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ORIGINAL ARTICLE

Growth modeling of the crown and trunk of *Handroanthus heptaphyllus* and *Platanus x acerifolia* trees in the southern Brazilian urban forest

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Abstract

Key message Crown diameter of *H. heptaphyllus* and *P. acerifolia* stabilizes around 40 years, reaching 15 m and 13 m respectively, and models guide spacing planning and ecosystem service estimates in urban forests.

Abstract The growth pattern of urban trees influences both planning of urban forest composition and estimating ecosystem services, with crown diameter (CD) being the most important variable. However, there is a lack of models that relate diameter at breast height (DBH) growth to crown diameter, especially under the environmental conditions of Brazilian cities. In this study, we fitted models to estimate the temporal growth of DBH and CD for two species widely planted in southern Brazil: *H. heptaphyllus* and *P. acerifolia*. Models relating CD and DBH, DBH growth models, and CD growth curves over time were developed. The best models for estimating CD based on DBH showed the following goodness-of-fit statistics: adjusted $R^2 = 0.56$, Syx(%) = 13.42, and RMSE = 1.67 for *H. heptaphyllus*; and adjusted $R^2 = 0.82$, Syx(%) = 8.42, and RMSE = 0.89 for *P. acerifolia*. The Chapman-Richards model showed adjusted $R^2 = 0.85$ and $S_{yx}(\%) = 37.96$ for *H. heptaphyllus*, and adjusted $R^2 = 0.87$ and $S_{yx}(\%) = 36.72$ for *P. acerifolia*. The CD growth curves reach stabilization at around 40 years of age, with mean crown diameters of 15 m and 13 m for *H. heptaphyllus* and *P. acerifolia*, respectively. The information generated is relevant for urban forest planning and management, supporting conflict prevention with urban infrastructure and maximization of the ecosystem services provided by urban trees.

Keywords Growth modeling · Tree crown diameter · Urban trees · Urban forestry

Introduction

The dynamics of urban growth and expansion not only have direct implications for the population's quality of life, but also for the health and survival of vegetation elements which provide ecosystem services (Kanniah 2017; Ossola and Hopton 2018; Stroud et al. 2022). The reduction in the number of trees and green spaces has intensified environmental problems. Consequently, urban green areas and street tree plantings are increasingly recognized for their importance in promoting the physical and mental well-being of urban residents, functioning as green infrastructures. This provides a range of ecosystem services such as microclimate regulation and thermal comfort, stormwater retention and runoff reduction, air pollutant removal, and biodiversity support, among others (Ahern 2013; Anguluri and Narayanan 2017; Amer et al. 2023).

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In this context, sustainable urban planning emerges as a strategic tool to address the socio-environmental challenges of contemporary cities, especially when it values the expansion and maintenance of the quantity and quality of trees (Ahern 2013; Kanniah 2017). However, despite the growing recognition of the importance of urban trees, a critical limitation persists: the scarcity of spaces available for tree planting. This is a point of concern because, in addition to surviving the adversities of the urban ecosystem, trees must also be able to develop large and healthy canopies, essential for maximizing the desired ecosystem services (Bobrowski and Biondi 2012; Vendruscolo et al. 2023).

Therefore, it is essential to understand and predict the growth of trees planted in urban environments (Blood et al. 2016; North et al. 2017; Coombes et al. 2019; Mata et al. 2020; Yang et al. 2023). Appropriate species selection and estimation of their growth potential over time are fundamental pieces of information for ensuring sustained provision of ecosystem services, while avoiding conflicts with urban infrastructure (Hilbert et al. 2020; Mata et al. 2020; Martin et al. 2012; Fauk and Schneider 2023). Each tree species exhibits a unique growth pattern which is influenced by edaphoclimatic conditions, water availability, the degree of competition with other trees, and the intensity of human interventions such as pruning (Vaz Monteiro et al. 2016; North et al. 2017; Hilbert et al. 2020; Maria et al. 2020; Yang et al. 2023).

Despite the relevance of this topic for street tree planning, research providing species-specific growth models for urban trees remains scarce, especially for Brazilian cities and particularly regarding the relationship between structural variables such as diameter at breast height (DBH) and crown diameter (CD). These variables are not only essential for estimating tree volume and the area occupied by crowns, but also for quantifying the ecosystem services provided by urban trees (Moser et al. 2015; Pretzsch et al. 2022; Amer et al. 2023; Fauk and Schneider 2023). Moreover, understanding crown diameter growth over time is crucial for estimating the extent of urban canopy cover, planning tree spacing, and anticipating the need for pruning or other interventions, thereby reducing operational costs and minimizing conflicts with built structures (Pretzsch et al. 2015; Hilbert et al. 2020; Mata et al. 2020; Fauk and Schneider 2023; Yang et al. 2023).

Research at the international level has shown that the accuracy of models for the relationship between diameter at breast height (DBH) and crown diameter (CD) is generally lower than that commonly obtained for data from monospecific commercial stands, with R^2 values ranging from 0.43 to 0.96, as observed in models developed by Semenzato et al. (2011), Martin et al. (2012), Pretzsch et al. (2015), Vogt et al. (2015), Westfall et al. (2020), Pretzsch et al. (2022), Amer et al. (2023), and Yang et al. (2023). Differences in model accuracy in these studies were related to varying numbers of trees per species, different numbers of sampled species, as well as data collected in one or multiple cities. However, none of these studies fitted models to estimate DBH growth or crown diameter growth over time.

In light of this gap, the present study is a pioneer in urban tree growth research which aimed to analyze the growth patterns of two species widely used in street tree planting in southern Brazilian cities: *H. heptaphyllus* (pink trumpet tree) and *Platanus × acerifolia* (London plane tree). This study seeks to fit crown diameter growth models as a function of DBH over time, using partial stem analysis techniques and tree morphometric data based on the biological Chapman-Richards model. Emphasis is placed on estimating crown diameter growth as a key variable for urban tree crown cover planning and urban forest management.

The information generated by this work aims to contribute to more rational and effective planning of urban forest composition, to provide technical support for species selection, spatial allocation of trees within the urban fabric, and to develop public policies which promote a balance between vegetation and urban infrastructure. By understanding crown growth behavior, urban managers will be able to anticipate potential conflicts with sidewalks, power lines, and buildings, optimize management actions and promote more resilient and sustainable cities.

