		1.2242	1.961	44.51	155	54.8	15.5
	QR50	0.0216	1.2583		0.1565	1.476	35.39	159	14.3	3.1
	QR75	0.0620	1.0656		−0.8229	1.733	42.7	169	54.6	15.4
M3	ONLS	0.2872	0.0166		−0.0226	1.476	37.79	159	16.0	3.7
	QR25	−0.2030	0.0160		1.2711	2.036	45.49	155	59.3	16.8
	QR50	−0.0221	0.0209		0.1690	1.509	36.32	161	19.1	4.6
	QR75	0.4665	0.0181		−0.9890	1.837	46.59	172	69.7	20.0
M4	ONLS	−1.0834	0.0664	−0.0004	0.0197	1.413	34.83	157	7.2	1.0
	QR25	−1.0001	0.0454	−0.0002	1.1712	1.926	43.30	155	51.0	14.3
	QR50	−1.4932	0.0786	−0.0005	0.1958	1.426	34.41	159	11.8	2.4
	QR75	−1.0524	0.0751	−0.0005	−0.9018	1.759	42.20	166	52.5	14.8
M5	OLS	−0.5654	0.0930	−0.0003	$−3.1 \times 10^{-17}$	1.447	36.15	159	12.2	2.5
	QR25	−0.1709	0.0499	−0.0001	1.1749	1.945	43.67	156	53.3	15.0
	QR50	0.0241	0.0405	0.0003	0.2256	1.512	35.39	161	18.6	4.5
	QR75	−0.3750	0.0964	−0.0002	−0.8021	1.716	42.27	171	55.4	15.6

The RMSE values of the models created to estimate the mean increment as calculated for the last 20-year period ranged between 1.4 and 1.9 mm/year and the mean absolute error (MAE) percentage between 33.6 and 44.9%. According to the relative rank method, the best model was M4, fitted with the nonlinear least squares method. This model estimated diameter increments with a mean absolute error of 33.9% (Table 6).

Table 6. Regression coefficients, goodness-of-fit statistics, and relative ranking values of the models developed to predict the periodic mean diameter increment calculated based on the last 20-year period.

MODEL	RT	β_0	β_1	β_2	BIAS	RMSE	MAE (%)	AIC	ΣR	Overall Rank
M1	OLS	0.1595	0.0605		5.16×10^{-18}	1.438	35.44	157	14.2	2.0
	QR25	0.0445	0.0396		1.1517	1.905	41.48	148	51.8	14.6
	QR50	−0.3178	0.0682		0.0963	1.450	34.48	157	14.5	2.1
	QR75	−0.1531	0.0813		−0.7164	1.665	41.89	171	54.2	15.4
M2	ONLS	0.0803	0.9419		−0.0011	1.438	35.52	157	14.3	2.0
	QR25	0.0450	0.9746		1.1449	1.900	41.37	148	51.3	14.4
	QR50	0.0382	1.1179		0.1302	1.453	34.47	157	15.1	2.3
	QR75	0.0588	1.0684		−0.6700	1.649	41.09	171	51.6	14.6
M3	ONLS	0.2767	0.0167		−0.0208	1.473	36.80	159	19.4	3.7
	QR25	−0.2183	0.0168		1.2093	1.982	42.67	149	58.0	16.7
	QR50	0.0599	0.0193		0.1928	1.494	35.64	160	21.6	4.5
	QR75	0.4448	0.0178		−0.8293	1.729	44.56	174	64.9	19.0
M4	ONLS	−0.9589	0.0616	−0.0004	0.0189	1.424	33.86	157	11.3	1.0
	QR25	−0.9235	0.0430	−0.0002	1.1125	1.885	40.56	149	49.6	13.9
	QR50	−1.1584	0.0643	−0.0004	0.1391	1.436	33.58	157	13.2	1.6
	QR75	−0.9037	0.0705	−0.0005	−0.9624	1.802	44.88	171	67.8	20.0
M5	OLS	−0.3259	0.0824	-2.1×10^{-4}	-5.16×10^{-18}	1.453	35.63	159	16.5	2.7
	QR25	−0.1219	0.0485	-7.8×10^{-5}	1.0961	1.888	40.57	150	50.2	14.1
	QR50	−0.3162	0.0681	6.9×10^{-7}	0.0966	1.468	34.48	159	16.6	2.8
	QR75	−0.0279	0.0740	7.2×10^{-5}	−0.6826	1.674	41.30	173	54.5	15.5

