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ENVIRONMENTAL FACTORS AFFECTING THE CONDITION OF *PLATANUS* x *ACERIFOLIA* (AITON) WILLD. URBAN STREET TREES IN SOFIA

Svetlana ANISIMOVA[1], Elena TSVETKOVA[1], Gergana ZAEMDZHIKOVA[2]

[1]University of Forestry, 10 St. Kliment Ohridski Blvd, 1797, Sofia, Bulgaria
[2]Forest Research Institute-BAS, 132 St. Kliment Ohridski Blvd, 1756, Sofia, Bulgaria

Corresponding author email: sanisimova@ltu.bg

Abstract

Street trees are the most vulnerable element of the urban green infrastructure and are subjected to many stressors. In recent years, there has been a noticeable increase in Platanus x *acerifolia (Aiton) Willd. presence in the streetscapes of Sofia. The aim of this research is to identify important environmental abiotic and anthropogenic factors as well as biotic ones affecting its condition. The following influencing factors of tree performance in highly urbanized streetscapes were analyzed: meteorological indicators, air pollution, streetscape morphology, maintenance practices; and pests and diseases. Data for 1,824 street trees were collected by a field survey in alignments of the primary and secondary street network, distributed in commercial zones and residential areas, in the whole variety of possible orientations of streets. The analysis indicated the dominant presence (86.68%) of young trees (DBH < 25 cm), while 4.22% were over 50 cm in diameter. According to our research, the key factors that contributed to the poor performance, structural damage, and health decline of London plane street trees were drought and poor arboricultural practices. A considerable proportion of mature specimens (74.09%) had unclosed pruning wounds with diameter over 25 cm. Late removal of large branches of mature trees for crown lifting, reduction, or removal of structural defects led to decayed pruning wounds (53.64%) and development of water sprouts (20%), respectively. The lower trunk cavities in 13.18%, leaning trunk in 8.18%, branch dieback in 52.27% and unbalanced crowns in 11.36% of investigated mature specimens make them potentially hazardous. Some of young specimens displayed different human-caused damage (7.27%). Regarding the biotic factors, the degree of damage caused by pests and diseases was low – an average of 15%. The results revealed a statistically significant difference in DBH between two groups of young trees – one in median grass strips with a irrigation system and the other without. The analysis of heavy metals in the leaves as an indicator for pollution showed a significant correlation between the accumulation of Al and Pb, Ni and Cr (r=0.91÷0.96) and between Pb and Cr (r=0.98). The results provide guidance for the management of Platanus* x *acerifolia street trees in the urban green infrastructure in order to enhance their environmental benefits.*

Key words: *London plane; green infrastructure; stressors.*

INTRODUCTION

Platanus x *acerifolia* (Aiton) Willd. is among the most commonly planted species in urban areas, favoured for its hardiness and ability to thrive in adverse urban conditions (Caneva et al., 2020; Sanusi & Livesley, 2020; Galle et al., 2021; Roman & Eisenman, 2022; Wang et al., 2023). London plane trees demonstrate high environmental stress tolerance in streetscapes in terms of resilience to water stress and toxic ambient urban pollutants (Tiwary et al., 2016; Haase & Hellwig, 2022). The species is valued and widely used as a street tree in urban environments due to its numerous ecological benefits. Platanus trees provide significant ecosystem services, including air purification, stormwater runoff reduction, urban heat island mitigation, microclimate regulation, and thermal comfort improvement, contributing to the enhancement of biodiversity by providing habitat for urban wildlife (Wang et al., 2018; Wood & Esaian, 2020; Duval et al., 2022; Shen et al., 2023).

The economic, aesthetic, and social benefits of London plane street trees are substantial, with significant contributions to energy savings, increased property values, enhanced aesthetic appeal of urban areas, and improved quality of life (Rotherham, 2010; Wang et al., 2018; Xiong et al., 2019).

Platanus x *acerifolia* plays a significant role in the urban green spaces of the city of Sofia. It is one of the most prevalent species in the whole city street network, especially among the plantings in the last decades (Anisimova, 2023).

However, the health of plane trees is compromised by climate change effects (Dobrescu & Fabian, 2017; Sanusi & Livesley, 2020), pests and diseases (Pelleteret et al., 2017), which severely impact their vitality and reduce their ecosystem service benefits when they are most needed. Urban environments pose several challenges for Platanus trees, including soil compaction, pollution, and limited water availability. These factors can lead to health issues and reduced longevity (Gillner et al., 2015; Ordóñez et al., 2018).

