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STUDYING THE GROWTH CHARACTERISTICS OF URBAN TREES USING AN EXAMPLE FROM SZEGED, HUNGARY

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Summary: The spatial expansion of urbanised areas and the steady increase in the urban population, as well as climate change trends, are increasing the need for the development of adequate urban green infrastructure. The social demand for combating climate change is accompanied by the revaluation of green spaces, and in this context woody vegetation plays a key role. In a changing climatic context and under intense anthropogenic stress, the challenge of developing a tree population that is climate-friendly and resistant to disturbance is a major one. In our research, we investigate all growth parameters of the newly planted trees from the start of a street reconstruction involving a complete tree replacement (Gutenberg Street, Szeged). The structural analysis of the revealed not only the growth rate over the 8 years since planting, but also the significant differences between the two sides of the street. In order to find a possible reason for this, we examined (using SAGA GIS software) potential incoming solar radiation of the street, which could explain the significant difference in growth rate. The data collected also provided an opportunity to analyse the allometric relationships. This will partly allow the prediction of the growth rate and can provide baseline data for planning and decision-making processes in the dilemma of whether to retain older trees or plant new stocks.

Keywords: urban tree population, potential incoming solar radiation, allometry, forecasting

1. INTRODUCTION

The spatial expansion of cities as well as transport infrastructure and air pollution are constantly putting pressure on wildlife, with parks being the main exception (Mezősi 2007). Trees are central to the design of climate-smart urban green infrastructure (Moser et al. 2015), but the ability to adapt to the stress of the urban environment can vary among species, varieties and even age classes (Bennett et al. 2015, Gillner et al. 2016). An indirect positive effect of retaining long-lived trees is that their removal does not result in carbon emissions from fossil fuels (Nowak and Crane 2002, Nowak et al. 2002), but after a period of time, as age-related vulnerability increases, so do tree maintenance costs (O'Brien et al. 1992, McPherson et al. 2016). In contrast, younger trees have the advantage of much lower initial expenses and the selection of appropriate trees can reduce later costs (McPherson et al. 2016, Isaifan and Baldauf 2020). Selecting tree species that can withstand harsh conditions is as much a problem for urban tree stock planners as increasing diversity (Sjöman and Nielsen 2010). Careful species and variety selection can therefore minimise costs and maximise the value provided by trees.

Determining and possibly forecasting certain growth parameters can help to identify environmental benefits and costs. In many urban environments, tree growth is characterised by specific dynamics, as overhead power lines and vehicle access to streets limit the growth potential of trees (Bardóczi et al. 2018). When surveying tree populations, landscape architects ideally create detailed databases that allow for the allometric correlation of trees, which provides information about the effects of one physical parameter on another (Song et al. 2020). The study of allometric correlation in urban tree stands and the predictive analysis of the growth of physical parameters also have a history of less than two decades in international literature (McPherson and Peper 2012). Allometric equations that describe the growth of the trunk or the crown among others can help to predict the space- and soil volume requirements, maintenance (e.g. irrigation or pruning) demand or growing of the ecosystem services of the urban trees (McPherson et al. 2016). The resulting baseline data on trees will contribute to the cost-effective development of urban green spaces.

During our research, we had the opportunity to investigate the growth dynamics of a young tree stand from Szeged-Hungary, to establish the relationships between the parameters and to use them to predict their growth in the near future. The findings can greatly contribute to the preparation of reconstruction plans for the surrounding streets and to a more precise theoretical understanding of the growth relationships of urban trees in the southern part of the Great Hungarian Plain.

2. STUDY AREA

Szeged is one of the largest cities in the Southern Great Plain region with about 160,000 inhabitants [1], and is located in the Lower Tisza region (Dövényi 2010). Its climatic conditions are characterised by a warm and dry climate (Péczely 1979). The study area is located in the densely built-up city centre of Szeged, in a narrow street canyon oriented NW-SE, called Gutenberg Street. We repeatedly mention the differences in the results observed on the right and left side of the street, which should be interpreted from the standpoint of Tisza Lajos Boulevard (Fig. 1).

