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Original article

Phenological effects of artificial light at night on urban trees: A case study on microclimate and light pollution

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ABSTRACT

Artificial light at night (ALAN) is a pervasive but understudied stressor for urban trees, significantly affecting their phenology. The study investigates the impact of ALAN on autumn leaf colouring (LC10 % and LC100 %) in *Acer pseudoplatanus, Acer platanoides*, and *Betula pendula* in urban settings during 2016 and 2023. Using Linear Mixed Models, we analyzed phenological timing in illuminated (L) *versus* non-illuminated (N) crown parts, considering meteorological factors. Our results show that ALAN significantly delays the initial leaf colouring (LC10 %), suggesting an extension of the growing season. However, this effect did not significantly vary across species or crown parts, indicating a broad initial sensitivity. For complete leaf colouring (LC100 %), ALAN's direct influence diminished, with meteorological conditions emerging as primary drivers. Both species-specific traits and microclimatic differences within the crown consistently proved highly significant for both phenophases, highlighting inherent variability. Crucially, although ALAN's overall effect on species-specific senescence timing was not statistically distinct, species that naturally senesce later (e.g., *Betula pendula*) experienced disproportionately greater ALAN-induced delays in LC100 %. This strong positive correlation between natural senescence onset and ALAN-induced delay for complete leaf colouring underscores a critical vulnerability for late-season species. These findings emphasise the complex interplay between ALAN, meteorological factors, and species-specific responses in urban tree phenology. Understanding these dynamics is vital for sustainable urban trees management, guiding species selection and lighting design to mitigate negative impacts on tree health and urban ecosystem services.

1. Introduction

The escalating impacts of climate change and urbanisation are fundamentally altering urban ecosystems, making a comprehensive understanding of how urban trees respond to various environmental stressors. These phenomena are described in more detail in several papers, e.g. Ordóñez & Duinker (2014), Brelsford et al. (2019), Wohlfahrt et al. (2019), Lukasová et al. (2021), Středová et al. (2021), Halecki et al., (2023), Yan et al. (2023), Yang et al. (2023) and Lehnert et al. (2024). While rising temperatures and drought have long been recognised as challenges, the pervasive influence of artificial light at night (ALAN) has emerged as a significant anthropogenic factor impacting urban vegetation. These combined pressures create novel microclimatic conditions for tree species, with profound implications for urban green infrastructure (Haase and Hellwig, 2022).

ALAN is increasingly recognised as a global environmental pollutant (Falchi et al., 2016), that disturbs natural biological systems, including nocturnal pollination networks, natural photoperiods, and the phenological processes of woody plants (Bennie et al., 2016; Smith, 2020; Lian et al., 2021). Its spatial extent and intensity in urban areas need to be understood in terms of ecological consequences within urban ecosystems (Murphy et al., 2022; Wei et al., 2023). Consequently, cities worldwide are exploring measures, such as the use of decision on trees structure in urban lighting projects (Tastan et al., 2023) and quantifying

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light burdens (Hao et al., 2023; Lo Piccolo et al. 2023), to mitigate light pollution and its effects on the urban environment.

Research into ALAN's effects on trees is diverse, examining impacts on their physiological parameters like sugar content (Czaja & Kołton, 2022), chlorophyll metabolism and carotenoid levels (Chi et al., 2022; Lo Piccolo et al., 2021), and visible changes in leaf colouration and abscission (Massetti, 2018). Conversly, some studies suggest a positive effect of ALAN on the reproductive success of tropical urban trees, potentially due to increased photosynthate production and delayed leaf senescence (Dzul-Cauich and Munguía-Rosas, 2022). Recent work, such as Lo Piccolo et al. (2024), also focuses on the dynamic growth responses of trees to LED nighttime illumination, prompting considerations for selecting species more resilient or responsive to artificial light to minimise negative ecological outcomes (Singhal et al., 2019; 2021). This issue is discussed in more detail in the review study by Friulla and Varone (2025).

Leaf phenology, particularly in temperate regions, serves as a highly sensitive bioindicator of ongoing climate change, responding acutely to temperature fluctuations. While temperature is a primary driver of spring phenophases (Wang et al., 2014; Jochner and Menzel, 2015; Güsewell et al., 2017; Fu et al., 2019; Li et al., 2019; Liu and Zhang, 2020), the influence of ALAN on these processes is gaining recognition (French-Constant et al., 2016; Li et al., 2021; Zheng et al., 2021). Historical accounts, such as Matzke (1936)'s observations in New York City, first documented the impact of nighttime artificial lighting on autumnal leaf colouring and abscission. More contemporary studies (Škvareninová et al., 2017; Massetti et al., 2020; Massetti et al., 2019; Du et al., 2022) continue to explore how varied light pollution conditions influence autumn phenophases, despite the added complexity of temperature effects and other factors like frost and drought (Estrella & Menzel, 2006; Gallinat et al., 2015; Estiarte & Peñuelas, 2015).

Although less studied than spring phenology, autumn phenology is equally important, affecting the length of the growing season and the reproductive cycles of trees (Donnelly et al., 2018). Furthermore, photoperiod emerges as another critical factor influencing temperature-related changes and the growing season, even in urban environments (Lang et al., 2019; Czaja and Kołton, 2022). In temperate and boreal regions, photoperiod, alongside temperature, serves as a stable signal for seasonal plant responses (Basler and Körner, 2012). While photoperiod can constrain responses to warming by setting thresholds for species-specific cues, its role in the cessation of autumn activity and the onset of dormancy, though present, is not typically the dominant trigger (Delpierre et al., 2016).

Changes in phenology, such as delayed senescence, timing demonstrated species-specific responses, often compounded by other urban stressors like heat and drought. Despite an increased interest, knowledge gaps remain concerning the species-specific responses and the effects of light spectra as well as the long-term consequences on three physiological aspects (Friulla and Varone, 2025). Therefore, the aim of our research was to analyse the effect of ALAN on the autumn phenophase in individual parts of the crown of selected tree species. We intended on proving that the tree crown creates its own ALAN microclimate. We also focused on the influence of other factors (drought, heat and photoperiod), which are not negligible in this period.

2. Material and methods

2.1. Study area and tree selection

The study was conducted in the city of Zvolen, Slovakia (Central Europe), specifically from 2016 to 2023. Zvolen is situated at an elevation of 293 m a.s.l. (48°34′42″N 19°07′24″E). The region is characterised by a warm, slightly moist climate, with a valley climate prone to frequent temperature inversions (Střelcová, 2013). The average annual precipitation is 703 mm (Lapin et al., 2002). The monitored zone within the city, including the locations of the monitored trees and the meteorological station, is depicted in Fig. 1.

Phenological monitoring was focused on three common urban tree species which most often occur in plantings due to the city's basin location and urban heat island conditions: Sycamore maple (*Acer pseudoplatanus* L.), Norway maple (*Acer platanoides* L.), and Silver birch (*Betula pendula* Roth.). All species are naturally distributed in Central Europe and are widely used in urban greenery. Eight individuals of each species were selected for observation. All monitored trees were approximately 40 years old and located in alley plantings along urban sidewalks or roads, directly exposed to artificial nighttime lighting. Before the start of observations, basic characteristics such as DBH (in cm) and total height (in m) were recorded for each tree (Table S1).

2.2. Light pollution assessment

Two types of streetlamps were installed within the designated monitoring area. Both lamps feature LED technology and were equipped with a round luminaire shield combined with a cylindrical glass luminaire enclosure. Each light source is specified to operate at a colour temperature of 4000 K.

Light pollution levels were quantified by measuring Night Sky Brightness (NSB) using a Sky Quality Meter (SQM), manufactured by Unihedron, Canada. Continuous NSB measurements were conducted at 10-minute intervals at a reference meteorological station (MS in Fig. 1), where a statically mounted SQM-LU-DL device was used. Simultaneously, NSB was also manually measured at six specific sites where the monitored trees were located, using a portable handheld SQM device. The visual context of these measurements and the spatial distribution of light intensity around a representative tree (APS 1) are shown in Fig. 2. The instruments measure in units of magnitudes per square arcsecond (mag/arcsec^2), and these values were subsequently converted to millicandelas per square meter (mcd/m^2) for analysis.

2.3. Measurement protocol for light intensity

Mobile measurements were performed at four specific points around the perimeter of each studied tree at a height of 1.5 m (Fig. 3). These points were strategically located: Point A was positioned in the illuminated part (L) of the crown, along the main axis intersecting the tree crown below the streetlamp. Point B was in the opposite, non-illuminated part (N) of the crown, along the same main axis. Two additional points, C and D, were measured at the edges of the crown along a secondary axis perpendicular to the main one. All measurements were strictly conducted during astronomical night, ensuring both the Moon and the Sun were sufficiently below the horizon to minimize natural light interference.

2.4. Phenological observations

The autumn phenophase of leaf colouring was chosen for observation due to its significance as an indicator of the cessation of physiological activity in trees and its sensitivity to changes induced by artificial light, temperature, and photoperiodism.

Phenological monitoring followed the methodology of the Slovak Meteorological Institute (Braslavská-Kamenský, 1996), which corresponds to the numerical codes of the international BBCH scale (Meier, 1997), widely used across European phenological station networks. Observations for each tree were recorded separately for two different crown parts (Fig. 4):

- Illuminated part (L): The section of the crown directly exposed to artificial nighttime light.
- Non-illuminated part (N): The section of the crown not directly exposed to artificial nighttime light.

