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Effects of pruning on growth and ecosystem services of plane trees in urban environment

Thomas Rötzer[a,*,1], Astrid Moser-Reischl[a,2], Nayanesh Pattnaik[a,3], Stephan Pauleit[a,4], Qiguan Shu[b,5], Ferdinand Ludwig[b,6]

[a] *Strategic Landscape Planning and Management, School of Life Sciences Weihenstephan, Technical University of Munich (TUM), Freising, Germany*
[b] *Green Technologies in Landscape Architecture, TUM School of Engineering and Design, Technical University of Munich, Munich, Germany*

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ABSTRACT

Pruning is one of the most common management practices of urban trees to ensure safety, for aesthetic reasons or to remove dead plant parts. A tree's growth performance and ecosystem services such as evaporation and shading can also be affected by pruning. This research study investigated how the growth of naturally grown *Platanus x hispanica* trees in Germany differs from that of table-topped pruned trees of the same species. The influence of this kind of pruning on photosynthesis, leaf area, growth and ecosystem services was demonstrated. We found that leaf level photosynthesis of table-topped trees was 20 % higher and leaf level transpiration rate 56 % higher than in naturally grown trees of the same age. Conversely, canopy photosynthesis and canopy latent heat flux was significantly lower in table-topped trees (47 % and 82 %). Our results clearly indicate a decrease in both size and diameter increment for table-topped trees compared to naturally grown trees, which confirms the reduction in the physiological processes photosynthesis and transpiration on canopy level. The changed physiology resulted in reduced stem diameter growth for table-topped plane trees in the year after pruning for 39 %. Crown projection area and the crown volume of naturally grown plane trees is 2 times and 2.7 times higher than the ones of table-topped plane trees of the same diameter size, while leaf area is on average 30 % larger for table-topped trees. The allometric relationships clearly differed. Our results show that specific environmental conditions should be considered when pruning trees in terms of growth and ecosystem services. A possible reduction in growth and services due to pruning can be mitigated by improving site conditions (e.g., low soil sealing, large root volume). However, especially in water-scarce environments or with high soil sealing, the reduction in transpiration following this type of tree pruning can be potentially beneficial. Our study, though, did not investigate sociocultural motives or aesthetic reasons for pruning. Our investigations focused exclusively on the growth and ecosystem services of a single species, *P. x hispanica*. Future studies should fill this gap by conducting a holistic study of the ecological, social, and aesthetic impacts of tree pruning that also includes other species with different growth and drought characteristics.

1. Introduction

Compared to forests, cities represent highly modified habitats for trees, characterized by narrow and often highly sealed planting pits, lack of water, limited above and belowground growing space, heat and pollutant input (Allen et al., 2020; Czaja et al., 2020). In addition, urban trees are exposed to management practices such as the pruning of crown sections, heavily affecting the shape and size of tree crowns. Pruning is by far the most common practice in the regular maintenance of urban trees (Speak and Salbitano, 2023). The reasons for pruning trees are

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* Correspondence to: Technical University of Munich, Chair for Strategic Landscape Planning and Management, Emil-Ramann-Str. 6, Freising 85354, Germany.
E-mail address: Thomas.roetzer@tum.de (T. Rötzer).

[1] 0000-0003-3780-7206
[2] 0000-0002-1288-411X
[3] 0000-0002-7547-1347
[4] 0000-0002-0056-6720
[5] 0000-0003-3856-2191
[6] 0000-0001-5877-5675

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varied and include safety reasons, such as reducing the risk of wind breakage, ensuring road visibility, avoid collisions with large vehicles, reduce interferences with buildings, aesthetics and the removal of dead plant parts or pest infestations (Muscas et al., 2024; Suchocka et al., 2021). Moreover, pruning might decrease the water uptake of a plant, conserving soil moisture and increasing drought tolerance of trees in cities (Hipps et al., 2014).

Pruning the crown requires the removal of biomass from the tree; it is a major management practice affecting the crown size, density and shape (Comin et al., 2025). This has further effects on biomass production and the provision of ecosystem services (ES) such as cooling through transpiration and shading, runoff reduction and pollutant filtering (Ferrini et al., 2017). It is well established that pruning can promote tree growth (Clark and Matheny, 2010; Pinkard and Beadle, 2000), improves timber quality (Maurin and DesRochers, 2013; O'Hara, 1991; Pinkard and Beadle, 2000) and reduces failure risk (Badrulhisham and Othman, 2016; Maruthaveeran and Yaman, 2010). However, the opposite effects of pruning on tree growth have also been observed (see e.g. Amateis and Burkhart (Amateis and Burkhart, 2011) depending on the tree species, site type, technique and intensity of pruning. The variability in the results of previous studies shows that there is a critical lack of knowledge about the responses of certain species to different pruning methods (Hevia et al., 2016), especially in cities and urban trees that is necessary for an effective pruning management.

Further, the impact of tree pruning on ES is still intensively discussed in numerous research studies. As Fini et al. (Fini et al., 2023) showed, routinely pruned street trees assimilated 20–70 % less CO_2 compared to even-aged, natural grown park trees due to their smaller crown radius, rather than changes in photosynthetic rate per unit of leaf area (Comin et al., 2025). Speak and Salbitano (Speak and Salbitano, 2023) found a 6.5 % reduction in the provided ES due to regular pruning after six years. Another study of Comin et al. (Comin et al., 2025) showed that trees with topped crowns had a reduced latent heat dissipation of up to 81.1 % due to the smaller total leaf area. Pruning can also cause an up to 91 % increase in carbon emissions due to pruning, reducing the positive carbon footprint of urban trees (Kim and Jo, 2022; Liu et al., 2024).

The effect of pruning on tree growth, recovery and ES provisions varies depending on the timing (within the year and intervals), intensity (e.g., percentage of branch biomass or buds removed), target structure and pruning method (e.g., types of pruning cuts adopted) (Comin et al., 2025; Dujesiefken and Stobbe, 2002; Gilman and Knox, 2005; Muscas et al., 2024; Pinkard and Beadle, 2000). Intense pruning measures using harmful techniques are mostly regarded as detrimental to tree growth and recovery (Muscas et al., 2024; Smiley and Kane, 2006; Suchocka et al., 2021), as they create wounds and increase tree susceptibility to disease and insect infestation (Ehsen, 1987; Gilman et al., 2015; Speak and Salbitano, 2023). Species react differently to pruning measures and have different pruning needs. While several tree species react very sensitive to pruning (Hevia et al., 2016), species from *Acer* and *Tilia* genera as well as *Platanus x hispanica* though, are known to be very pruning tolerant (Sajdak et al., 2014) and have been extensively used for this reason, for instance in European Baroque gardens.

P. x hispanica is a common urban tree species used in temperate regions, especially in parks and along roadsides. This is mainly due to its high resistance to drought, insect infestation, air pollution and root compaction, as well as its rapid growth and ease of transplanting (Sajdak et al., 2014). In addition to their natural growth form, *P. x hispanica* trees are also available as a so-called table-topped form. Here the crowns are shaped into a flat layer through labor-intensive maintenance (Shu et al., 2024). This form probably originates from Baroque gardens, where plants were kept in an orthogonal manner to enhance the orientation or perspective (Dobrilovič, 2010). Due to the expansion of the crown like an umbrella, it is still used in European cities nowadays for shading squares and pedestrian areas (e.g., the central square at Labouheyre, France) (Shu et al., 2022).

Although there has been considerable research on the influence of different types of pruning on the growth and ES of certain species, particularly in forestry and sometimes also in urban areas, few direct comparisons have been made between pruned and unpruned or naturally grown individuals of a species in urban environments. With our study, we aim to demonstrate how the growth of naturally grown *P. x hispanica* trees differs from that of table-toped trees. In particular, we are investigating the differences in photosynthesis, leaf area, and ES provision, between naturally grown (i.e. unpruned) and table-topped (i.e. pruned) trees in urban areas. Our research questions are:

(1) Are there significant differences in the photosynthesis rates and transpiration sums of *P. x hispanica* trees between naturally grown and table-topped individuals?
(2) Can the changes of leaf area index (LAI), leaf biomass and leaf area by the pruning technique table topping be quantified?
(3) How does the stem diameter and the basal area increment of naturally grown and table-topped *P. x hispanica* trees differ after pruning?
(4) To what extent does the pruning technique table topping change tree dimensions of *P. x hispanica* trees in urban environments?

