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RESEARCH PAPER

Assessing the vitality of Norway maple trees in an urban setting near streets within pits and strips using morphological and ecophysiological methods

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A R T I C L E I N F O

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A B S T R A C T

Climate change-related stressors are leading to early tree deaths in cities worldwide, often before they reach their expected sizes. This study assessed the health of Norway maples (*Acer platanoides* L.), the most common urban tree in central Europe, in Karlsruhe, Germany. We combined observational and experimental methods at several street sites, comparing tree vitality in different site types (pits vs. strips) near streets. We also explored how various biotic and abiotic factors impacted tree health. During the 2022 growing season, we collected data on morphology, eco-physiology, and environmental conditions from 235 randomly chosen trees across two site types. For each tree, we calculated leaf area index (LAI), building index (reflecting neighboring building competition), and Hegyi's competition index (indicating competition from nearby trees). Using generalized linear models and linear mixed-effects models, we analyzed the influence of factors such as pit vs. strip location, crown height, distance to roads, light exposure, vegetation cover, competition indices, crown volume, pruning, and others on traits including leaf area, crown projection, crown openness, crown loss, dieback, discoloration, sun scald, epicormic shoots, stomatal conductance, and electron transport rate. Trees in strips had, on average, five times more open surface area than those in pits. Site types (pits vs. strips) had a statistically significant impact on variables such as crown dieback, discoloration, and sun scald. Dieback, leaf discoloration, and crown openness were notably higher in pits. Neighborhood tree competition reduced crown projection and density, increased crown loss, and prevented sun scalding. Vegetation cover reduced crown loss and stomatal conductance. High light exposure negatively impacted most measured variables. Overall, the study highlights the need for a comprehensive arboricultural approach to understand and manage urban trees. It seeks to balance canopy size and density to optimize cooling and shading benefits while maintaining tree health.

Introduction

Global climate forecasts indicate potential environmental disasters and extreme events in this century (IPCC, 2014). Urban regions worldwide are highly susceptible to climate-related extremes such as droughts, heatwaves, and floods, leading to severe water shortages, air pollution, health issues, and declining tree vitality (Román-Palacios & Wiens, 2020). Rising temperatures contribute to the urban heat island effect, resulting in higher air and surface temperatures in cities compared to rural or natural areas (Oke, 1982). This subsequently causes thermal discomfort and health risks for urban residents (Yan & Dong, 2018).

According to the World Health Organization (WHO), Urban Green Spaces are defined as “all urban land covered by vegetation of any kind” (Thompson et al., 2016). This encompasses grass, trees, shrubs, and other types of vegetation, including urban parks, community gardens, cemeteries, street trees, rooftops, vertical gardens, meadows, and urban forests (De Haas et al., 2021). In the context of global environmental changes, infrastructure like parks, street trees, and urban forests in densely built-up cities is gaining increasing attention because urban green spaces directly impact the health and safety of city residents and greatly enhance urban living quality (Gómez-Baggethun et al., 2013). Urban trees help reduce heat stress by providing shade and facilitating transpiration, serve as habitats for insects, birds, and small mammals, absorb carbon dioxide, and help muffle noise (Dimoudi & Nikolopoulou, 2003; Nowak et al., 2013; Gilstad-Hayden et al., 2015; Scholz et al., 2018). The shade from street trees lowers temperatures and cuts cooling energy needs for buildings, resulting in overall energy savings (Akbari

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et al., 2001). Moreover, street trees are effective in removing air pollutants and mitigating urban air pollution, significantly helping to address environmental degradation caused by rapid urbanization and climate change (Chaudhary & Rathore, 2018). However, urban growing conditions pose more challenges for trees than rural environments (Gillner et al., 2014).

Cities create a complex environment with many human-induced influences that significantly affect trees' requirements. Urban surfaces like roads, buildings, and parking areas are characterized by high imperviousness, low reflectivity, and high heat absorption. This absorbed heat is stored and released at night, hindering cooling and raising urban temperatures. Excess heat can impair tree growth through morphological and physiological issues, such as poor leaf development (Teskey et al., 2015). Light availability in cities varies greatly; large buildings cast shadows affecting photosynthesis (Tan & Ismail, 2014), while artificial lights at night alter seasonal growth patterns (Rajkhowa, 2014). Additionally, increased pollutants and particulate matter can harm plant physiology and induce oxidative stress, especially in street trees (Chaudhary & Rathore, 2018).

Beyond above-ground factors like light, air quality, and temperature, below-ground conditions also impact trees. Urban soils are constantly changing and deteriorating, leading to compaction, disrupted water-air balance, surface runoff causing water shortages, elevated soil temperatures, pollution, salinity, high pH, and reduced organic matter and minerals (Czaja et al., 2020). Poor soil quality limits growth and crown development and raises mortality risks (Layman et al., 2016). Moreover, urban soils often originate from human activity; a common type is Technosol, formed from waste soils, road surfaces with unconsolidated material underneath, and built-up soils (IUSS Working Group WRB, 2014). A further growth constraint is limited rooting space—trees are often planted in pits or strips, constrained by structures or sealed surfaces, which reduces the available soil volume. These stressors diminish tree vigor, decrease productivity, and disrupt the balance between carbon sinks and sources, ultimately leading to dieback (Xu et al., 2020).

Trees' dieback involves a complex process driven by a long-term decline in overall tree vitality. Since vitality itself is hard to measure directly, researchers rely on morphological and ecophysiological indicators as proxies to evaluate it (Dobbertin, 2005). Standard assessment metrics include trunk diameter, tree height, and leaf area. The leaf area index (LAI) quantifies the leaf area per square meter of surface, providing valuable insights. Measuring leaf area not only aids in understanding physiological and functional processes more accurately but also serves as an early stress indicator (Zheng & Moskal, 2009). Signs of stress—such as dieback of branch tips or whole branches, sun scalds on stems, or abnormal foliage—can signal underlying health issues (United States Department of Agriculture, 2010).

Another approach to evaluate tree health in urban open conditions involves physiological assessments. The unitless quantum efficiency at steady state, PhiPSII (Tan & Ismail, 2014), is a standard indicator of leaf photosynthetic capacity. Stomatal conductance serves as a marker for water deficiency (Fotelli et al., 2000), since stomata control water vapor and CO2 exchange between the leaf and the atmosphere, adjusting their openings according to environmental conditions. Moreover, the electron transport rate (ETR) indicates the balance between photodestruction and repair, making it a valuable measure of photoinhibition, photosynthetic capacity, and thermal stress (Figueroa et al., 2019).

While numerous studies focus on the long-term development and adaptation of forests, the vulnerability of urban trees to climate change and environmental stressors is comparatively less explored, posing challenges for urban planning (Ordóñez & Duinker, 2015). It is crucial to choose suitable planting strategies during the design and planning phases to enhance tree vitality (Rahman et al., 2013). These factors can vary significantly depending on the planting site, such as a pit or a strip, due to differences in potential water intake area and proximity to competing trees. Incorporating biotic factors or the available open surface area in analyses can help address important interactions affecting outcomes.

Norway maples are common trees in urban areas. GALK E.V. (2021) states that these plants need little soil, tolerate heat fairly well, and are generally suitable for cities, though they are sensitive to soil compaction. Despite their heat tolerance, Gillner (2012) observed that drought and rising temperatures negatively impact them, recommending planting Norway maples in areas with less sealing and more soil volume. The mixed views on their suitability as street trees, combined with their high presence in the study area, highlight the need for more detailed research on how different sites and environmental factors affect them. This study aimed to assess the health of Norway maples growing along urban streets at various locations in Karlsruhe, southwest Germany, in the Upper Rhine River Valley. This region is experiencing high tree dieback in urban forests due to consecutive heatwaves, diseases, and droughts (Lv et al., 2024a). Additionally, we investigated how biotic and abiotic factors influence their morphological and ecophysiological traits. To achieve this, randomly selected Norway maples were initially classified into two site types: pit and strip.

We formulated two research questions:

1) How does the vitality of Norway maple trees in urban street areas vary between different growing sites (pits vs. strips)?
2) Which environmental (biotic and abiotic) factors affect the vitality of these Norway maple trees in urban streets?

Materials and methods

Study site

This study was carried out in Karlsruhe's municipal area (see Fig. 1). Covering 17,342 hectares, Karlsruhe's land is approximately 39.5 % developed with buildings and roads (Amt für Stadtentwicklung - Statistikstelle, 2022). As of 2021, it has a population of 306,500, making it one of the major cities in Baden-Württemberg, located on the Upper Rhine Plain. The city lies in a transitional climate zone between oceanic and continental types, with an average annual temperature of 10 °C and about 750 mm of precipitation annually. The soil mainly consist of brown earth and para-brown earth derived from gravel and terrace sediments. However, urban soils are Technosols, heavily influenced by human activity and often containing building rubble mixed with other substrates (Stadt Karlsruhe, 2021a). The elevation varies from 110 to 200 m above sea level, from the city center to the mountain villages (Stadt Karlsruhe, 2021b).

Study design

Pre-selection of the trees from the city tree cadaster

We utilized Karlsruhe city's tree cadastre data to select our target trees. Our aim was to examine how various urban environments influence the health of Norway maple (*Acer platanoides* and its varieties). Norway maple was selected because it is the most prevalent species in Karlsruhe, with 22,000 trees planted throughout the city. We chose trees with similar elevation and heat exposure to ensure comparability. Elevation was determined by visual comparison with the terrain geodata of the city of Karlsruhe (Stadt Karlsruhe, 2021a), following that criteria, we chose trees situated between 110–120 m above sea level (Stadt Karlsruhe, 2021b). We used the temperature field map of the urban framework plan for the city of Karlsruhe (Beermann et al., 2015) as a database for urban heat islands. It is a georeferenced database with three categorical situations (cold, medium, hot). Subsequently, only trees in the medium category were used as our target sample trees, and the values were assigned to the point data of these trees. Further, each tree was categorized according to land cover types from the Urban Atlas 2018, provided by Copernicus (2022). Trees located in parks, green spaces, or forests were omitted. The remaining Norway maples were classified into four groups: healthy (0–10 % damage), unhealthy (10–60

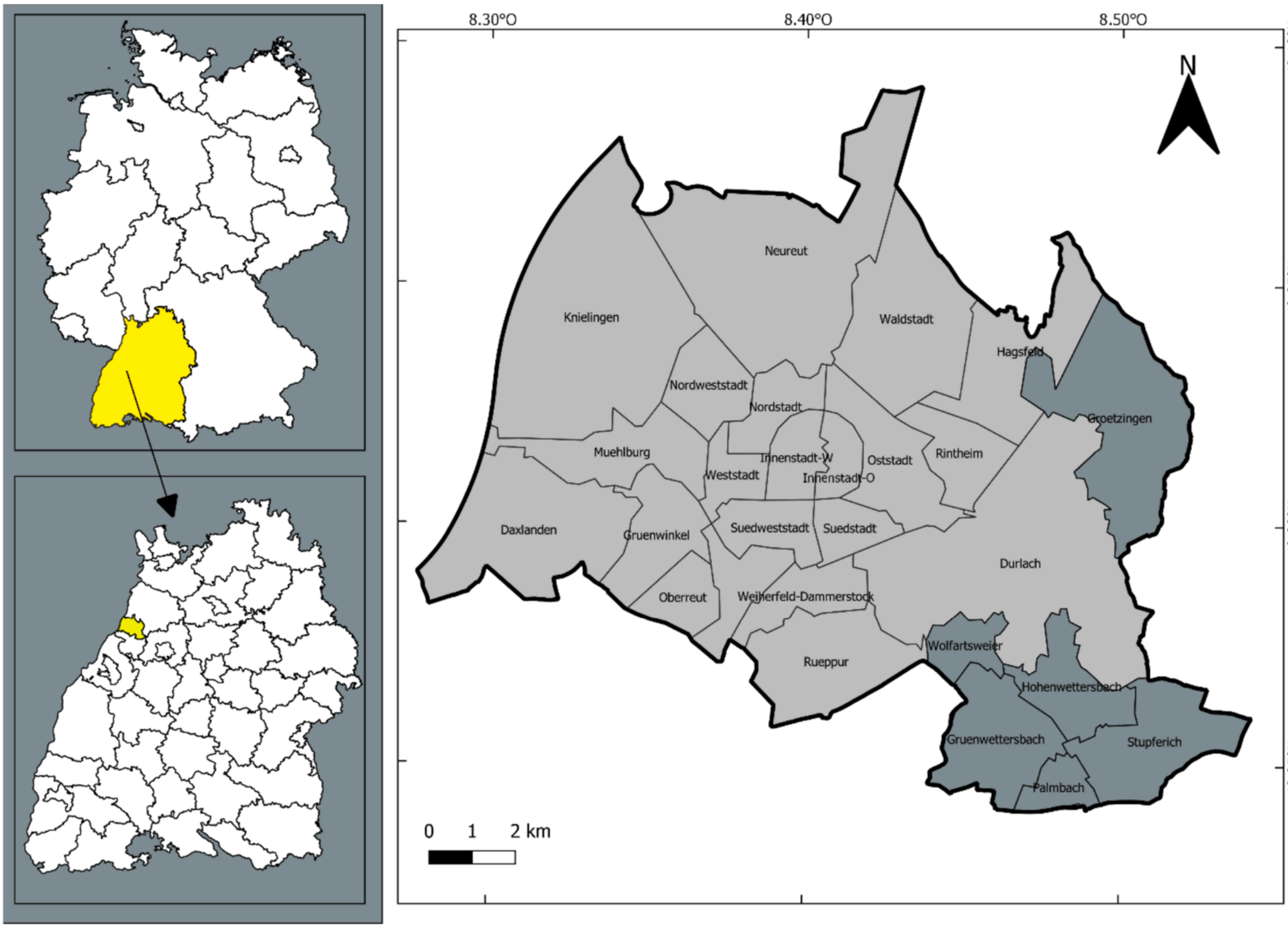

Fig. 1. Geographical classification and overview map of the study area. Due to the higher elevation, the darker area in the city was excluded from the study.