The aim of this research is to identify the most important environmental abiotic, biotic, and anthropogenic factors affecting the overall performance of London plane urban street trees in the city of Sofia.

MATERIALS AND METHODS

The field-based survey was carried out during the period from 2021 to 2024, which included street alignments of all classes of the primary and secondary street network of the city of Sofia – II (Urban highways with intermittent traffic regime); III (Regional arterial streets); IV (Main streets), V (Collectors).

Overall performance of trees

The attributes that have been examined, collected and evaluated by field studies to characterize the overall performance of trees were: diameter at breast height (DBH); stem injuries and problems, crown damage and defects, and leaf damage by pests and diseases. Along with the tree phytosanitary status assessment, the poor maintenance practices and conflicts with the city's infrastructure (width of the sidewalk, distance of the stem from the street curb and the buildings) were considered.

The condition of the foliage of each specimen was visually assessed according to the degree of defoliation and degree of foliage transparency (Eichhorn et al., 2020) on a scale from 0 to 100%, with a step of 5%.

The following obvious tree defects were examined: leaning trunk, wounds and cracks on the bark and stem, wood decay in the lower trunks and cavities, fruiting bodies of a basidiomycete (basidiocarp), and bacterial bleeding canker. Crown states were analyzed for an unbalanced crown, wood decay in unsealed pruning cuts, broken branches, dieback of twigs or branches, and epicormics (water) sprouts.

Meteorological and air pollution data

The abiotic factors that have been analyzed were temperature, relative humidity, and air pollution. Data on hourly values of meteorological variables: air temperatures (°C), relative humidity (%), and average hourly concentrations of PM_{10}, $PM_{2,5}$ and O3 for the period 2015-2024 from 5 Automatic Measuring Stations of the Executive Environmental Agency (EEA) were used.

Samples for leaf analysis were taken from 15 trees from 5 streets from II and III class. The sampling was carried out in August.

Statistical analysis

Descriptive statistics and single regression analysis were performed. Correlation coefficients (R) at selected significance thresholds of 95% and 99% probability were determined. For significant relationships, linear models of the type: y=b.x+a were inferred. Excel was used for mathematical-statistical and graphical data processing.

RESULTS AND DISCUSSIONS

Street tree data for 1,824 tree specimens of *Pl.* x *acerifolia* were collected by a field survey in street alignments of all classes of the primary and secondary street network of the city of Sofia – II (17.84%), III (62.79%), IV (6.75%), V (12.62%).

The street plantings were located in different administrative territorial units of Sofia Municipality. The dendrometric indicator DBH of the surveyed street trees serves as an approximate assessment of the age of the specimens and was classified into categories (Figure 1). The analysis of DBH indicated the dominant presence (86.68%) of young trees (DBH < 25 cm), while 4.22% were over 50 cm in diameter. Most of the young trees were planted in the last two decades.

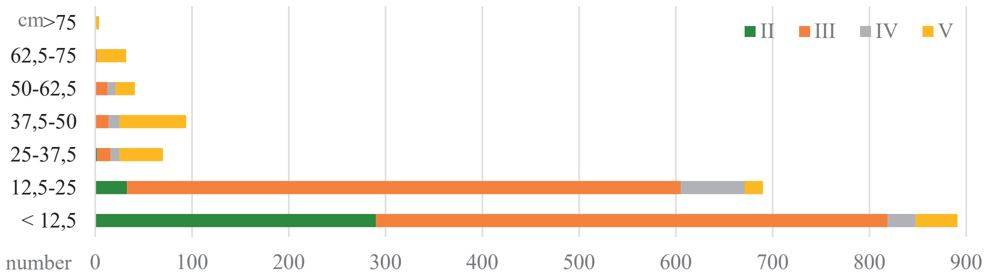

Figure 1. DBH class structure of *Platanus* x *acerifolia* trees for the main street classes

The age of the studied specimens ranged between 10 and 100 years.

The following influencing factors of tree performance in highly urbanized streetscapes were determined: abiotic, incl. soil conditions, meteorological indicators, air pollution, streetscape morphology, and maintenance practices; and biotic, including pests and diseases.

Abiotic and anthropogenic factors

Streetscape morphology and growing medium

The tree alignments were distributed along 20 streets and 10 boulevards in commercial zones and residential areas (Figure 2).