2. Materials and methods

2.1. Study sites and pruning techniques

The study on the impact of table-top pruning on London plane trees (*Platanus x hispanica* or *Platanus acerifolia*) was carried out at two sites in Germany, representing different growth settings and climate influences. One was at the Bruns nursery in Bad Zwischenahn in northern Germany (longitude: 8.001°, latitude: 53.184°, elevation: 7 m) and the other in the urban area of Munich in southern Germany (longitude: 11.575°, latitude: 48.138°, elevation: 520 m). The annual precipitation in Munich with 940 mm is clearly higher than in Bad Zwischenahn with 627 mm. The mean annual air temperature is at 10.1°C in Munich and 10.0°C in Bad Zwischenahn.

Table-top pruning forms a flat crown with straight vertical sides, i.e. a horizontally aligned tree canopy. To create such forms, at the beginning young trees have to be intensively trimmed, i.e., six branches are bent horizontally into different directions with equal angles in between at a height of approximately 3 m. Hereby, table-topped trees with one layer are made up of one layer with six main branches, while table-topped trees with two layers are made up of two times six main branches at two levels. In the following years new shoots or some of the older shoots are selected and pruned to enable shoot growth only at desired positions. This pruning is repeated in subsequent years, resulting in a table-top branching pattern (Shu et al., 2024).

This pruning technique of plane trees was performed in August (Bad Zwischenahn, Munich) or in September (Munich) in the years before the measurements. The sites in Munich were selected to ensure that the stem diameter distribution of naturally grown and table-topped trees was roughly the same. In Bad Zwischenahn, the plots were selected in a way that naturally grown and table-topped trees of the same dbh could be compared.

In Bad Zwischenahn, light pruning (less than 10 % of leaf biomass) was carried out on the naturally grown trees to maintain their natural shape in the years 2021 and 2023. To keep their shape table topped trees in Bad Zwischenahn were pruned annually in August by app. 44 % (2 layers) up to app. 76 % (1 layer) of their initial leaf biomass.

In Munich, naturally grown trees have not been pruned in recent years, while pruning of the table topped trees was done in the years before the measurements. The amount of the removed biomass could not be quantified; According to the Munich City Horticultural Office, the biomass removed can be estimated at 40–50 % of the leaf biomass.

Tree structure measurements (dbh, tree height, crown dimensions) and allometric analyses were performed for plane trees at all sites, while due to time constraints, hemispherical recordings, i.e. leaf area analyses, could only be performed at a limited number of sites (Table1).

In Bad Zwischenahn diameter at breast height (dbh) was recorded monthly from March to September for the years 2023 and 2024 to derive monthly basal area increments in the course of the two years. Removal of foliage biomass by pruning was measured at the Bad Zwischenahn sites in 2023 where both naturally grown and table trees of the same dbh were present (Table 1).

In Munich dbh was measured annually in autumn 2023 as well as in autumn 2024. Based on repeated measurements stem diameter increment of naturally grown and table-topped plane trees could be calculated for the site Technisches Rathaus in Munich. Photosynthesis and transpiration of leaves were measured at the four sites in Munich (Table1).

For the nursery stands in Bad Zwischenahn, it should be remarked that the trees were irrigated when necessary.

2.2. *Tree data and measurements in Munich*

The measurements were taken on table-topped plane trees at 7 sites and on naturally grown plane trees at 21 sites (Fig. 1). The sites represent a range of open space and planting types, from parks with unsealed to highly sealed surfaces.

The measurements on naturally grown trees were carried out between 2019 and 2024. In 2023 and 2024, measurements were performed on table-topped trees that had been pruned in the previous year.

At all sites tree structural dimensions, i.e., measurements of diameter at breast height (dbh), tree height (h), crown diameter (cd) and crown length (cl) were obtained. The mean dbh of the 93 table-topped trees in Munich was 20.7 cm and thus close to the average dbh of the 137 naturally grown trees with 20.3 cm (Table2). No significant difference was found for the dbh of the trees grown in Munich ($p > 0.05$). The tree height, crown base, and crown radius of the table topped trees were significantly smaller than those of the naturally grown trees in Munich and also differed significantly ($p < 0.05$). In Bad Zwischenahn, the naturally grown trees had a mean dbh of 14.8 cm, slightly larger than those of the table-topped trees with 13.8 cm. Again, there was no significant difference between the average dbh values ($p > 0.05$). However, the naturally grown trees in Bad Zwischenahn were more than twice as tall as the table-topped trees (significantly different with $p < 0.05$), and the crown base and crown radius were also significantly higher and larger for naturally grown trees ($p < 0.05$). For all naturally grown trees and table-topped trees together, it can be seen that the dbh and crown base are hardly any different ($p > 0.05$), whereas the tree height and crown radius for naturally grown trees are significantly higher and larger, respectively ($p < 0.05$).

Because the structure of the trees at the site “Technisches Rathaus” was measured in 2023 as well as in 2024, the annual increments of dbh, tree height and crown dimensions of table-topped and naturally grown trees could be calculated.

Hemispherical photos were taken of a selection of trees in July to derive the LAI. Further, transpiration and photosynthesis rates of the leaves of table-topped and naturally grown plane trees were measured on sunny days in June and July 2024. They were recorded on 212 sun and shade leaves of pruned and on 79 sun and shade leaves of naturally grown plane trees at the two Munich sites “Arabellaplatz” and “Technisches Rathaus”.

2.3. *Tree data and measurements in Bad Zwischenahn*

In Bad Zwischenahn, the annual development of the dbh of 16 table-topped and 18 naturally grown *P. x hispanica* trees were recorded from January 2023 until October 2024 (Table2). The measurements were carried out on four plots each with table-topped pruned and naturally grown trees. According to nursery standards, for naturally grown trees

Table 1

Overview of measurements and number of measured trees per site for the single analyses (Abbreviations: long = longitude, lati = latitude, struc = tree structural measurements, hemi = hemispherical pictures, ps, trans = photosynthesis and transpiration, inc dbh = dbh increment, bred = leaf biomass reduction by pruning).

site	long [°]	lati [°]	struc	hemi	ps,trans	inc dbh	bred
naturally grown trees							
Munich, Astrid Lindgren Straße	11.7056	48.1307	12				
Munich, Am Harras	11.5381	48.1169	6				
Munich, Arabellapark	11.6206	48.1512	1	1	5		
Munich, Infanteriestraße	11.6902	48.1593	2				
Munich, Olof Palme Straße	11.6902	48.1362	5				
Munich, Ruth Beutler Straße	11.7011	48.1289	9				
Munich, Schwere Reiter Straße	11.5547	48.1615	8				
Munich, Genfer Platz	11.4900	48.0947	1				
Munich, Herzog-Wilhelm-Straße	11.5667	48.1365	1				
Munich, Stadtzentrum	11.5754	48.1371	3				
Munich, Willy Brandt Allee	11.6980	48.1333	5				
Munich, Pasing	11.4615	48.1414	15	15			
Munich, Rosenkavallierplatz	11.6183	48.1522	7				
Munich, Rudi-Hierl-Platz	11.5589	48.1485	5				
Munich, Technisches Rathaus	11.6122	48.1302	4	4	4	4	
Munich, Wettersteinplatz	11.5749	48.1092	9				
Bad Zwischenahn	8.0010	53.1840	18	18		18	5
Summe			**111**	**38**	**9**	**22**	**5**
table topped shaped trees							
Munich, Friedenstraße	11.6113	48.1301	18	18			
Munich, Schlierseestraße	11.5915	48.1146	12	12			
Munich, Kirchenstrasse	11.6037	48.1335	6	6			
Karlsfeld, Krenmoosstraße	11.4723	48.2238	5				
Munich, Romanplatz	11.5116	48.1555	9	9			
Munich, Arabellapark 23	11.6206	48.1512	19		6		
Munich, Arabellapark 24	11.6206	48.1512	19	19	6		
Munich, Leopoldstraße	11.5859	48.1681	1	1	1		
Munich, Technisches Rathaus 23	11.6121	48.1306	21	20	7	21	
Munich, Technisches Rathaus 24	11.6121	48.1306	21	21			
Munich, Winzerer Straße	11.5606	48.1711	6	6	6		
Bad Zwischenahn	8.0010	53.1840	16	16		16	4
Summe			**153**	**128**	**26**	**37**	**4**