A more detailed analysis was carried out for two specific stages of the

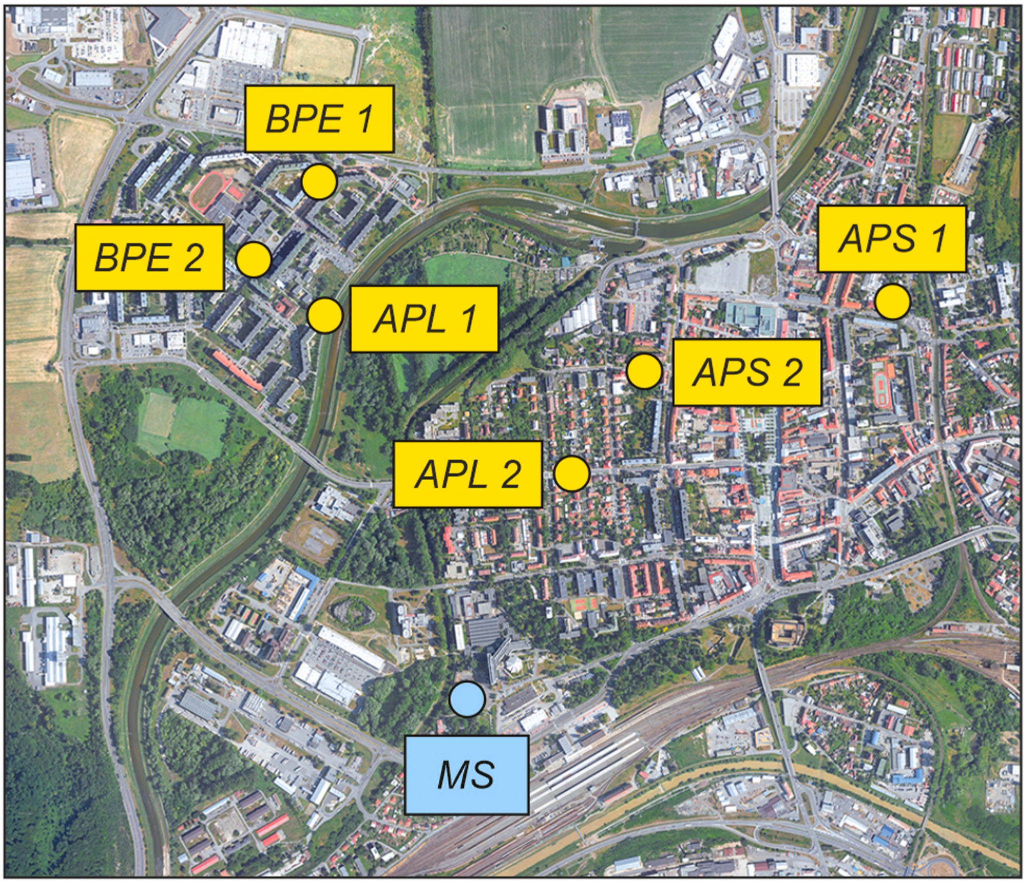


Fig. 1. Monitored zone of tree species in the city of Zvolen: Betula pendula - BPE, Acer pseudoplatanus - APS, Acer platanoides - APL and the meteorological station with a sky quality meter (MS). Basemap source:GKÚ Bratislava, NLC.

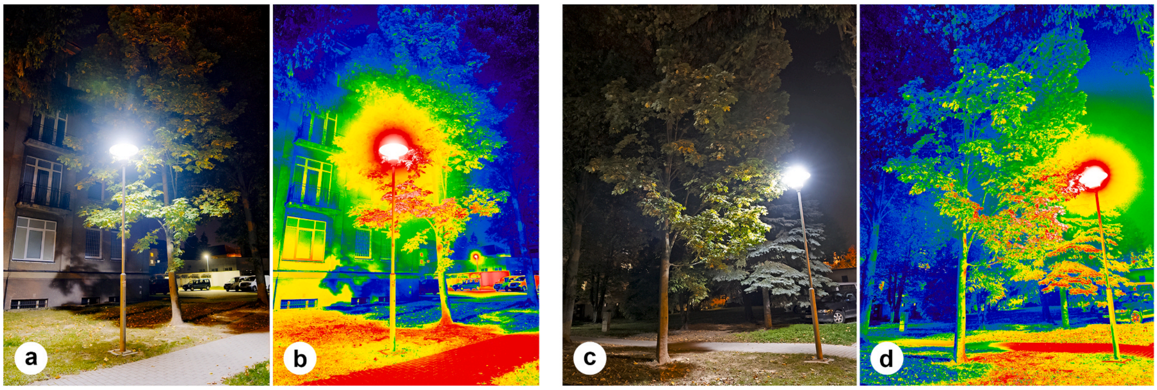


Fig. 2. Real photography and light intensity gradient map Acer pseudoplatanus. a) East side real photography: Visible-light photograph of the tree and its urban surroundings, illuminated by a streetlamp. b) East side light intensity map red/yellow for high, green/blue for low. c) South side real photography: Visible-light photograph of the tree and its surroundings also illuminated by a streetlamp. d) South side light intensity map: Pseudo-coloured light intensity map from the south, illustrating the distribution and fall-off of artificial light.

leaf colouring phenophase:

- Beginning of leaf colouring (LC 10 %, BBCH 92): Defined as the occurrence of coloured leaves on less than half of the observed group or crown part in individual trees.
- Complete leaf colouring (LC 100 %, BBCH 94): Defined as colour changes present on the majority of individuals in the group or nearly the entire observed crown section in individual trees.

Observations were conducted within eight years (2016–2023). More detailed phenological analysis was performed on two individuals of each species in 2022 and 2023, which represented meteorologically extreme years during the study period.

2.5. Statistical analyses and hypothesis testing

All statistical analyses were performed using Statistica, version 12 (StatSoft). A significance level of $\alpha = 0.05$ was applied to all tests.

Data were checked for completeness and consistency during preliminary analyses. Descriptive statistics (mean, median, standard

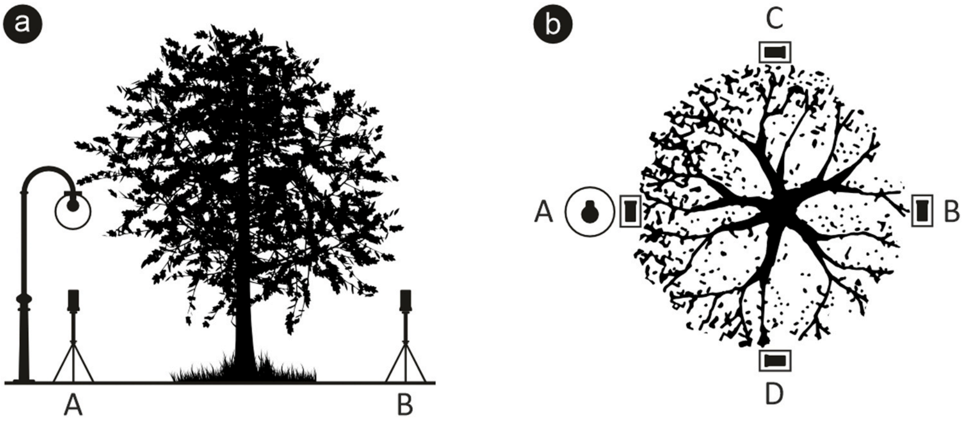


Fig. 3. Schematic diagram of measurement positions under the tree canopy. a) Side view: Illustrates the vertical setup of measurements relative to the tree and streetlamp. b) Top view: Shows the horizontal placement of four measurement points (A, B, C, D) around the crown: A (illuminated), B (non-illuminated) along the lamp's axis, and C, D at canopy edges.

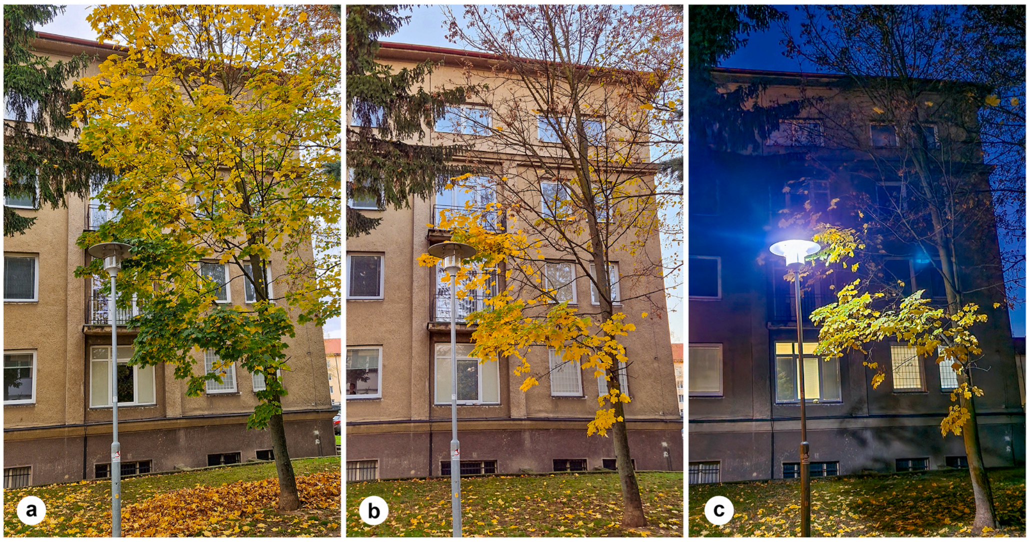


Fig. 4. Phenological progression and lighting conditions at site APS 1 - Acer pseudoplatanus. a) Day view (early colouring) b) Day view (advanced colouring) c) Night view (active illumination).

deviation, and range) were calculated for all key variables.