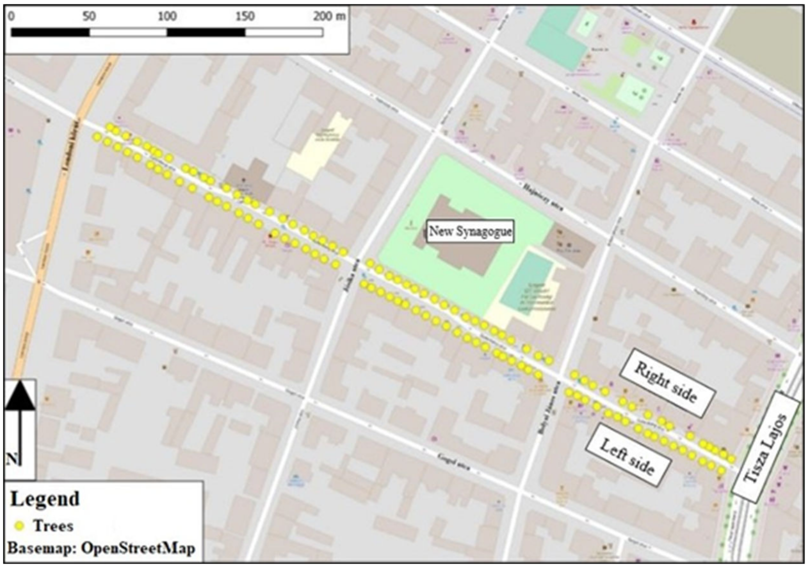

Fig. 1 Surveyed trees in the Gutenberg Street (study area)

The surveyed street is about 450 metres long and, like many of the surrounding streets, is characterized by a stand of old Japanese pagoda trees (*Sophora japonica*; 50-60 years old) on both sides. In 2012, a complete street reconstruction was carried out financed by EU funds. Silver linden trees (*Tilia tomentosa* 'Szeleste') replaced the old trees, which were twice-schooled saplings of 14/16 cm (trunk circumference in centimetres). As a result of the changes, the street pavement was replaced with permeable pavement everywhere, so that rainfall infiltration can first reach the saplings planted here, and then, when this layer becomes saturated, the drainage system. The green lanes on both sides of the street were widened considerably, forming in many places 2-3 m wide "bays" with tree, shrub and perennial plant cover and a thick layer of mulch. A protective pipe runs under the pavement instead of a utility tunnel. Over the years, a total of eight trees have been added to the stand due to additional planting.

3. DATA AND METHODS

The tree population was measured using the same methodology in the year of the street reconstruction (2012) and every year from 2016 to 2020. The data of all trees were collected and recorded in a GIS-based database according to Hungarian and international standards. Recordings were made during the active growing period in order to determine canopy parameters as best as possible. Examples include canopy width (hereafter CW), live and dead heights of the tree, percentage of missing and dead parts detectable in the canopy. In addition, two trunk data, trunk height and diameter at breast height (hereafter DBH), were also recorded. The Vertex III ultrasonic tree height measuring instrument was used for accurate height measurements. For further analyses, we measured on a scale from 0 to 5 (at maximum value, the tree receives sufficient light from above and from all four cardinal directions) the number of directions from which the particular individual receives sunlight, which is an important factor for photosynthetic activity and carbon sequestration and thus indirectly for growth rate.

The SAGA GIS modules for digital elevation models and field analysis allow for the analysis of the potential incoming solar radiation in a given area. For the analysis, the raster dataset of the relative heights of the building database in the neighborhood of Gutenberg Street was used for modelling, both on an annual and seasonal basis. For the seasonal calculations, the starting and ending points were the first day of the first month and the last day of the last month of the respective seasons.