% damage), and two size categories (18–33 cm and 34–50 cm trunk diameter).

Following the specified criteria, 5933 trees were identified, and 600 of them were randomly chosen. These chosen trees were matched with satellite imagery and the 3D features of the Karlsruhe Geoportal (Stadt Karlsruhe, 2021b) to classify them based on their site type categories (pit and strip) and crown light exposure values. Trees that could not be assigned to either site category or had a crown light exposure below three were excluded. From the remaining pool, trees from each category were again randomly sampled, resulting in a total of 235 trees studied (see Fig. 2 and Table 1).

A subset of 20 trees from the smaller diameter group of 235 was chosen for measuring stomatal conductance and chlorophyll fluorescence. Each category—pit healthy, pit unhealthy, strip healthy, and strip unhealthy—contained 5 trees. An experiment using rectangular flash optimization was conducted to find the best flash intensity. Incorrect intensity could lead to fluorescence not reaching saturation or cause flash-induced quenching (LI-COR Biosciences GmbH, 2022a). Therefore, Norway maple leaves were tested beforehand with various intensities, from 5000 to 10,000 μmol m^{-2} s^{-1}. The data were analyzed using the FlashAnalysis software, which plots demodulated fluorescence against time. The optimal intensity was identified as the one showing a rapid fluorescence increase followed by stabilization, and for the maple leaves, this was at 6000 μmol m^{-2} s^{-1}.

Data collection and indices preparation

Tree-level data collection. Fieldwork took place from June to August 2022. During this period, data on morphological traits such as diameter at breast height (DBH), crown extension, and overall tree height were gathered. Additionally, variables indicating tree health— including crown dieback, crown openness, crown missing, discoloration, defoliation, branch cuts, sun scald, and epicormic branches—were recorded based on i-tree Pest Detection Field Guide (United States Department of Agriculture, 2010; i-Tree-eco, 2021; https://www.itreetools.org/documents/243/I-PED%20Field%20Guide.pdf) (Table 2). Calculations were made from the inventory data for other parameters like crown volume, crown projection area, and cut score. A similar protocol from i-tree-eco has also been integrated into the web application of the "Healthy Trees Healthy Cities" initiative, allowing citizens to participate in tree health assessments through citizen science activities (Hallett & Hallett, 2018; https://hthc.itreetools.org/home). The field assessment was conducted by graduate student Diana Kramer, who received detailed training in tree health evaluation from Somidh Saha. Her qualitative estimates were verified and validated, and ultimately, she conducted all assessments to ensure objectivity and minimize personal bias.

Site-level data collection. In addition to the tree-related variables, site variables were gathered, including the size of the respective pit or strip, the percentage of open surface area covered by vegetation, the estimated percentage of impervious surface within a 10-meter radius, and the distance of each tree from buildings and roads (Table 3). Using that site level data, Hegyi's tree competition index and the building index were then calculated.

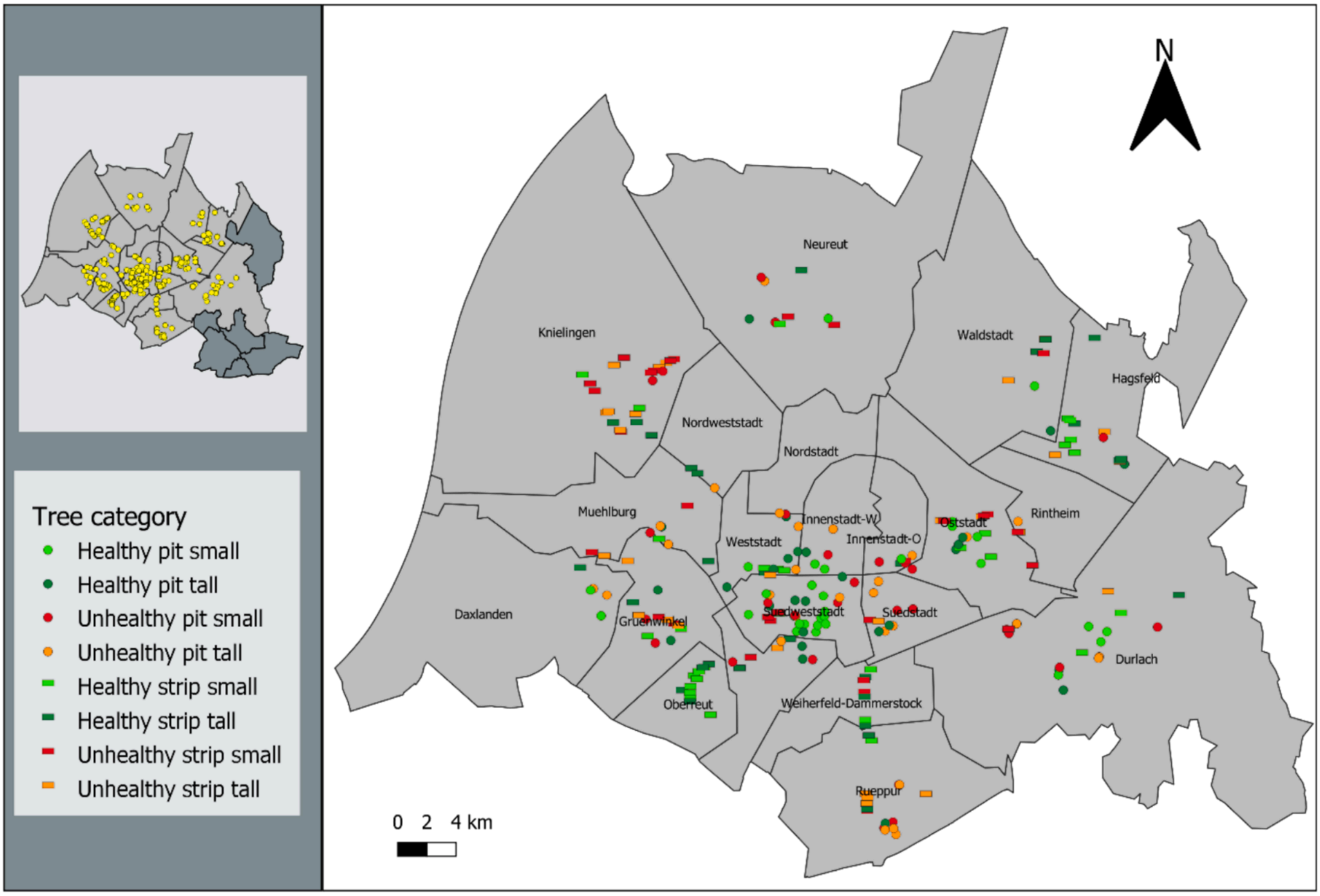

Fig. 2. Overview of the distribution of trees in each category.

Table 1
Factor table of pre-selected trees and actual sampled trees in square brackets for morphological variables.

	18–33 cm trunk diameter		34–50 cm trunk diameter	
	healthy	unhealthy	healthy	unhealthy
pit	29	29	28	28
strip	31	30	29	31

Competition index as a measure of interaction between trees. The Hegyi index (Hegyi, 1974) was used to measure competition for each target tree, focusing on light and space competition and its effects on morphological and physiological traits (see Eq. (1)). This index depends on the size of neighboring trees and their distance from the target. A standard guideline for urban tree planting recommends a minimum distance of 10 m (Mertens, 2021). Consequently, competitor trees within this radius were recorded, as they are likely to cast significant shade and impact photosynthesis. The Hegyi index was calculated following the method of Daniels and Burkhart (1975).

$$\textit{Hegyi index} = \sum_{j=1}^{n} \left[\frac{\left(\frac{d_j}{d_i} \right)}{D_{ij}} \right] \tag{1}$$

d_i=DBH in cm of target tree
d_j=DBH in cm of competitor tree
D_ij=Distance between competitor and target tree

Leaf area index. During data collection, a hemispherical image was captured for each tree using a Sony ILCE-6100 camera with a fish-eye lens through the WinSCANOPY system (Regent Instruments Inc., 2020). The photos were taken at 1.3 m height and one meter away from the tree. The images were then analyzed with WinSCANOPY 2020 software. For *Acer platanoides*, the LAI 2000 method (Welles and Norman, 1991) yielded the most reliable results. The WinSCANOPY variables related to light and radiation include canopy openness—the percentage of open sky visible in a given area above the lens—and the average total (direct and diffuse) PPFD above and below the canopy during the growing season (Regent Instruments Inc., 2020).

Building index as a measure of the impact of building on trees. A building index relevant to urban tree growth was created here for the first time to assess the possible impact of buildings on the target trees (see Eq. (2)).

$$\textit{Building index} = \sum_{j=1}^{n} \frac{(W_{Hj} + W_{oj})}{\textit{Distance}_j} \tag{2}$$

Each variable was assigned a weighting factor categorized into three classes (1–3), as shown in Table 4. In the Northern Hemisphere, trees mainly receive sunlight from the south for most of the year, with no direct sunlight coming from the north. Consequently, buildings facing south towards the trees block more sunlight and receive the highest weight, whereas north-facing buildings block the least and were assigned the lowest weight. Similarly, tall buildings were considered to have a greater shading effect than medium or smaller structures because they cover more of the crown. Following that, low indicates the building was shorter than the tree canopy, medium means the building was roughly as tall as the tree canopy, and high signifies the building was

Table 2
Tree variables of the data collection with their short description.

Variables	Unit	Short description	Use in analysis
DBH	cm	Diameter measured at the breast or 1.3 m height	To calculate the Hegyi Index
Total height	m	Total height of the tree	To calculate crown volume and projection area
Crown base	m	Height to the beginning of the crown	
Crown top	m	If different from total height: height to the upper top of the crown	
Crown width	m	Distance of outer points of the crown to the trunk in north-south (NS) and east-west direction (EW)	
Branch cut	number	Counting residues of cut branches	Calculation of the cut score
Major branch cuts	number	Counting residues of major branches	
Crown openness	%	Estimated percentage of missing leaves within a 1 m^3 cubic (5 % intervals, starting at 10 %)	Response variable for the Generalized linear model
Crown dieback	%	Estimated percentage of dead branches and twigs (5 % intervals, starting at 10 %)	
Defoliation	%	Estimated percentage of defoliation caused by insects (5 % intervals, starting at 10 %)	
Discoloration	%	Estimated percentage of foliage with visible discoloration (5 % intervals, starting at 10 %)	
Crown missing	%	Estimated percentage of missing crown volume (5 % intervals, starting at 10 %)	
Epicormic shoots	number	Number of epicormic shoots along 25 % of the total tree height	
Sun scald	number	Counting cracks in the trunk caused by high temperatures and sunlight	

taller than the tree canopy. Only buildings within a 10-meter radius were included, as they exert the strongest influence on sunlight availability. A higher index indicates more significant shading.

The building index was also compared with two light variables—photosynthetically active photon flux density (PPFD) over the canopy and under the canopy, measured using WinSCANOPY—to validate the underlying assumptions. The results showed a negative correlation between the building index and PPFD over the canopy (Spearman's rank correlation $= -0.28$, $p < 0.001$), as well as between the building index and PPFD under the canopy (Spearman's rank correlation $= -0.21$, $p < 0.001$). These findings support the idea that higher building index values are associated with reduced light availability for photosynthesis (i.e. PPFD) during the growing season.