The models created to determine the periodic mean increments as calculated for the last 25-year period estimated diameter increments with mean absolute error percentages between 32.3 and 43.2%. The most successful model was M4, which was fitted using the quantile regression technique with $q = 0.50$. This model predicted with an RMSE = 1.39 mm/year and MAE = 32.3% (Table 7).

Table 7. Regression coefficients, goodness-of-fit statistics, and relative ranking values of the models developed to predict the periodic mean diameter increment calculated based on the last 25-year period.

MODEL	RT	β_0	β_1	β_2	BIAS	RMSE	MAE (%)	AIC	ΣR	Overall Rank
M1	OLS	−0.0283	0.0649		5.4×10^{-17}	1.398	34.36	155	17.1	2.5
	QR25	−0.0652	0.0431		1.1167	1.857	39.68	144	52.5	14.6
	QR50	−0.3115	0.0687		0.0961	1.404	33.77	156	18.6	3.0
	QR75	−0.3086	0.0852		−0.7269	1.634	40.1	167	55.5	15.6
M2	ONLS	0.0622	1.0085		−0.0005	1.398	34.37	155	16.8	2.5
	QR25	0.0334	1.0603		1.0862	1.830	39.14	144	50.2	13.8
	QR50	0.0398	1.1104		0.1238	1.406	33.72	156	19.0	3.1
	QR75	0.0536	1.0955		−0.6959	1.619	39.61	167	53.6	14.9
M3	ONLS	0.2299	0.0177		−0.0240	1.438	36.09	157	22.6	4.4
	QR25	−0.3107	0.0191		1.1618	1.918	40.11	143	55.4	15.6
	QR50	−0.0262	0.0204		0.2885	1.475	34.69	158	27.1	5.9
	QR75	0.3361	0.0199		−0.8466	1.736	43.16	170	68.4	20.0

Table 7. Cont.

MODEL	RT	β_0	β_1	β_2	BIAS	RMSE	MAE (%)	AIC	ΣR	Overall Rank
M4	ONLS	−1.1242	0.0662	$−3.9 \times 10^{-4}$	0.0247	1.379	32.75	155	14.1	1.4
	QR25	−0.5094	0.0276	$−7.5 \times 10^{-5}$	1.1348	1.909	39.42	144	54.2	15.2
	QR50	−1.4527	0.0756	$−4.5 \times 10^{-4}$	−0.0128	1.391	32.27	154	12.7	1.0
	QR75	−0.8544	0.0660	$−4 \times 10^{-4}$	−0.8569	1.692	40.60	164	58.3	16.6
M5	OLS	−0.3423	0.0790	$−1.4 \times 10^{-4}$	6.5×10^{-17}	1.415	34.48	157	19.3	3.3
	QR25	0.7011	0.0103	2.9×10^{-4}	1.1555	1.925	39.75	144	55.7	15.7
	QR50	−0.1675	0.0621	5.7×10^{-5}	0.1157	1.423	33.75	158	20.9	3.8
	QR75	−0.6876	0.1057	$−1.9 \times 10^{-4}$	−0.8048	1.692	41.23	168	61.4	17.6

A comparison of the observed values and the values obtained from the best selected model for the mean increment of inside-bark diameter at breast height and the values obtained for different period lengths is shown graphically in Figure 2.