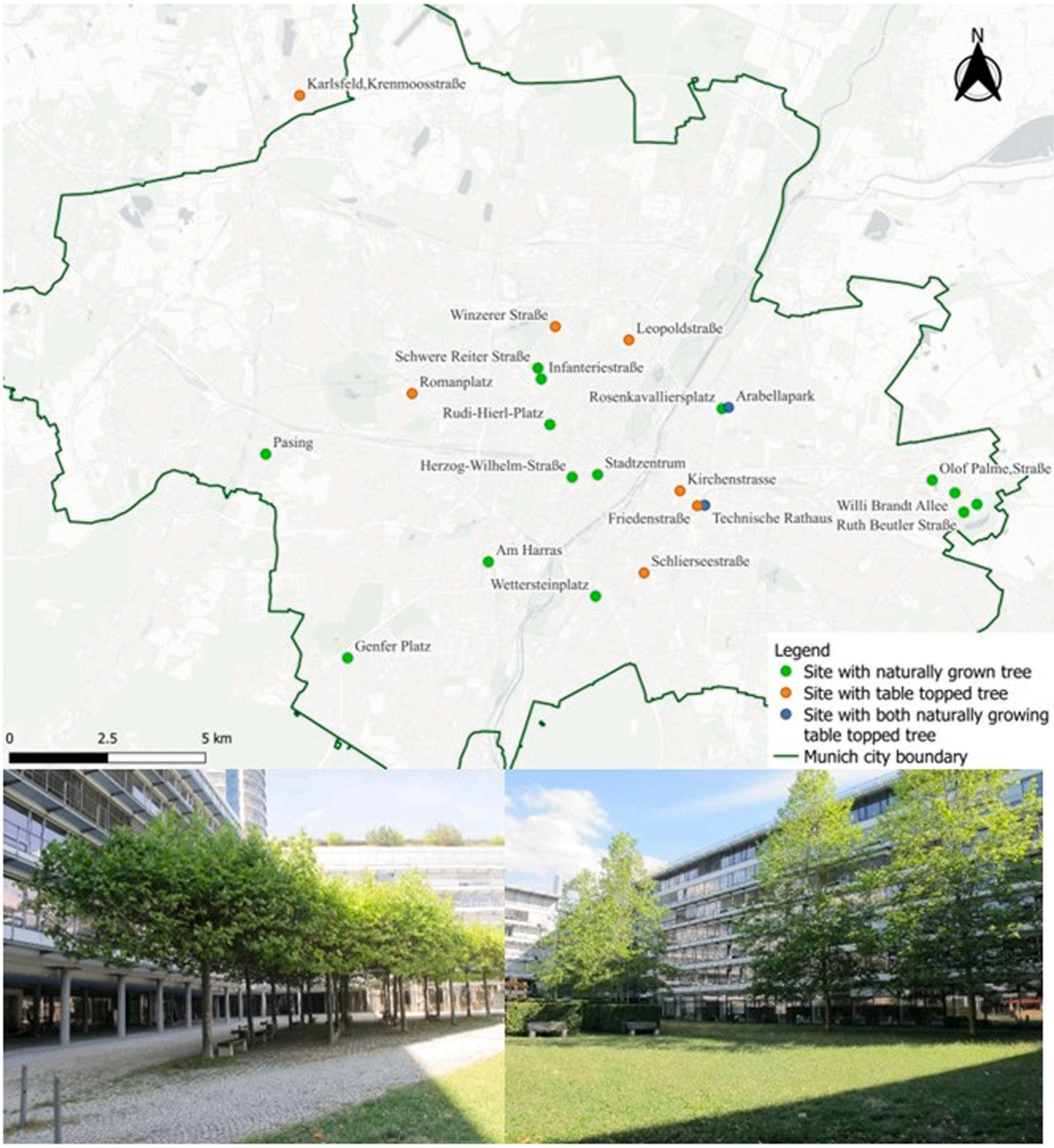

Fig. 1. Sites of measured table-topped and naturally grown *P. x hispanica* trees in the city of Munich (above) and table-toped shaped (below left) and natural grown (below right) *P. x hispanica* trees in June 2023 at the "Technisches Rathaus" in Munich.

the crown base was lifted to 2.5 meters height. The table-topped trees of 3 plots consist of one flat crown layer, i.e. one layer of main branches, one plot is composed of two flat crown layers of main branches (=two layers, see Fig. 2, plot R358–2). Because the trees of plot R1 were replanted in June 2024, from this plot only the records of the year 2023 were used for the analysis. Recording was done monthly for naturally grown and for table-topped trees of four size classes.

In addition to the structural measurements of the 34 plane trees two hemispherical pictures were taken per tree in June 2023 to estimate the LAI. In August 2023, the pruned leaf biomass was collected from one table-top shaped tree each from the plots R342, R348, 358–1, 358–2 and from 4 naturally grown trees from plot R1.

2.4. Measurements, calculations and statistics

2.4.1. Crown dimensions

Based on the measured tree height (h) [m] and crown base (cb) [m], crown length (cl) [m] can be defined as

$$cl = h - cb \qquad (1)$$

According to Pretzsch et al. (2015) and by using the crown radius (r) [m] measured in eight cardinal directions (North, Northeast, East, Southeast, South, South-west, West, Northwest) the mean crown radius (cr) [m] can be calculated by

$$cr = \sqrt{\frac{\sum_{i=1}^{8} r_i^2}{8}} \qquad (2)$$

The crown projection area (cpa) [m^2] is estimated by

$$cpa = cr^2 * \pi \qquad (3)$$

As the table-toped shaped trees of the Bruns nursery have a rectangular form, the cpa of these trees is calculated by

Table 2
Structural characteristics of the measured trees at the sites in Munich and the plots of the Bruns nursery in Bad Zwischenahn (SD= standard deviation).

Plot	Pruning type	n	dbh (cm) ± SD	tree height (m) ± SD	crown base [m] ± SD	crown radius [m] ± SD
Munich						
-	naturally grown	93	20.7 ± 6.2	11.3 ± 2.1	3.0 ± 0.9	3.6 ± 1.0
-	table-top	137	20.3 ± 6.4	6.5 ± 2.0	3.0 ± 0.6	2.5 ± 0.7
Bad Zwischenahn						
R1016	naturally grown	5	8.8	7.5	2.5	1.2
R1	naturally grown	5	13.7	9.2	2.6	2.0
R1200	naturally grown	5	17.8	10.5	2.6	2.5
507	naturally grown	3	21.3	10.6	2.6	2.7
total	**naturally grown**	**18**	**14.8 ± 4.6**	**9.3 ± 1.4**	**2.5 ± 0.2**	**2.0 ± 0.6**
R342	table-top, 1 layer	5	7.8	2.8	2.5	0.9
R348	table-top, 1 layer	5	13.3	3.4	2.8	1.1
358–1	table-top, 1layer	3	15.9	5.1	4.2	1.0
358–2	table-top, 2 layers	3	22.4	7.1	4.2	2.1
total	**table-top**	**16**	**13.8 ± 5.3**	**4.2 ± 1.6**	**3.2 ± 0.8**	**1.2 ± 0.4**
All						
	naturally grown		**19.8 ± 6.3**	**11.0 ± 2.1**	**3.2 ± 0.9**	**3.3 ± 1.1**
	table-top		**19.6 ± 6.6**	**6.3 ± 2.1**	**3.1 ± 0.6**	**2.4 ± 0.8**

$$cpa = (2^*cr)^2 \tag{4}$$

According to Franceschi et al. (2022) naturally grown *P. x hispanica* trees have an ovoid crown shape, the crown volume (cv) can be calculated by

$$cv = (0.333^*cl + 0{,}667^*cr)^* \pi\ ^*cr^2 \tag{5}$$

The crown volume of table-topped trees is calculated on the base of the cpa and the crown length:

$$cv = cpa\ ^*cl \tag{6}$$

2.4.2. *Leaf area index*

Hemispherical photography was selected to estimate the LAI of the trees. By using a Nikon D7500 camera with a Sigma fisheye lens, LAI is determined by photographing the tree crown from bottom to top (Jonckheere et al., 2004). The fisheye lens enables pictures with an angle of 180° degrees, so that the tree crowns are visible with their full extension on the picture. The pictures were taken in June and July to get the maximum leaf area of the trees. Two pictures were taken of each tree (at a 90° angle) at a height of 0.5 m and approximately 1 m away from the stem.