Descriptive statistics are provided in Supplementary Table S2. Model assumptions were thoroughly evaluated. Normality of residuals was assessed using the Shapiro-Wilk test, and homogeneity of variances (homoscedasticity) was checked using Levene's test. A detailed summary of these assumption tests is provided in Supplementary Table S4. Data transformations were applied where necessary to meet model assumptions.

The specific statistical approaches, dependent and independent variables, and the testing framework for each alternative hypothesis (H1, H2, and H3) are comprehensively outlined in Fig. 5. The primary tool for hypothesis testing (H1 and H2) was the Linear Mixed Model (LMM). The significance of fixed effects was determined using Type III F-tests, and in complex models, this was supplemented by the Wald χ^2statistic. All test statistics (F and p-values) are consolidated in Supplementary Table S3, ensuring clarity in the Results section.

3. Results

The results of our study highlight the complex interplay among artificial light, tree species, and meteorological conditions on autumn phenology in urban environments.

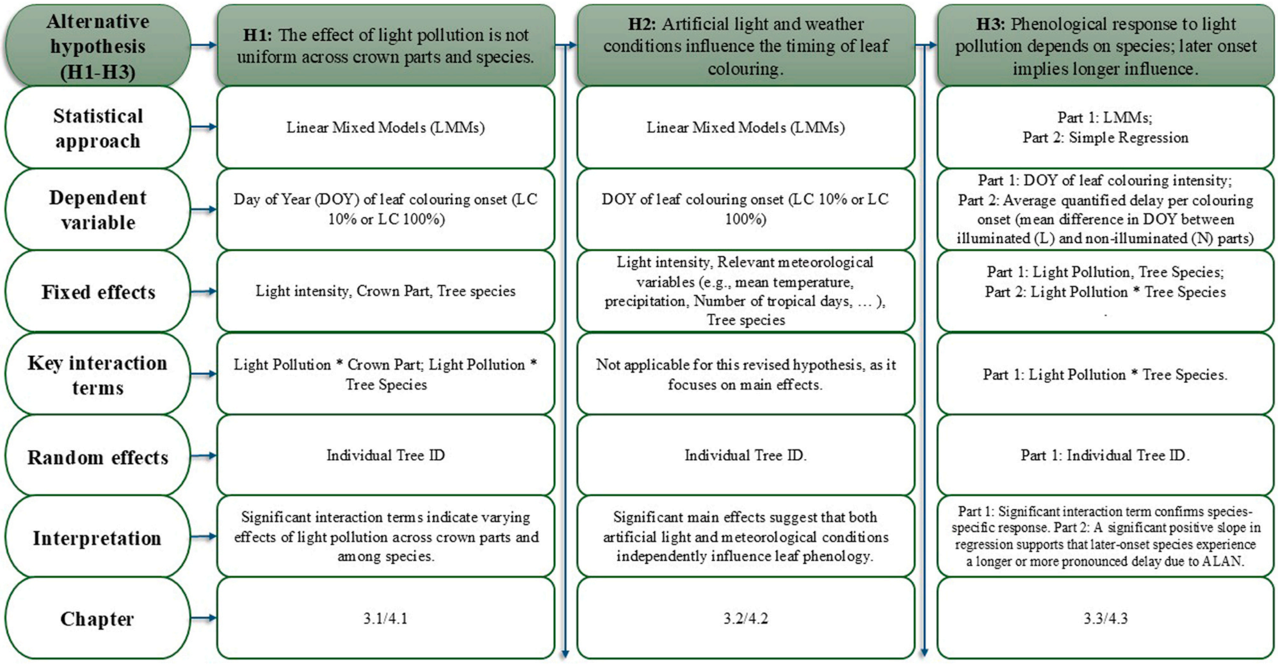
3.1. *Overall phenological response to light pollution*

3.1.1. *Average phenological onset and light intensity distribution*

The phenological response of tree species to artificial light was found to be varied (Table 1). The earliest onset of both phenophase stages (LC 10 % and LC 100 %) was recorded for *Acer pseudoplatanus*. In the initial stage (LC 10 %), differences between the illuminated (L) and non-illuminated (N) crown parts were relatively consistent across all species (6–8 days). However, the largest difference, 16 days, was observed in *Betula pendula* during the LC 100 % leaf colouring phase.

Fig. 6 illustrates the distribution of light intensity and phenophase onset for the studied tree species. *Betula pendula* consistently experiences lower light conditions with the least variability. *Acer pseudoplatanus* encounters higher average light intensity and greater variability than *Betula pendula*. *Acer platanoides*, while having a comparable average light exposure to *Acer pseudoplatanus*, exhibits the greatest variability in light intensity, suggesting its adaptability to a broader range of light environments (see also Supplementary Table S2 for complete descriptive statistics). The generally wide distributions of light intensity for all species underscore the diverse light conditions prevalent at the measurement sites.

Regarding phenophase onset, *Acer pseudoplatanus* and *Acer*



Alternative hypothesis (H1-H3)	H1: The effect of light pollution is not uniform across crown parts and species.	H2: Artificial light and weather conditions influence the timing of leaf colouring.	H3: Phenological response to light pollution depends on species; later onset implies longer influence.
Statistical approach	Linear Mixed Models (LMMs)	Linear Mixed Models (LMMs)	Part 1: LMMs; Part 2: Simple Regression
Dependent variable	Day of Year (DOY) of leaf colouring onset (LC 10% or LC 100%)	DOY of leaf colouring onset (LC 10% or LC 100%)	Part 1: DOY of leaf colouring intensity; Part 2: Average quantified delay per colouring onset (mean difference in DOY between illuminated (L) and non-illuminated (N) parts)
Fixed effects	Light intensity, Crown Part, Tree species	Light intensity, Relevant meteorological variables (e.g., mean temperature, precipitation, Number of tropical days, …), Tree species	Part 1: Light Pollution, Tree Species; Part 2: Light Pollution * Tree Species
Key interaction terms	Light Pollution * Crown Part; Light Pollution * Tree Species	Not applicable for this revised hypothesis, as it focuses on main effects.	Part 1: Light Pollution * Tree Species.
Random effects	Individual Tree ID	Individual Tree ID.	Part 1: Individual Tree ID.
Interpretation	Significant interaction terms indicate varying effects of light pollution across crown parts and among species.	Significant main effects suggest that both artificial light and meteorological conditions independently influence leaf phenology.	Part 1: Significant interaction term confirms species-specific response. Part 2: A significant positive slope in regression supports that later-onset species experience a longer or more pronounced delay due to ALAN.
Chapter	3.1/4.1	3.2/4.2	3.3/4.3

Fig. 5. Alternative hypothesis (H1-H3). The diagram provides a structured overview of the study's three alternative hypotheses (H1, H2, H3) and the methodology used to test them. Each hypothesis is detailed with respect to its statistical approach (Linear Mixed Models), dependent variables LC10 %, LC100 %), fixed effects, key interaction terms, random effects, interpretation of results, and the chapters in which they are discussed. Before to modelling, all data were checked for completeness, and model assumptions (normality and homoscedasticity) were verified as described in Section 2.5.

Table 1
Average onset (date/day of year-DOY) and difference of LC phenophase stages (LC 10 % and LC 100 %) for illuminated (L) and non-illuminated (N) crown parts, 2016–2023.

Tree species	N10 %	LC L10 %	Δ L-N	N100 %	LC L100 %	Δ L-N
Acer pseudoplatanus	29.9./ 272	5.10./ 278	6	16.10./ 289	22.10./ 295	6
Acer platanoides	4.10./ 277	12.10./ 285	8	19.10./ 292	28.10./ 301	9
Betula pendula	7.10./ 280	14.10./ 287	7	29.10./ 302	14.11./ 318	16

platanoides consistently display an earlier onset of 10 % leaf colouring (around DOY 269–270) compared to *Betula pendula* (around DOY 278–279). Conversely, the 100 % leaf colouring stage occurs significantly later for all species, with *Betula pendula* (around DOY 300) and *Acer platanoides* (around DOY 299) exhibiting similar late-season timing. The narrow, symmetrical distributions of phenophase onset across all species and stages suggest a relatively consistent timing of these events within the measured populations or environmental conditions. This comprehensive graphical analysis provides valuable insights into ecological differences among these tree species concerning their light requirements and phenological timing.

3.1.2. *Results of linear mixed model analysis on leaf colouring onset (Hypothesis H1)*

The primary hypothesis (Hypothesis 'H1': "Effect of light pollution on leaf colouring is non-uniform across crown parts and species") was tested via interaction terms (Light_intensity_ Crown_Part and Light_intensity_Species, see Supplementary Table S3 for full LMM statistics).

The LMM results for the initial 10 % leaf colouring (LC10 %) phenophase revealed a statistically significant main effect of Light_intensity. Conversely, neither the Light_intensity*Crown_Part interaction nor the Light_intensity*Species interaction was statistically significant. Significant main effects were, however, observed for Species and Crown_Part.

The LMM results for the complete 100 % leaf colouring (LC100 %) phenophase, showed that the main effect of Light_intensity was not statistically significant. Similarly, neither the Light_intensity_Crown_Part interaction nor the Light_intensity. Species interactions were statistically supported. Consistent with the LC10 % model, highly significant main effects were found for Species and Crown_Part.