The IBM SPSS statistical analysis program was used to search for the data pairs with the strongest correlation between the physical parameters of the surveyed tree population. We primarily examined DBH as a function of age, and total height (hereafter TTH), CW, and crown height (hereafter CH) as a function of DBH. Due to the differences in the tree lines, which will be discussed later, the input data pairs were divided into two parts, the left and right side of the street. Curve fitting was used to determine allometric equations for the two sides based on the best-fit functions, taking into account the coefficient of determination (close to 1 is good) and the standard error of the estimate (close to 0 is good). The physical parameters were then estimated for the year 2030 by substituting the required values.

4. RESULTS

4.1. Structural analysis results

In Gutenberg Street, there is a 'monoculture' of silver linden (*Tilia tomentosa* 'Szeleste'), a tree stand that is about 16 years old and consists of 117 specimens, which was planted in 2012 as a result of a complete street reconstruction to replace the old Japanese pagoda trees (*Sophora japonica*). Gaps in the canopy and dead parts due to dry branches were not present in the year of the planting, but as time passed, canopy degradation occurred in an increasing number of specimens, reaching up to 20% in some individuals. In 2017, the tree line underwent a drastic but not entirely professional pruning. In the case of young linden trees, a so-called crown lightening is necessary to prevent future static problems. Typically, the main branches of linden trees branch from one point that causes internal stress in the crown base (Fig. 2a). This species-specific problem has not been addressed in the Gutenberg Street specimens, and most trees now display a stressed canopy base. One of the dangers of this is that the main branches may spontaneously break off, which can lead to accidents. The scars from the pruning on the right side have not yet fully healed (Fig. 2b).

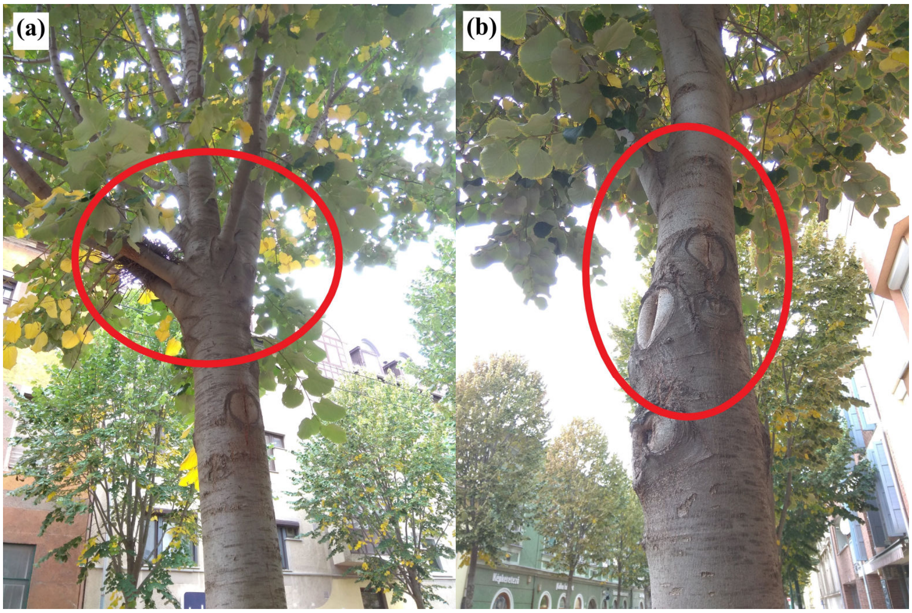

Fig. 2 Stressed crown base (a) and healing scar (b)

Literature data show that the growth rate of trees is almost linear at the beginning (McPherson et al. 2016). Table 1 shows the average increase and the absolute value of the growth of the trees in two sides of the street. Based on the literature data we calculated the average annual increase of the difference between 2016 and 2012 using the number of years that passed to obtain the values for the years with data gaps (Table 1). DBH for the entire street increased by about 1.9 cm per year, and TTH increased by just over half a meter. These two parameters were less affected by the maintenance works, so the difference in growth between the two sides is more pronounced, compared to trunk height and CW. For the left side of the tree line, the annual increase in height was 12 cm greater than that of the right side, resulting in a height difference of almost 1.5 m by 2020.