Using the WinSCANOPY Pro 2020a program (Regent Instruments, Canada), LAI was calculated according to the instructions provided by Regent Instruments Inc. (2020). The “LAI2000Glog” function was applied for the LAI calculation (Welles and Norman 1991). This function uses linear regression to determine the LAI value from the gap fraction at five viewing angles Regents Instruments INC. 2020). A multi-step process is required to calculate the LAI. First, the hemisphere is identified in the image. Then, pixel classification is performed, whereby all pixels are classified as either tree (black) or sky (white). The aim of pixel classification was to recognize even very small leaves as such, but not to classify parts of the sky as leaves. After pixel classification, the area around the tree canopy was masked to achieve a clear distinction from other trees, buildings, other artificial objects, or the sky. Finally, the LAI is calculated. Further details can be found in Moser-Reischl et al. (2025).

2.4.3. *Leaf area*

The leaf area (la) [m^2] of the individual trees was calculated based on the LAI [$m^2\ m^{-2}$] and the crown projection area [m^2]:

$$la = LAI\ ^*\ cpa \tag{7}$$

2.4.4. *Leaf biomass*

To determine the dry matter of the pruned leaves from the trees of the Bruns nursery the leaves were separated from branches and twigs, weighed freshly cut and then dried in a drying oven at 65°C. Once the leaf weight remained constant during the drying process after several measurements, this was recorded as dry leaf biomass.

Fig. 2. Hemispherical pictures from June 2023 (above) and photos from November 2023 (below) of table-topped and natural grown *P. x hispanica* trees after pruning in August from plot R342 (far left), R348 (left), R358–1 (center), R358–2 (right) and R1016 (far right) at the Bruns nursery in Bad Zwischenahn.

For the calculation of the leaf biomass before pruning for the trees at the Bruns nursery we have to calculate the leaf area la (i.e., in the absence of LAI). By using the allometric formula la is (see chapter 3.4 / Fig. 7):

$$\text{Naturally grown trees:} la = 2.9958 * dbh \tag{8}$$

$$\text{Table-topped trees: } la = 3.6111 * dbh \tag{9}$$

To derive the leaf biomass (bm_{lp}) [kg] from the la we use the specific leaf area (sla) for *P. x hispanica* of 7.79 $m^2 kg^{-1}$ (McPherson et al., 2016):

$$bm_{lp} = la / sla \tag{10}$$

2.4.5. *Basal area increment*

For stem growth we used basal area increment (bai) [cm^2] to also account for tree size:

$$bai = [(dbh_i / 2)^2 - (dbh_{i-1} / 2)^2] * \pi \tag{11}$$

with dbh_i = dbh of time i, dbh_{i-1} = dbh of time i-1 with i = month

2.4.6. *Leaf photosynthesis and leaf transpiration*

Leaf gas exchange and chlorophyll fluorescence measurements were conducted using a portable photosynthesis system (Li-6800F, LiCOR, Lincoln, Nebraska, USA) to assess tree ecophysiology. The system, equipped with a 6 cm^2 leaf cuvette and fluorometer leaf chamber (6800–01 A), measured key physiological parameters including net assimilation rate (A), transpiration rate (E), and stomatal conductance (gs). All measurements were conducted between 11:00 h and 16:00 h. Measurements were performed under ambient air temperature and humidity conditions, with CO_2 concentration at ambient levels and airflow rate set to 700 µmol s^{-1} . For each tree specimen, measurements were taken from three to five healthy, mature sun-exposed leaves and two shaded leaves, following established urban tree physiological measurement protocols (Konarska et al. 2016; Rahman et al., 2015; Pattnaik et al., 2024). We then upscaled the measurements from leaf level to tree level to calculate the latent heat flux per tree according to the Eq. 12:

$$Q_L = E * L * la \tag{12}$$

With Q_L = latent heat flux per tree (W $tree^{-1}$), E = transpiration rate is in $g/m^2/s$ and L = latent heat of vaporization (= 2.45 kJ g^{-1}) and la = leaf area calculated from Eq. 7. This upscaling approach allowed us to quantify the total cooling effect provided by individual trees through transpiration, enabling more meaningful comparisons between table-topped and naturally grown specimens in terms of their ES provision. Similarly, we upscaled the measurements from the leaf level to calculate net photosynthetic rate per tree to estimate the total carbon assimilation capacity of individual trees of and compare the photosynthetic performance according to Eq.13:

$$P_{tree} = A_{net} * la \tag{13}$$

where P_{tree} is the total net photosynthesis per tree (µmol s^{-1} $tree^{-1}$), A_{net} is the average leaf-level net photosynthetic rate (µmol m^{-2} s^{-1}), and la is total leaf area per tree (m^2).

2.4.7. *Statistics*

Statistical analyses were conducted with R, version 4.3.3 (R Core Team, 2024). Statistical differences between table-topped and naturally grown trees were checked by Wilcoxon-Tests, since assumptions on normal distribution and homogeneity of variances were mostly not given, followed by a *t*-test (Welch two-sample *t*-test) to statistically determine the differences between the variables.

With regression analysis, the associations between tree structures such as tree height, crown length, crown diameter, leaf area with dbh were determined. All regressions were performed using log-transformation of the tree structures, following Pretzsch et al. (2012), Stoffberg et al. (2008) and Peper et al. (2001).

3. Results

3.1. *Leaf biomass reduction by pruning*

Leaf biomass and leaf area are key parameters for quantifying the ES of trees. Fig. 3 shows the leaf biomass reductions of *P. x hispanica* trees for three different diameter classes of table-top shaped and naturally grown trees after pruning in August 2023.

For the single-layered table-topped trees the reduction of leaf biomass by pruning increases with increasing dbh (from 1.6 kg with 7.3 cm dbh to 5.7 kg with 16 cm dbh). In comparison, the removal by pruning for the natural grown trees was quite small with 0.4 kg. Based on the leaf biomass before pruning, there was a reduction of more than 47 % in the single-layered table topped trees and a reduction of 44 % in the double-layered table topped trees. In contrast, the reduction in naturally grown trees was very low at 7 %.

3.2. *Influence of pruning on leaf photosynthesis and leaf transpiration*

After pruning trees their physiological processes changed significantly. Our measurements on table-topped and naturally grown *P. x hispanica* trees in Munich showed a significant difference ($p < 0.05$) in the photosynthesis rates of the leaves of table-topped and naturally grown plane trees (Fig. 4a). Table-topped trees exhibited a 20 % higher mean leaf level photosynthesis rate than the naturally grown trees.

Higher differences were found for the transpiration rates at leaf level (Fig. 4b): The transpiration of table-topped trees is with 12.2 mmol m^{-2} s^{-1} significantly ($p < 0.001$) stronger than the transpiration rates of naturally grown trees with 6.8 mmol m^{-2} s^{-1} , which means an increase of 56 %. Canopy level responses showed opposite trends. Canopy photosynthesis was significantly lower in table-topped trees ($p < 0.05$) compared to naturally grown trees (mean canopy photosynthesis of 1239 µmol s^{-1} $tree^{-1}$ compared to 1998 µmol s^{-1} $tree^{-1}$) (Fig. 4c). Similarly, canopy latent heat flux was significantly reduced ($p < 0.01$) in table-topped trees (mean =1439 W $tree^{-1}$) compared to naturally grown trees (3437 W $tree^{-1}$) (Fig. 4d).

3.3. *Tree growth of table-topped and naturally grown P. x hispanica trees*

On the base of the monthly measurements of 34 *P. x hispanica* trees at the Bad Zwischenahn plots (see Tables 1 and 2) the development of the basal area increment (BAI) of table-topped and naturally grown trees was compared for four dbh classes (Fig. 5).

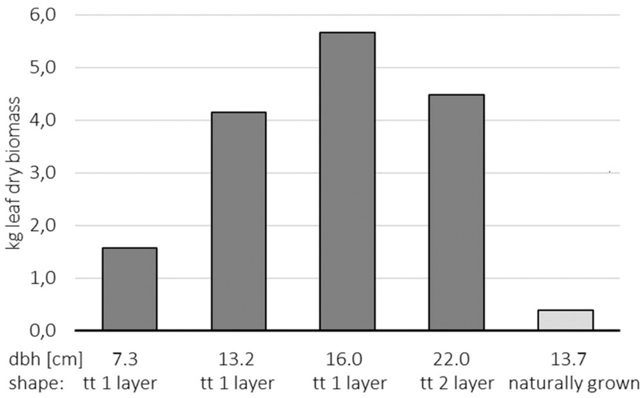

Fig.: 3. Removed leaf biomass *of P. x hispanica* trees by pruning in August 2023 for different dbh classes for table-top shaped (=tt) plane trees (dark grey) and naturally grown trees in Bad Zwischenahn (table-topped trees have one or two layers).