Hypothesis 'H1' was not statistically supported for either phenophase, as the effect of light pollution intensity on leaf colouring onset did not significantly vary based on tree species or crown part. The significant overall influence of light pollution intensity was detected only for the initial (LC10 %) but not the complete (LC100 %) leaf colouring phase. Both tree species and crown parts independently exerted a strongly significant influence on the timing of leaf colouring change onset across both phenophases.

3.2. *Influence of meteorological factors and artificial light*

3.2.1. *Overview of meteorological conditions and phenological observation*

Autumn phenology in urban environments is significantly influenced by meteorological elements, particularly air temperature and precipitation during the growing season. Therefore, these elements (Table 2) were included in our analysis. The year 2022 was characterised by a dry and warm early summer. The highest number of tropical days (47) occurred during the summer months, leading to the earliest leaf colouring across all species (Fig. 7). *Acer pseudoplatanus* reacted most sensitively to weather extremes, while *Betula pendula* was the least sensitive. The opposite extreme was recorded in 2023, when late summer and early autumn (August, September) were warmer with sufficient rainfall. Warm weather in September (mean temperature = 17.9 °C) with 5 tropical days, delayed leaf colouring for all species until mid-October. For *Betula pendula* and *Acer platanoides*, many green leaves remained in the illuminated crown part until mid-November, eventually being damaged by the first autumn frosts rather than completing their

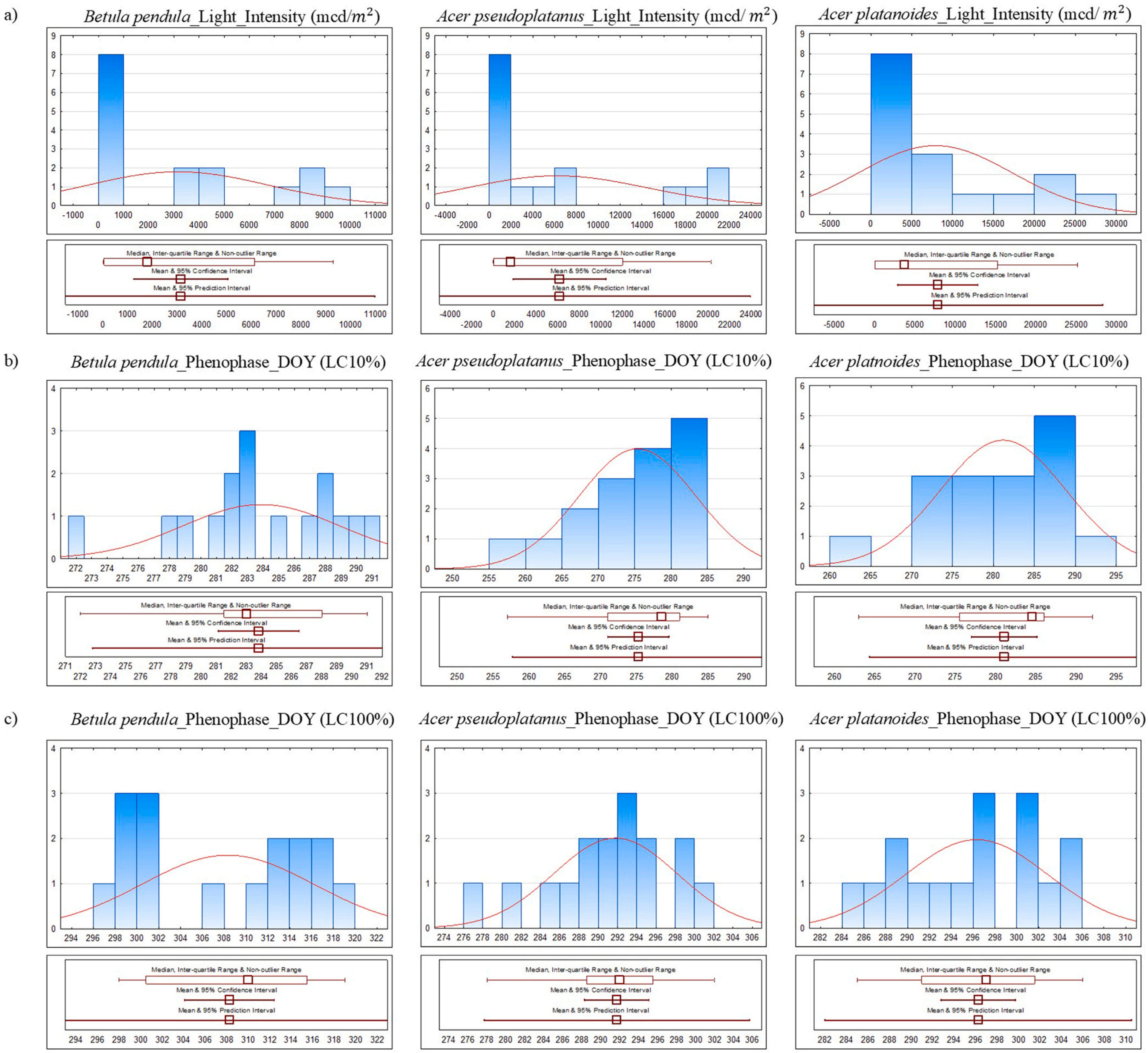


Fig. 6. Distribution of light intensity and phenophase onset for selected tree species. This figure presents histograms and corresponding boxplots illustrating the distribution of a) light intensity (mcdlm^2) and b) and c) the Day of year (DOY) for two key phenophase stages (10 % and 100 % leaf coloration) in Betula pendula, Acer pseudoplatanus, and Acer platanoides. The graphical representations provide insights into the central tendency and spread of the observed data for each species and measured parameter.

natural colouring.

3.2.2. *Influence of artificial light and meteorological factors on leaf colouring (Hypothesis H2)*

Detailed LMM statistics for H2 are presented in Supplementary Table S3.

The main effect of Light_intensity for initial leaf colouring (LC10 %) was statistically significant in the models incorporating Avg. temp. September and Autumn_Rainfall_Total, but was not significant when paired with Number of tropical days_Jul_Sept, Mean_Temp_Jul_Sept, or Cum_Precip_Jul_Sep. Regarding the meteorological factors, Avg. temp. September and Autumm_Rainfall_Total exhibited highly significant main effects, while the other three factors were not statistically significant.

The main effect of Light_intensity for complete leaf colouring (LC100 %), was consistently not statistically significant across all tested models. Conversely, the meteorological factors Avg. temp. September, Autumn_Rainfall_Tota, and Number of tropical days_Jul_Sept all showed statistically significant main effects, with only Mean_Temp_Jul_Sep and Cum_Precip_Jul_Sep lacking significance.

The main effects of Species and Crown_Part were consistently highly significant across almost all models for both phenophases.

These results support Hypothesis H2, indicating that artificial light (specifically for LC10 % in models with September temperature/rainfall) and various meteorological conditions independently influence the timing of leaf colouring. The most influential meteorological predictors were Avg. temp September and Autumn_Rainfall_Total for both phenophases. Due to software limitations, the statistical evaluation of interactions between artificial light and meteorological conditions was not possible, preventing conclusions on whether specific conditions modulate the effects of light pollution.

Table 2
Selected temperature and rainfall characteristics (June-September) in Zvolen, 2016–2023.

Years	Average month temperature (°C) / Number of tropical days				Month rainfall sum (mm) / Absolute max. daily rainfall (mm)			
	VI.	VII.	VIII.	IX.	VI.	VII.	VIII.	IX.
2016	19.5 / 5	20.4 / 10	18.4 / 1	15.8 / 4	72 / 26	94 / 22	130 / 31	43 / 17
2017	20.3 / 9	19.4 / 3	20.7 / 15	13.9 / 1	77/ 41	112 / 22	60 / 18	108 / 2
2018	19.2 / 4	20.6 / 12	21.6 / 17	15.5 / 0	103 / 27	36 / 12	81 / 28	49 / 27
2019	21.9 / 11	20.1 / 11	20.9 / 11	14.3 / 1	55 / 24	56 / 26	67 / 21	73 / 31
2020	18.5 / 2	19.8 / 2	20.6 / 10	15.4 / 0	141 / 33	108 / 36	62 / 15	8 1/ 29
2021	20.6 / 14	22 / 10	17.9 / 3	14.2 / 0	70 / 30	130 / 40	110 / 30	34 / 20
2022	21.1 / 12	22 / 17	21.8 / 18	13.7 / 0	20 / 6	52 / 21	78 / 24	104 / 1
2023	18.8 / 2	20.7 / 7	20.7 / 13	17.9 / 5	59 / 22	32 / 11	92 / 25	48 / 15

3.3. Analysis of extreme years and species-specific responses

3.3.1. Overview of analysis and light measurements in 2022 and 2023

A more detailed phenological analysis of leaf colouring was conducted on two randomly selected individuals of each studied species (*Acer pseudoplatanus* L., *Acer platanoides* L., and *Betula pendula* Roth.) alongside detailed measurements of artificial light at night (ALAN) in 2022 and 2023. Even in these extreme years, *Acer* species generally demonstrated higher sensitivity to all evaluated factors, while *Betula pendula* individuals exhibited the slowest leaf colouring in the urban environment. This observation highlights that meteorological elements are a significant factor within urban climatic conditions. Leaf colouring at 100 % (LC100 %) for these selected individuals in illuminated (L) and non-illuminated (N) crown parts for 2022 and 2023 is presented in Fig. S1.