Table 1 Absolute values and average increase (marked by grey) of the tree parameters per total street and sides

Data	2012	2013	2014	2015	2016	2017	2018	2019	2020	Growth
Diameter at breast height (cm)	3.2	5.5	7.9	10.2	12.6	14.1	15.2	17.0	18.4	1.9
Right side	3.1	5.5	7.8	10.1	12.4	14.0	15.1	16.8	18.0	1.86
Left side	3.2	5.6	8.0	10.3	12.7	14.2	15.4	17.3	18.8	1.95
Total tree height (m)	5.3	5.8	6.3	6.9	7.3	8.0	8.8	9.6	10.4	0.64
Right side	5.2	5.6	6.1	6.5	7	7.6	8.4	9.0	9.7	0.56
Left side	5.5	6.1	6.6	7.2	7.7	8.3	9.3	10.2	11.1	0.7
Height to crown base (m)	2.0	2.1	2.2	2.3	2.4	3.0	3.2	3.0	3.1	0.14
Crown width (m)	2.2	2.6	3.0	3.4	3.9	3.8	3.3	3.3	3.8	0.2

In 2017 a larger than justified pruning was carried out to remove a significant amount of canopy, resulting in a reduction of more than 550 m^2 of the leaf area of the total stand (Fig. 3). As Fig. 3 shows the tree stand could not reach the pre-pruning level even by 2020.

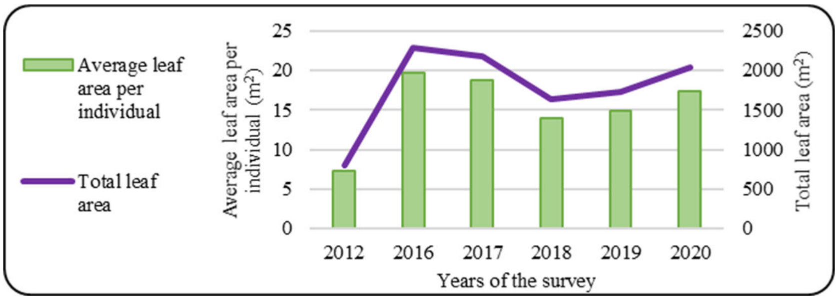

Fig. 3 Average leaf area per individual and total leaf area for the whole street in square metres

Fig. 4 shows the differences between the two sides of the street in the survey years. The average leaf area of the trees on the left side exceeded the average calculated for the whole stand of the street, and by 2020 it had reached approximately the value that characterized it before the 2017 pruning. Although both sides were equally affected by the pruning, by 2018 this difference was again visible, with the left-hand tree line again producing a larger average leaf area with a higher growth rate. The difference between the two sides has persisted since then and has not levelled out over the years.

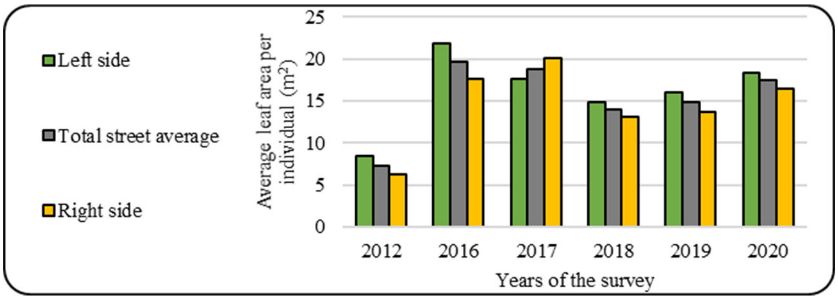

Fig. 4 Difference between the two sides of the street for leaf area per tree

4.2. Analysis of potential incoming solar radiation

In order to find the reason for the differences in physical parameters, we modelled the degree of potential incoming annual solar radiation (direct and diffuse radiation together) and the results show that the difference is significant between the two sides of the street (Fig. 5). Due to the angle of the incoming sunlight and the height of the buildings, the right side of the street receives an average of 1230.8 kWhm^{-2} of energy over a year based on the pixel readings, which is one and a half times the energy received by the left side (809.5 kWhm^{-2}). On the shaded side of Gutenberg Street, only the intersecting streets have values similar to the sunny side, around 1000 kWhm^{-2}. The model results therefore confirm that the right side of the street receives significantly more solar energy than the shadier left side. The value of annual incoming direct solar radiation on the left side is 408.1 kWhm^{-2}, while on the brighter right side the surface receives twice as much, 848.6 kWhm^{-2}.