Material and methods

Study area and selected species description

The study was conducted in the city of Irati, Paraná, which is located in the south-central region of the state (Fig. 1). It is approximately 156 km far from the state capital, Curitiba, and situated between coordinates 25º27′56" S latitude and 50º37′51" W longitude, on the Second Paraná Plateau at an average altitude of 900 m a.s.l. The regional climate is classified as Cfb (Temperate oceanic climate or subtropical highland climate) according to the Köppen-Geiger climate classification system, characterized by distinct seasons, well-distributed precipitation throughout the year, and occasional periods of severe frost. The city presents an average maximum temperature of 24.2 °C; average minimum temperature of 11.0 °C, average monthly rainfall of 194 mm and average monthly relative humidity of 79.6% (Andrade et al. 2010).

The species selected for this study, *H. heptaphyllus* and *P. acerifolia*, are part of the landscaping composition of two different green infrastructures within Irati's Urban Forest (Street Tree Planting and Urban Park). The species were



Fig. 1 Location of the State of Paraná in Brazil (**A**), the municipality of Irati within the State of Paraná (**B**), and the sampling areas within the city of Irati, namely the Aquatic Park (**C**) for the species *P. acerifolia* (**C1**), and Liberdade Street (**D**) for the species *H. heptaphyllus* (**D1**)

selected based on the availability of at least 30 individual trees along the same street or within the same site to minimize the variability of factors influencing tree growth. Trees showing signs of pruning, structural deformation due to dieback, or other management interferences were excluded from the sample in this study. Measurements were only conducted on open-grown trees free from competition and conflicts with local urban infrastructure, aiming to obtain more accurate predictions of the maximum tree crown development for each species, as suggested by Pretzsch et al. (2015). *H. heptaphyllus* individuals are planted along the sidewalk of Liberdade Street (Fig. 1, D1), in the city center of Irati, adjacent to the railway line, in permeable tree pits covered with grass. *P. acerifolia* individuals are part of the landscape design of the Aquatic Park and are planted in a permeable area also covered with grass (Fig. 1, C1). There is no official historical record from the city government regarding the year of planting for these trees. However, unofficial local information indicates that these species were introduced to the area between 1991 and 1993.

Methodological procedures

The assessments were performed in two distinct periods. The first stage took place during January and February 2018, with the purpose of measuring tree crown spread in relation to the cardinal and intercardinal directions. This period was chosen because it corresponds to summer, the season in which tree canopies are at their peak vegetative vigor, thereby favoring collection of representative measurements (Neuwirthová et al. 2021).

The second stage was conducted during autumn 2018, between March and June, and focused on collecting tree growth data. This timeframe follows the recommendation of Zanon and Finger (2010), who indicate this period as the most appropriate for dendrometric measurements due to reduced rainfall and lower temperatures which result in decreased vegetative growth and consequently provide greater measurement stability.

Accordingly, diameter at breast height (DBH) and tree crown projection radii were measured for each tree to later determine the mean tree crown diameter (CD). The variables total height and crown height were also recorded to characterize the trees in general. In addition, annual diameter growth was determined in the laboratory from wood samples taken at 1.30 m above ground level using a Pressler increment borer (Figueiredo Filho et al. 2017).

Tree crown diameter modeling

Crown diameter (CD) modeling is essential for understanding and quantifying the ecosystem services provided by the urban forest (Moser et al. 2015). Accurate estimates of tree crown dimensions also support urban space planning, delineation of conservation areas, and development of management and conservation strategies (Mata et al. 2020).

In this study, models used for tree species in different countries were tested (Table 1) to estimate CD using DBH as the independent variable (Nutto et al. 2001; Tonini and Arco Verde 2005; Schneider and Schneider 2008; Semenzato et al. 2011; Martin et al. 2012; Peper et al. 2014). Model fitting was performed separately for each of the evaluated species (*H. heptaphyllus* and *P. acerifolia*) to achieve

Table 1 Models tested to estimate CD from DBH of trees from the species *H. heptaphyllus* and *P. acerifolia*

Model	Author	Equation
$CD = \beta_0 + \beta_1.\mathrm{DBH} + \varepsilon_i$	Nutto et al. (2001)	(01)
$\ln CD = \beta_0 + \beta_1.\ln\mathrm{DBH}$	Tonini and Arco Verde (2005), Pretzsch et al. (2015)	(02)
$\mathrm{CD} = \beta_0 + \beta_1.\mathrm{DBH} + \beta_2.\mathrm{DBH}^2 + \varepsilon_i$	Schneider and Schneider (2008), Martin et al. (2012)	(03)
$\mathrm{CD} = \beta + \beta_1.\mathrm{DBH} + \beta_2.\mathrm{DBH}^2 + \beta_3.\mathrm{DBH}^3 + \varepsilon i$	Semenzato et al. (2011)	(04)
$\ln CD = \beta_0 + \beta_1.\ln(\mathrm{DBH} + 1) + \varepsilon_i$	Peper et al. (2014)	(05)

Where: CD = tree crown diameter (m); DBH = diameter at breast height (cm); β_0, β_1, β_2, β_3 = coefficients to be estimated through regression; εi = random error.

the highest possible estimation accuracy for each one. We proceeded like this, considering the differences in crown architecture, crown format, and tree size, but also species location that could add more variability if treated together. We used k-fold cross-validation (k = 5) to test model predictive performance and robustness, so that in each iteration 80% of the trees (n = 24) were used for calibration and 20% (n = 6) for validation. Cross-validation was chosen as an appropriate strategy for this small dataset, as it allows all observations to contribute both to model fitting and evaluation, reducing the variance of the performance estimate compared to a single hold-out, for example, 70/30 (Simon and Aliferis 2024).

DBH growth modeling

First, two cylindrical wood samples (increment cores) were extracted at 1.30 m above ground level (DBH) using a Pressler increment borer (5 mm in diameter and 40 cm in length) to perform a partial Stem Analysis for the tree diameter growth analysis. Next, coring was extended to the pith of the trunk to ensure that all growth rings were captured. Thereafter, two perpendicular increment cores were extracted per tree to ensure greater representativeness given the natural irregularity of stem circularity.

All 30 trees from *P. acerifolia* were sampled; however, it was not possible to sample all *H. heptaphyllus* trees due to the high wood density, ranging from 0.90 to 1.07 g.cm^{-3} (Carvalho 2003), and the presence of extractives that hindered the coring process. Therefore, two samples were collected from the first 14 trees for this species, and single samples from an additional four individuals, totaling 18 sampled trees.