Concurrent with phenological monitoring, detailed ALAN measurements were performed on these individuals from August 1st to October 30th in both 2022 and 2023. Night Sky Brightness (NSB) values at the reference site showed a fluctuating character (Fig. S2). Considering the selected summer and autumn seasons, these values were lower compared to the average annual NSB value for the urban intravillan (19.94 mag/arcsec^2) according to the World Atlas of Light Pollution. On two different dates (September 4th and October 14th in 2022–23), consistently differing NSB values were found between the illuminated and non-illuminated crown parts (Fig. S3). The NSB value was consistently lower (indicating brighter conditions) in the illuminated (L) parts of the trees compared to the opposite non-illuminated (N) parts. Specifically, the lowest L-part value (7.68 mag/arcsec^2) was measured on *Acer platanoides 2* (2022), while the highest L-part value (12.81 mag/arcsec^2) was observed for *Betula pendula 1* (2023). Conversely, the lowest N-part crown value (14.76 mag/arcsec^2) was measured for *Betula pendula* 2 (2022), and the highest N-part value (19.44 mag/arcsec^2) for *Acer pseudoplatanus* 1 (2023). The intensity of light pollution at measured points around the crown perimeter on the selected date of October 14th is further illustrated in Fig. 8.

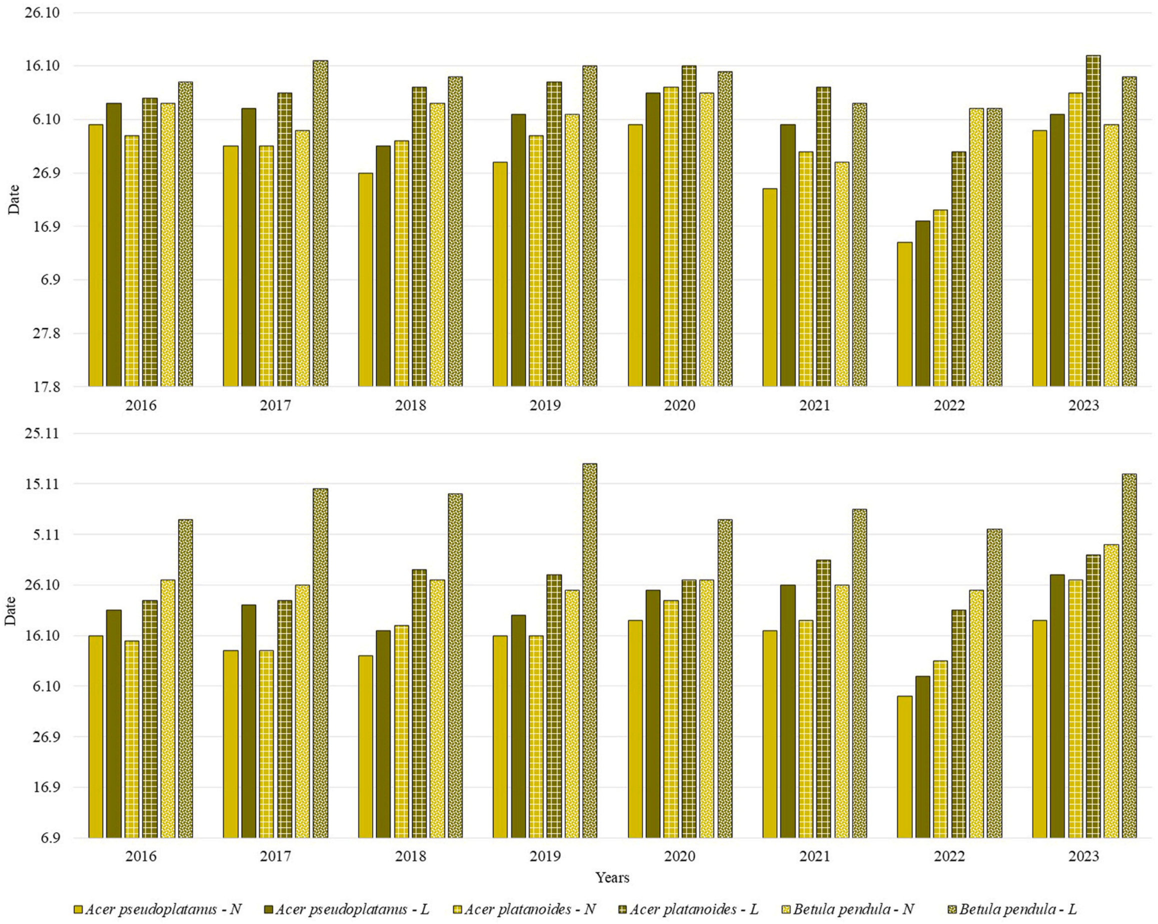


Fig. 7. Average onset of leaf colouring in Zvolen, 2016–2023. a) Beginning of leaf colouring (LC10 %). b) Complete leaf colouring (LC100 %).

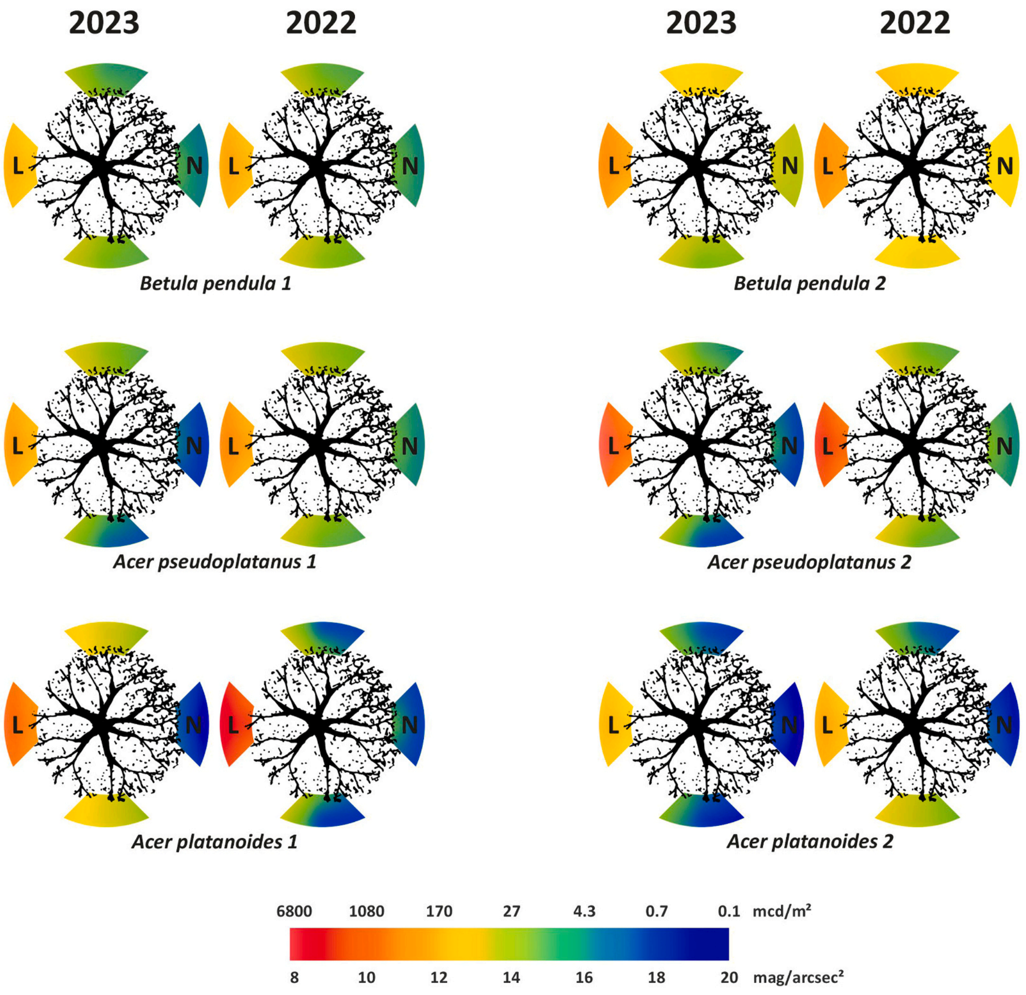


Fig. 8. Comparison of light intensity distribution in illuminated (L) and non-illuminated (N) crown parts on October 14th in 2022 and 2023. The pseudo-coloured segments indicate light intensity (in mcd/m^2 and mag/arcsec^2) in the illuminated (L) and non-illuminated (N) sections of each tree's crown.

3.3.2. *Species-specific phenological response to light pollution (Hypothesis H3)*

Hypothesis H3, which postulates that the phenological response to artificial light at night (ALAN) depends on species and that a later onset of senescence implies a longer influence, was evaluated using Linear Mixed Models (LMMs) and simple linear regression (for detailed LMM and regression statistics, see Supplementary Table S3).

To test the first part of the hypothesis – whether the phenological response to ALAN is species-specific – an LMM assessing the interaction between Species and Crown_Part revealed that this interaction was not statistically significant for either LC10 % or LC100 % onset. Thus, the first part of Hypothesis H3 is not supported, as the effect of ALAN on the onset of autumn leaf senescence does not statistically differ among the studied tree species.

The second part of Hypothesis H3, proposing that a later onset of senescence correlates with a longer influence of ALAN, was investigated through simple linear regression. The regression analysis for LC10 % showed a very weak and non-significant relationship (R^2=0.0155). Conversely, the analysis for LC100 %, a very strong positive relationship was observed (R^2=0.9931). This result suggests that species with a generally later onset of 100 % leaf colouring tend to experience a substantially greater delay in senescence due to ALAN.