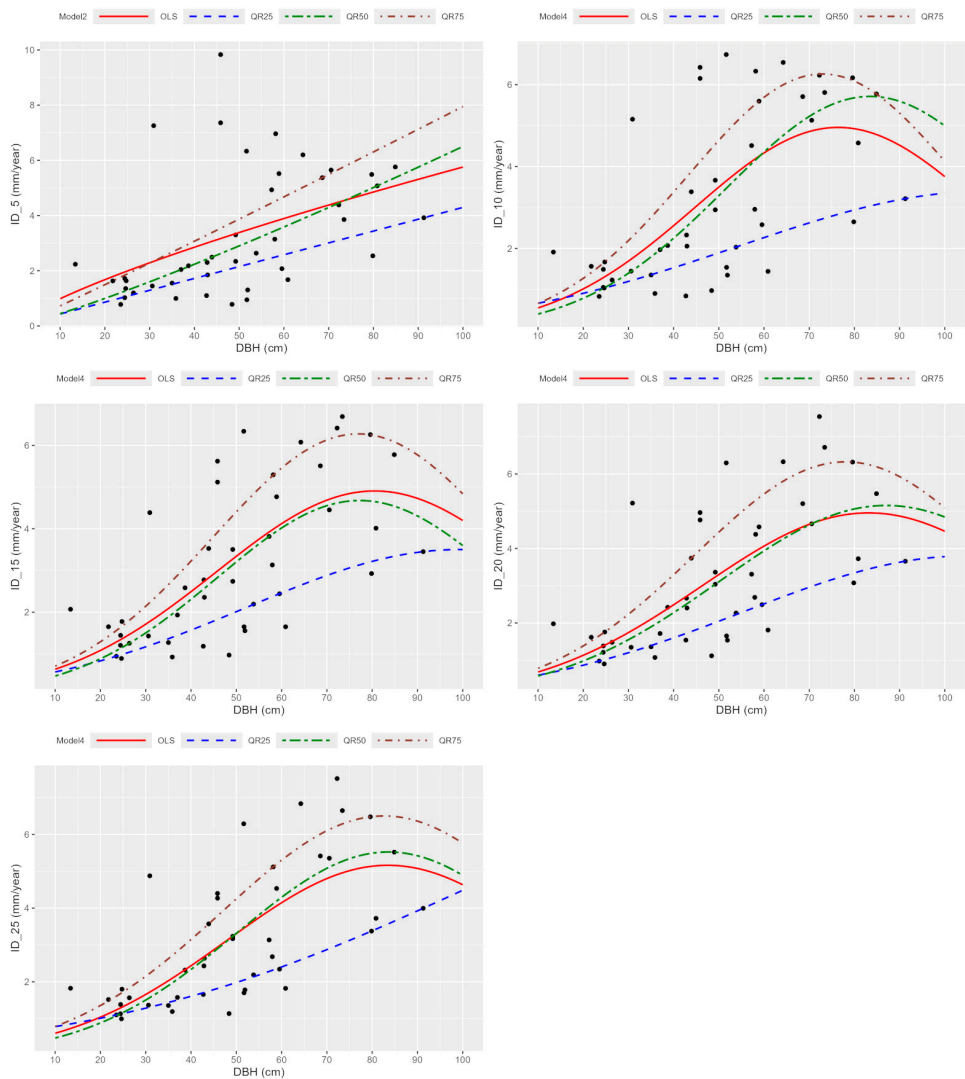


Figure 2. Comparison of the observed values with the values obtained from the best selected models for each period.