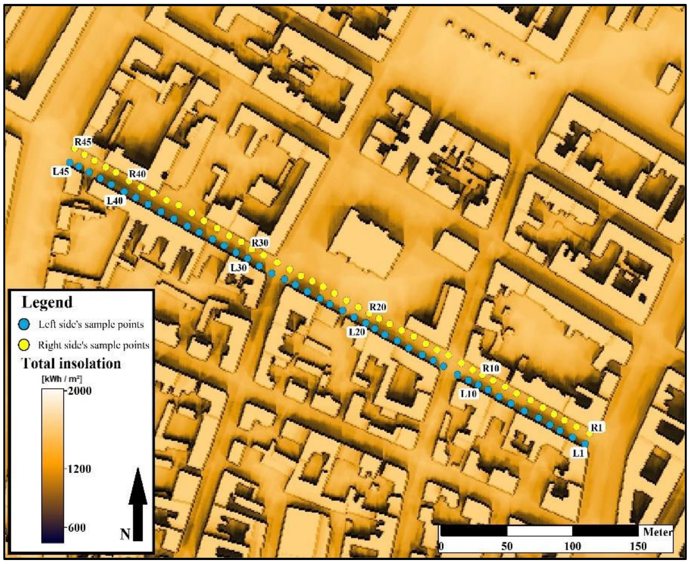

Fig. 5 Total annual insolation and sample points

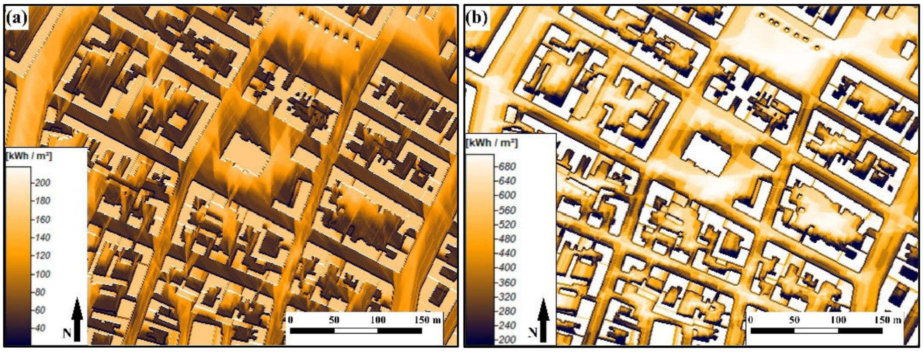

Fig. 6 Total insolation in winter (a) and in summer (b)

Due to the orientation of the street, the angle of incoming sunlight and the height of the buildings, an average of around 60-80 kWhm^{-2} of energy reaches the entire street in winter (Fig. 6a). In contrast, in the summer season, there is already a significant difference in favour of the right-hand side (greater than 600 kWhm^{-2}), which is clearly due to the larger angle of solar radiation's incidence (Fig. 6b).

4.3. Correlation and prediction of tree parameters

In line with references in the literature, the analysis looked for relationships between TTH, CW, CH and DBH, whereas DBH was analysed in relation to age. SPSS gives the value of the elements of the equations it uses after the analyses have been run, the coefficient of determination (R^2), which is the square of the correlation coefficient (R), and the standard deviation of the points entered as the standard error of the estimate (SEE). A deterministic relationship exists when R^2 is as close as possible to 1 and SEE is as close as possible to zero.