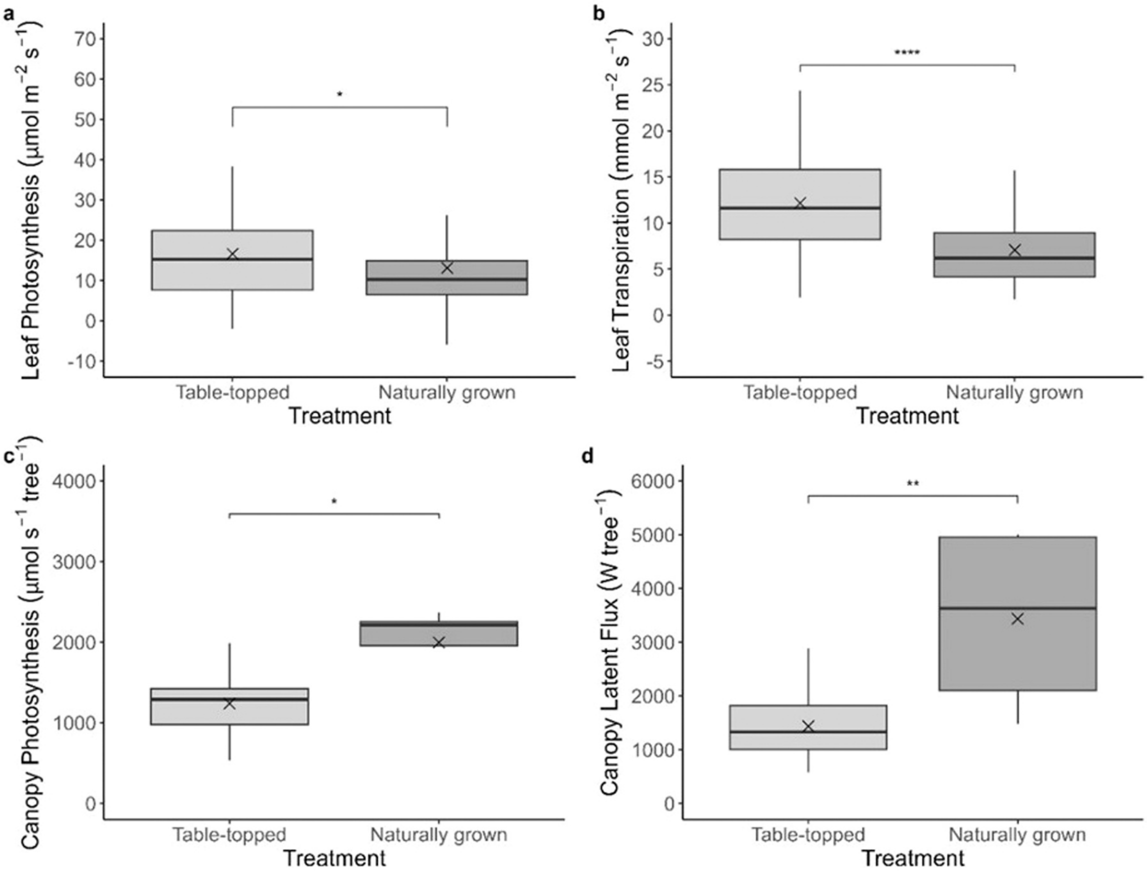

Fig.: 4. Effects of pruning treatments on the physiological responses of *P. x hispanica* trees: (a) leaf photosynthesis rates, (b) leaf transpiration rates, (c) canopy photosynthesis, and (d) canopy latent heat flux comparing table-topped versus naturally grown trees. Significance levels: $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.0001$.

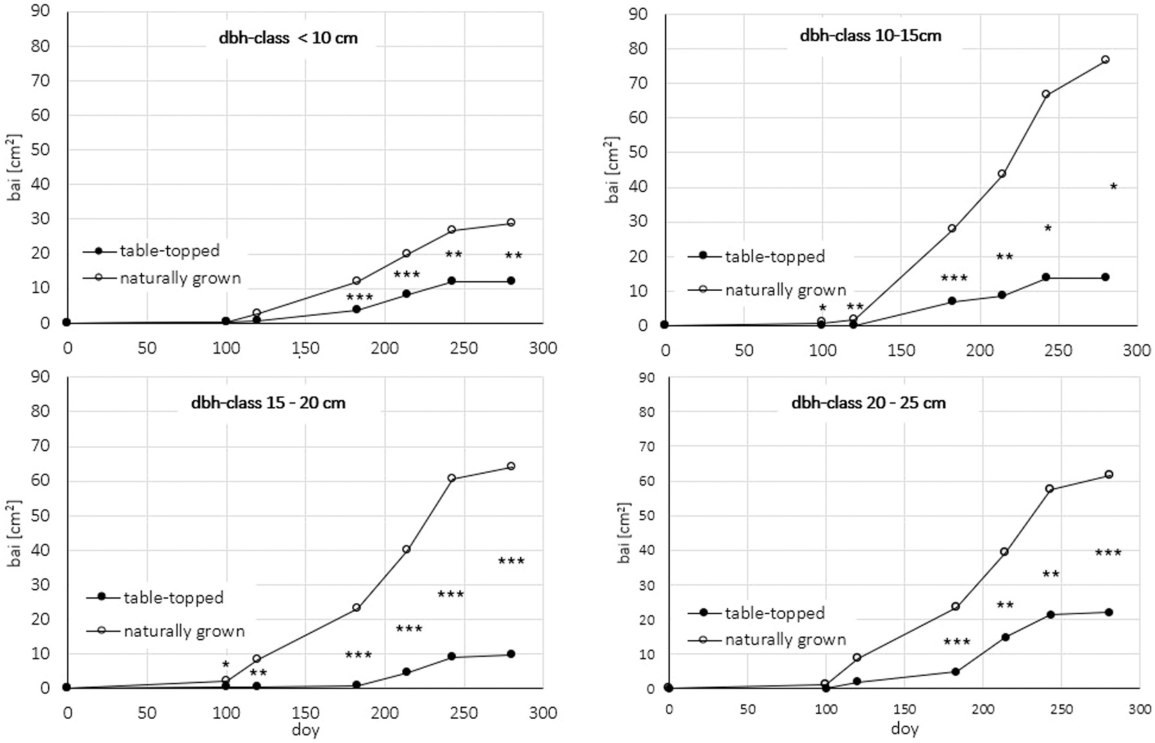

Fig. 5. Development of basal area increment (BAI) of table-topped and naturally grown *P. x hispanica* trees over the year averaged over the years 2023–2024 (except dbh class 13–14 cm: only 2023) in Bad Zwischenahn (doy = day of the year). Significance levels: $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.0001$.

The results clearly show that bai of table-topped trees, which were table topped pruned in August of the previous year, starts later and increases less over the year than for naturally grown trees. For example, the growth of table-topped plane trees (15–20 cm dbh class) was reduced by 85 % compared to the naturally grown ones. For the other table-topped plane trees, the reduction was 68 % for the dbh class < 10 cm and 82 % for the dbh class 10–15 cm. The double layer table topped plane trees of the dbh class 20–25 cm, on the other hand, show a decrease of 65 % by the end of the year. Many of the results are statistically significant, especially the bai for the later doys, which differ greatly.

The annual increment of dbh, tree height, cpa and of the table-topped and the naturally grown *P. x hispanica* trees at the site “Technisches Rathaus” in Munich is shown in Table 3. While the growth of naturally grown trees hardly differed in the two years (only LAI significant for $p < 0.05$), the table-topped trees showed significantly higher growth in height and crown parameters (radius, length, basal area, and volume) in 2024 compared to 2023.