4. Discussion

The periodic mean increment at different period lengths showed a positive significant relationship with the inside-bark diameter at breast height according to the correlation analysis results. As the period length increased, the correlation coefficient values increased from 0.457 to 0.674 (Table 2). However, there is no relationship between periodic mean increment and tree age at breast height, with correlation coefficient values ranging from -0.118 to -0.046 . Although there is no significant relationship, which is in line with the literature, the periodic mean increment decreases as trees age, and there is a negative correlation between them (Figure 2). For these reasons, diameter increment models were developed using the inside-bark diameter at breast height as the explanatory variable as it shows a significant relationship with diameter increment. Schelhaas et al. [37] state that although it is known that age is one of the best predictors of growth, diameter is used as an explanatory variable in models developed to estimate diameter increases because age cannot be measured directly. They also indicate that diameter increment models based solely on diameter (tree size) can explain up to 53% of the variation in diameter growth even with the exclusion of the age variable, which is one of the best predictors of growth, alongside environmental and soil properties.

The main results obtained from the present study show that the 25-year periodic mean diameter increment model provides more accurate and consistent predictions. Again, as the period length increases, the predictive success of the increment models also increases, and the error percentage decreases (Table 8). Tanhuanpää et al. [6] state that the models they developed are generally based on easily available measurements, such as the diameter at breast height (DBH), and provide highly accurate estimations.

Table 8. Goodness-of-fit statistics of the best selected diameter increment models for each period.

ID _n	MODEL	RT	BIAS	RMSE	MAE (%)
ID_5	M2	QR50	0.3968	2.093	40.27
ID_10	M4	QR50	0.0425	1.678	36.71
ID_15	M4	ONLS	0.0197	1.413	34.83
ID_20	M4	ONLS	0.0189	1.424	33.86
ID_25	M4	QR50	-0.0128	1.391	32.27

Another important result is that the most successful diameter increment model in all the period lengths except for the five-year period is M4, which has an exponential form. In this model structure, the diameter increments of the trees increase up to a certain value and then decrease. This indicates that the incremental potential of the trees decreases with age. The selected model structure was not only successful in terms of goodness-of-fit statistics but was also found to be suitable for biological processes. Similarly, Pretzsch et al. [38] emphasized that the DBH increases sharply from seedlings to young trees, pauses during the growth period, and decreases after maturity is reached. Trees growing freely in the open expend their growth energy to build their above-ground components at an early age and tend to increase in diameter after a certain tree architecture is established. In this regard, Ciftci et al. [39] argue that open-grown amenity trees generally have wider crowns, numerous, larger branches, and a tapered trunk with multiple co-dominant stems that often split into two. Again, referring to the structural architecture of free-growing trees, Zhou et al. [40] report that open-grown trees with their larger crowns are empirically expected to have more branches compared to their other tree components. This architectural feature of an open-grown tree leads to a redistribution of biomass between tree parts and changes in the specific gravity of the tree. Thus, the accumulation of more branch biomass can have different consequences for the diameter increment of trees. Likewise, the periodic mean diameter increments of the trees sampled in the present study varied widely between 0.78 and 9.83 mm/year. For ease of comparison, albeit for different tree species, Moser et al. [41] measured increments of 3.9 mm/year for *Robinia pseudoacacia* and 3.2 mm/year for *Tilia cordata* in the parks, streets, and squares of Munich, Germany. The findings of Franceschi