Annual growth rings were identified and delineated based on the species-specific wood anatomical description. *H. heptaphyllus* exhibits poorly defined annual growth rings, which are delimited by tangential bands formed by flattening and thickening of fibers, together with interrupted bands defined by marginal parenchyma (Mattos et al. 2003). Species of the *Platanus* genus, in contrast, are suitable for dendrochronological studies, with distinct annual rings, large rays, simple and scalariform perforation plates, and opposite arranged vessels in horizontal lines (Schoch et al. 2004; Bush et al. 2008).

The wood samples extracted from each stem were mounted on wooden supports measuring 0.50 m in length and 3.0 cm in width, with a central groove of 0.5 cm in width and 0.2 cm in depth to hold the core. Then, the samples were fixed with adhesive tape to prevent cracking during natural drying. After drying, the increment cores were polished with sandpaper of grits 80, 100, 180, and 320 grains/cm^2 to highlight and facilitate visualization of the growth rings. The growth rings were marked according to the characteristics of each species using a stereoscopic magnifying lens (Figueiredo Filho et al. 2017). After verifying the markings, the growth ring widths were measured with a LINTAB 6 Tree-ring station connected to TSAP-Win software, with a precision of 0.01 mm (Figueiredo Filho et al. 2017).

Next, the annual increment and diameter growth analysis for each species were performed based on the growth ring width measurements using an Excel spreadsheet. The biological Chapman-Richards model (06) was fitted using StatSoft, Inc. (2014) STATISTICA (Data Analysis Software System), version 12 to generate the mean diameter growth curve over the years.

$$\mathrm{DBH} = \beta_0\left(1 - \mathrm{e}^{-\beta_1 \mathrm{A}}\right)^{\beta_2} + \varepsilon_i \quad (06)$$

In which:

DBH = Diameter at Breast Height (cm).

A = age (in years)

β_0, β_1, β_2 = coefficients estimated through regression

εi = random error

It was initially necessary to analyze the relationship between DBH_{bb} (with bark) and DBH_{wb} (without bark) to estimate the DBH with bark (DBH_{bb}) since the increment cores provide diameter measurements without bark over time, whereas the bark is included in field measurements taken with calipers or circumference tapes. Therefore, the following model was fitted to estimate DBH_{bb} for each species

(Eq. 07). The intercept β₀ was set to zero in both models to avoid overestimating bark thickness at a zero diameter.

$$DBH_{bb} = \beta_0 + \beta_1 \bullet DBH_{wb} + \varepsilon_i \quad (07)$$

In which:

DBH_{bb} = Diameter at Breast Height, with bark (cm).

DBH_{wb} = Diameter at Breast Height, without bark (cm).

β_0, β_1 = coefficients estimated through regression

εi = random error

Model precision assessment and selection

All fitted models were comparatively assessed based on the standard error of estimate (S_{yx}), adjusted coefficient of determination (R^2_{adj}), root mean square error (RMSE), and graphical analysis of residuals to guide model selection and evaluate precision. The residuals of the fitted models were analyzed for normality (Shapiro–Wilk test), homoscedasticity (Breusch-Pagan test), and autocorrelation (Durbin-Watson test). Both the model fitting and the verification of model assumptions were performed using the *car*, *caret*, *lmtest*, *broom*, *metrics* and *ggplot2* packages in R Studio.

Estimation of tree crown diameter growth over time

Diameter at Breast Height (DBH) was estimated annually from year one to year 50 based on the fitted model for estimating DBH over time for each species. Tree crown diameter (CD) was then estimated for each age within the same time frame using the best model for estimating CD as a function of DBH for each species. Since it is possible to obtain DBH at different ages, the relationship between the equations enabled projecting estimated CD values over time, resulting in a defined growth trend line for the two species analyzed in this study. Considering that the tree crown is the main structure responsible for modulating and providing ecosystem services, this approach enables estimating the space occupied by trees at different ages under the specific climate and typology conditions of the study area (urban areas in a Cfb climate). This information can thereby support urban tree planting design and management strategies.

Results

Modeling tree crown diameter estimations by DBH

The *H. heptaphyllus* trees had a mean DBH of 0.45 m (CV = 23.71%), a mean total height of 16.53 m (CV = 25.68%), a mean crown height of 13.33 m (CV = 29.92%), and a mean crown diameter of 12.90 m (CV = 18.81%). In turn, the sampled *P. acerifolia* trees had a mean DBH of 0.33 m (CV = 28.09%), a mean total height of 12.96 m (CV = 16.49%), a mean crown height of 10.37 m (CV = 18.54%), and a mean crown diameter of 10.76 m (CV = 18.69%).

The allometric relationship between crown diameter (CD) and DBH for both *H. heptaphyllus* and *P. acerifolia* shows that trees generally tend to have an increasing linear relationship, but this is more evident for *H. heptaphyllus*, where the crown diameter increases more markedly as DBH increases. However, trees with larger DBH do not always have the largest crown diameter (CD), and vice versa (Fig. 2). The Pearson's correlation coefficient (r) between CD and DBH was 0.71 for *H. heptaphyllus* and 0.89 for *P. acerifolia*, indicating a strong positive correlation between the two variables for the species studied.

The tested models showed varied goodness-of-fit statistics (Table 2) and different outcomes regarding compliance with the regression assumptions (Table 3), with residual

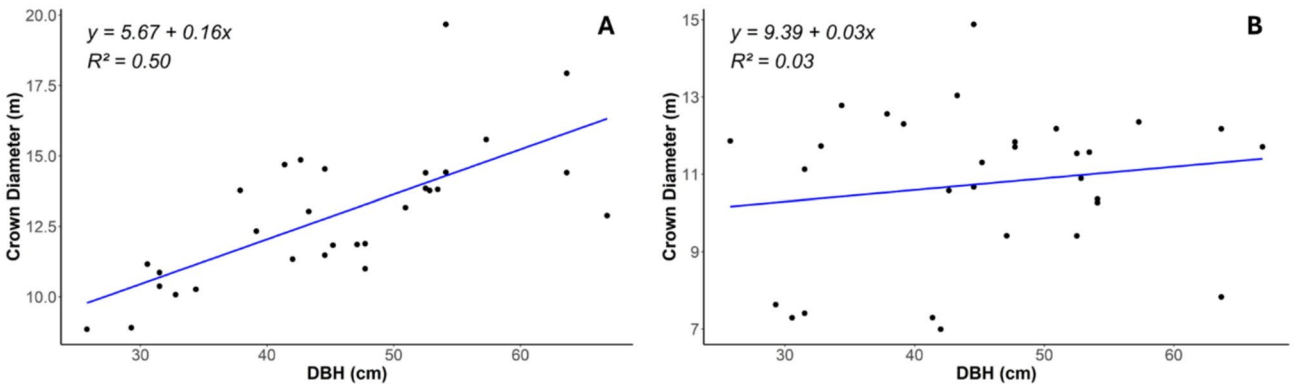

Fig. 2 Allometric relationships between tree crown diameter (CD) and diameter at breast height (DBH) for H. heptaphyllus (**A**) and P. acerifolia (**B**)