The greater growth of the naturally grown plane trees can be clearly seen, albeit it is not statistically significant. Their diameter increment is 39 % above that of the table-topped trees ($p > 0.05$). The increment in height and crown radius is also 0.2 m and 0.3 m higher in the naturally grown plane trees. In contrast, the crown length increment of 0.3 m in the naturally grown plane trees is less pronounced than that of the table-topped trees (0.4 m). For the cpa and the crown volumes of the naturally grown trees, this results in clearly higher increments of 19.5 m^2 and 239 m^3 respectively compared to the table-topped trees with 5.0 m^2 and 24 m^3 respectively. The LAI of the naturally grown plane trees also increases markedly. However, the naturally grown trees are clearly bigger in dbh as well as in size after a long period of regularly pruning the trees by table topping.

3.4. *Influence of pruning on tree dimensions and leaf area*

To analyse the influence of pruning on tree height, crown dimensions, and leaf area of *P. x hispanica* trees with table-topped crowns and naturally grown crowns, the stem diameters of the trees are in a range between 5 cm and 35 cm (Table 4).

The average dbh of naturally grown trees is only slightly larger than the dbh of the table-topped trees and no significant differences were found. The crown base is also not significant different between both groups. At the same time, however, the other measured size variables mean tree height, mean crown diameter and the mean crown length are significantly higher in the naturally grown trees compared to the table-topped trees (all $p < 0.001$). This indicates that the crown projection area and crown volume of table-topped plane trees are 2.0 and 2.7 times smaller than those of naturally grown trees. The functional canopy metrics LAI and leaf area were also measured. Both, on the other hand, are significantly higher in table-topped plane trees (LAI $p < 0.001$ and leaf area $p < 0.01$). For the leaf area, this means a reduction of 30 %.

Depending on physiological reactions, changed leaf biomasses and a change in stem growth between table-topped and naturally grown *P. x hispanica* trees also alter allometric relationships. Fig. 6 displays the relationships between tree height, crown radius and crown length from dbh of table-topped and naturally grown trees.

All relationships show very strong correlations with R^2 ranging between 0.51 (dbh vs. crown length for naturally grown trees) and 0.73 (dbh vs. tree height for table-topped trees). For the tree height, the increase per cm dbh is nearly identical at 0.27 m per cm dbh increment. Only the dbh-independent constant for the table-topped trees with 1.0 m has a clearly lower value than that of the naturally grown trees at 5.6 m. In contrast, for dbh-cr relationship, the constant for the table-topped and naturally grown trees is almost the same at 0.48 m, while the slope for naturally grown trees is significantly lower at 0.15 m per cm dbh increment (table-topped trees: 0.10 m per cm dbh increment). Crown length shows the same pattern as tree height: differences in the constant but almost equal increases per increasing dbh.

Based on the changes of cr and cl, cpa, cv and la also varied with dbh for table-topped and naturally grown trees (Fig. 7).

With increasing dbh the cpa of naturally grown *P. x hispanica* trees has increased by 2.1 m^2 per cm dbh more than the cpa of table-topped trees, which has increased by 1.0 m^2 per cm dbh. The crown volume of naturally grown plane trees is also substantially higher than that of table-topped trees. For example, a naturally grown plane tree with a dbh of 25 cm has a 2.8 times higher crown volume compared to a table-topped tree with the same dbh.

The leaf area of naturally grown trees, which increases by 3.0 m^2 per cm dbh, is smaller than that of table-topped trees, which increases by 3.6 m^2 per cm dbh (Fig. 8 below). This reveals that, after pruning by table topping in the previous year, a table-topped plane tree with a dbh of 30 cm has a leaf area that is 20 % larger than that of a naturally grown tree in summer.

4. Discussion

4.1. *Influence of pruning by table topping on tree physiology and water balance*

Our study revealed significant differences between table topped pruned and naturally grown trees in both photosynthetic and transpiration rates. At the leaf level, table-topped trees demonstrated almost 2 times and 1.2 times higher transpiration and photosynthesis compared to naturally grown trees respectively. These findings align with previous research examining various tree species in urban environments. For instance, Fini et al. (2015) and Comin et al. (2025) reported similar increases in photosynthesis and transpiration following pruning interventions. The enhanced photosynthetic activity in pruned table topped trees can be attributed to "compensatory photosynthesis", a phenomenon documented across multiple studies where trees exhibit increased photosynthetic rates following pruning or defoliation (Fini et al., 2015). Several mechanisms may explain this response, such as changes in nitrogen partitioning per remaining leaf in the tree crown (Maurin and DesRochers, 2013) and improved light environment due to a reduction in leaf area, which boosts the photosynthesis capacity (Trumble et al., 1993). Although the precise physiological mechanisms remain under debate in the literature (Fini et al., 2015), these compensatory responses appear to be a widespread adaptation that allows trees to maintain carbon gain despite reduced leaf area. Additionally, the timing of the pruning treatment table topping likely influenced our observations. Our measurements potentially captured a

Table 3
Tree structural data of the years 2023 and 2024 as well as annual increment of table-topped and naturally grown *P. x hispanica* trees at the site “Technisches Rathaus” in Munich (inc. =increment, SD= standard deviation).

		n	Dbh ± SD [cm]	height ± SD [m]	cr ± SD [m]	cl ± SD [m]	cpa ± SD [m^2]	cv [m^3] ± SD	LAI ± SD [m^2/m^2]
Natur-ally grown	2023	4	27.4 ± 3.2	18.8 ± 2.7	4.6 ± 0.8	15.8 ± 2.7	68.4 ± 23.4	646 ± 328	1.5 ± 0.3
	2024	4	28.3 ± 3.6	19.3 ± 3.4	5.2 ± 1.2	16.0 ± 3.2	88.0 ± 38.9	885 ± 534	2.4 ± 0.9
	inc.	4	0.9	0.5	0.6	0.3	19.5	239	0.9
Table-top pruned	2023	21	19.8 ± 1.7	5.7 ± 0.5	2.5 ± 0.2	2.8 ± 0.4	20.2 ± 7.5	56 ± 21	3.7 ± 0.7
	2024	21	20.5 ± 1.9	6.0 ± 0.3	2.8 ± 0.3	3.2 ± 0.4	25.2 ± 5.6	80 ± 21	3.5 ± 0.5
	inc.	21	0.65	0.3	0.3	0.4	5.0	24	-0.2

Table 4

Mean, standard deviation, minimum, maximum and statistically significant differences of the tree parameters of table-topped and naturally grown *P. x hispanica* trees in Munich and Bad Zwischenahn within a dbh range from 5 cm to 35 cm (n = number of trees; sd=standard deviation, min=minimum, max=maximum, sign=significance). Significance levels: *$p < 0.05$, **$p < 0.01$, ****$p < 0.0001$.

parameter	naturally grown					table-topped					Sign
	n	mean	sd	min	max	n	mean	sd	min	max	
dbh [cm]	111	19.8	6.3	8.5	32.4	153	19.6	6.6	5.6	35.5	ns
height [m]	111	11.0	2.1	7.3	17.2	153	6.3	2.1	5.6	11.2	***
crown base [m]	111	3.2	0.9	1.3	8.0	153	3.1	0.6	5.6	5.0	ns
crown radius [m]	111	3.3	1.1	1.0	5.5	153	2.4	0.8	5.6	4.5	***
crown length [m]	111	7.8	2.1	2.0	13.9	153	3.2	1.8	5.6	8.2	***
cpa [m^2]	111	38.8	23.5	3.2	96.2	153	19.6	12.3	5.6	62.6	***
cv [m^3]	111	216.1	167.8	8.2	707.1	153	79.6	86.3	5.6	513.5	***
LAI [m^2/m^2]	38	2.1	0.7	0.8	3.7	128	3.3	1.1	5.6	6.8	***
leaf area [m^2]	38	45.3	32.4	7.7	118.2	128	63.7	40.0	5.6	196.7	**

higher proportion of younger leaves in pruned trees, which naturally exhibit greater photosynthetic activity regardless of pruning status. This temporal aspect of leaf development introduces an important consideration when interpreting our results.

When upscaling our measurements from individual leaves to whole-tree level, the differences between table-topped and naturally grown trees not only became larger but also reversed the trend. Table topped pruned crowns had a reduced latent heat dissipation and reduced photosynthesis rate by 82 % and 47 % respectively, primarily due to the significant reduction of leaf area (ca. 30 % reduction). The substantial decrease in whole-tree function despite increased leaf-level activity demonstrates that structural changes can outweigh physiological compensatory responses.