The analysis revealed a split outcome for Hypothesis H3. The first part of the hypothesis was not supported; the influence of light pollution on senescence onset did not statistically differ among the studied tree species. However, the second part of the hypothesis was strongly supported for the complete colouring change (LC100 %). This indicates that ALAN disproportionately extends the autumn canopy period for species that naturally senesce later.

4. Discussion and future research

Autumn leaf colouring is influenced by temperature, precipitation and photoperiod (Estrella & Menzel, 2006; Smith, 2020; Way & Montgomery, 2015). Our findings from 2022 and 2023 highlighted the influence of these factors. Leaf colouring under the influence of these factors and ALAN is discussed further.

4.1. *Impact of light pollution on leaf colouring within the tree crown and across species*

This study employed Linear Mixed Models to investigate ALAN's impact on initial (LC10 %) and complete (LC100 %) leaf colouring. Our primary hypothesis (Hypothesis H1) was assessed through interaction terms in the models.

Our findings revealed a nuanced relationship between light pollution and leaf colouring onset. For LC10 %, light intensity showed a statistically significant main effect, indicating ALAN delays the first signs of colouring. This aligns with descriptive patterns (Table 1) showing 6–8 day delays in illuminated crown parts, corroborating earlier observations of prolonged leaf greenness under streetlights (Matzke, 1936; Massetti, 2018).

In contrast, for LC100 %, Light_intensity did not exhibit a statistically significant main effect or interactions. This implies ALAN's influence diminishes as colouring progresses to completion, with other unmodeled factors or high variability playing a more dominant role. The descriptive 16-day delay in *Betula pendula* for LC100 % (Table 1), while striking, was not statistically supported by the LMM. Factors like accumulated chilling requirements or severe meteorological events may become more influential drivers of final leaf colouring stages (Czaja & Kołton, 2022).

Sarala et al. (2013) reported no phenological changes in birch under ALAN. They found a significant interaction between leaf colour change and time on chlorophyll and carotenoid concentrations. According to these authors, the result may be due to the low tested light intensity at the sampling site, which is likely farther from the source. According to our results, light from streetlamps slowed down leaf colouring of *Betula pendula* in the immediate vicinity of the light source. We assume that chlorophyll and carotenoid degradation occurred more slowly in illuminated leaves, which is why the remained green until mid-November. These different tree responses may be due to the species ́specific sensitivity to external stimuli, since winter dormancy is also influenced by photoperiod and temperature, or by a combination of both factors (Lauria et al., 2024; Zhang et al., 2020).

Despite ALAN's nuanced role, our LMMs consistently identified highly significant main effects for both Species and Crown_Part for both LC10 % and LC100 %. This underscores inherent phenological variability among species and within the crown, independent of ALAN. *Acer pseudoplatanus*, for instance, consistently showed the earliest leaf colouring. The photoperiod is only one of the stimuli for the cessation of autumn tree activity, but the effect is not dominant (Delpierre et al., 2016). This was also confirmed by our results, where the effect of photoperiod was weaker in species with an earlier phase onset (maples) than in a species (birch) with a phase onset in the later autumn. Our descriptive data also suggest combined effects of ALAN, photoperiod, and air temperature uniquely shape annual leaf colouring patterns, with extended green leaf retention in illuminated sections potentially linked to delayed dormancy and elevated chlorophyll (Piccolo et al., 2023; Massetti, 2018; Meng et al., 2020).

4.2. The role of artificial light and meteorological factors in autumn leaf senescence

Consistent with Hypothesis H2, both ALAN (for LC10 %) and various meteorological conditions significantly influence autumn phenophases. For LC10 %, ALAN showed a significant effect in models incorporating September average temperature and autumn total rainfall, suggesting a direct, context-dependent influence on senescence initiation (Gaston and Sánchez de Miguel, 2022; Meng et al., 2022; Cesarz et al., 2023). However, ALAN's main effect was consistently not statistically significant for LC100 %, indicating this later stage is less dictated by ALAN and more robustly driven by meteorological conditions.

Meteorological factors played a crucial role for both phenophases. Average September temperature, autumn total rainfall, and the number of tropical days in July-September significantly influenced LC10 % and LC100 %. These findings underscore that temperature and precipitation regimes are primary drivers of autumn senescence (Anderson-Teixeira et al., 2013; Ge et al., 2015). Autumn phenology will therefore depend on the relative importance of each factor in specific conditions and years, which was also confirmed by the work of Estiarte – Peñuelas (2015).

Furthermore, Species and Crown_Part consistently emerged as highly significant factors across nearly all models. This highlights inherent physiological differences among species and localised light conditions within the crown. *Acer* species, known for denser foliage (Konôpka et al., 2021) and potentially greater resistance to high light intensity (Pereira and Kozlowski, 1978), might respond differently to light exposure compared to *Betula*. Light penetration within the crown is influenced by tree characteristics and external lighting (Valladares and Niinemets, 2007; Balakrishnan and Jakubiec, 2023).

In conclusion, autumn leaf colouring in urban environments is a complex process influenced independently by species-specific traits, crown light exposure, and significant meteorological variables. While ALAN shows a direct role in initiating senescence (LC10 %), its impact on the complete process (LC100 %) appears less pronounced than that of climatic factors.

The work of Wang et al. (2025) comprehensively analyses the relationship between air temperature and ALAN on vegetation phenology using a satellite system. The authors stated that in Central Europe with mild climatic conditions, the later end of the growing seasons was influenced by a higher effect of ALAN. However, the earlier end of the growing season was related to the heat island effect and higher temperature in cities. These findings are consistent with our data from 2022, when the hot summer led to an earlier onset of colouring. The work does not evaluate precipitation, which is important for the onset of the autumn phase in the urban environment, because it alleviate drought stress and, with optimal amounts and timing during the summer, delays the onset of the autumn phase. This creates conditions for a longer effect of ALAN. This phenomenon was confirmed in our results in 2023. Due to the lack of data on precipitation in urban environments, it is not possible to unambiguously compare and confirm their impact.

4.3. Species-specific phenological response to light pollution and its relation to onset timing

Hypothesis H3 explored observed species-specific phenological responses to ALAN and their relation to natural senescence timing. Contrary to expectation, LMM analysis found no statistically significant interaction between Species and Crown_Part for either LC10 % or LC100 %. This suggests that the magnitude of ALAN's influence on autumn leaf senescence does not widely vary among the studied *Acer* and *Betula* species, implying a more uniform response pattern despite differences in overall phenological timing.

However, the second part of Hypothesis H3, proposing that a later natural onset of senescence implies a longer ALAN influence, received strong support for the LC100 % phenophase. Our regression analysis demonstrated a highly significant positive relationship between the average DOY of senescence in non-illuminated crown parts and the average delay caused by ALAN for LC100 % (R2 of 0.9931). This indicates that observed species or individuals that naturally reach complete leaf colouring later in the season experience a substantially longer growing season due to ALAN. For instance, *Betula pendula*, generally with a later LC100 % onset, showed the largest delay due to ALAN. This extended exposure may disrupt physiological processes as natural dormancy cues are masked by illumination. Conversely, for LC10 %, this relationship was not observed ($y = -0.0321x+16.525$, $R2 = 0.0155$), suggesting initial colouring stages might be less sensitive to this cumulative effect.

Observed findings are critical for urban forest management. While ALAN's differential impact on individual species' senescence timing might not be statistically distinct, the strong correlation for LC100 % implies that later-senescing observed species are disproportionately affected by ALAN-induced delays. This knowledge can guide decision processes on species selection for urban planting and strategic lighting placement to minimise negative impacts on tree health and ecosystem services.

5. Conclusion

This study elucidates the complex influence of artificial light at night (ALAN) on the autumn phenology of selected urban trees (maple and birch), specifically leaf colouring (LC10 % and LC100 %). Our long-term data and Linear Mixed Models reveal that while ALAN significantly delays the initial onset of leaf colouring (LC10 %) across observed species and crown parts, its effect diminishes in the final stages of senescence (LC100 %), which are more strongly governed by meteorological factors.

Crucially, September temperature and autumn rainfall emerged as dominant drivers of autumn phenology. Furthermore, we found that selected species with a naturally later onset of complete leaf colouring (LC100 %) experience a disproportionately greater delay due to ALAN, with significant implications for their natural dormancy and susceptibility to early frosts.

Our results provide new insights into the detailed measurement of artificial light intensity in individual crown parts. The ALAN creates a distinct nocturnal microclimate within the immediate vicinity of light sources. We define this phenomenon as the ALAN microclimate – a localised nocturnal microenvironment formed around vegetation exposed to artificial illumination, characterised by altered radiative conditions relative to unlit surroundings. Such localised alterations of the canopy energy balance can influence physiological processes and phenological development, leading to spatially asymmetric timing of seasonal events within individual trees or stands. The concept of the ALAN microclimate thus extends classical microclimatology by incorporating anthropogenic nocturnal radiation as an additional factor shaping the microenvironmental conditions experienced by urban vegetation.

The results point out the sensitivity of tree species (maple and birch), which are often found in urban plantings in other surrounding cities and regions. Therefore, the listed tree species can be used in urban planning and strategic lighting design to mitigate light stress. The integrating of our understanding of ALAN's phenological impacts with urban planning is vital for fostering resilient and healthy urban forests trees in an increasingly illuminated world.

CRediT authorship contribution statement

Jana Škvareninová: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Stanislav Kaniansky:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jaroslav Škvarenina:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Michaela Korená-Hillayová:** Writing – review & editing, Formal analysis. **Radoslava Kanianska:** Writing – review & editing.