Table 2 Functions with the strongest correlation

Data pairs	**Side**	**Function type**	**R**	**R^2**	**Adj. R^2**	**SEE**
DBH and TTH – as a function of DBH	left	Power	0.943	0.890	0.889	0.085
	right		0.920	0.846	0.846	0.083
DBH and CW – as a function of DBH	left	S-curve	0.824	0.679	0.678	0.218
	right		0.574	0.330	0.327	0.254
DBH and CH – as a function of DBH	left	Power	0.916	0.839	0.838	0.156
	right		0.856	0.733	0.732	0.179
DBH and age – as a function of age	left	Power	0.913	0.834	0.833	0.142
	right		0.902	0.813	0.812	0.110

Since in general the two sides of the street had different parameters, the allometric relationships of the two sides were examined separately. All surveys were used in the modelling and the deficit due to pruning works was not taken into account. The data pairs on both sides of the street were correlated for the same function type, but the elements of the equations used were assigned different values (Table 2). In all cases, the data pairs on the right-hand side of the street had a weaker correlation. This could be described with the observation that due to the higher amount of incoming radiation in the summer season, the right side is characterized with more extreme microcliatic and soil conditions (which results also in the lower degree of leaf biomass production). These circumstances might cause the differences compared to the "normal" growth, which are indicated in the lower correlation values between the investigated allometric parameters. In most cases, the correlation between the parameters studied was described by the power function. The strongest correlation between DBH and CW was shown by the function that differed from the other data pairs. This pair of data already shows a weaker relationship with the fitted curve, and the difference between the two sides of the street is also more significant. After the execution of the programs, the SPSS program also displays a visual representation of the function curve fitted to the set of points. The strongest correlation was found between the DBH and TTH values (Fig. 7a). The points fitted significantly to the curve mainly at the intersection of DBH of 15-20 cm and the height of 8-10 m. In contrast, the correlation between DBH and CW was not as straightforward as for the other pairs of data examined (Fig. 7b). The reason of the higher correlations with THT instead of CW lies in the fact that pruning affects primarily the width of the crown, it has no significant effect on total tree height. The 15-20 cm DBH range is associated with broader CWs on the left side than on the right. DBH size explains 67.9% of the trends in CW on the left, but only 33% on the right. The curves fitted to the points of DBH and CH, and age and DBH, show a similar picture to the relationship between DBH and TTH, with minor differences. For the former, the difference is that the tree line on the right is associated with a higher CH for DBH. In the latter case, the second strongest correlation among the data pairs is observed, with a negligible difference between the two sides.

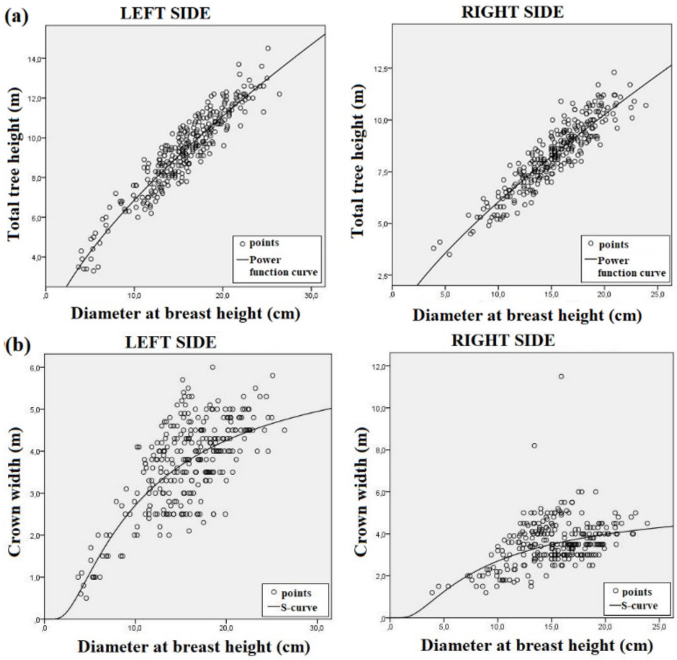

Fig. 7 Allometric relationship on both sides of the street between DBH and TTH (a) as well as between DBH and CW (b)