4.2. *Change of LAI, leaf biomass and leaf area through pruning by table topping and its effects on tree growth*

After pruning by table topping in the previous year the stem growth, i.e. the basal area increment of all dbh classes is significantly smaller for the table-topped trees compared to naturally grown ones. This is most likely due to changes in physiological processes and changes in the in the carbon producing leaf area. The LAI and thus leaf area of a tree are along with the photosynthetic capacity critical parameters influencing a tree's growth and performance (Eyster and Beckage, 2023; Lin and Tsai, 2017; Zhang et al., 2023). The carbon obtained through photosynthesis in the leaves is distributed to the various parts of a tree, such as branches, trunk, and roots, as described by the pipe model and functional balance theory (Deckmyn et al., 2006; Mäkelä, 1986). Pruning can change the carbon allocation within a tree. (Comin et al., 2025) for example found that after pruning trees show a higher investment in crown growth at the cost of stem enlargement.

In our studies we found that the photosynthesis rate of the leaves of table-topped trees in July is 20 % higher than that of naturally grown trees (Fig. 4). With a LAI of 3.4 m^2 m^{-2}, the LAI of table-topped plane trees is also greater than that of naturally grown ones. They show an LAI of 2.1 m^2 m^{-2}, which is consistent with the LAI measurements of plane trees by Moser-Reischl et al. (2025) in summer in Munich with 2.4 m^2 m^{-2}. Ötztürk (2016) found an average LAI of 2.76 m^2 m^{-2} for *Platanus orientalis* trees (dbh range 26.5–38.2 cm) in a greenway system for the provinces of Bartin and Karabük in Turkey for mid-June, which also matches the results obtained in this study. On the other hand, the mean LAI of 162 plane trees in the entire Munich urban area determined by Moser-Reischl et al. (2025) was higher at 3.0 m^2 m^{-2}. However, this could be due to the higher number of larger trees, i.e. the mean dbh according to Moser-Reischl et al. (2025) of 40.8 cm was clearly higher than the mean dbh of this study of 19.8 cm. Fini et al. (2023) measured an average LAI of 3.6 m^2 m^{-2} for plane trees in streets and 4.8 m^2 m^{-2} for plane trees in parks in Rimini /Italy, which means that the LAI can vary markedly depending on the site conditions. Also Zhang et al. (2023) reported that the environmental conditions cause difficulties in comparing the LAI of trees in the field with values from the literature and databases.

In addition to the LAI, the crown projection area is important for the determination of the leaf area. In our study cpa of naturally grown plane trees is 2 times higher than the cpa of table-topped plane trees of the same dbh-size. For the leaf area, this results in an average 30 % larger leaf area in July for table-topped trees (Table4). A larger production area and a higher photosynthesis rate from June/July onwards lead to stronger growth in table-topped plane trees compared to naturally grown ones. However, as numerous studies, such as by Comin et al. (2025), Lodolini et al. (2023), Huang et al. (2023) and Hevia et al. (2016), show, topped trees often show different growth patterns, with higher investment in crown growth at the cost of stem enlargement. In contrast, stem diameter growth, i.e. the increment of the basal area starts already at the end of March/beginning of April and has its main growth period in the months of May-July. At this phase in early spring, the energy and sugar reserves of pruned trees are low because of the strong reduction of biomass by pruning in the previous year. In our studies, for example, the reductions range between 42 % and 85 %. As a result, the increments in basal area of *P. x hispanica* of all dbh classes were significantly lower in table-topped trees compared to naturally grown trees.

4.3. *Effects of pruning by table topping on tree dimensions*

Pruning a tree means a removal of foliage and branches, i.e. reducing its biomass (Comin et al., 2025). Accordingly, pruning also has an influence on tree dimensions and future growth. Our results clearly show that the dataset of our measured table-topped and naturally grown trees is very similar regarding stem diameter and the crown base. However, pruning by table topping obviously influences tree growth and the resulting tree dimensions, especially the size of the crown and its expansion. We found significant larger tree heights and crown parameters such as crown radius and crown length for naturally grown trees compared to table-topped trees, leading to the conclusion that management measures such as pruning by table topping has a negative effect on tree height and crown growth of the trees.

It is particularly interesting to look at the future development of the tree parameters of trees after a pruning event. Due to the small trunk diameter of the table-topped trees in the study area, only naturally grown trees with a trunk diameter of up to 35 cm were included in the analysis. As the allometric relationships showed, the growth rate slope) for tree height and crown length based on dbh were not much different. However, the crown radius of naturally grown trees grew clearly faster. The effects of pruning by table topping on cpa and crown volume growth, on the other hand, are much more pronounced. Pruning causes a significant reduction in cpa and crown volume growth compared to naturally grown trees. The gradient, i.e. the slope or speed of growth, is only a third (cv) or half (cpa) as great for naturally grown trees. Regarding tree height, crown length and crown radius, our findings are

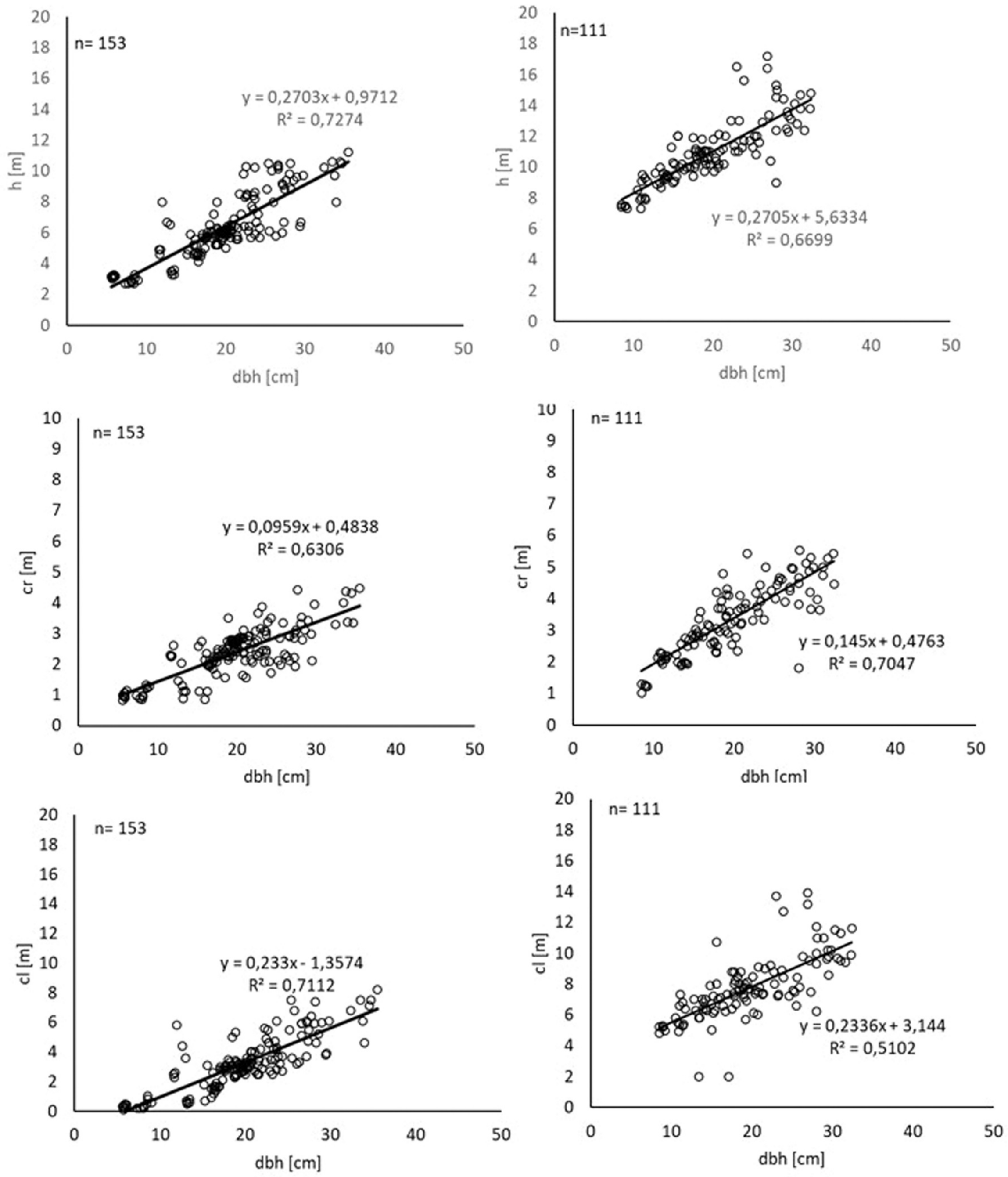

Fig. 6. Dependency of tree height (above), crown radius (middle) and crown length (below) from dbh of table-topped (left) and naturally grown (right) *Platanus x hispanica* trees of all sites in Munich and Bad Zwischenahn.

in line with research of Coombes et al. (2019), describing that light pruning has no statistically significant impact on allometric relationships of urban tree structures. As Speak and Salbitano (2023) showed, trees can on average recover from pruning after three to four years. However, this is species-specific. *P. x hispanica*, the species of our study, is affected most severely by pruning measures (Speak and Salbitano, 2023). Further, Comin et al. (2025) clearly stated that heavy pruning significantly affects the dimensions and growth of trees, even if the effects of pruning diminish with the time that has passed since pruning.