Table 2 Estimated parameters for the fitted models, with respective adjusted coefficients of determination (R^2_{adj}), standard error of the estimate (S_{yx} %), and root mean square error (RMSE) for estimating CD in *H. heptaphyllus* and *P. acerifolia*

		Coefficients				Statistics		
Species	Model	β_0	β_1	β_2	β_3	R^2_{adj}	S_{yx} (%)	RMSE
H. heptaphyllus	01	5.6720	0.1592			0.4808	13.55	1.69
	02	0.3893	0.5681			0.5639	13.41	1.67
	03	−0.7416	0.4553	−0.0032		0.4935	13.38	1.63
	04	9.4488	−0.2586	0.0126	−0.0001	0.4785	13.58	1.63
	05	0.3249	0.5816			0.5633	13.42	1.67
P. acerifolia	01	4.4122	0.1891			0.7780	8.51	0.92
	02	0.2319	0.6121			0.8230	8.39	0.87
	03	−0.8748	0.5314	−0.0051		0.8310	7.68	0.78
	04	−4.4252	0.8785	−0.0157	0.0001	0.8262	7.79	0.78
	05	0.1407	0.6326			0.8216	8.42	0.89

Table 3 Results of the regression assumptions tests, based on the Shapiro–Wilk (SW), Durbin-Watson (DW), and Breusch-Pagan (BP) tests

Model	*P. acerifolia*			*H. heptaphyllus*		
	SW test	DW test	BP test	SW test	DW test	BP test
Model 1						
Test value	0.9391	1.4650	1.4606	0.9287	1.4683	2.5165
p-value	0.0859	0.0681	0.2268	0.0453	0.0608	0.1127
Model 2						
Test value	0.9105	1.2491	0.0126	0.9647	1.4582	1.7296
p-value	0.0153	0.0161	0.9104	0.4047	0.05518	0.1885
Model 3						
Test value	0.9186	1.0536	2.7991	0.9315	1.5979	2.3734
p-value	0.0247	0.0030	0.2467	0.0539	0.1101	0.3052
Model 4						
Test value	0.9108	1.0483	4.4467	0.9272	1.5939	2.2015
p-value	0.0156	0.00261	0.2171	0.0415	0.1115	0.5317
Model 5						
Test value	0.9117	1.2591	0.0136	0.9647	1.4569	1.7215
p-valor	0.0165	0.0174	0.9069	0.4055	0.0547	0.1895

distributions being similar across all models for both species (Fig. 3) and (Fig. 4), and no clear distinction between models with the best fit statistics and the others. Only Model 4 did not fully meet the regression assumptions (normality, homoscedasticity, and independence of residuals) for *H. heptaphyllus*. In contrast, only Model 1 fully satisfied all regression assumptions for *P. acerifolia*.

Next, Models 2 and 5 showed the best performance among the models tested for the crown diameter (CD) estimation for *H. heptaphyllus*, with higher adjusted coefficients of determination (R^2_{adj}), lower standard errors of estimate (S_{yx}), and lower RMSE values (Table 2). However, although models 2 and 3 performed well in terms of fit statistics for *P. acerifolia*, the diagnostic tests indicated violations of assumptions, such as non-normality of residuals (SW < 0.05) and significant residual autocorrelation (DW < 1.5 and p-value < 0.05).

On the other hand, although Model 1 produced results that comply with the regression assumptions, its use for estimating CD in *P. acerifolia* and *H. heptaphyllus* presents significant practical and biological limitations. From a statistical perspective, Model 1 yielded relatively low adjusted coefficients of determination (R^2_{adj}) compared to the other models. In addition, the standard errors of estimate (S_{yx}%) and RMSE values were higher, indicating greater residual dispersion and lower estimation precision.

Beyond the lower statistical precision, it was observed that the estimated intercept (β_0) for Model 1 in both species was significant ($p < 0.01$), but with values exceeding four (*P. acerifolia*: 4.41; *H. heptaphyllus*: 5.67). This suggests that the predicted CD would range from 4.0 to 5.0 m for hypothetical trees with a DBH equal to one, which is biologically inconsistent, since the expected CD for young individuals in such cases would be much closer to one. Therefore, the equations used for CD estimation were derived from Model 5 for *H. heptaphyllus* and *P. acerifolia* (Eq. 08).