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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2025.129241.

References

Anderson-Teixeira, K.J., Miller, A.D., Mohan, J.E., Hudiburg, T.W., Duval, B.D., DeLucia, E.H., 2013. Altered dynamics of forest recovery under a changing climate. Glob. Change Biol. 19 (7), 2001–2021. https://doi.org/10.1111/gcb.12194.

Balakrishnan, P., Jakubiec, J.A., 2023. Trees in daylight simulation–measuring and modelling realistic light transmittance through trees. Leukos 19 (3), 241–268. https://doi.org/10.1080/15502724.2022.2112217.

Basler, D., Körner, C., 2012. Photoperiod sensitivity of bud burst in 14 temperate forest tree species. Agric. For. Meteorol. 165, 73–81. https://doi.org/10.1016/j.agrformet.2012.06.001.

Bennie, J., Davies, T.W., Cruse, D., Gaston, K.J., 2016. Ecological effects of artificial light at night on wild plants. J. Ecol. 104 (3), 611–620. https://doi.org/10.1111/1365-2745.12551.

Braslavská, O., Kamenský, L., 1996. Phenological Observation of Forest Plants. Methodological Prescription of SHMÚ. SHMÚ Publishing, Bratislava, p. 22.

Brelsford, C.C., Nybakken, L., Kotilainen, T.K., Robson, T.M., 2019. The influence of spectral composition on spring and autumn phenology in trees. Tree Physiol. 39 (6), 925–950. https://doi.org/10.1093/treephys/tpz026.

Cesarz, S., Eisenhauer, N., Bucher, S.F., Ciobanu, M., Hines, J., 2023. Artificial light at night (ALAN) causes shifts in soil communities and functions. Philos. Trans. R. Soc. B 378 (1892), 20220366. https://doi.org/10.1098/rstb.2022.0366.

Chi, D., Van Meerbeek, K., Yu, K., Degerickx, J., Somers, B., 2022. Foliar optical traits capture physiological and phenological leaf plasticity in *Tilia×euchlora* in the urban environment. Sci. Total Environ. 805, 150219. https://doi.org/10.1016/j.scitotenv.2021.150219.

Czaja, M., Kołton, A., 2022. How light pollution can affect spring development of urban trees and shrubs. Urban For. Urban Green. 77, 127753. https://doi.org/10.1016/j.ufug.2022.127753.

Delpierre, N., Vitasse, Y., Chuine, I., Guillemont, J., Bazot, S., Rutishauser, T., Rathgeber, C., 2016. Temperate and boreal forest tree phenology: from organ-scale processes to terrestrial ecosystem models. Ann. For. Sci. 73, 5–25. https://doi.org/10.1007/s13595-015-0477-6.

Donnelly, A., Liu, L., Zhang, X., Wingler, A., 2018. Autumn leaf phenology: discrepancies between in situ observations and satellite data at urban and rural sites. Int. J. Remote Sens. 39 (22), 8129–8150. https://doi.org/10.1080/01431161.2018.1482021.

Du, H., Wang, M., Liu, Y., Guo, M., Peng, C., Li, P., 2022. Responses of autumn vegetation phenology to climate change and urbanization at northern middle and high latitudes. Int. J. Appl. Earth Obs. Geoinf. 115, 103086. https://doi.org/10.1016/j.jag.2022.103086.

Dzul-Cauich, H.F., Munguía-Rosas, M.A., 2022. Negative effects of light pollution on pollinator visits are outweighed by positive effects on the reproductive success of a bat-pollinated tree. Sci. Nat. 109 (1), 12. https://doi.org/10.1007/s00114-021-01783-5.

Estiarte, M., Peñuelas, J., 2015. Alteration of the phenology of leaf senescence and fall in winter deciduous species by climate change: effects on nutrient proficiency. Glob. Change Biol. 21 (3), 1005–1017. https://doi.org/10.1111/gcb.12804.

Estrella, N., Menzel, A., 2006. Responses of leaf colouring in four deciduous tree species to climate and weather in Germany. Clim. Res. 32 (3), 253–267. https://doi.org/10.3354/cr032253.

Falchi, F., Cinzano, P., Duriscoe, D., Kyba, C.C.M., Elvidge, C.D., Baugh, K., Portnov, B., Rybnikova, N.A., Furgoni, R., 2016. The new world atlas of artificial night sky brightness. Sci. Adv. 2 (6), 1–25. https://doi.org/10.1126/sciadv.

French-Constant, R.H., Somers-Yeates, R., Bennie, J., Economou, T., Hodgson, D., Spalding, A., Mc.Gregor, P.K., 2016. Light pollution is associated with earlier tree budburst across the United Kingdom. Proc. R. Soc. B Biol. Sci. 283 (1833), 20160813. https://doi.org/10.1098/rspb.2016.0813.

Friulla, L., Varone, L., 2025. Artificial light at night (ALAN) as an emerging urban stressor for tree phenology and physiology: a review. Urban Sci. 9 (1), 14. https://doi.org/10.3390/urbansci9010014.

Fu, Y.H., Piao, S., Zhou, X., Geng, X., Hao, F., Vitasse, Y., Janssens, I.A., 2019. Short photoperiod reduces the temperature sensitivity of leaf-out in saplings of *Fagus sylvatica* but not in horse chestnut. Glob. Change Biol. 25 (5), 1696–1703 https://doi.10.1111/gcb.14599.

Gallinat, A.S., Primack, R.B., Wagner, D.L., 2015. Autumn, the neglected season in climate change research. Trends Ecol. Evol. 30 (3), 169–176. https://doi.org/10.1016/j.tree.2015.01.004.

Gaston, K.J., Sánchez de Miguel, A., 2022. Environmental impacts of artificial light at night. Annu. Rev. Environ. Resour. 47 (1), 373–398. https://doi.org/10.1146/annurev-environ-112420-014438.

Ge, Q., Wang, H., Dai, J., 2014. Phenological response to climate change in China: a meta-analysis. Glob. Change Biol. 21, 265–274.

Güsewell, S., Furrer, R., Gehrig, R., Pietragalla, B., 2017. Changes in temperature sensitivity of spring phenology with recent climate warming in Switzerland are related to shifts of the preseason. Glob. Change Biol. 23 (12), 5189–5202. https://doi.org/10.1111/gcb.13781.

Haase, D., Hellwig, R., 2022. Effects of heat and drought stress on the health status of six urban street tree species in Leipzig, Germany. Trees For. People 8, 100252. https://doi.org/10.1016/j.tfp.2022.100252.

Halecki, W., Belda, D., Plesiński, K., Ziernicka-Wojtaszek, A., 2023. River park assessment: 2D hydraulic watercourse modeling for nature-based solutions in urban area. Civ. Environ. Eng. Rep. 33 (2). https://doi.org/10.59440/ceer/173574.

Hao, Q., Wang, L., Liu, G., Ren, Z., Wu, Y., Yu, Z., Yu, J., 2023. Exploring the construction of urban artificial light ecology: a systematic review and the future prospects of light pollution. Environ. Sci. Pollut. Res. 30 (46), 101963–101988. https://doi.org/10.1007/s11356-023-29462-0.

Jochner, S., Menzel, A., 2015. Urban phenological studies – Past, present, future. Environ. Pollut. 203, 250–261. https://doi.org/10.1016/j.envpol.2015.01.003.

Konôpka, B., Pajtík, J., Šebeň, V., Surový, P., Merganičová, K., 2021. Woody and foliage biomass, foliage traits and growth efficiency in young trees of four broadleaved tree species in a temperate forest. Plants 10 (10), 2155. https://doi.org/10.3390/plants10102155.

Lang, W., Chen, X., Qian, S., Liu, G., Piao, S., 2019. A new process-based model for predicting autumn phenology: how is leaf senescence controlled by photoperiod and temperature coupling? Agric. For. Meteorol. 268, 124–135. https://doi.org/10.1016/j.agrformet.2019.01.006.

Lapin, M., Faško, P., Melo, M., Šťastný, P., Tomlain, J. (2002). Climatic regions 1:1 000 000. In: Country Atlas of the Slovak Republic. MŽP SR Bratislava, 344 p. ISBN 80-88833-27-2.

Lauria, G., Ceccanti, C., Lo Piccolo, E., El Horri, H., Guidi, L., Lawson, T., Landi, M., 2024. Metabolight": how light spectra shape plant growth, development and metabolism. Physiol. Plant. 176 (6), e14587. https://doi.org/10.1111/ppl.14587.

Lehnert, M., Jirmus, R., Květoňová, V., Geletič, J., Jurek, M., Středová, H., Frajer, J., 2024. Overheated children's playgrounds in Central European cities: the effects of surfaces and shading on thermal exposure during hot summer days. Urban Clim. 55, 101873. https://doi.org/10.1016/j.uclim.2024.101873.

Li, X., Duarte, F., Ratti, C., 2021. Analyzing the obstruction effects of obstacles on light pollution caused by street lighting system in Cambridge, Massachusetts. Environ, Planning B Urban Analytics City Sci. 48 (2), 216–230. https://doi.org/10.1177/2399808319861645.

Li, D., Stucky, B.J., Deck, J., Baiser, B., Guralnick, R.P., 2019. The effect of urbanization on plant phenology depends on regional temperature. Nat. Ecol. Evol. 3 (12), 1661–1667. https://doi.org/10.1038/s41559-019-1004-1.

Lian, X., Jiao, L., Zhong, J., Jia, Q., Liu, J., Liu, Z., 2021. Artificial light pollution inhibits plant phenology advance induced by climate warming. Environ. Pollut. 291, 118110. https://doi.org/10.1016/j.envpol.2021.118110.