Crown projection area and open surface area ratio. In arboriculture, it is commonly assumed that a tree's root system size corresponds to its canopy extent (Easdale et al. 2019), particularly when a tree grows freely in open field conditions without any above- or belowground barriers. To assess whether the open surface area beneath the crown adequately reflects the expansion of the assumed root system, the ratio of crown projection area to open surface area was calculated (Eq. (3)). A ratio above 1.0 indicates that the open surface area is insufficient, while a ratio below 1.0 suggests it is adequate.

$$\textit{Ratio} = \frac{\textit{Crown projection area}}{\textit{open surface area}} \tag{3}$$

Ecophysiological data collection. Three measurements were conducted sequentially in July and August 2022. Generally, plants respond to drought by closing their stomata to prevent excessive water loss (Schulze 2019). Since water availability can vary in pits and strips due to changes in soil volume, stomatal closure likely differed among trees at different sites. Measurements were taken twice daily, in the morning and afternoon, during periods when trees were expected to experience drought stress due to sustained temperatures above 25 °C and several days without rain. Trees sampled in the morning during one session were re-sampled in the afternoon during the next, and vice versa. This alternating schedule aimed to balance the effects of temperature and solar radiation that vary depending on the time of day.

Measurements were conducted using a Licor LI-600 Porometer/ Fluorometer (LI-COR Biosciences GmbH, 2022b). The device records data on porometry and fluorimetry. Measurements involved four leaf categories: sun leaves in both the lower and middle canopy, and shade leaves in the same canopy layers. For each category, two fully matured

Table 3
Site variables of data collection.

Variables	Unit	Short description	Use in analysis
Distance to building	m	Distance from the tree to buildings within a 10 m radius around the target tree.	Calculation of the building index
Height class building	Ordinal, value	Height classes (high, medium, low) of buildings within a 10 m radius in relation to the tree crown.	
Orientation of the building	degree	Direction from the tree to the building in degrees within a 10 m radius	
Trees per site	number	Number of trees on the same site type.	Calculation of the open surface area per tree.
Competition data	Measurements and values	Species, DBH, and distance of trees within a 10 m radius around the examined tree.	Calculation of the Hegyi index.
Distance to road	m	Distance from the tree to the nearest possible vehicular traffic, such as roads, but also parking lots.	Potential predictor for Generalized linear model and Linear mixed-effects model
Distance to major roads	m	Distance from tree to major roads with regular traffic.	
Crown light exposure (CLE)	Ordinal, number	Number of light-receiving crown sides, ranging between 0 and 5.	
Site size	m^2	Measurement of the open surface area.	
Vegetation cover	%	Estimated percentage of vegetation cover of the pit/strip.	
Impervious surface	%	Estimation of impervious surface within a 10 min radius around the tree.	
Tree number/ strip area	number	Ratio of trees to total strip area.	

Table 4
Weighting of building variables as a basis for building index.

Building Height	Weighting (WH)	Orientation	Weighting (WO)
High	3	135–225°	3
Medium	2	90–135°, 225–270°	2
Low	1	270–90°	1

leaves oriented south were measured, excluding large veins and spots such as powdery mildew. Due to their sensitivity to environmental factors and their frequent role as stress indicators (Fotelli et al., 2000; Uhrin et al., 2018), stomatal conductance, quantum efficiency in light, and electron transport rate were selected for further analysis.

Statistical data analysis

All variables were tested for Gaussian distribution using the Shapiro-Wilk test and visually inspected with histograms and Q-Q plots. Since most of the data did not follow the Gaussian distribution, non-parametric tests were used. Differences between the two site types, including morphological and ecophysiological data, were tested with the Mann-Whitney U test. The relationships were studied among morphological, biotic, and abiotic variables by using generalized linear models (GLM). For these models, the target variable distributions were visually matched using histograms, and the appropriate distribution was chosen for each model. For variables with integer values, the Poisson distribution was used, while for variables with decimal values, the Gamma distribution was selected. The sun scald variable was converted into a binary variable that indicated the presence or absence of sun scald, rather than counting the number of cracks. The association between ecophysiological data and environmental variables was examined using linear mixed-effects models (LMM). Since multiple measurements were taken on individual trees, tree ID and calendar week were included as random effects. To meet model assumptions, the data were transformed into approximately Gaussian distributions using square root and log transformations. A Spearman correlation matrix of the predictor variables was calculated before constructing the generalized linear and linear mixed- effects models to identify variables with high correlation. Fig. 3 displays the corresponding matrix. The correlation threshold was set at 0.5. Due to collinearity, variables such as DBH, total height, crown top, distance to major roads, size, imperviousness, trees per site, and trees per m ^{2} were excluded as predictors. The residual errors of the final models were checked for a Gaussian distribution. None of the differences between observed and predicted values followed a Gaussian distribution. Results were visualized using the corrplot package in R (Wei and Simko, 2021). Variables with correlation above 0.5 were not considered further for the generalized linear or mixed- effects models (Dormann et al., 2013). Model optimization was performed with the stepAIC and step functions in R, included in the MASS package (Ripley et al., 2022). We had followed the suggestions from Zhang (2016) and Spijkers et al. (2021) for model selection during generalized linear modeling. For example, two models for each analysis were independently estimated—one chosen based on the Akaike Information Criterion (AIC) and the other based on the Bayesian Information Criterion (BIC). Subsequently, the pseudo R^2 values of both models were calculated. The model with the higher pseudo R^2 and lowest AIC or BIC values was selected for further consideration (Zhang, 2016; Spijkers et al., 2021). The pseudo- R^2 was calculated using the McFadden method, available in the pR^2 function of the pscl package (Jackman, 2020). McFadden pseudo- R^2 values between 0.2–0.4 indicate a good model fit (Henscher & Stopher, 1979). The model with the higher pR^2 was chosen as the final. Conditional and marginal pseudo- R ^{2} for the linear mixed- effects models were calculated with the r. squaredGLMM function from the MuMIn package in R (Bartoń, 2022). Results from the generalized linear and mixed- effects models were plotted using predictorEffects in the effect package in R (Fox & Weisberg, 2022). P- values for predictors in the generalized linear model were obtained using the lmerTest package in R (Kuznetsova et al., 2022). The Spearman test was used for assessing

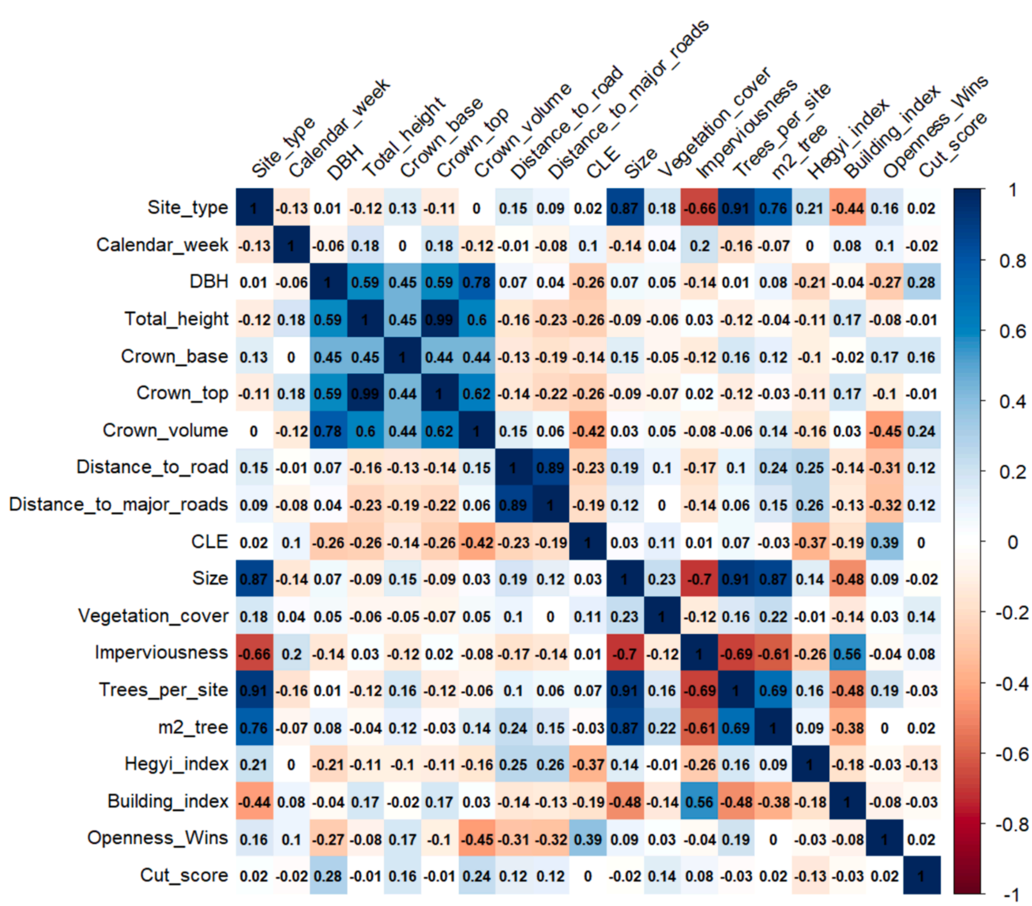

Fig. 3. Correlation matrix of predictor variables for generalized linear models and linear mixed-effects models before omitting collinear variables. CLE: crown light exposure.

significance in scatter plots. Scatter plots were visualized with ggplot 2 in R (Wickham, 2016). Residual errors were calculated by subtracting predicted values from observed ones using the predict function in R. The distribution of these residuals was tested for Gaussian distribution using the Shapiro- Wilk test.

Results

Tree dimension, morphological, and ecophysiological attributes

A total of 235 trees were recorded in the data. Of these, 114 were categorized as trees on pits and 121 as trees on strips. Hemispherical images were captured from 233 trees. Trees on pits had about 8.3 m^2 of open surface area per tree, whereas trees on strips had an average of 46.1 m^2 per tree. In pits, 98 % of trees had a crown projection area to open surface area ratio greater than 1, indicating inadequate open surface area. Conversely, in strips, 34 % of the trees had insufficient open surface area.

The results of the tree inventory are detailed in Table 5. Since many variables did not follow a Gaussian distribution, the median and standard error are listed alongside the mean and standard deviation. The canopy of Karlsruhe's urban Norway maple trees had an average volume of 178 m^3 and shaded an area of 38 m^2. The trees had approximately 0.9 m^2 of leaf area per square meter of ground. Crown openness averaged 29 %, with an estimated minimum of 0 % and a maximum of 80 %. Crown discoloration of at least 10 % was observed in 43 % of the trees, with discoloration increasing over the data collection period. For example, the average discoloration was 3.4 % in June, 5.6 % in July, and 10.1 % in August. On average, 26 % of the tree crowns were missing, and the average dieback was 8 %. Epicormic shoots were found in 29 % of the trees, with a maximum of 24 shoots on 25 % of the total tree height. Sun scalds were observed in 13 % of the trees.

Stomatal conductance averaged 0.0186 mol m^{-2} s^{-1} and was significantly higher on pits than on strips. The quantum efficiency was approximately 0.4385. The average electron transport rate was 51.12 µmol m^{-2} s^{-1}.

Influence of biotic and abiotic variables

Influence on morphological variables

Leaf area index. The best model for the leaf area index, with a pseudo-R^2 value of 0.76, included the predictor variables: site type, crown base, crown light exposure, canopy openness, and crown volume (Table 6). The leaf area index significantly increased as crown volume grew and significantly decreased with greater canopy openness (Fig. 4). Although the predictor site type was not statistically significant, it still contributed to a better model. The leaf area index in pits was slightly higher than in strips. The slope of canopy openness showed an exponential decline, flattening at an index below 1 and around 55 % openness.

Crown projection area. The GLM for the crown projection area included predictors such as crown base, crown light exposure, Hegyi index, and canopy openness. The pseudo-R^2 value was 0.05 (Table 7). All predictors were highly significant (Fig. 5). The crown base showed a positive correlation with the crown projection area. Conversely, increases in crown light exposure, Hegyi index, and canopy openness negatively affected the projected area.

Crown openness. The best model for crown openness, based on step selection from all available predictors, included even those not all of which were significant. The pseudo-R^2 value of this model was 0.07 (Table 8). Highly significant predictors included crown base, distance to the road, crown light exposure, vegetation cover, canopy openness, and cut score (Fig. 6). Crown openness increased with higher crown base height, greater distance to the road, increased canopy openness, and higher cut scores. Conversely, crown openness decreased as vegetation cover and crown light exposure grew. The results also indicated that larger crown volume significantly contributed to greater openness and that openness on pits was higher than on strips. The predictors Hegyi

Table 6
Coefficient table of the final generalized linear model for leaf area index based on the input variables site type, crown base, distance to road, crown light exposure, vegetation cover, Hegyi index, canopy openness, crown volume, and cut score.