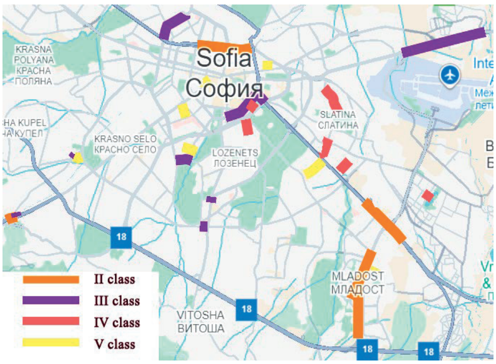

Figure 2. Surveyed streets in Sofia

The trees were located in the whole variety of possible orientations of streets – E-W (44.04%), N-S (22.32%), NW-SE (13.13%), NE-SW (20.51%) – and physical characteristics of the built environment. The width of the sidewalks varied between 2 and 8 m. 57.84% of the specimens were planted in median strips or grass verges (green strips between the road and sidewalk), while the rest were planted in single tree pits in concrete paving on streets with different building densities. There were limitations to this study related to the inability to analyze soil and light factors in dense urban environments. In relation to the insolation regime, some of the specimens on the same sidewalk of the streetscape were flanked by multi-story buildings creating a canyon effect, while others were exposed to total irradiation.

Soil conditions and the tree-planting sidewalk cut-out area also varied across different sites. The trees were planted directly in the ground without any soil improvements to the growing medium – no amendments or application of structural soil. The application of de-icing salts on roads and pavements in winter is also part of municipality maintenance practices. However, these attributes vary from year to year, seasonally, and depend on the street zone. About 1/4 of the trees in the median strips were provided with irrigation systems.

Data analysis of a case study involving two groups of 15-17-year-old fully irradiated London plane trees grown along the same boulevard in Sofia – one group in median strips/grass verges with a surface irrigation system and the other without – revealed a statistically significant difference in DBH between the two groups ($p = 2.73E\text{-}11$) and crown volume, respectively. A greater range of DBH was observed in the non-irrigated area (Figure 3): more than 1/2 of the examined specimens had a DBH between 8 and 10 cm, while only 1/4 of the trees reached a diameter of 15-16 cm. On the other hand, 3/4 of the trees under irrigated conditions exceeded these dimensions. Some individual specimens in the non-irrigated grass strips reached sizes around and slightly above 22 cm. It was found that these trees were adjacent to a drainage channel. The average diameter of the trees under irrigated conditions was about 5 cm larger. The mortality rate among non-irrigated specimens ranged between 10-15%. Optimized irrigation management, particularly with respect to tree phenology, could contribute to maximizing plane tree performance and survival in urban areas under climate change (David et al., 2018; Claude et al., 2024).

Plane trees planted in constrained environments, such as small tree pits or areas with concrete paving, tend to exhibit poorer health (Tan et al., 2022). Site factors variably affected stem caliper of plane street trees, which increased with a greater sidewalk cut-out area (Sherman et al., 2016). Soil conditions that influence tree performance in highly urbanized streetscapes frequently include: lack of soil volume available for adequate root growth; low soil nutrient and organic matter content; soil compaction, which hinders root development and water availability; elevated soil salinity, which causes osmotic stress to trees and frequently manifests as leaf chlorosis; high soil alkalinity, which can influence nutrient availability; and either poor drainage or low soil water-holding capacity.

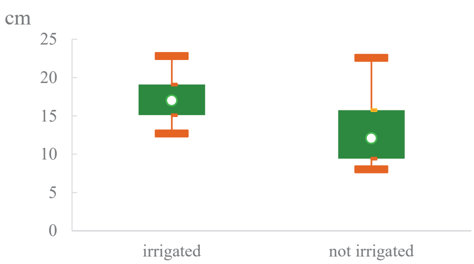

Figure 3. Box-plot diagrams of DBH of irrigated vs non-irrigated specimens

High soil salinity and alkalinity, along with physical damage and excessive sunlight exposure, have been linked to the decline of *Platanus* trees in urban settings (Ordóñez et al., 2018).

The importance of edaphic and irradiation factors has been recognized and deserves future investigation.