et al. [3] show slightly smaller increments compared to Moser et al. [40] (mean values of about 3.4 for *R. pseudoacacia* and 2.5 mm/year for *T. cordata*). In the city of Berlin, *Platanus x acerifolia* had a higher mean increment of 4.9 mm/year, compared to 3.7 mm/year measured in Paris [15] and 3.5 mm/year in Dresden [42]. These differences might be explained by the smaller size of the *P. x acerifolia* tree sample (mean DBH is 55.4 cm) compared to the larger (and therefore probably older) trees measured in other cities (mean DBH is 64.8 cm in Paris, 80 cm in Dresden). Kalliovirta and Tokola [43] emphasize similar occurrences and even point out that modeling should be conducted separately for young and old trees. Also, Fazan et al. [20] emphasize that the age of individual trees and the relationship between the age and diameter increment (ring width) are significant for conservation purposes. However, in their study on *Zelkova abelicea* (Ulmaceae), an endemic tree species in the Mediterranean mountains (Crete, Greece), their remarkable results showed that for dwarf trees, tree age has a good correlation with the DBH (64%), but this is not true of large-sized trees (11%) [20]. Drawing attention to tree species-specific growth behavior in terms of tree diameter/age distribution diagrams, Pretzsch et al. [4] indicate that the stable model fits quite well. However, they emphasize that allometric relationships do not provide information about the temporal dimension, i.e., whether the tree will reach a certain size earlier or later. They also note that the growth rate of the root diameter is highly variable, which prevents the establishment of general age–diameter relationships. However, they state that time-specific extrapolations become possible if the age of a particular tree is known or if the diameter increase over the last decade can be obtained from increment borer (annual ring) samples or occasionally from trees that are felled [4]. As a result of the modeling performed for the stone pine tree species in the present study, reliable diameter increment values with high accuracy were obtained based on the DBH without the need for those procedures (increment borer (year ring) samples, special extrapolations, etc.). In support of our findings, Tagliapietra Schons et al. [44] evaluated the diameter increment patterns of *Pinus taeda* trees growing freely and those growing with competition as a function of the DBH. They found a diameter increment of 0.83 cm/year for free-growing trees and 0.57 cm/year for those growing under competitive conditions. Also, with regard to open-grown trees, larger crown sizes had a significant effect on these growth differences, reflecting the more efficient usability of resources in free-growing trees [44]. Many researchers emphasize the need for allometric relationships specific to different free-growing tree species [1,2,15,45–48]. Some studies show that, in the case of free-growing trees, growth is affected by environmental conditions (climate, soil, etc.) and adverse environmental conditions (pollutants, climate change, etc.) [16,17,49–51], and many studies suggest that growth is suppressed by the trees' physiological characteristics (shade/light tolerance, osmotic control, etc.) [3,52–54].

5. Conclusions

In conclusion, the remarkable achievement of this study in the sustainable evaluation of urban stone pine trees is that the 25-year periodic mean diameter increment models give more reliable predictions. As a related main result, the predictive success of models can increase with decreasing error percentage if the period length increases. As concluded, tree growth occurs as a result of ecological and eco-physiological processes. The best indicators of this formation are the growth characteristics of trees, such as diameter increment. Urban trees have special growth, distribution of tree components, and architecture. They fight the adverse anthropogenic conditions brought about by urban ecosystems, and they provide especially important ecosystem functions. Therefore, they constitute a field of expertise. It is essential to conduct new studies on free-growing urban trees specific to species, environment of growth, and adverse conditions to ensure the sustainable conservation of urban trees and the continuity of their ecosystem functions.

Author Contributions: Conceptualization, H.A.U., E.Ö., S.S. and G.A.Ö.; methodology, S.S., E.Ö. and G.A.Ö.; software, E.Ö., S.S. and G.A.Ö.; validation, H.A.U., E.Ö., S.S. and G.A.Ö.; formal analysis, E.Ö., S.S., G.A.Ö. and E.M.; investigation, E.Ö., S.S., G.A.Ö. and E.M.; resources, H.A.U., E.Ö. and

S.S.; data curation, E.Ö., S.S. and G.A.Ö.; writing—original draft preparation, E.Ö., S.S., G.A.Ö. and E.M.; writing—review and editing, H.A.U., E.Ö., S.S., G.A.Ö. and E.M.; visualization, E.Ö., S.S. and G.A.Ö.; supervision, H.A.U. and E.M.; project administration, H.A.U.; funding acquisition, H.A.U. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No datasets were generated or analyzed during the current study.

Acknowledgments: We thank our colleagues for their valuable help in the field. All authors thank the three anonymous reviewers and the editor for their progressive and valuable comments and recommendations within the review of manuscript.

Conflicts of Interest: The authors declare no conflicts of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; and in the decision to publish the results.

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