Allometric equations can be used to predict the physical parameters of trees, but without factors affecting tree growth (climate, pruning, etc.), these values can only be estimated. The estimated values are calculated for 2030 (Fig. 8). The age of the trees was inserted into the equation of the power index function to obtain the expected DBH for 2030, which is expected to increase by an average of 15 cm per tree over the next ten years. The DBH values were then used to determine the estimated TTH and CW. The stand may become 5 m taller, while the CW (which is the most affected by pruning works) may become 1 m wider, which may result in the canopy of the two tree lines approaching each other significantly above the middle of the street. The pruning of the canopy cannot be abandoned in the future, as it already reaches buildings in some places. Compared to the silver linden trees of Szeged (excluding extreme values), the average DBH in the height range between 15 and 16 m is 38 cm, so the estimated values are realistic.

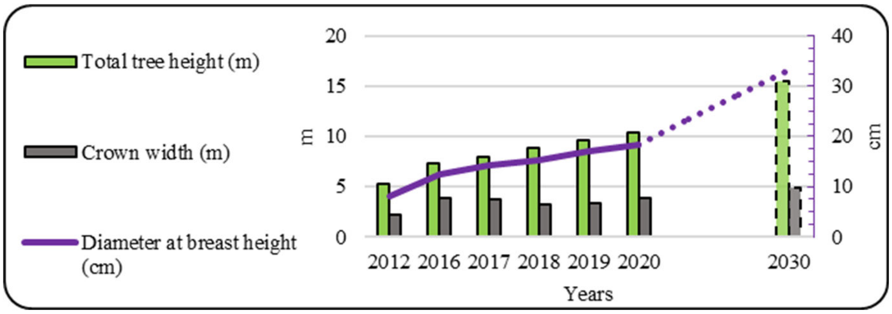

Fig. 8 Physical parameters measured so far and their estimation for the year 2030, estimated on average per individual trees

4.4. Summary discussion

Comparing the results for the potential incoming solar radiation and the structural analysis of the tree line, it is likely that the lower radiation intensity on the left side is one of the reasons for the higher trees. It is a general observation of plant physiology that plants grow longer stems under limited light conditions, while longitudinal growth slows down under high insolation. In order to maintain a tall and broad canopy, the trunk is thickened to provide a more efficient support system. However, it is also possible that the microclimate on the left side causes less evaporation and thus better water supply, which could also lead to higher growth.

The scars from the 2017 pruning on the south-facing side of the trees were far from healed, but were in a fully healed state on the shaded trunk. This suggests that the trees are more effective at healing pruning wounds (i.e. have faster tissue proliferation) on the side of the trunk that is not directly exposed to high amounts of sunlight. Early leaf loss in trees on the right side may also be due to increased insolation, which starts in summer. This is one of the highest areas of potential incoming solar radiation, and there is an open area to one side of the synagogue, which means that the air can be warmer and drier, which can lead to premature leaf drop. Further research is needed to answer this question more precisely.

5. CONCLUSIONS

Climatic conditions, resilience of tree species, and increasing biodiversity can be key factors when designing urban tree stands. However, the planting environment should also be considered, as it can determine the growth rate and form of trees that can be planted in a given area.

The significance of the study is that we can examine the condition of this initial tree line from the very beginning, and it is particularly interesting that a young tree line can develop a significant difference between the two sides of the street in such a short period of time. This underlines the complexity of the system to which an urban tree must adapt. Because of the differences resulting from the potential incoming solar radiation, the orientation of streets may also be a significant factor in future studies on similar topics, so that as a correction component can be established for this later on. By defining the sample area and species-specific equations, the prediction of parameters with a strong correlation can be a key part of decision-making processes and green space planning. Exploring these relationships in detail and predicting the future size of trees can be a key part of effective and climate-smart urban planning, as selecting the right species/variety can maximise their ecological services in a cost-effective way, even under the increasingly stringent conditions imposed by climate change.

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