In a study of "hot spots" in terms of physiological stress and traffic pollution in Bucharest, *Pl.* x *acerifolia* was found to be one of the species less affected by adverse microclimate and edaphic urban conditions. The results indicated that younger specimens suffered more under heavy traffic conditions (Dumitraşcu et al., 2010). Dendrochronological analyses revealed that the species was found to be less affected by a high degree of urbanization and exhibited higher drought tolerance, making it suitable for urban planting in temperate climates (Franceschi et al., 2023).

Human-induced damage

Pruning represents one of the most important maintenance practices for street trees. Its main objectives are improving safety, tree stability and health status, ensuring traffic clearance, and resolving conflicts with infrastructure. Some of young specimens displayed different human-caused damage, such as physical injuries to the crown, stem or root collar from vehicles or pedestrians, improper staking and arboricultural practices, and injury to the root collar area by grass trimmers (7.27%) (Figures 4 and 5).

The results show that a considerable proportion of mature London plane specimens (74.09%) had unclosed pruning wounds with diameter over 25 cm as a consequence of some improper pruning methods and techniques. Late removal of large branches of mature trees for crown lifting, reduction, or removal of structural defects led to decayed pruning wounds (53.64%) and development of water sprouts (20%), respectively (Figures 4 and 5). The process of callus and woundwood production (compartmentalization) is long and sometimes unsuccessful. Additionally, the lower trunk cavities in 13.18%, leaning trunk in 8.18%, branch dieback in 52.27% and unbalanced crowns in 11.36% of investigated matue specimens make them potentially hazardous.

The implementation of good formative pruning of recently planted *Pl.* x *acerifolia* street trees was found to be cost-effective, with lower costs compared to structural pruning of mature trees.

Improper pruning often leads to structural defects and health issues which can compromise the structural integrity of trees, making them more susceptible to failure. Pruning should be consistent with the biology of the species and good arboricultural practices. *Pl.* x *acerifolia* street trees, with their rapid growth, require a lot of pruning work to establish strong structural framework and maintain it to maturity (Ryder & Moore, 2013).

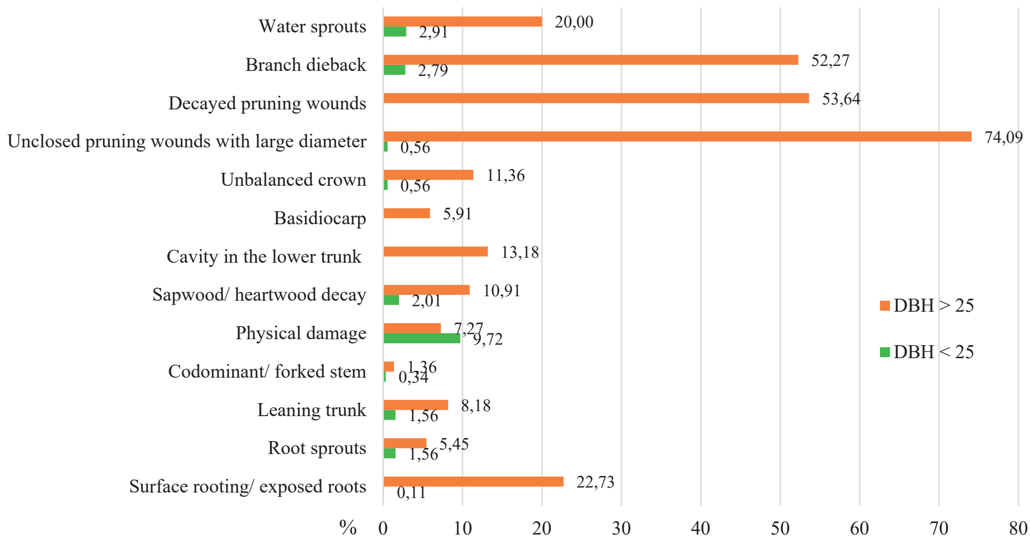

Figure 4. Percentage *Platanus* x *acerifolia* trees with structural defects, damage, and health issues