Liu, L., Zhang, X., 2020. Effects of temperature variability and extremes on spring phenology across the contiguous United States from 1982 to 2016. Sci. Rep. 10 (1), 17952. https://doi.org/10.1038/s41598-020-74804-4.

Lo Piccolo, E., Lauria, G., Guidi, L., Remorini, D., Massai, R., Landi, M., 2023. Shedding light on the effects of LED streetlamps on trees in urban areas: Friends or foes? Sci. Total Environ. 865, 161200 https://doi.org/10.1016/j.scitotenv.2022.161200.

Lo Piccolo, E., Lauria, G., Remorini, D., Massai, R., Guidi, L., Landi, M., 2021. Urban lighting alters chlorophyll metabolism and promotes CO2 assimilation during the night in Tilia plathyphyllos Scop. and Platanus x acerifolia (Aiton) Willd. Agrochimica 65 (4), 389–400. https://doi.org/10.12871/00021857202146.

Lo Piccolo, E.L., Torre, S., Lauria, G., De Quattro, C., Sebastiani, F., Guidi, L., Remorini, D., Massai, R., Landi, M., 2024. LED streetlamps alter tree architecture, downregulate the photosynthetic process and alter the sugar metabolism of *Populus alba* L. Environ. Exp. Bot., 105861 https://doi.org/10.1016/j.envexpbot.2024.105861.

Lukasová, V., Škvareninová, J., Bičárová, S., Sitárová, Z., Hlavatá, H., Borsányi, P., Škvarenina, J., 2021. Regional and altitudinal aspects in summer heatwave intensification in the Western Carpathians. Theor. Appl. Climatol. 146, 1111–1125. https://doi.org/10.1007/s00704-021-03789-5.

Massetti, L., 2018. Assessing the impact of street lighting on *Platanusxacerifolia* phenology. Urban For. Urban Green. 34, 71–77. https://doi.org/10.1016/j.ufug.2018.05.015.

Massetti, L., 2020. Drivers of artificial light at night variability in urban, rural and remote areas. J. Quant. Spectrosc. Radiat. Transf. 255, 107250. https://doi.org/10.1016/j.jqsrt.2020.107250.

Massetti, L., Petralli, M., Napoli, M., Brandani, G., Orlandini, S., Pearlmutter, D., 2019. Effects of deciduous shade trees on surface temperature and pedestrian thermal stress during summer and autumn. Int. J. Biometeorol. 63, 467–479. https://doi.org/10.1007/s00484-019-01678-1.

Matzke, E.B., 1936. The effect of street lights in delaying leaf-fall in certain trees. Am. J. Bot. 23 (6), 446–452. https://doi.org/10.2307/2436035.

Meier, U., 1997. Growth stages of plants – Entwicklungsstadien von Pflanzen– Estadios de las plants – Development des Plantes. Blackwell Wissenschaftsverlag. BBCH-Monograph, Berlin und Wien, p. 622.

Meng, L., Mao, J., Zhou, Y., Richardson, A.D., Lee, X., Thornton, P.E., Ricciuto, M., Xuercao, L., Yongiju, D., Xiaoying, S., Jia, G., 2020. Urban warming advances spring phenology but reduces the response of phenology to temperature in the conterminous United States. Proc. Natl. Acad. Sci. 117 (8), 4228–4233. https://doi.org/10.1073/pnas.1911117117.

Meng, L., Zhou, Y., Román, M.O., Stokes, E.C., Wang, Z., Asrar, G.R., Mao, J., Richardson, A.D., Gu, L., Wang, Y., 2022. Artificial light at night: an underappreciated effect on phenology of deciduous woody plants. PNAS Nexus 1 (2), pgac046. https://doi.org/10.1093/pnasnexus/pgac046.

Murphy, S.M., Vyas, D.K., Sher, A.A., Grenis, K., 2022. Light pollution affects invasive and native plant traits important to plant competition and herbivorous insects. Biol. Invasions 1–4. https://doi.org/10.1007/s10530-021-02670-w.

Ordóñez, C., Duinker, P.N., 2014. Assessing the vulnerability of urban forests to climate change. Environ. Rev. 22 (3), 311–321. https://doi.org/10.1139/er-2013-0078.

Pereira, J.S., Kozlowski, T.T., 1978. Diurnal and seasonal changes in water balance of *Acer saccharum* and *Betula papyrifera*. Physiol. Plant. 43 (1), 19–30. https://doi.org/10.1111/j.1399-3054.1978.tb01561.x.

Piccolo, E.L., Lauria, G., Guidi, L., Remorini, D., Massai, R., Landi, M., 2023. Shedding light on the effects of LED streetlamps on trees in urban areas: Friends or foes? Sci. Total Environ. 865, 161200. https://doi.org/10.1016/j.scitotenv.2022.161200.

Sarala, M., Tahkokorpi, M., Niinimaa, A., Laine, K., Taulavuori, E., Taulavuori, K., 2013. Street lamp light does not delay autumnal leaf colouration of *Betula pendula*. Trees 27 (4), 1193–1199. https://doi.org/10.1007/s00468-013-0841-9.

Singhal, R.K., Chauhan, J., Jatav, H.S., Rajput, V.D., Singh, G.S., Bose, B., 2021. Artificial night light alters ecosystem services provided by biotic components. Biol. Futur. 72, 169–185. https://doi.org/10.1007/s42977-020-00065-x.

Singhal, R.K., Kumar, M., Bose, B., 2019. Eco-physiological responses of artificial night light pollution in plants. Russ. J. Plant Physiol. 66, 190–202. https://doi.org/10.1134/S1021443719020134.

Škvareninová, J., Tuhárska, M., Škvarenina, J., Babálová, D., Slobodníková, L., Slobodník, B., Středová, H., Mindas, J., 2017. Effects of light pollution on tree phenology in the urban environment. Morav. Geogr. Rep. 25 (4), 282–290. https://doi.org/10.1515/mgr-2017-0024.

Smith, J.D., 2020. Impact of the Urban Heat Mosaic on the Leaf Senescence in Two Acer Species. University Honors Theses. 833 p. https://doi.org/10.15760/honors.852 species in a temperate forestPlants10215510.3390/plants10102155.

Středová, H., Chuchma, F., Rožnovský, J., Středa, T., 2021. Local climate zones, land surface temperature and air temperature interactions: case study of Hradec Králové, the Czech Republic. ISPRS Int. J. GeoInf. 10 (10), 704. https://doi.org/10.3390/ijgi10100704.

Střelcová, K., 2013. Climatic conditions in Zvolen and surroundings. In: Bebej, J. (Ed.), Príroda, Zvolen City Monograph. Zvolen Town Office, pp. 22–35.

Taştan, G.G.K., İplik, I., Yağmur, Ş., 2023. Practical Evaluation of Light Pollution Problem in Urban Lighting with "Decision Tree" Method. A+ Arch Design International. J. Archit. Des. 9 (2), 84–100.

Valladares, F., Niinemets, Ü., 2007. The architecture of plant crowns: from design rules to light capture and performance. Functional plant ecology (pp. 101-150). CRC Press.

Wang, L., Meng, L., Richardson, A.D., Hölker, F., Li, H., Mao, J., Longcore, T., Xia, L., She, D., 2025. Artificial light at night outweighs temperature in lengthening urban growing seasons. Nat. Cities 2, 506–517. https://doi.org/10.1038/s44284-025-00258-2.

Wang, T., Ottlé, C., Peng, S., Janssens, I.A., Lin, X., Poulter, B., Yue, Ch, Ciais, P., 2014. The influence of local spring temperature variance on temperature sensitivity of spring phenology. Glob. Change Biol. 20 (5), 1473–1480. https://doi.org/10.1111/gcb.12509.

Way, D.A., Montgomery, R.A., 2015. Photoperiod constraints on tree phenology, performance and migration in a warming world. Plant Cell Environ. 38 (9), 1725–1736. https://doi.org/10.1111/pce.12431.

Wei, Y., Li, Z., Zhang, J., Hu, D., 2023. Influence of night-time light pollution on the photosynthesis and physiological characteristics of the urban plants *Euonymus japonicus* and *Rosa hybrida*. Ecol. Process 12, 38. https://doi.org/10.1186/s13717-023-00449-6.

Wohlfahrt, G., Tomelleri, E., Hammerle, A., 2019. The urban imprint on plant phenology. Nat. Ecol. Evol. 3 (12), 1668–1674. https://doi.org/10.1038/s41559-019-1017-9.

Yan, M., Chen, L., Leng, S., Sun, R., 2023. Effects of local background climate on urban vegetation cooling and humidification: Variations and thresholds. Urban For. Urban Green. 80, 127840. https://doi.org/10.1016/j.ufug.2023.127840.

Yang, Y., Qiu, X., Yang, L., Lee, D., 2023. Impacts of Thermal Differences in Surfacing Urban Heat Islands on Vegetation Phenology. Remote Sens. 15 (21), 5133. https://doi.org/10.3390/rs15215133.

Zhang, S., Dai, J., Ge, Q., 2020. Responses of autumn phenology to climate change and the correlations of plant hormone regulation. Sci. Rep. 10 (1), 9039. https://doi.org/10.1038/s41598-020-65704-8.

Zheng, Q., Teo, H.C., Koh, L.P., 2021. Artificial light at night advances spring phenology in the United States. Remote Sens 13, 399. https://doi.org/10.3390/rs13030399.