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)	Significance level
Intercept	-0.7536	0.1555	−4.8470	<0.0001	***
Site type	0.0696	0.0467	1.4910	0.1374	
Crown base	0.0802	0.0337	2.3780	0.0182	*
Crown light exposure	0.0760	0.0327	2.3260	0.0209	*
Canopy openness	0.0225	0.0015	14.7930	<0.0001	***
Crown volume	-0.0006	0.0001	-3.7990	0.0002	***

Table 5
Tree inventory data for the total number of trees surveyed and divided into pit and strip trees. The two site types were compared using the Mann-Whitney U test. Significant results with a p-value < 0.05 are symbolized by *. SD: standard deviation and SE: standard error; CPA: crown projection area, LAI: leaf area index.

Variable		Total sample				Pit				Strip				U test
	Unit	Mean	SD	Median	SE	Mean	SD	Median	SE	Mean	SD	Median	SE	
Morphological														
Crown length	m	5.60	1.92	5.5	0.13	5.99	2.15	5.75	0.20	5.24	1.60	5.30	0.15	*
Crown volume	m^3	177.87	146.08	147.85	9.52	179.60	153.47	142.12	14.37	176.24	139.37	156.95	12.67	
CPA	m^2	38.34	23.08	33.38	1.22	37.54	22.48	33.38	1.84	39.10	23.70	33.66	1.62	
LAI	m^2/m^2	0.92	0.53	0.84	0.3	0.94	0.46	0.88	0.04	0.90	0.58	0.72	0.05	
Openness	%	28.60	16.06	25	1.04	28.90	16.71	25	1.56	28.31	15.50	25	1.41	
Discoloration	%	6.34	9.63	0	0.63	7.37	10.77	0	1.01	5.37	8.35	0	0.75	
Missing	%	25.51	13.29	20	0.87	24.12	13.07	20	1.22	26.82	13.42	25	1.22	
Dieback	%	8.36	7.92	10	0.52	8.38	8.29	10	0.77	8.35	7.59	10	0.69	
Epicormics	number	1.39	3.72	0	0.24	1.02	3.10	0	0.29	1.74	4.21	0	0.38	*
Sun scald	number	0.13	0.34	0	0.04	0.12	0.33	0	0.05	0.14	0.35	0	0.06	
Ecophysiological														
Stomatal conductance	mol m^{-2} s^{-1}	0.0186	0.0193	0.0127	0.0009	0.0204	0.0205	0.0149	0.0013	0.0166	0.0176	0.0116	0.0012	*
Quantum efficiency	%	0.4385	0.3013	0.5959	0.0134	0.4397	0.2997	0.6266	0.0194	0.4374	0.3034	0.4593	0.0280	
Electron transport rate	$\mu mol * m^{-2} * s^{-1}$	51.12	60.32	32.71	2.75	50.08	52.42	35.74	3.38	52.16	67.33	37.11	3.63	

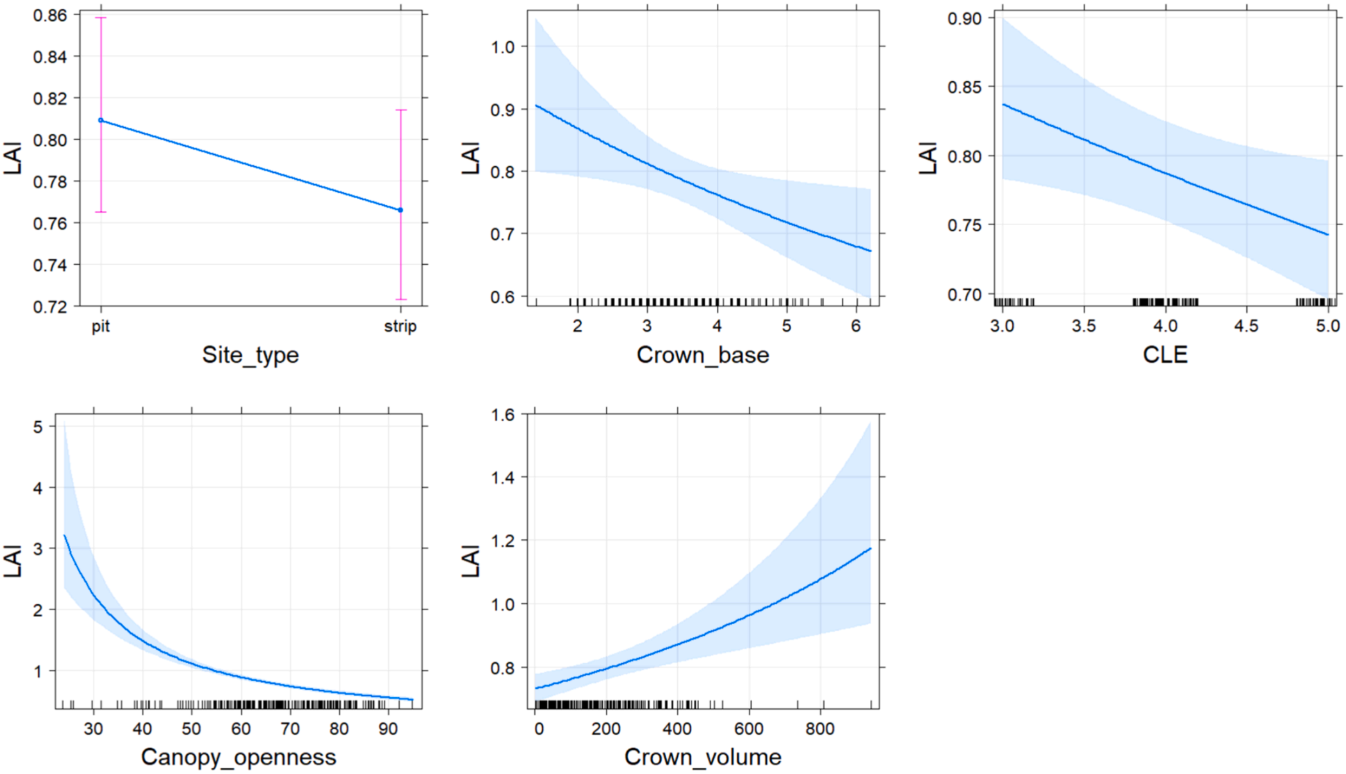

Fig. 4. Generalized linear model of leaf area index (LAI) based on site type, crown base, crown light exposure (CLE), canopy openness, and crown volume. The 95 % confidence intervals for the fitted values are shown as blue-shaded areas for numeric predictors and as pink bars for the site type predictor.

Table 7
Coefficient table of the final generalized linear model for crown projection area based on the input variables crown base, crown light exposure, Hegyi index, and canopy openness.

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)	Significance level
Intercept	-0.0028	0.0068	−0.4120	0.6810	
Crown base	-0.0051	0.0009	−5.6050	<0.0001	***
Crown light exposure	0.0065	0.0014	4.6110	<0.0001	***
Hegyi index	0.0305	0.0064	4.7940	<0.0001	***
Canopy openness	0.0003	0.0001	5.2510	<0.0001	***

index and building index were not significant.

Crown missing. The model for missing crowns was based on predictor variables such as site type, crown base, crown light exposure, vegetation cover, Hegyi index, crown volume, building index, and cut score. The pseudo-R^2 was 0.10 (Table 9). Significant factors included site type, crown base, Hegyi index, crown volume, and cut score (Fig. 7). According to the model, crowns were more likely to be missing on strips, and this likelihood increased with higher crown base, Hegyi index, and cut score. As crown volume grew, the proportion of missing crowns decreased. The building index was also a significant predictor, showing an increase in crown missing with higher index values. Most of the predictor plot slopes were approximately linear.

Dieback. The vitality variable dieback was best explained by the predictor's site type, crown base, distance to road, crown light exposure, canopy openness, and building index. The pseudo-R^2 value was 0.05 (Table 10). The predictor's distance to the road, crown light exposure, canopy openness, and building index were highly significant (Fig. 8). As the distance to the road increased, dieback also increased. The same applied to rising crown light exposure and canopy openness. In contrast, a higher building index was associated with lower dieback. Lower dieback was also observed with lower crown base height. For the two site types, higher dieback was related to pits.

Discoloration. The discoloration of leaves was best explained by factors such as the predictor's site type, calendar week, crown base, distance to the road, crown light exposure, vegetation cover, and crown volume. Because discoloration increased over time during data collection, the calendar week of each sampling was included as an additional predictor. The pseudo-R^2 value was 0.10 (Table 11). Significant predictors included calendar week, crown base, distance to the road, and crown volume (Fig. 9). Discoloration tended to increase as the calendar week advanced and decreased with a higher crown base. It also increased with greater distance from the road, larger crown volume, and more vegetation cover. Site types showed smaller discoloration on strips compared to pits. Additionally, there was a slight positive effect of crown light exposure on discoloration, where higher exposure was associated with lower discoloration.

Sun scald. The occurrence of sun scald was best predicted by the Hegyi index and crown volume. The pseudo-R^2 value was 0.09 (Table 12). Both predictors were significant (Fig. 10). As the Hegyi index increased, sun scald occurrence decreased. The same was true for increasing crown volume.

Epicormic shoots. The occurrence of epicormic shoots was explained by the predictor's site type, crown base, distance to the road, crown light exposure, vegetation cover, Hegyi index, crown volume, and building index. The value of the pseudo-R^2 was 0.19 (Table 13). A highly significant influence was exerted by distance to the road, crown light exposure, vegetation cover, Hegyi index, and crown volume (Fig. 11). Increases in distance to the road, crown light exposure, Hegyi index, and crown volume led to a decrease in epicormic shoots. A higher percentage

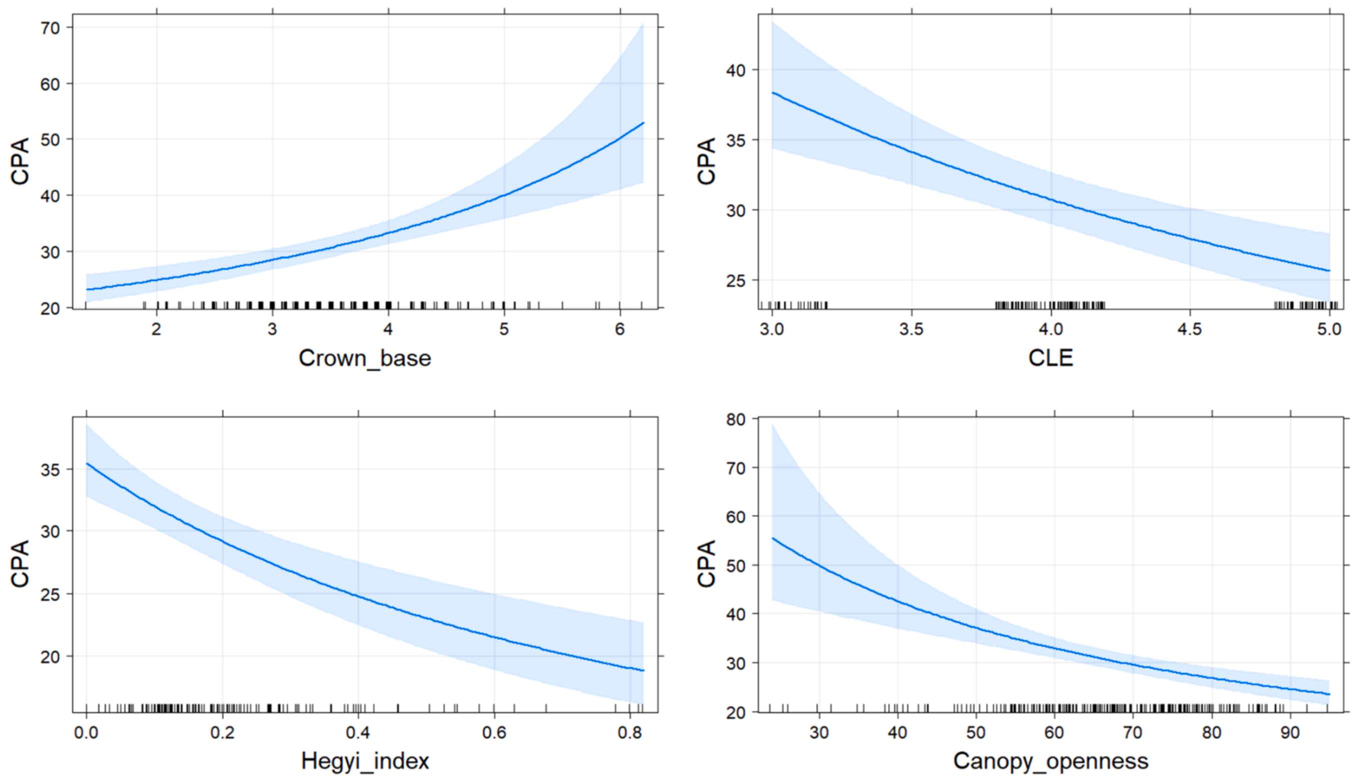

Fig. 5. Generalized linear model of crown projection area (CPA) depending on crown base, crown light exposure (CLE), Hegyi index, and canopy openness. The 95 % confidence intervals for the fitted values are shown as blue-shaded areas.