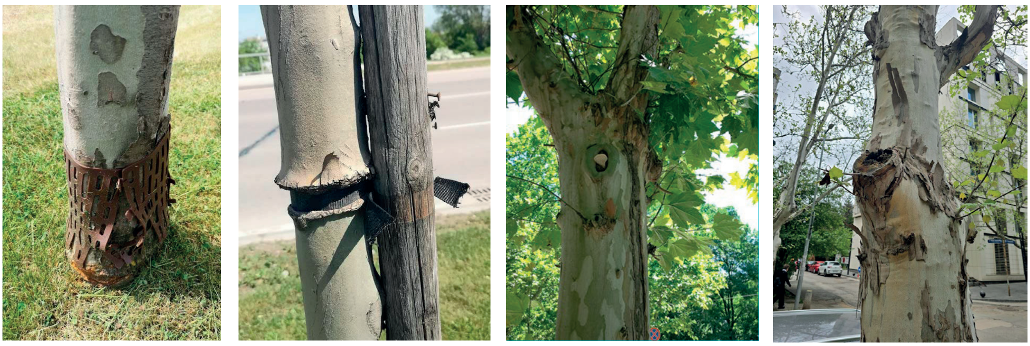

Figure 5. *Human-induced damage* of *Platanus* x *acerifolia* trees

Regular, moderate pruning of the London plane is recommended to maintain tree health and structure. This approach helps optimize the tree's ecosystem services, such as increased crown carbon sequestration and air quality improvement (PM_{10} capture). Pruning represents an opportunity to increase the crown carbon stock by up to 65%, taking into account the full reestablishment of the crown. Over-pruning can lead to increased susceptibility to diseases, branch dieback occurrence, and reduced capacity to provide ecosystem services (Muscas et al., 2024). Disease spread in *Platanus* street trees can be prevented through appropriate management and planting practices. Proper pruning, larger pits with less concrete paving, and the presence of tree grates or guards can impact the health condition of trees (Tan & Shibata, 2022). The results of this study are consistent with recent findings about the adverse effects of improper pruning practices on the health status and aesthetic value of horse chestnut street trees in Sofia (Pencheva & Anisimova, 2016).

Meteorological indicators

In the present study, the analysis of daily maximum temperature data for Sofia over a 10-year period (2015-2024) showed extremes of up to 48.1°C. These heat waves were recorded mainly from the last ten days of July to the second ten days of August. During these periods of elevated summer temperatures, leaf colour modification and early leaf drop of the plane trees were observed, especially in the areas with no irrigation. Extreme heat, such as heatwaves, can lead to canopy leaf loss in *Platanus* x *acerifolia*, reducing ecosystem service benefits, such as shade cooling and human well-being in urban areas. A study in Melbourne observed 30-50% canopy loss in London plane trees following a heat wave with temperatures above 43°C (Sanusi & Livesley, 2020).

During the winter period, daily minimum temperatures in the range of -10 to -20°C were found. These low temperatures, combined with inversions that trap air pollutants in the ground layers, adversely affect the health of plane trees. Fluctuations in temperature conditions in urban environments were common during the study period. Temperature amplitudes in excess of 20°C per day were observed. This was especially true for the end of February, the second half of March and April, as well as during the first ten days of August.

The minimum value of relative humidity in the annual cycle was observed from June to September. During the same period, the onset of the dry period was expected. There were quite a few cases of relative humidity below 50%, and in certain periods, this value dropped below 30%, i.e. an indicator for atmospheric drought. In general, drought conditions exacerbate the vulnerability, especially of young plane trees, because, along with earlier foliage loss, they suffer from leaf chlorosis during drought periods and heat waves (Akhbarfar et al., 2023). Drought stress leads to a decline in chlorophyll content, net assimilation rate, and relative water content, which are particularly critical for the health and growth of young trees. Severe drought has been found to induce defoliation in London plane trees when extractable soil water content decreases below 25% (Claude et al., 2024). During periods of heat waves and drought, the maintenance of green alignments in Sofia rarely includes watering. The UHI effect, prolonged heat waves in combination with drought, lead to heat stress on street trees. Plane trees respond to water deficit with a time lag, resulting in lower growth in the years following the drought (Hirsch et al., 2023). The consequences of these urban conditions include failure to establish, retarded growth rates, tree decline and mortality.

The health status of the urban population of *Pl.* x *acerifolia* has been negatively and most significantly influenced by long-term precipitation amount, higher precipitation amount in May, and a higher number of freezing days in winter. During the period of the highest damage, the specimens were additionally affected by the fungal pathogen *Apiognomonia veneta* (Sacc. et Spegg.) Höhn (Gregorová et al., 2010). Its spread is heavily influenced by high humidity and precipitation (Ivanová et al., 2010).