$$\mathbf{CD} = e^{\beta_0} \times (DBH + 1)^{\beta_1} \quad (08)$$

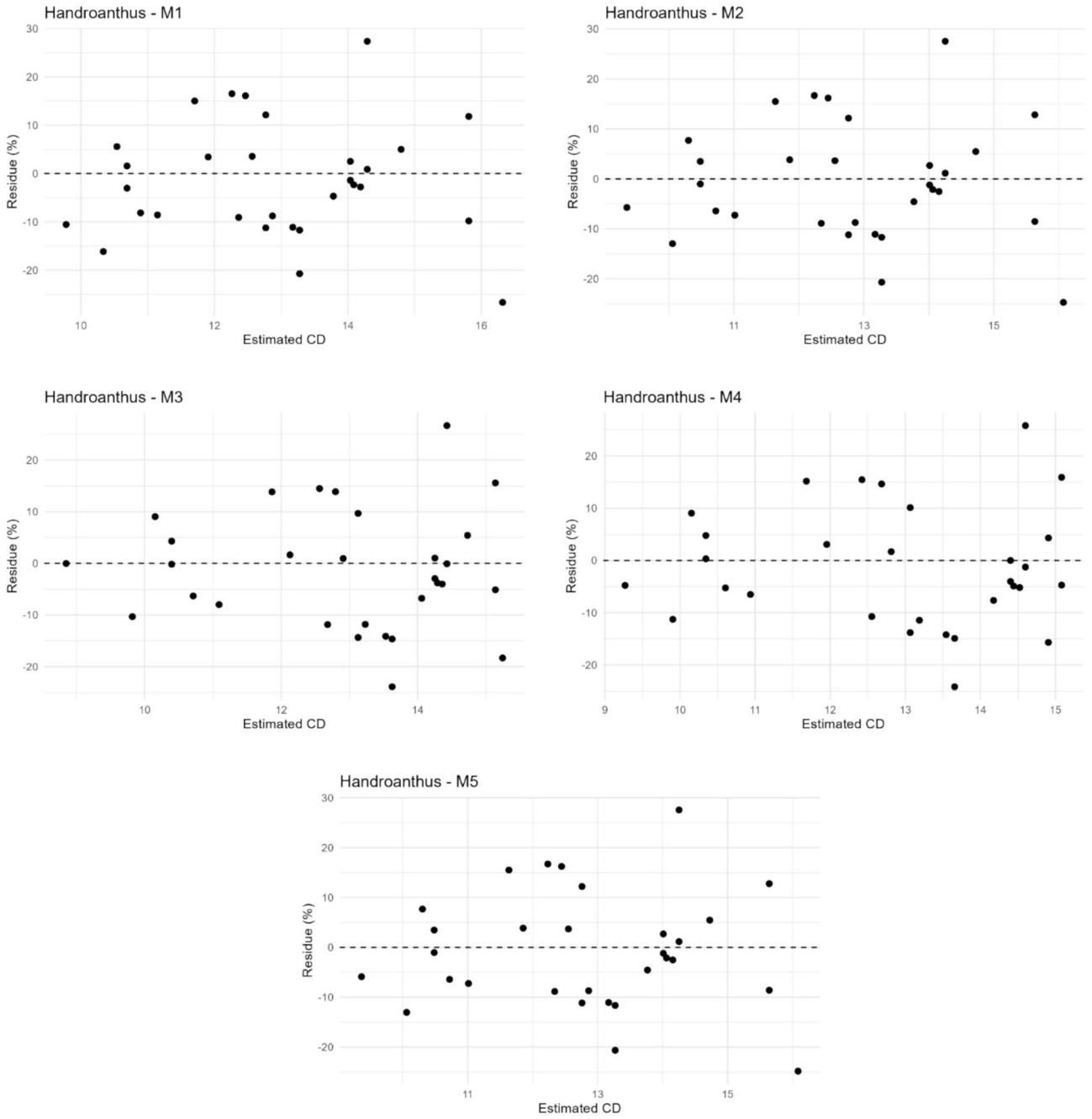

Fig. 3 Residual distribution as a function of different crown diameters (CD) for the fitted models (Model 1: M1 to Model 5: M5) in *H. heptaphyllus*

The mean RMSE values obtained via fivefold cross-validation ranged from 1.63 to 1.88 for *H. heptaphyllus*, and from 0.96 to 1.08 for *P. acerifolia* across the five models tested. These values were deemed acceptable given the natural variability in crown architecture and the limited sample size (n = 30 per species), as they correspond to approximately 10% of the mean crown diameter values recorded for the assessed trees (12.90 m for *H. heptaphyllus* and 10.37 m for *P. acerifolia*).

Modeling the growth of urban trees

We estimated the diameter with bark (DBH_{bb}) over the years, given that the partial stem analysis samples provide information on diameter growth over time without accounting for bark thickness. Therefore, the increment core data were fitted using a model that estimates the field-measured DBH (which inherently includes bark) to align the growth estimates produced by the model with field measurements.