Contrastingly, leaf parameters were found with opposite patterns to the tree structural parameters described above. A significantly higher LAI and leaf area of the table-topped compared to the naturally grown trees was observed. This is different compared to the results found by Comin et al. (2025) for the LAI. However, (Comin et al., 2025) also found that pruning increased leaf density significantly. And Fini et al. (2015) found a larger leaf area after pruning, which is consistent with our results.

Pruning measures and topping often stimulates resprouting from cutted branches, increasing thereby the leaf area in the following years (Fini et al., 2015). The effects of pruning on the leaf area could also be influenced by the timing of pruning, whereby pruning in winter could lead to a second budding and thus to an increase in leaf mass and leaf area as shown in our study.

4.4. *Study limitations*

Several limitations should be acknowledged in our study. We were unable to measure leaf and soil water potential or soil moisture, which

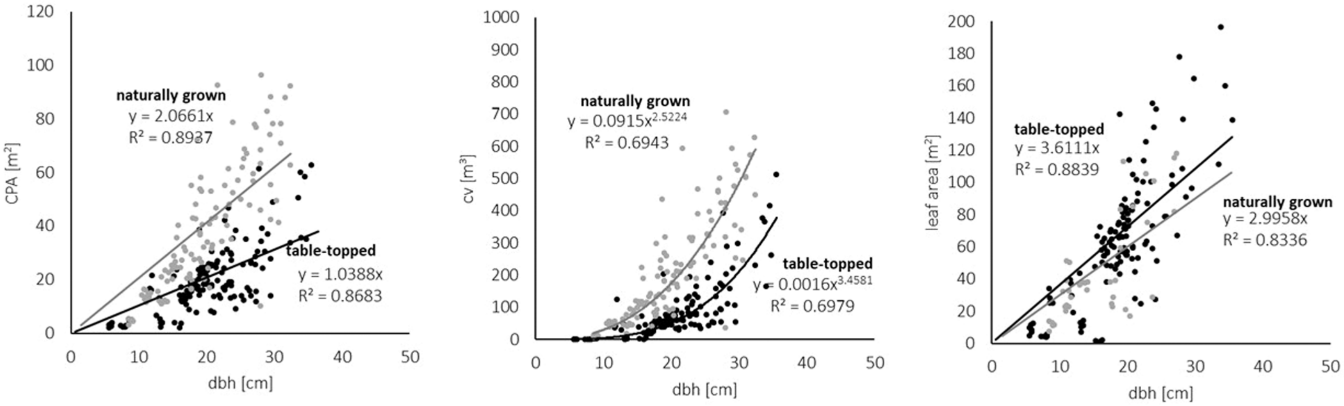

Fig. 7. Dependency of crown projection area cpa (left), crown volume cv (middle) and leaf area la (right) from dbh of table-topped and naturally grown *Platanus x hispanica* trees in Munich and Bad Zwischenahn.

would have provided a more comprehensive understanding of water usage in table topped pruned and naturally grown trees. We have found that table-topped pruned trees consume less water at the canopy level than naturally grown trees. However, it is unclear what this implies for the resistance of plane trees to drought. Future studies should include the above-mentioned measurements to develop a more complete understanding of how pruning affects whole-tree water relations under varying levels of water availability.

We focused exclusively on transpiration-based cooling and did not quantify shading benefits, which would have required additional instrumentation and assessments (radiation sensors, surface temperature monitoring) unavailable for our study. Given the differences in crown projection areas between table-topped and naturally grown trees, shading benefits would likely show more pronounced reductions between pruning treatments. Future research should integrate both cooling mechanisms for comprehensive ecosystem service evaluations.

The age of the trees is the preferred variable for comparing the growth of naturally grown and table-topped trees, as it is a direct indicator of their development, but this information is not available for urban trees in Munich. Manual measurements of tree dimensions, such as assuming a crown shape (here ovoid for plane tree crowns), increase the inaccuracy of structural dimensions and also of the calculation of ecosystem services. More accurate measurements, such as those obtained using TLS, also increase the data on the influence of pruning on growth and ecosystem service. Additionally, long-term monitoring would be valuable to determine whether the observed physiological responses persist over multiple growing seasons or if trees eventually return to pre-pruning function levels. Finally, our study focused on a single tree species. Extending this research to different tree species with contrasting pruning regimes, different tree dimensions, growth and ecological characteristics would strengthen the applicability of our results to varying urban forest compositions.

5. Conclusion

Pruning is an essential maintenance measure for urban trees. Regular pruning is often required for safety reasons, to fit into limited spaces, not to obstruct mobility and for aesthetic reasons (Hoyle et al., 2017; Ow et al., 2013). Pruning may also be necessary to adapt the size and dimensions of the tree to environment (Höpfl et al., 2022) and is conducted due to aesthetical or social reasons (M et al., 2024). Our investigations focused exclusively on the effects of table-topping on growth and service provision of a single species (*P. x hispanica)*, while social and aesthetic reasons for pruning were not considered further.

However, effects of pruning on urban tree growth and ecosystem service provision have been rarely studied. Results from our study on the impacts of pruning by table-topping on the growth of plane trees and the physiological responses show that pruning reduces stem diameter growth, tree dimensions and the ES of trees. We found that this kind of pruning can remove up to 50 % of the leaf biomass, which can significantly reduce basal area growth by up to 85 %. In the year after pruning the LAI is higher for table-topped trees than for naturally grown trees due to their compact crowns. However, attention must be paid to the type of pruning, the amount of pruning as well as to the tree species and its physiological reaction to pruning to allow the tree to recover quickly. The effects of pruning on tree growth can be minimized by improving the site conditions of urban trees, e.g. by using large tree pits or selecting suitable tree species, e.g. for limited aboveground spaces.

Our findings hold significant implications for urban forestry management practices. If pruning leads to such large drops in whole-tree photosynthesis, managers may need to rethink how and when to prune, especially in climates where carbon gain is already limited. Conversely, in water-limited environments, the reduction in transpiration following pruning could potentially be beneficial. Pruning thus represents a physiological trade-off - decreased growth potential in exchange for reduced water requirements. The optimal balance of this trade-off depends on the specific environmental constraints and management objectives for a given site.

In addition, special pruning techniques such as table topping allow the size and geometry of trees to be controlled. This is the only way to reconcile the different requirements of some dense urban situations, such as shade for pedestrians and daylight for indoor spaces. This makes it possible to plant trees in places where naturally growing trees would not be suitable because they would cause too many conflicts see Ludwig et al. (2024).

Our findings can also inform growth models such as iTree (2025) or CityTree (Rötzer et al., 2019) to consider maintenance measures of urban trees. Using models that include a 'pruning module' the impact of pruning measures on growth and ecosystem services can be estimated in advance by considering site conditions (e.g. soil sealing, horizon restriction), the city's climate, tree size and tree species. This allows pruning measures to be adapted to a specific site so that growth and ecosystem services are maintained or reduced to a minimum.

CRediT authorship contribution statement

Qiguan Shu: Writing – original draft, Funding acquisition. **Ferdinand Ludwig:** Writing – original draft, Project administration, Funding acquisition, Conceptualization. **Nayanesh Pattnaik:** Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Stephan Pauleit:** Writing – original draft, Funding acquisition, Conceptualization. **Thomas Rötzer:** Writing – review & editing, Writing – original draft, Validation, Software, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Astrid Moser-Reischl:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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