Air pollution

In Bulgaria, particulate matter (PM_{10} and $PM_{2,5}$) has been identified as a major pollutant adversely affecting the near-surface atmosphere and air quality. The monitoring of air pollution in Sofia for the last decade during the vegetation period reported peak hourly concentrations per day of PM_{10} that exceed 100 μg/m³. PM pollution is most often due to dust deposited on the streets as well as to deteriorated green areas in the capital, traffic and construction. Domestic heating with solid fuels during the winter months is also a source of dust pollution. Mineral dust transport from long distances, mostly originating from the Sahara Desert, is also a significant contributor. More than 104 days of the vegetation period have been reported with atmospheric circulations carrying Sahara Desert dust (AHB, 2022, 2023). From March to the first half of April, PM_{10} values exceeded 250 μg/m³. Towards the end of June, levels in the range of 450-550 μg/m³ were recorded in 2016 (543 μg/m³) and 2019 (464 μg/m³), respectively. In the second half of August, pollution was also detected reaching maximum hourly levels of 513 μg/m³. The dynamics of maximum hourly mean concentrations of $PM_{2,5}$ largely duplicate the PM_{10} load at the beginning of the plane vegetation period in March. At the beginning of the study period, peak values in March reached 134 μg/m³, and in June – 96 μg/m³.

These fine particles deposited on the leaf blade negatively affect physiological and metabolic processes of plane trees. High concentrations have also been recorded at the end of the vegetation period and in fall. Values for the autumn season reach levels of up to 87 μg/m³.

Street trees have been found to improve thermal comfort by lowering air temperatures and reducing PM levels, thereby improving outdoor urban environmental conditions (Miao et al., 2023). However, the presence of street trees can also prevent the dispersion of air pollutants in street canyons, leading to the accumulation of street pollutants (Wang et al., 2024).

One of the main sources of heavy metal emissions in Sofia during the vegetation season is traffic. According to the latest data, more than half of the PM pollution is due to vehicles in the capital. Airborne PM in Sofia is loaded with polymetallic substances. Plane leaves coated with tiny, fine, stiff hairs retain significant amounts of fine PM, and this is also true for heavy metals. This is how they contribute significantly to improving air quality. The study found that 33% more dust was accumulated on the leaves of street trees in comparison to those of park specimens: 1.05 mg/cm^2 in heavy traffic vs. 0.79 mg/cm^2 in a park area, respectively.

Information on air pollution in hotspots of the city can be easily extracted from the concentration of heavy metals in the assimilation organs of trees. The analysis of the results showed a significant positive linear correlation between the accumulation of Al in leaves, on the one hand, and that of Pb, Ni and Cr on the other. Moreover, a strong positive linear correlation was found between the accumulation of Pb and Cr in the leaves of street plane trees (Table 1).

Table 1. Correlation coefficients and coefficients of determination and linear equations of significant relationships between heavy metal content in *Platanus acerifolia* leaves

	Al	Zn	Cu	Ni	Pb	Cd	Cr
Mn	0,75	-0,03	-0,29	0,74	0,80	0,74	0,77
Al		-0,50	-0,39	**0,94***	**0,96****	0,43	**0,91***
Zn			0,21	-0,37	-0,29	-0,01	-0,26
Cu				-0,66	-0,21	-0,74	-0,02
Ni					0,87	0,61	0,76
Pb						0,34	**0,98****
Cd							0,22

*Legend: *p < 0,05; **p < 0,01*

$R^2 = 0,8802$
$Ni = 0,0196.Al - 0,642$
$Al = 44,796.Ni - 39,604$
$R^2 = 0,9177$
$Pb = 0,0069.Al - 0,2742$
$Al = 132,9.Pb + 43,888$
$R^2 = 0,8191$
$Cr = 0,0187.Al - 0,5573$
$Al = 43,772.Cr + 40,768$
$R^2 = 0,9617$
$Cr = 2,813.Pb + 0,1496$
$Pb = 0,3419.Cr - 0,0377$

Tropospheric ozone can cause some damage to tree leaves and reduce biomass production, influencing tree decline, respectively (Xu et al., 2015). The calculated values of AOT40 for the study period, averaged over a 5-year period, exceeded the long-term target standard of 6,000 $\mu g/m^3.h$ by 1.08 to 1.33. Between 2017-2021, 6 ozone days were recorded with mean hourly pollutants above 180 $\mu g/m^3.h$.

Biotic Stress Factors. Damage caused to Pl. acerifolia by biotic factors

Platanus acerifolia is susceptible to various pests and diseases, which – along with factors, such as pollution and climate change – contribute to the likelihood of death and failure of plane trees (Pelleteret et al., 2017).