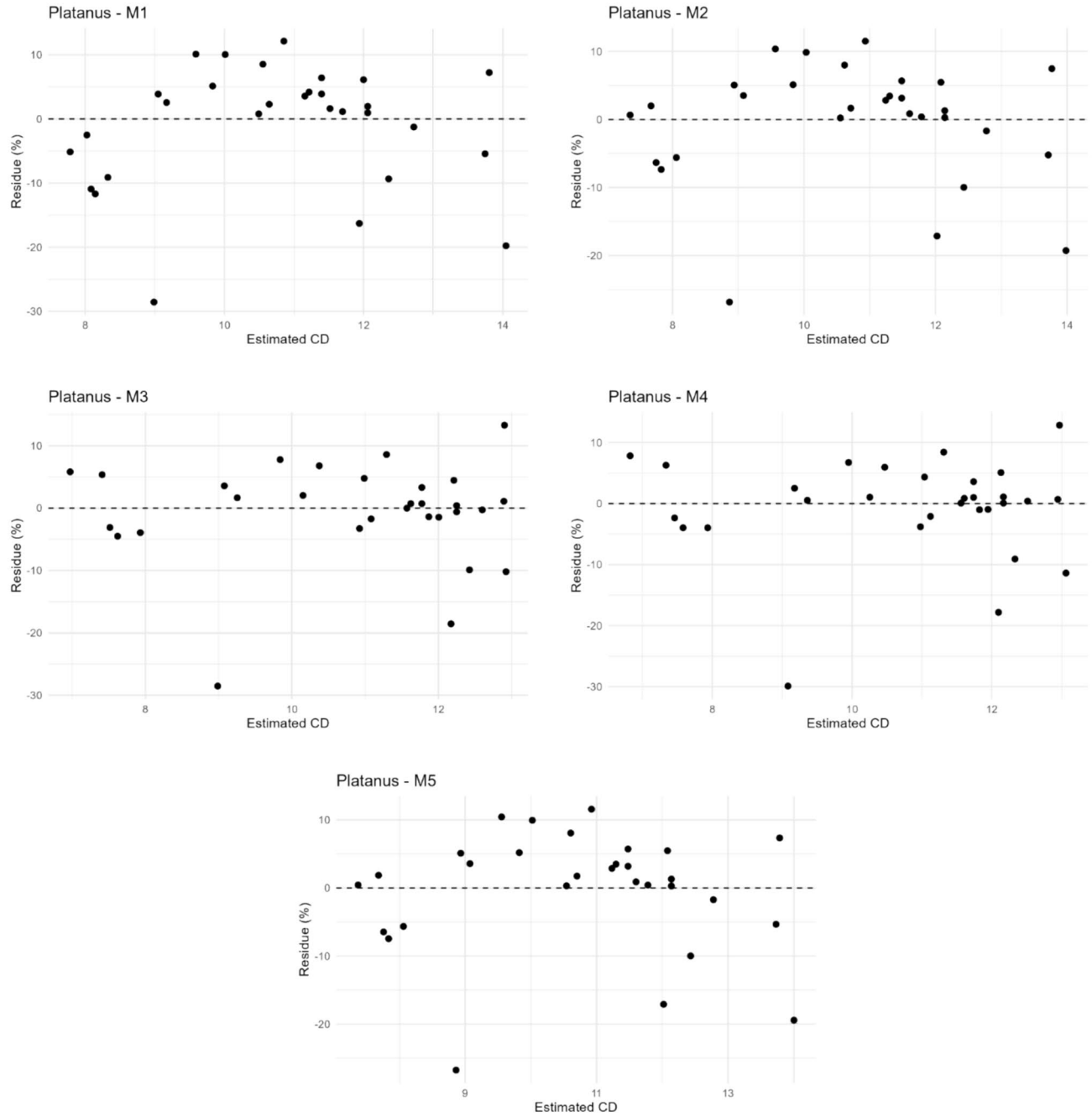

Fig. 4 Residual distribution as a function of different crown diameters (CD) for the fitted models (Model 1: M1 to Model 5: M5) in *P. acerifolia*

Based on the fitted equations, it can be stated that the linear model was effective for estimating DBH with bark for both species (Table 4). The biological Chapman-Richards model was fitted to estimate diameter growth over time for the two species (Table 5), yielding satisfactory results for the coefficient of determination, although the standard error of estimate values was above 10%.

We estimated CD growth to understand how this variable evolves over time, considering that crown diameter models can be applied to demonstrate how much the crown of a given species will expand when combined with partial stem analysis, which allows estimating DBH at any age. The CD growth curves (Fig. 5) for both species show a marked reduction in growth rate and stabilization beginning around age 45, with only minimal additional growth beyond that age under the environmental conditions of the species analyzed. However, this stabilization occurs earlier for *P. acerifolia* compared to *H. heptaphyllus*. In their mature/senescent

Table 4 Resulting equations for estimating diameter at breast height with bark (DBH_{bb}) as a function of diameter at breast height without bark (DBH_{wb}), with adjusted coefficients of determination (R^2_{adj}) and standard error of estimate (S_{yx}%) for *H. heptaphyllus* and *P. acerifolia*

Species	Model adjusted	R^2_{adj}	S_{yx} (%)
H. heptaphyllus	$DBH_{bb} = 1.5330 \times DBH_{wb}$	0.9090	19.03
P. acerifolia	$DBH_{bb} = 1.0613 \times DBH_{wb}$	0.9370	17.88

Where: DBH_{bb} = Diameter at Breast Height with bark (cm); DBH_{wb} = Diameter at Breast Height without bark (cm); R^2_{adj} = adjusted coefficient of determination; S_{yx} (%) = standard error of estimate.

phase, *H. heptaphyllus* trees can reach average crown diameters of approximately 15.0 m, while *P. acerifolia* trees can reach around 13.0 m, which is an important aspect for planning the integration of these species into urban spaces of compatible dimensions. Considering the approximate age of the trees at the time of sampling (2018), between 28 and 30 years, the mean crown diameter estimated by the growth curve is similar to the field data obtained (12.90 m for *H. heptaphyllus* and 10.37 m for *P. acerifolia*).

Discussion

The results of this study presented suitable and accurate models for estimating crown diameter (CD) based on DBH, as well as for projecting CD growth over time by combining DBH growth models with models describing the CD/DBH relationship. The selection constraints applied (trees without signs of pruning and located within the same area) limited the size of the dataset but made it possible to achieve the positive results obtained.

Research related to modeling the relationship between DBH and CD for urban trees has shown that there is a moderate to strong correlation between these variables (ranging from 0.61 to 0.91) for different species planted under open-growing conditions without competition (Peper et al. 2001; Grabosky and Gilman 2004; Martin et al. 2012). However, the correlation may be lower depending on the variability in CD and species-specific characteristics, a pattern expected among trees in urban forests, especially regarding CD values. This is because trees are constantly in conflict with various types of infrastructure and often experience improper management practices or grow under more stressful environmental conditions (Peper et al. 2001; Martin et al. 2012).

Quigley (2004) demonstrated that the growth pattern of trees over time, even for the same species, is not always consistent, despite strong correlations among dimensional variables (DBH, CD, crown height). On the other hand, estimates as a function of age can be influenced by site characteristics (such as soil permeability, shading, and street conditions), among other variables typical of urban areas (Lukaszkiewicz and Kosmala 2008; Pretzsch et al. 2023). For this reason, site quality should be considered as an input variable in the model and can be measured, for example, through vigor analysis or leaf area assessment (Troxel et al. 2013). Given that current datasets for Brazilian urban forests are largely restricted to DBH and total height measurements, the development of adequate databases for urban tree modeling in Brazil remains a significant gap.

When evaluating the DBH growth of *Araucaria angustifolia* (between 35 and 39 trees per sampling site) located in different typologies (street trees, yard trees near houses,

Table 5 Results of the Chapman-Richards model fit for estimating diameter at breast height (DBH) across different ages for *H. heptaphyllus* and *P. acerifolia*

Species	Model adjusted	R^2_{adj}	S_{yx} (%)
H. heptaphyllus	$DBH_{bb} = 70.1239 \times [(1 - \exp(-0.05268 \times I))]^{1.8446}$	0.8509	37.96
P. acerifolia	$DBH_{bb} = 72.6748 \times [(1 - \exp(-0.04279 \times I))]^{2.4218}$	0.8790	36.72

Where: DBH_{bb} = Diameter at Breast Height with bark (cm); DBH_{wb} = Diameter at Breast Height without bark (cm); R^2_{adj} = adjusted coefficient of determination; S_{yx} (%) = standard error of estimate.

trees in squares, residential and industrial neighborhoods) within the urban forest of the city of Araucária, Brazil, Canetti et al. (2017) obtained an R^2 greater than 0.96 for all environments assessed, with errors lower than those found in the present study. The authors stated that urban trees tend to show a low correlation between growth chronology because urban sites are highly heterogeneous, resulting in substantial variation in growth rates. Based on this, they suggest stratifying the study area according to the degree of urbanization. Although our study had a limited sample size, we minimized environmental heterogeneity and could promote this suggested stratification by selecting trees from a single location, either within one urban park or along the same street.