Table 8
Coefficient table of the final generalized linear model for crown openness based on the input variables site type, crown base, distance to road, crown light exposure, vegetation cover, Hegyi index, canopy openness, crown volume, building index and cut score.

Coefficients	Estimate	Std. Error	z value	Pr(>|z|)	Significance level
Intercept	2.8167	0.1318	21.3680	<0.0001	***
Site types	-0.0735	0.0286	−2.5670	0.0103	*
Crown base	0.1118	0.0173	6.4740	<0.0001	***
Distance to road	0.0112	0.0032	3.5310	0.0004	***
Crown light exposure	-0.0746	0.0225	−3.3100	0.0009	***
Vegetation cover	-0.0019	0.0004	−4.5700	<0.0001	***
Hegyi index	0.1397	0.0880	1.5880	0.1124	
Canopy openness	0.0065	0.0012	5.4420	<0.0001	***
Crown volume	0.0003	0.0001	2.8430	0.0045	**
Building index	-0.0335	0.0222	−1.5100	0.1311	
Cut score	0.0327	0.0095	3.4360	0.0006	***

of vegetation cover increased the number of epicormic shoots. A higher crown base also correlated with more epicormic branches. In contrast, as the building index increased, the number of shoots decreased. Pits had fewer epicormics compared to strips. The slopes of most numerical predictors showed a slight curvature. The slope of the distance to the road decreased exponentially. The curve flattened noticeably at a 7 m distance to the road. The canopy volume also decreased exponentially, with flattening occurring at about 300 m^3.

Influence on ecophysiological variables

Stomatal conductance. The best linear mixed-effects model for stomatal conductance included vegetation cover as a fixed effect, which measured the open surface area covered by vegetation, with tree ID and calendar week as random effects. The marginal R^2 was 0.11, and the conditional R^2 was 0.53 (Table 14). The relationship was significant (Fig. 12). As the vegetation cover of the respective pit or strip increased, stomatal conductance decreased.

Electron transport rate. The best linear mixed-effects model for electron transport rate included the predictor’s site type, crown base, crown light exposure, Hegyi index, canopy openness, and cut score as fixed effects, with calendar week as a random effect. The marginal R^2 was 0.09, and the conditional R^2 was 0.12 (Table 15). All predictors were significant (Fig. 13). The electron transport rate decreased as the Hegyi index increased. It also increased with greater canopy openness. A positive relationship was observed between the electron transport rate and crown base height. A higher cut score and increased crown light exposure reduced the electron transport rate. The electron transport rate was higher in pits.

Discussion

This study aimed to (1) evaluate specific morphological and ecophysiological variables and (2) analyze how abiotic and biotic environmental factors affect these variables in Norway maples growing in pits and strips. In bivariate comparisons, only crown length, epicormic shoots, and stomatal conductance showed significant differences between the two settings. To understand how multiple explanatory variables influence tree traits, generalized linear models and linear mixed-effects models were used. These analyses revealed that several variables had significant effects, indicating that analyzing site type alone is insufficient to explain variations in tree traits fully.

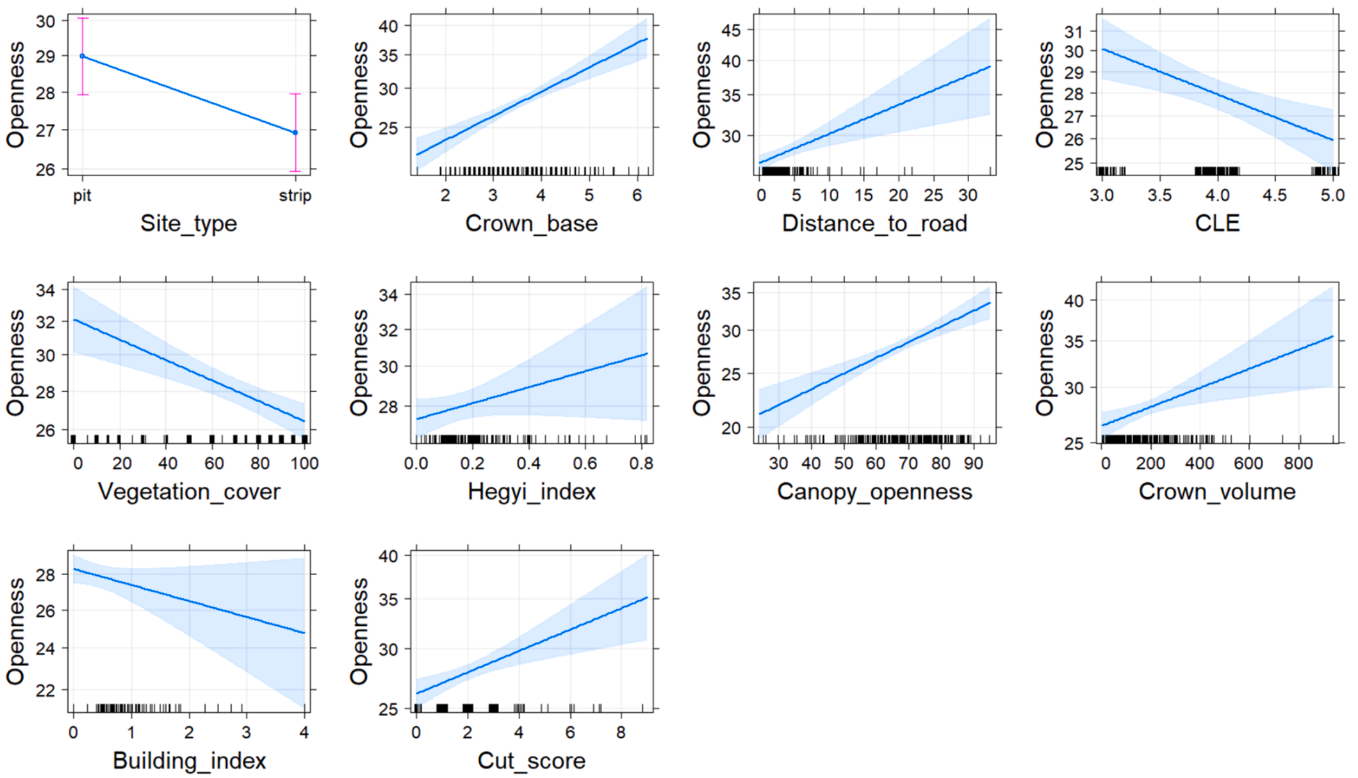

Fig. 6. Generalized linear model of crown openness based on site type, crown base, distance to road, crown light exposure (CLE), vegetation cover, Hegyi index, canopy openness, crown volume, building index, and cut score. The 95 % confidence intervals for the predicted values are displayed as blue-shaded areas for numeric predictors and as pink bars for the site type predictor.

Table 9
Coefficient table of the final generalized linear model for crown missing based on the input variables site type, crown base, distance to road, crown light exposure, vegetation cover, Hegyi index, crown volume, and cut score.

Coefficients	Estimate	Std. Error	z value	Pr(>|z|)	Significance level
Intercept	2.6115	0.1344	19.4300	<0.0001	***
Site types	0.1110	0.0297	3.7320	0.0002	***
Crown base	0.1557	0.0168	9.2890	<0.0001	***
Crown light exposure	0.0384	0.0230	1.6690	0.0952	
Vegetation cover	−0.0007	0.0005	−1.5250	0.1273	
Hegyi index	0.2936	0.0891	3.2940	0.0010	***
Crown volume	−0.0015	0.0001	−11.1760	<0.0001	***
Building index	0.0493	0.0236	2.0870	0.0369	*
Cut score	0.0477	0.0099	4.8340	<0.0001	***

Morphological attributes

Leaf area index

The leaf area index is influenced by various factors, including site quality—characterized by climate and soils—shade tolerance of the species, and the availability of nitrogen and water (Vose et al., 1994). It is not only an important indicator of stress but also vital for ecosystem services. Tree species with a higher leaf area index provide significantly greater cooling than those with a lower index (Tukiran et al., 2016). While site type alone did not significantly impact the leaf area index, it remained a significant predictor in the generalized linear model. Trees on pits tended to have a higher leaf area index despite occupying smaller open surfaces. This might be due to the increased competitive pressure from trees, annual plants, and shrubs on strips. High competition can lower the leaf area index, as seen in eucalyptus trees (Wirabuana et al., 2022). Although literature suggests urban spaces have lower competition (Rötzer et al., 2021), this study indicates a strong influence of competition. Additionally, the site type's effect on leaf area index may relate to the placement of pits and strips. About 64 % of trees on pits are within 10 m of buildings, compared to 26 % of trees on strips. These buildings are likely connected via underground drains and service pipes. Such infrastructure can cool the soil or leak moisture from water pipes, benefiting root growth. When the temperature difference between the water inside the pipe and the surrounding soil is large, pore space formation is more likely at the pipe-soil interface. If the pipe is cooler, moisture condenses around it, creating favorable conditions for roots (Coder, 1998; Randrup et al., 2001). The overall height of the crown might also explain why pits generally show a higher leaf area index than strips (Table 5), as larger crown height allows more leaf layers. More leaves per square meter of ground increase the leaf area index, which could also explain why the index rose with growing crown volume calculated from total crown length.

Crown projection area

The two primary ecosystem services provided by urban trees—-shading and cooling—are primarily defined by the size of the tree crown (Dahlhausen et al. 2016). However, crown structure is highly adaptable and varies significantly, as trees often modify the shape and size of their crowns in response to competition for light and space with neighboring trees (Jucker et al., 2015). This adaptation often results in reduced crown expansion (Thorpe et al., 2010), which is reflected in the findings. Both canopy openness and crown light exposure serve as indicators of light availability for the tree. Although Norway maples generally require high light levels (GALK e.V., 2021), the crown projection area was negatively associated with both light variables. This may be because, although light is essential for plant growth, excessive light can impair photosynthesis and growth, especially when combined with other environmental stressors (Barber and Andersson, 1992).

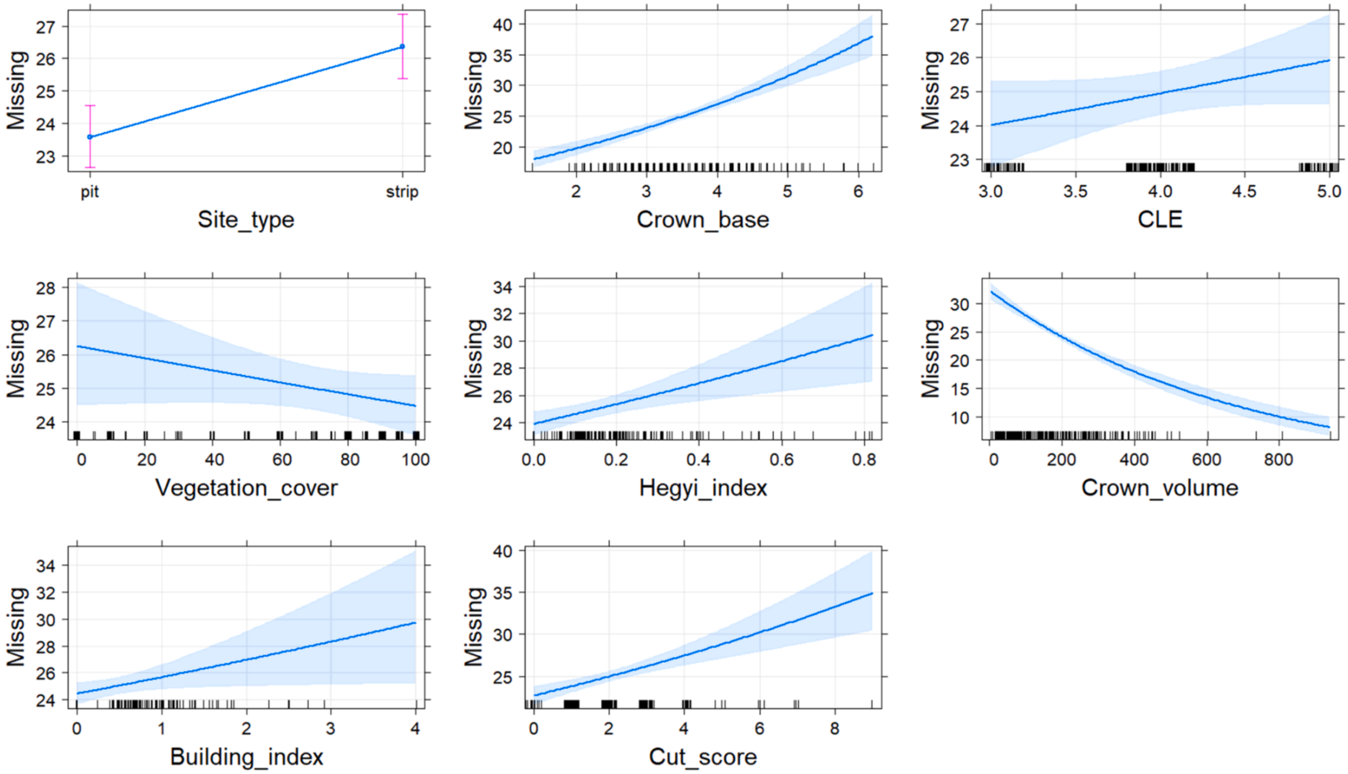

Fig. 7. Generalized linear model of crown missing based on site type, crown base, crown light exposure (CLE), vegetation cover, Hegyi index, crown volume, building index, and cut score. The 95 % confidence intervals for the fitted values are shown as blue-shaded areas for numeric predictors and as pink bars for the site type predictor.