Three insect species and two fungal pathogens causing damage to the crown of plane street trees were established, respectively: *Corythucha ciliata* (Say, 1832) (Hemiptera: Tingidae), *Phyllonorycter platani* (Staudinger, 1870) (Lepidoptera: Gracillariidae), *Metcalfa pruinosa* (Say, 1830) (Hemiptera: Flatidae), *Apiognomonia veneta* (Sacc. et Speg.) Höhnel. and *Erysiphe platani* (Howe) Braun & Takam. The species composition of pests and fungi, as well as the degree of damage caused by them, are given in Table 2. The degree of damage caused by pests and diseases in the study area and period was low – an average of 15%. Regarding the biotic factor, it can be concluded that the health status of the plane tree is good, because all inventoried trees had an average degree of damage ≤ 20%.

Table 2. Damage caused to *Platanus acerifolia* street trees by biotic factors

Species	Assessed trees, N	Average degree of damage, %
*Corythucha ciliata**	190	16
*Phyllonorycter platani**	51	16
*Metcalfa pruinosa**	74	13
*Apiognomonia veneta***	85	17
*Erysiphe platani***	17	8

*insect pests **fungal pathogens

The relative share of plane trees affected by the insect pests is as follows: *C. ciliata* (45.6%) – almost half of the inventoried specimens, while *Ph. platani* (12.2%) and *M. pruinosa* (17.7%) were represented with a low frequency among street trees. *Corythucha ciliata* is an invasive exotic pest native to North America that is widely distributed in Europe, as well as in Bulgaria (Dobreva et al., 2013). It is known that the leaf damage caused by nymphs and adults of *C. ciliata* and larvae of *Ph. platani* can cause significant leaf loss in plane trees, as well as physiological and aesthetic damage (Mutun, 2009; Tóth & Lakatos, 2018; Florian et al., 2022). Here, the degree of damage caused by these pests to London plane street trees in Sofia was negligible (Table 2). The development and fecundity of *C. ciliata* were found to decrease significantly as temperature increased. The optimal developmental temperature was determined to be 30°C, indicating a potential increase in pest infestation under extreme heat conditions (Ju et al., 2011; Lesovoy et al., 2023). For the first time in Bulgaria, we observed nymphs and adults of M. pruinosa on young shoots of plane trees. M. pruinosa is a very polyphagous native insect in North America and is currently a serious pest in Europe (Strauss, 2010; Chireceanu & Gutuie, 2011).

The pathogen *A. veneta* – a causal agent of plane tree anthracnose, was found to infect 20.4% of the inventoried trees, while powdery mildew (*E. platani*) infected only 4.1% of the trees. The degree of damage caused by these fungal pathogens was 17% and 8%, respectively (Table 2). *Apiognomonia veneta* is one of the most frequent and severe diseases affecting plane trees in Europe, leading to a weakening of the trees (Tello et al., 2005; Ivanová et al., 2010; Tubby & Pérez-Sierra, 2015). A negative effect on the health status of urban plane tree by the fungal pathogens *A. veneta* and invasive pest *C. ciliata* in Sofia was reported by Georgieva et al. (2023).

Trees in warmer urban areas are more water-stressed and in worse condition, which can exacerbate pest infestations. The stress from heat island effects and increased impervious areas surrounding them makes trees more susceptible to pests, leading to a vicious cycle of declining tree health and increasing pest problems (Dale et al., 2016).

Effective management, including regular maintenance and monitoring, is crucial to mitigate the risks of tree failure and ensure the health of *Platanus* street trees (Wang et al., 2023).

CONCLUSIONS

Platanus street trees play a vital role by providing numerous benefits to urban environments. However, their successful integration and long-term contribution require strategic planning and implementing effective management practices to maximize their positive impact in the urban green infrastructure. According to our research, the factors that contributed the most to the poor performance, structural damage, and health decline of plane street trees were drought and poor arboricultural practices. Therefore, best practices for sustainable management of London plane street trees should include: provision of enough space in the street design for development; formative pruning to establish strong structural framework, that should be maintained to maturity; irrigation of young specimens; systematic monitoring, and early detection of pests and diseases.

Further investigation into other factors that have been suggested as possible causes for poor street tree performance and their cumulative effect on urban London plane decline should be conducted.

The results from the research could be used to guide decision-making on species selection and management strategies.

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