Models fitted to estimate crown diameter and/or crown projection area of open-grown urban trees exhibit variable precision and goodness of fit, influenced by species-specific growth patterns, sample size per species, and the heterogeneity of the environmental conditions (Peper et al. 2014; Pretzsch et al. 2015; Blood et al. 2016; Vaz Monteiro et al. 2016; Coombes et al. 2019; Lee et al. 2024). The precision statistics respectively obtained for *H. heptaphyllus* and *P. acerifolia* (R^2_{adj} of 0.56 and 0.82, S_{yx}(%) of 13.42 and 8.42, and RMSE of 1.67 and 0.89, respectively) for the sample size used in this study (30 trees per species) indicate that the models are satisfactory for estimating CD of mature trees starting from the threshold of 5.0 m in diameter. This threshold also corresponds to the size of trees in the early post-planting years under open-grown conditions. Additionally, the projected CD growth curve enables estimates for smaller diameters from the early growth stages of the trees.

North et al. (2017) evaluated the performance of urban trees based on DBH, crown projection area (CPA), relative growth index (BRATIO), and tree performance index (TPI) using 292 mature trees from four species (*Acer platanoides*, *Celtis occidentalis*, *Gleditsia triacanthos*, and *Tilia* spp.), distributed along streets and in urban parks in the cities of Minneapolis and Saint Paul, Minnesota, USA. The study showed that sample size and the inclusion of different urban environments (street and park) strongly influenced model precision. The models explained between 18 and 66% of the observed variation, with the highest R^2 found for the CPA variable. The use of composite indices such as BRATIO and TPI enabled integrating both past and recent growth, providing a more comprehensive view of future growth potential and tree health across the different urban conditions analyzed.

Yang et al. (2023) developed allometric models for 15 common species in the urban forest of Qingdao, China, based on 5,648 sampled individuals across an urban–rural gradient. The species included *Platanus* × *acerifolia*, *Fraxinus chinensis*, *Ginkgo biloba*, *Styphnolobium japonicum*,

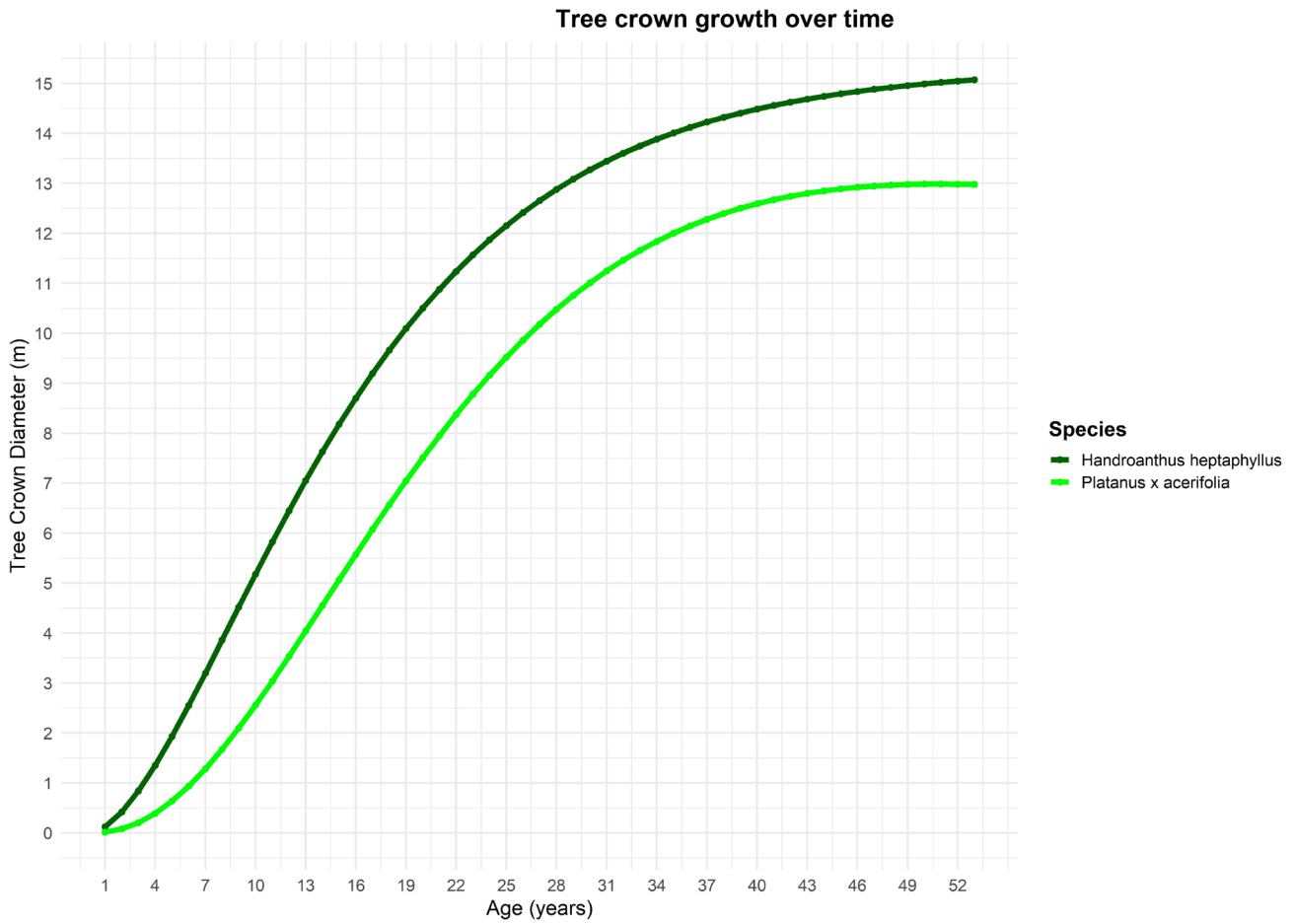

Fig. 5 Trend curves of crown diameter growth over time for *H. heptaphyllus* and *P. acerifolia*

among others. Model precision varied by species and variable, with CD showing a stronger relationship with DBH than height did. The authors observed that morphological and management differences, such as pruning and available growing space, as well as potential sampling limitations for some species affected the characteristics and precision of the models.