Table 10
Coefficient table of the final generalized linear model for dieback based on the input variables site type, crown base, distance to road, crown light exposure, vegetation cover, Hegyi index, canopy openness, crown volume, and cut score.

Coefficients	Estimate	Std. Error	z value	Pr(>|z|)	Significance level
Intercept	1.0624	0.1947	5.4570	<0.0001	***
Site types	−0.1271	0.0500	−2.5430	0.0110	*
Crown base	−0.0995	0.0307	−3.2430	0.0012	**
Distance to road	0.0352	0.0045	7.8050	<0.0001	***
Crown light exposure	0.1657	0.0357	4.6410	<0.0001	***
Canopy openness	0.0108	0.0020	5.3470	<0.0001	***
Building index	−0.1494	0.0441	−3.3870	0.0007	***

Crown openness

Crown openness is a highly subjective perception, influenced by a complex interaction of many factors, as indicated by the numerous predictor variables. Notably, the effect of site type on openness showed opposite trends compared to leaf area index. Since both variables relate to the number of leaves, a similar pattern would have been expected. However, openness more heavily considers the three-dimensional distribution of leaves and serves as a qualitative measure of foliage density. These findings align with those of Lv et al. (2024b). The relationship between foliage density and other metrics varies depending on factors such as the tree's developmental stage, location, and climate. Consequently, meaningful interpretation of foliage density variations requires extensive experimental or observational data on the factors that could influence tree health in the study area (Frampton et al., 2001). For instance, based on available data, it is not possible to definitively explain why crown light exposure reduced openness—an indicator of high leaf density—despite decreasing the leaf area index. Further research is needed to clarify this.

Crown missing

The partial absence of a fully developed tree crown results from various morphological factors. Common reasons for crown gaps include pruning, defoliation, dieback, dwarfism, sparse foliage, and uneven crown development (i-Tree-eco, 2021). This issue is especially significant in densely built environments. The growth of the crown is strongly affected by the distance to structures like buildings, depending on the tree species' shade tolerance and growth habits (Franceschi et al., 2022). Buildings can also shield trees from sunlight, leading to lower temperatures in shaded areas. Cold conditions can cause ice formation in tree pits during winter, potentially resulting in basal rot and a shortened growing season (Yang et al., 2012). These factors may explain the observed increase in crown missing with higher building indices. Conversely, greater vegetation cover tends to reduce crown missing, as it lowers air temperatures through evapotranspiration (Dimoudi and Nikolopoulou, 2003) and blocks radiation from heating the soil (Snir et al., 2016). By decreasing ambient and soil temperatures, ground vegetation may impose less stress on trees over time, which correlates with less crown loss. Pruning also emerged as a highly significant factor in predicting crown missing, represented here by the cut score. During data collection, it was noted that crowns are often pruned near tram and railroad lines for safety reasons, which can lead to crown loss unrelated to tree health. Therefore, in urban areas, categorizing crown missing solely as an indicator of tree health is limited.

Dieback

Roadside maple tree dieback often results from winter road salt, over-maturity, and water stress (Ciesla & Donaubauer 1994). Additionally, the total or partial dieback of trees and branches is worsened by drought and heat waves (Allen et al. 2010). Consistent with these

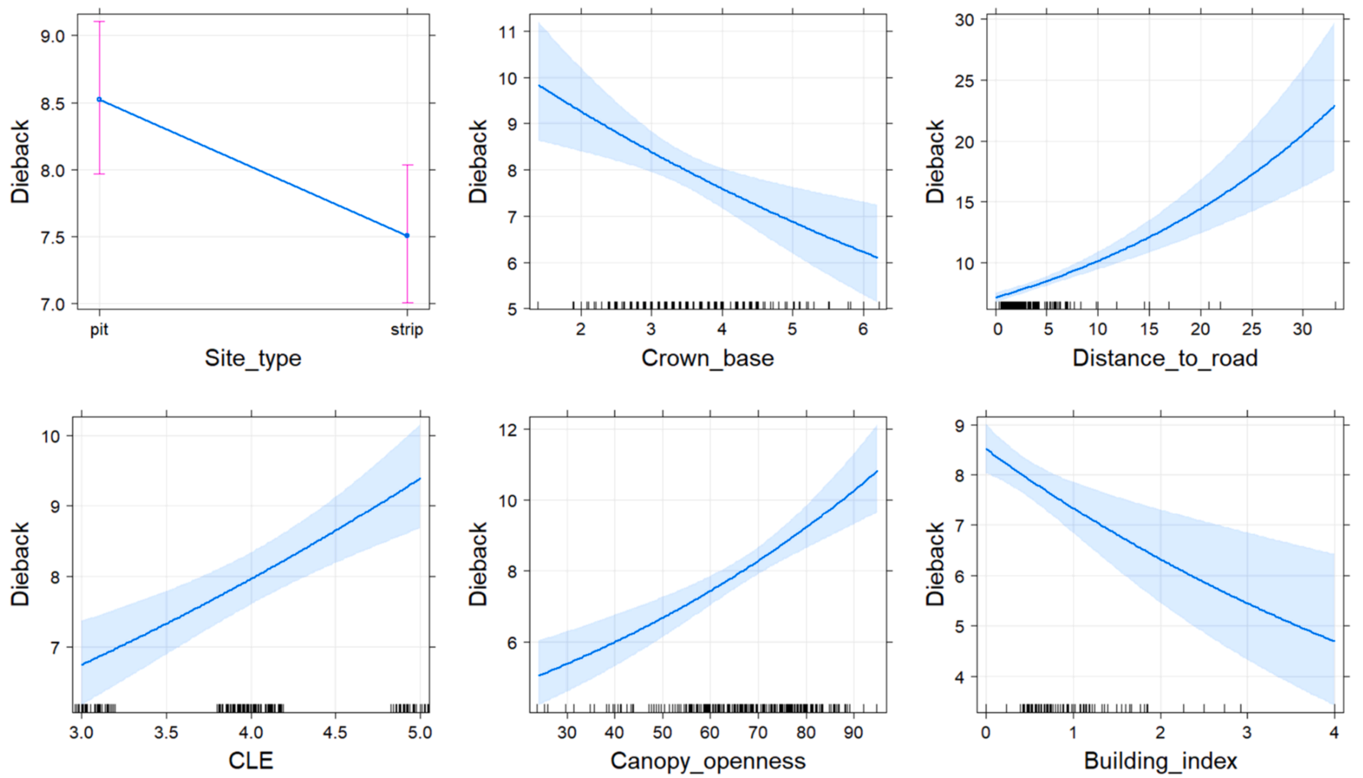

Fig. 8. Generalized linear model of dieback depending on site type, crown base, distance to road, crown light exposure (CLE), canopy openness, and building index. The 95 % confidence intervals for the fitted values are shown as blue-shaded areas for numeric predictors and as pink bars for the site type predictor.

Table 11
Coefficient table of the final generalized linear model for discoloration based on the input variables site type, calendar week, crown base, distance to road, crown light exposure, vegetation cover, Hegyi index, canopy openness, crown volume, and cut score.

Coefficients	Estimate	Std. Error	z value	Pr(>|z|)	Significance level
Intercept	−1.9341	0.3509	−5.5120	<0.0001	***
Site type	−0.1823	0.0562	−3.2410	0.0012	**
Calendar week	0.1458	0.0098	14.9480	<0.0001	***
Crown base	−0.1421	0.0353	−4.0260	0.0001	***
Distance to road	0.0267	0.0055	4.8270	<0.0001	***
Crown light exposure	−0.1018	0.0407	−2.5020	0.0124	*
Vegetation cover	0.0028	0.0009	3.1340	0.0017	**
Crown volume	0.0010	0.0002	5.6590	<0.0001	***

factors, this study also found that high sunlight exposure negatively impacted plant health, with dieback increasing significantly as light availability and open surface area grew. Another study supports this, suggesting that intense sunlight may cause heat stress and soil moisture loss (Ordóñez et al., 2018). Shading from nearby buildings can reduce heat stress and moisture loss, possibly explaining why dieback decreased when the building index was high. Although some research highlights the benefits of trees on buildings (Akbari, 2002; McPherson & Simpson, 2003; Lindal & Hartig, 2015), few studies confirm the positive influence of buildings on urban trees. Roads affect surrounding vegetation through construction disturbance and air quality decline from traffic, which leads to dust deposits and changes in leaf properties (Battipaglia et al., 2010; Joshi & Swami, 2007; Pourkhabbaz et al., 2010). Urban tree pruning practices might explain the observed increase in dieback with distance from roads. For instance, dead branches near roads are often removed to protect vehicles and pedestrians, meaning trees close to roads may experience more dieback—though this is not always evident due to regular pruning.

Discoloration

Discoloration can indicate leaf damage caused by pathogens, pollution, insect infestations, nutrient deficiencies, diseases, or natural events like senescence (United States Department of Agriculture, 2010). Due to its typical white, flour-like coating, powdery mildew is often identified as the leading cause of discoloration during fieldwork. For very heavy infestations, the fungus needs warm and dry conditions (Schneidewind, 2005).

Since the summer of 2022 was among the warmest and driest on record (Deutscher Wetterdienst, 2022), growing conditions favored the fungus. A key indicator that drought and heat periods promoted the fungus's emergence was the notable increase in leaf discoloration over the summer, as shown by the calendar week predictor. Although the disease is usually less damaging in mature trees, a powdery mildew infection covering more than 50 % of the leaf surface can significantly shorten the lifespan of the affected leaves (Hajji et al. 2009). Discoloration decreased as crown light exposure increased. This finding is supported by experiments on powdery mildew in grapes exposed to sunlight, which showed that sunlight can inhibit the fungus's development. This effect is partly due to UV radiation damaging the spores and the fungal structures (Austin & Wilcox, 2012). Poor soils and drought make trees more vulnerable to pests and diseases, which may also appear as discoloration or dieback (United States Department of Agriculture, 2010). Because of the smaller exposed surface area, both stress factors are likely more intense in pits.