Coombes et al. (2019) evaluated the allometric relationship between diameter at breast height (DBH) and crown diameter (CD) in 400 urban trees of four species (*Quercus robur*, *Acer pseudoplatanus*, *Betula pendula*, and *Acer platanoides*) distributed across two cities in the United Kingdom (Norwich and Peterborough). The quadratic model fitted for all species combined yielded an adjusted R^2 of 0.82, highlighting a strong relationship between the variables. The mean CD/DBH ratio varied only slightly among species, with values ranging from 1:24 to 1:27. These ratios were lower than those observed for *H. heptaphyllus* (mean 1:29, range 1:19–1:36) and *P. acerifolia* (mean 1:33, range 1:25–1:41). In this study, authors found that sampling location (city), soil type, pruning history, and the percentage of impervious surface around the tree had little or no significant influence on the CD/DBH relationship. The results suggest that species and site factors have limited influence on this allometric relationship under urban conditions in the UK, allowing the use of general equations for practical estimates, although they noted that extreme genetic or environmental variation may result in different outcomes.

Vaz Monteiro et al. (2016) developed allometric models relating to DBH, total height, and crown width for seven common urban tree species in Great Britain based on 2,163 individuals sampled across eight cities. The species studied were divided into small and large size classes, covering *Acer campestre*, *Betula pendula*, *Ilex aquifolium*, *Acer pseudoplatanus*, *Fagus sylvatica*, *Fraxinus excelsior*, and *Quercus robur*. Their analyses showed that the coefficients of determination (R^2) ranged from 0.10 to 0.88, with better fit generally observed for the relationship between DBH and CD. The study highlighted significant variation in allometric parameters among locations, even for the same species, with maximum differences in mean tree heights exceeding 10 m and crown widths varying by up to 4 m between different locations. In addition to location, tree size class (small

or large) and developmental stage (young or mature) influenced model precision.

Based on the studies detailed above, modeling urban tree growth and the relationship between CD and DBH is inherently more complex than in forest stand conditions. In urban environments, these relationships may or may not be affected by environmental variables, depending on local site characteristics that are highly heterogeneous. Additionally, intrinsic factors such as genetic variability, tree management (pruning), and tree age further contribute to this complexity.

However, studies which provide model fitting and practical application of crown diameter and crown area estimates based on DBH and total height are common, with results that can support management practices, pollutant retention estimates, biomass production assessment, carbon stock estimation, and stormwater interception evaluations, among others (Yoon et al. 2013; Nielsen et al. 2014; Song et al. 2020; Selbig et al. 2022; Yang et al. 2023). It is possible to generate basic information from results of simple models like those developed for *H. heptaphyllus* and *P. acerifolia* to support planning the urban forest composition in parks and squares, but especially for street tree planting, since this is the most challenging environment for tree establishment and where major conflicts arise from tree–people–infrastructure interactions (Pretzsch et al. 2015; Mata et al. 2020).

Despite the satisfactory results for the models and the crown diameter growth curve indicating plausible estimates over time, this study presents some limitations that could be addressed in future modeling approaches for urban tree growth to support planning activities for Brazilian urban forests, which still lack adequate data and models. The tree sampling was limited to 30 individuals per species due to strict selection criteria (trees unpruned and located in the same area), but the sample size could be increased by incorporating data from other Brazilian cities in the southern region, although sampling location can be an important source of variation in forest data modeling. There is a shortage of CD/DBH relationship models for the diverse range of native and exotic species planted in Brazilian urban ecosystems, which would foster studies with broader results and greater regional impact for urban tree planning. One limiting factor in this study was the stem sampling of *H. heptaphyllus* given the high wood density and presence of extractives, which made it difficult to obtain growth samples from mature trees. In this case, establishing continuous inventories with permanent plots should be adopted as a standard practice for more robust studies of forest species under urban growth conditions (Bobrowski et al. 2012; Bobrowski and Biondi 2012). Another limitation to address is that we don't have a method for analyzing crown-diameter growth in mature trees based on branch growth characteristics and elongation patterns across growing seasons to recover past growth rates, similar to how stem growth is reconstructed from tree rings.

Despite limitations related to sample size, restricted geographic scope, and the lack of stratification by urbanization level, the models developed in this study can already support preliminary public policies for street tree planting. The models and growth curves provide a technical reference for urban forestry professionals to estimate the tree crown space required for full crown development, helping to prevent future conflicts with overhead utility lines and buildings. Moreover, even if models are refined in the future using longer time series and permanent plot data, they can already guide the planning of minimum spacing between trees and forecast operational costs for preventive pruning of the studied species. In doing so, they hel strenghten integrated management and resilience of the urban forest in other cities with environmental conditions comparable to those of Irati, Paraná.

Conclusions

The results of this study demonstrate that modeling the growth of urban trees can be successfully conducted using allometric equations and biological growth models such as the Chapman-Richards function. The fitted equations showed accuracy in estimating crown diameter (CD) based on diameter at breast height (DBH), and the growth projection over time provides valuable support for planning urban tree composition in parks, squares, and street settings.

Concerning the models for CD estimation, preciseness' statistics were moderate to good considering the intrinsic variability of urban tree data. Statistics varied from 0.47 to 0.56 (R^2_{adj}), 13.41 to 13.58 (S_{yx}%) and 1.63 to 1.67 (RMSE) for *H. heptaphyllus*, and from 0.77 to 0.83 (R^2_{adj}), 7.68 to 8.51 (S_{yx}%) and 0.78 to 0.92 (RMSE) for *P. acerifolia*. For models related to DBH growth, statistics varied from 0.85 to 0.87 (R^2_{adj}), and 37.96 to 36.72 (S_{yx}%), respectively for *H. heptaphyllus and P. acerifolia.*

Under the climatic and environmental conditions of the city of Irati, Paraná, the species *H. heptaphyllus* and *P. acerifolia* are expected to reach crown growth stabilization around 45 years of age, attaining average crown diameters of approximately 15 m and 13 m, respectively. This information is essential for defining appropriate planting distances, predicting potential conflicts with urban infrastructure, and quantifying the ecosystem services provided.

Although sample size and sampling conditions pose certain limitations, the models generated can serve as an initial reference for other cities with similar environmental characteristics. For future research, it is recommended to consider larger sample sizes, expand sample areas, include different

urbanization levels, and implement continuous monitoring of permanent plots to refine growth models for urban trees within the Brazilian context.

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Data Availability All data used in this research are publicly available upon request to the corresponding author.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to declare.

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