Sun scald

Rapid temperature changes within tree bark, driven by intense solar radiation during the day and quick cooling after sunset, can cause sun scald (Yang et al., 2012). In Norway maples, sun scald is also frequently a response to water stress (Roppolo & Miller, 2001). This study supports

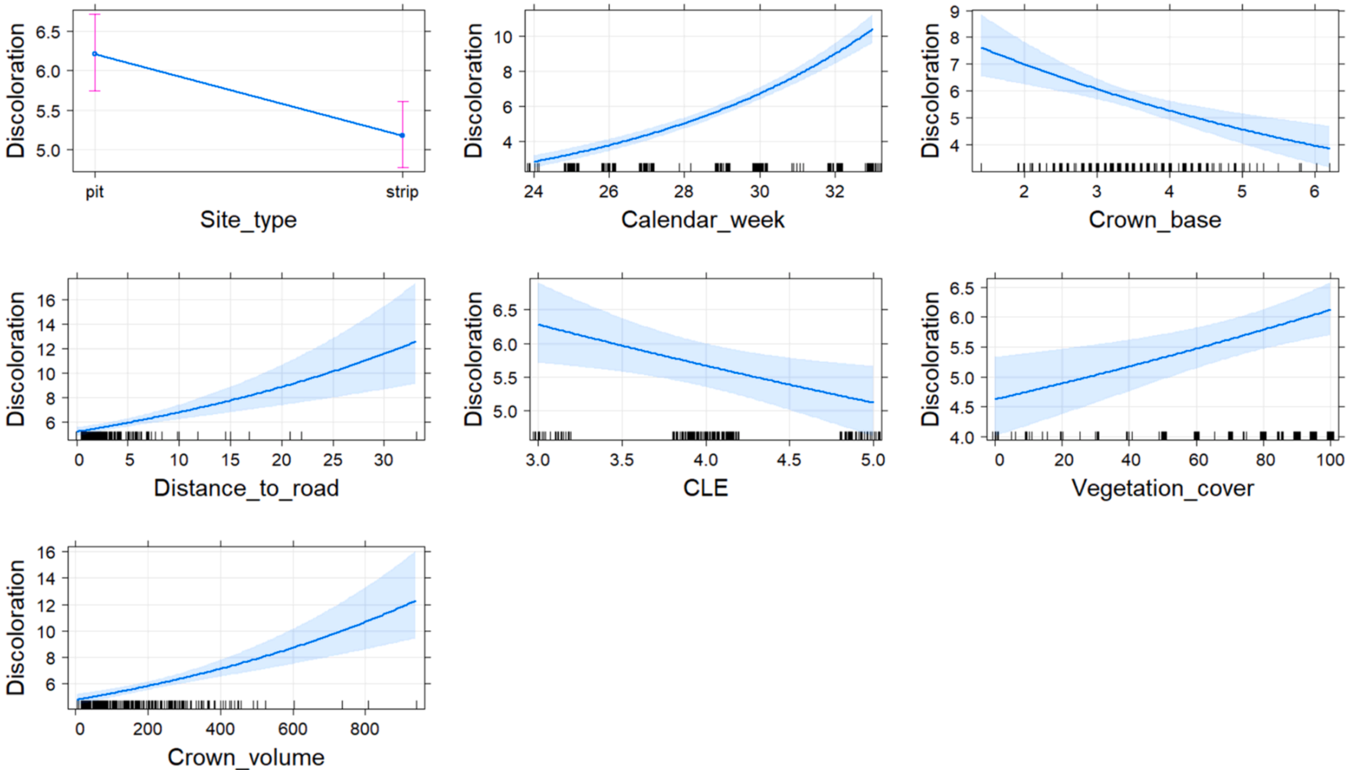

Fig. 9. Generalized linear model of discoloration depending on site type, calendar week, crown base, distance to road, crown light exposure (CLE), vegetation cover, and crown volume. The 95 % confidence intervals for the fitted values are shown as blue-shaded areas for numeric predictors and as pink bars for the site type predictor.

Table 12
Coefficient table of the final generalized linear model for the occurrence of sun scald based on the input variables site type, crown base, distance to road, crown light exposure, vegetation cover, Hegyi index, canopy openness, crown volume, and cut score.

Coefficients	Estimate	Std. Error	z value	Pr(>|z|)	Significance level
Intercept	−0.4874	0.3806	−1.2810	0.2003	
Hegyi index	−3.3018	1.5518	−2.1280	0.0334	*
Crown volume	−0.0069	0.0022	−3.0820	0.0021	**

these factors by demonstrating that reducing radiation can diminish sun scald. Indicators like the Heygi index and crown volume reflect shading levels. Generally, more nearby trees imply greater shading of the trunk by competitors, and a larger tree canopy can block incident radiation. Such shading prevents excessive heating of the bark, thereby reducing temperature fluctuations between day and night.

Epicormic shoots

Epicormic shoots are often used as indicators of stress in trees (Leers et al., 2018). According to Meier et al. (2012), these shoots may form as a response to a physiological imbalance in the canopy, signaling a need to increase leaf area for better survival or resource uptake. This study confirmed that large crowns typically do not produce such shoots, as no epicormic branches were observed in Norway maples with substantial crown volumes. The roles of light exposure and pruning date are also frequently considered as potential causes for epicormic shoot development (McDonald & Ritchie, 1994; Selby et al., 2005; Gordon et al., 2006). However, no correlation was found with higher crown light exposure; it did not promote shoot formation. Colin et al. (2008), studying sessile oaks in planted forests, proposed that increased competition reduces light on the stems, leading to fewer epicormic shoots. This hypothesis is supported by the observed decrease in shoots with higher Hegyi index values in this study. Additionally, only the number of cuts was recorded; data on the timing of cuts or whether pruning influenced shoot behavior are lacking. Another complicating factor is potential tree management, as some shoots might have been removed for aesthetic reasons, making it harder to analyze the true causes of epicormic shoot formation.

Ecophysiological attributes

Stomatal conductance

Stomatal conductance is affected by various environmental factors, leaf age, and canopy position (Moradi et al., 2017). Controlling stomatal aperture, and thus conductance, is a key plant response to water deficit and drought tolerance (Schulze, 2019). Although Norway maples are considered drought-resistant (Roloff et al., 2009; Sjöman et al., 2015), drought combined with heat stress can negatively impact their survival (Carón et al., 2015). The Mann-Whitney U test revealed a significant difference in stomatal conductance between the two site types. Typically, stomatal conductance decreases during drought (Schulze, 2019), but it was notably higher in pits, likely due to high temperatures during the survey. Some well-watered species close stomata during heat waves, while drought-stressed species may keep stomata open to cool leaves through evaporation (Urban et al., 2017; Marchin et al., 2022), highlighting a trade-off between cooling and vulnerability to damage like xylem embolism (Lahr et al., 2018). Since pits had a higher proportion of impervious surfaces, they probably experience greater thermal load. The increased conductance in pits may be a response to higher heat stress, potentially an adaptation to urban heat, allowing leaves to avoid overheating while balancing water conservation by stomatal closure during drought. The trees in more sealed sites maintained their conductance under combined heat and water stress, possibly reflecting better drought

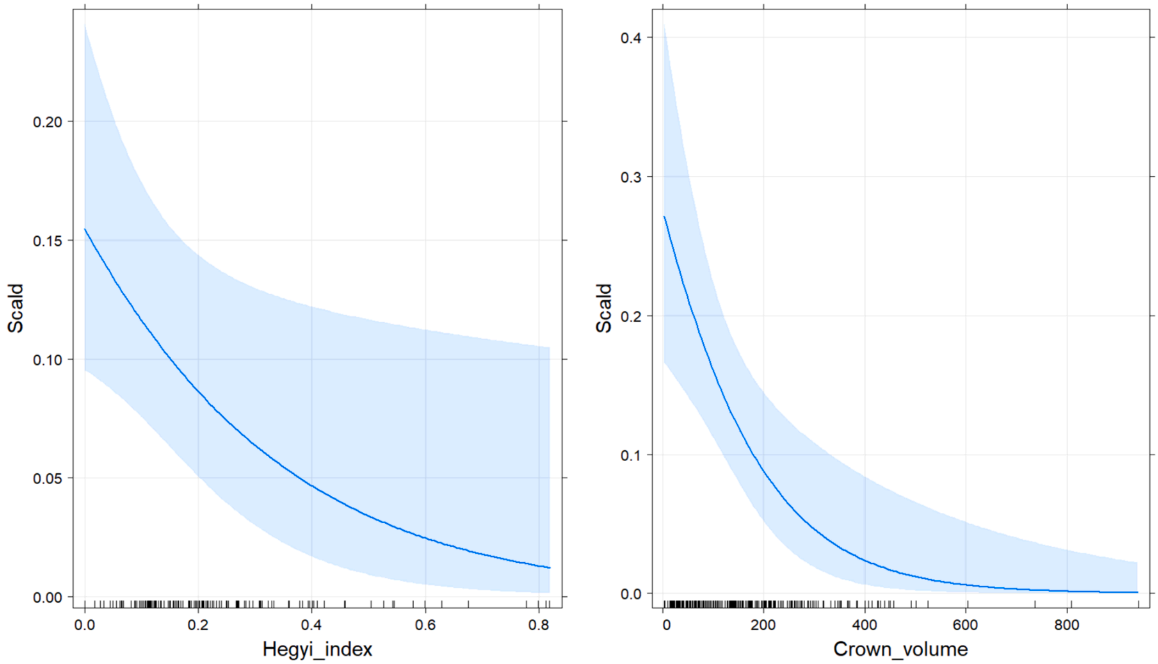

Fig. 10. Generalized linear model of sun scald based on Hegyi index and crown volume. The 95 % confidence intervals for the fitted values are shown as blue-shaded areas.

Table 13
Coefficient table of the final generalized linear model for epicormic shoots based on the input variables site type, crown base, distance to road, crown light exposure, vegetation cover, Hegyi index, canopy openness, crown volume, and cut score.

Coefficients	Estimate	Std. Error	z value	Pr(>|z|)	Significance level
Intercept	2.4051	0.6384	3.7670	0.0002	***
Site type	0.3353	0.1405	2.3860	0.0170	*
Crown base	0.2006	0.0707	2.8360	0.0046	**
Distance to road	−0.3002	0.0440	−6.8150	<0.0001	***
Crown light exposure	−0.3809	0.1102	−3.4560	0.0005	***
Vegetation cover	0.0080	0.0024	3.3410	0.0008	***
Hegyi index	−2.2565	0.4801	−4.7000	<0.0001	***
Crown volume	−0.0065	0.0007	−8.7170	<0.0001	***
Building index	−0.3641	0.1312	−2.7760	0.0055	**

adaptation than heat resistance. However, Montague and Kjelgren (2004) observed that Norway maples reduced stomatal conductance over impervious surfaces to limit water loss, and Kjelgren and Montague (1998) found no conductance difference between asphalt and turf surfaces. Literature on the combined effects of urban heat and drought on Norway maples' ecophysiology is limited, necessitating further research to understand this interaction. The linear mixed-effects model showed that as vegetation cover increased, conductance decreased, possibly due to reduced albedo and increased solar absorption, leading to lower heat stress and less evaporation. Conversely, higher vegetation cover might also restrict soil water, causing stomata to close to conserve moisture. Therefore, the decline in conductance could result from the cooling effects of vegetation or increased water deficits due to competition. The comparison between pits and strips supports the idea that vegetation cooling reduces conductance, but controlled studies are needed to clarify this relationship.

Electron transport rate

The electron transport rate, a key component of photosynthesis, measures the linear flow of electrons through photosystem I and II (Schulze, 2019). A lower rate indicates reduced photosynthetic efficiency and is helpful in assessing urban tree performance (Uhrin et al., 2018). In this study, the rate increased with greater light availability, such as increased canopy openness, but declined under very high light exposure. This aligns with literature showing that electron transport rises with light until photoinhibition occurs at excessive levels (Kothari et al., 2021). Sun leaves exhibit significantly higher electron transport rates than shade leaves (Schulze, 2019), a pattern reflected in the Hegyi index and crown base data. As noted in Section 4.1.1, a higher crown base correlates with a larger crown radius, making the canopy less likely to be shaded by upper crown parts. Nearby trees can also cause shading, lowering electron transport rates. The study also found a negative link between cutting intensity and the electron transport rate. Pruning timing affects photosynthesis: leaves transitioning from shade to light need time to adapt (Yu et al. 2014), and high temperatures can impair damaged leaves' recovery (Murchie & Niyogi, 2011). The combination of pruning timing and high temperatures might explain this negative correlation, though precise conclusions are limited due to the unknown timing of pruning. Pits exhibited higher electron transport rates than strips, consistent with another study showing that 30 min of obscuration increased electron transport in urban trees more than in park trees (Uhrin et al., 2018). The higher rate in pits may result from elevated root zone temperatures due to less open surface area and higher imperviousness. A study on maize seedlings indicated that root zone temperatures up to 30 °C promote electron transport (Xia et al., 2021). Conversely, higher soil temperatures in urban trees generally harm tree health (Tubby & Webber, 2010; Czaja et al., 2020). More research is needed to clarify the factors influencing this variable, which aligns with the conclusions of Uhrin et al. (2018).

Methodological comments and limitations

Challenges arose with the variable sun scald. It was often difficult in the field to clearly identify whether trunk injuries were caused by frost, heat, or other mechanical factors. Additionally, sun damage was only observable in 31 trees, and this small sample size may limit the significance of the findings. Another limitation was the lack of information

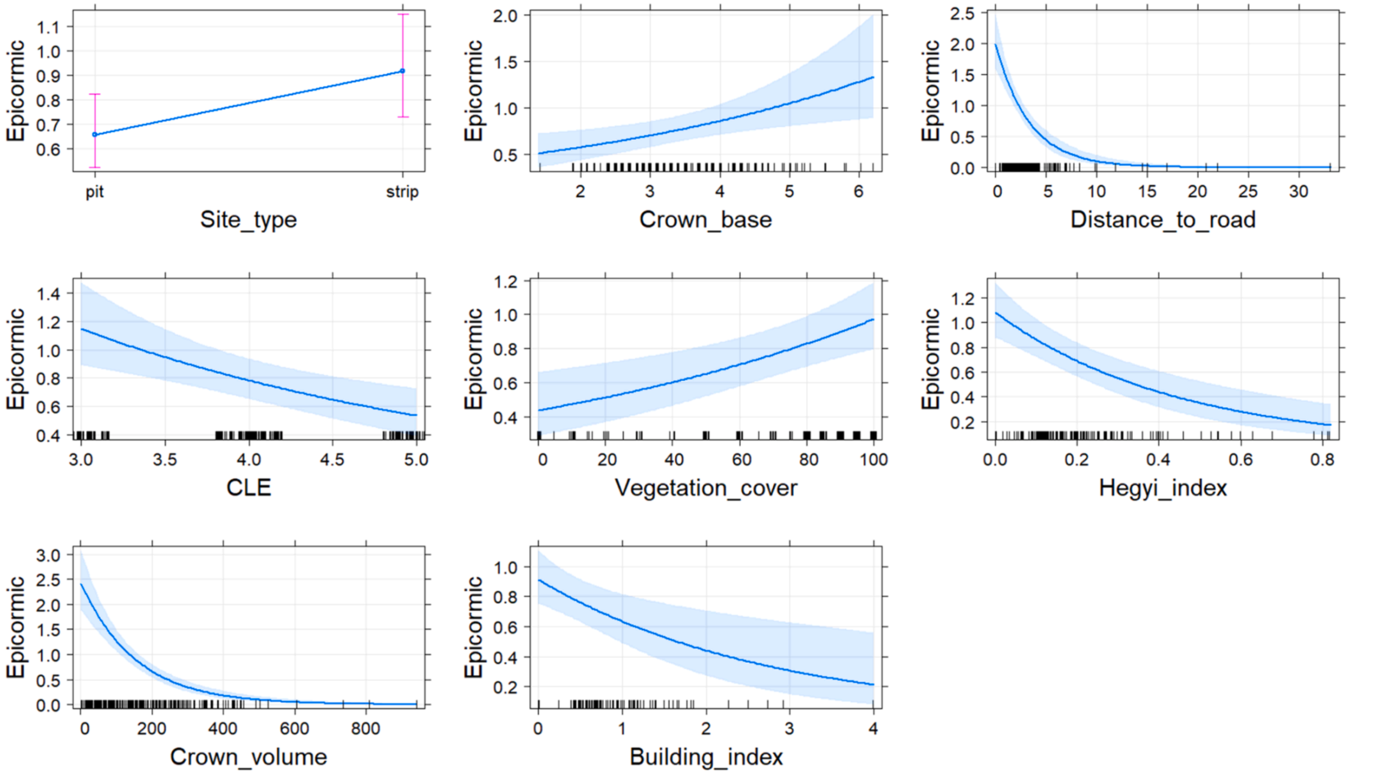

Fig. 11. Generalized linear model of epicormic shoots based on site type, crown base, distance to road, crown light exposure (CLE), vegetation cover, Hegyi index, crown volume, and building index. The 95 % confidence intervals for the predicted values are shown as blue-shaded areas for numeric predictors and as pink bars for the site type predictor.

Table 14
Coefficient table of final linear mixed-effects model for square root transformed stomatal conductance based on the input variables site type, crown base, distance to road, crown light exposure, vegetation cover, Hegyi index, canopy openness, crown volume, and cut score. The tree ID and calendar week were set as initial random effects.

Coefficients	Estimate	Std. Error	df	*t*-value	Pr(>|t|)	Significance level
Intercept	0.1729	0.0266	8.6978	6.4930	0.0001	***
Vegetation cover	−0.0008	0.0003	17.7831	−3.0730	0.0066	**

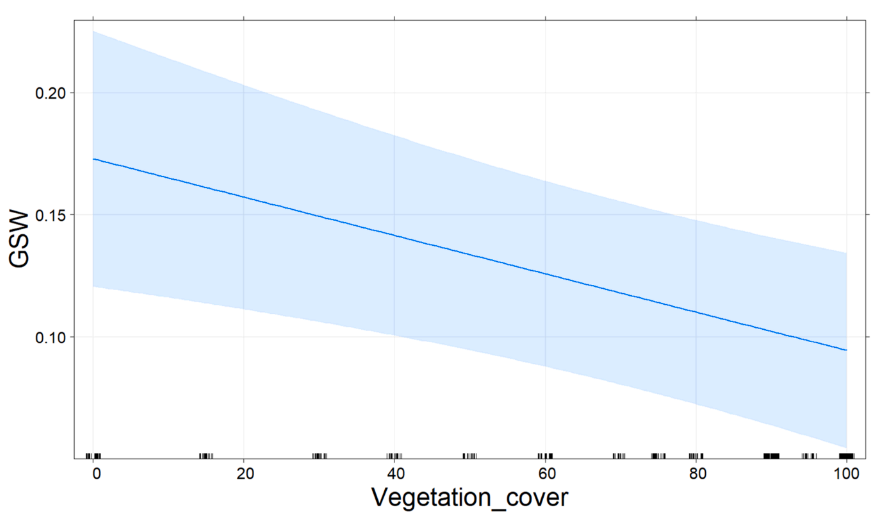

Fig. 12. Linear mixed-effects model of square root transformed stomatal conductance (GSW) as a function of vegetation cover as a fixed effect. The 95 % confidence interval for the fitted values is shown as a blue-shaded area.

Table 15
Coefficient table of final linear mixed-effects model for log-transformed electron transport rate based on the input variables site type, crown base, distance to road, crown light exposure, vegetation cover, Hegyi index, canopy openness, crown volume, and cut score. The tree ID and calendar week were set as initial random effects.

Coefficients	Estimate	Std. Error	df	*t*-value	Pr(>|t|)	Significance level
Intercept	3.3659	0.5305	292.7764	6.3450	<0.0001	***
Site type	−0.2619	0.1187	473.0010	−2.2060	0.0279	*
Crown base	0.1501	0.0678	473.0228	2.2130	0.0274	*
Crown light exposure	−0.2356	0.0858	473.0019	−2.7470	0.0063	**
Hegyi index	−1.2565	0.2739	473.0017	−4.5870	<0.0001	***
Canopy openness	0.0176	0.0045	473.0021	3.9470	0.0001	***
Cut score	−0.0802	0.0382	473.0024	−2.0960	0.0366	*

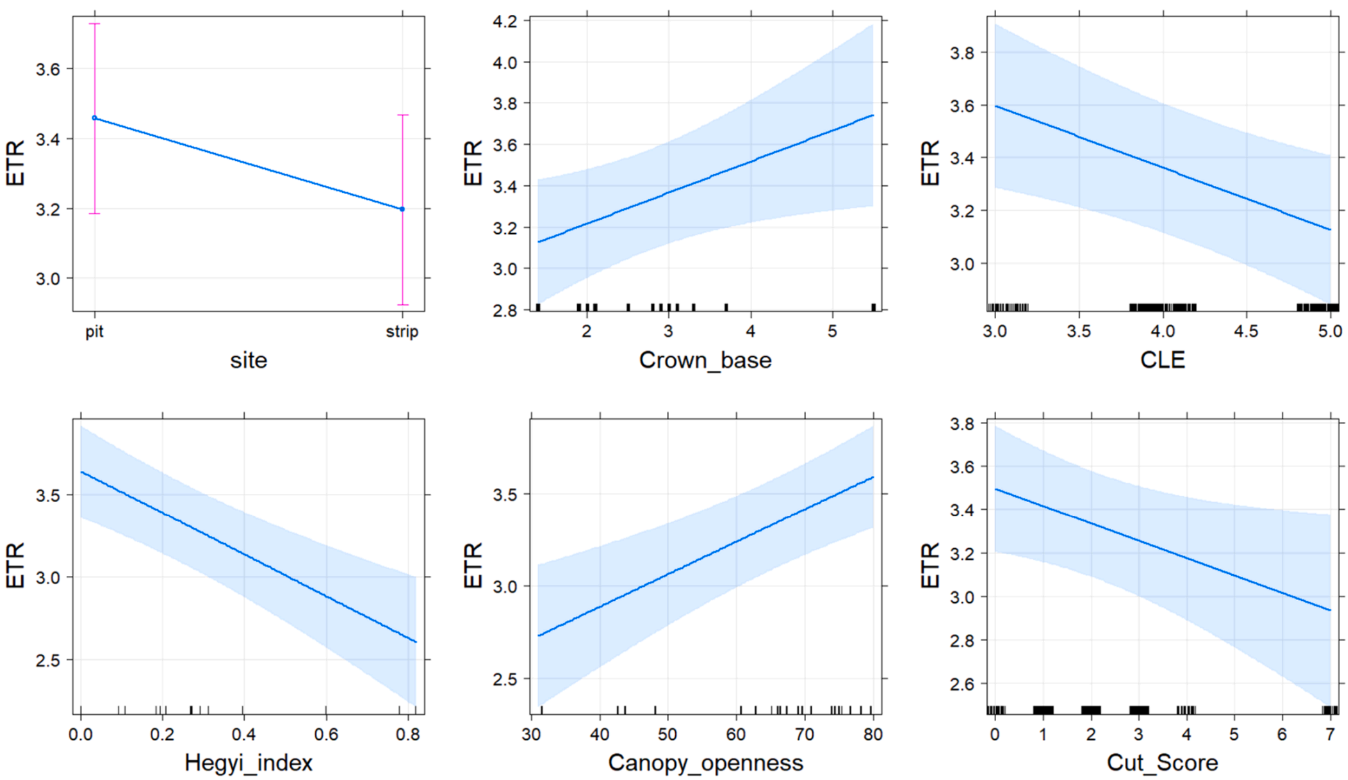

Fig. 13. Linear mixed-effects models of log-transformed electron transport rate (ETR) depending on site type, crown base, crown light exposure (CLE), Hegyi index, canopy openness, and cut score. The 95 % confidence intervals for the fitted values are shown as blue-shaded areas and pink bars for the site type predictor.

about the soil in the tree pits and strips. As a result, conclusions about nutrient or water availability and their possible effects could not be made. It was also not feasible to determine the root depth and volume due to time and technical constraints. While ground-penetrating radar could have been used to measure root volume nondestructively, access to this technology was unavailable. Despite these limitations, the study offers a valuable foundation and motivation for further research. A key knowledge gap remains in understanding the soil's influence on the studied tree variables. Future studies should include soil analysis to assess nutrient levels, contaminants, and water content in pits and strips, and examine their impact along with abiotic and biotic factors. Investigating the relationship between soil moisture at specific depths and the presence of water pipes would be particularly insightful. Besides such access to water or increased soil moisture, proximity to buildings might create a different microclimate—potentially extending growing seasons through radiant heat or offering shade depending on the aspect. We addressed light availability as much as possible in this study. Our calculated canopy openness is not based solely on a single measurement; it also considers annual variations in sunlight and the sun's position from east to west, using the modeled output from WinSCANOPY software from Regent Inc., Montreal (https://www.regentinstruments.com/assets/winscanopy_about.html). For each tree, we used GPS data to determine the Earth's declination relative to the sun on the day the hemispherical photo was taken with the WinSCANOPY camera system, as the software required this data. WinSCANOPY provided data on photosynthetically active photon flux density and canopy openness, and we favored canopy openness because it explained more variation in the data. Additionally, we developed a novel building index as a competition index based on built structures to assess whether this index could explain variations in response variables. This approach proved to be helpful in this context. We also employed the traditional and easy-to-measure Crown Light Exposure variable from i-tree-eco to qualitatively estimate the light near a building. However, we could not measure any detailed changes in soil water availability, relative humidity, air temperature, and nutrient levels, as this would require continuous monitoring with sensors for at least one to two years or more. We recommend that future research include such measurements and discuss this point. Additionally, at the species level, research on *Acer platanoides* under controlled drought and heat conditions is necessary to better understand how ecophysiological variables, like stomatal conductance, respond to heat and drought stress, with clear practical applications for managing Norway maple trees in urban environments.

Conclusion

This study revealed clear links between indices of tree vitality and environmental as well as morphological and ecophysiological factors. Some factors negatively impacted on certain tree variables, while the same factors positively influenced others. For example, increased crown light exposure raised the percentage of dead branches but decreased leaf discoloration. Vegetation cover helped prevent soil drying and warming but also competed for nutrients and water. Shading from buildings hindered tree growth but offered protection from excessive sunlight. The findings highlight the complexity of interactions, showing that focusing only on-site factors like pits or strips is insufficient to explain variations in tree characteristics. Those findings also suggest trade-offs between ecosystem services; for instance, wide crowns tend to reduce the leaf area index and cooling effect under the tree, yet they provide more extensive shading. Urban tree management must therefore weigh whether dense canopies with higher cooling or spreading canopies with larger shaded areas are better for climate adaptation. Further research is essential to clarify how specific predictors relate to response variables. Overall, this study enhances understanding of how urban factors affect tree performance and supports efforts to maintain healthy urban forests.

Data availability

Data can be made available upon request from the corresponding author.

CRediT authorship contribution statement

Tamalika Chakraborty: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation. **Diana Kramer:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ferdinand Betting:** Writing – review & editing, Methodology, Investigation, Data curation. **Somidh Saha:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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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