



Microclimatic influence and water state characteristics of introduced tree species in urban park stands

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The article presented the results of research on the potential ability of introduced tree species to develop microclimatic conditions of urban green spaces in the Steppe zone (using the example of park plantings in Dnipro city). The goal of the work was to determine the role of introduced tree species in optimizing the air and soil temperature and humidity, taking into account the species-specific features of leaf water state. The research was conducted in Taras Shevchenko Central Culture and Leisure Park and Ivan Starov Square during the growing season, 2023. Temperature and humidity measurements in atmospheric air and soil, and measurements of leaf physiological traits were taken using modern devices and classical techniques. The objects of research were 12 introduced tree species aged 40–50 years: *Acer negundo* L., *Acer saccharum* Marshall, *Aesculus hippocastanum* L., *Ailanthus altissima* (Mill.) Swingle, *Celtis occidentalis* L., *Fraxinus pennsylvanica* Marshall, *Gleditsia triacanthos* L., *Gymnocladus dioica* (L.) K. Koch, *Robinia pseudoacacia* L., *Ulmus pumila* L., *Quercus rubra* L., *Styphnolobium japonicum* (L.) Schott. The research outputs showed that during daylight hours air temperature decreased by an average of 1–2 °C, and relative humidity increased by 3–5% beneath the tree crowns compared to open sites. The soil temperature within the crown projection area was 2–4 °C lower, while the humidity almost doubled. Indicators of the leaf water state (Relative Water Content and Water Deficit) revealed significant interspecific differences. So, *S. japonicum*, and *A. altissima* were characterized by a high relative water content, whereas *A. hippocastanum* and *Q. rubra* showed lower values and a greater lack of moisture. The outputs of cluster analysis allowed the groups of tree species to be distinguished based on their sustainability and phytoclimatic effects. This indicates the feasibility of combined use of different tree species in formation of urban plantings having significant regulatory functions.

Keywords: introduced tree species; urban plantings; microclimate; relative water content; water deficit.

Introduction

Modern approaches to adapting cities to climate change are based on optimizing the ecological functionality of green infrastructure and prioritizing ecosystem services over socio-cultural ones (Gómez-Baggethun & Barton, 2013; Wong, et al., 2018). Moreover, tree stands were recognized to have the greatest potential to control and counteract the consequences of global climate change, reducing the effect of "urban heat islands" and promoting the development of comfortable conditions for people due to their significant climate-regulating effect (Hardin & Jensen, 2007). By data of Zölch et al. (2016), tree stands provide a 13% reduction in Physiological Equivalent Temperature in recreational areas compared to other types of urban vegetation.

Urban tree stands are crucial for microclimate regulation in urbanized areas (Kunakh et al., 2022; Shupranova et al., 2022), which is particularly important due to the negative impact of climate change manifestations. They provide a decrease in air and soil temperature during the warm season and significantly affect dynamics of water circulation by shading, reducing surface albedo, evapotranspiration, interception, changes in soil infiltration properties and reducing surface runoff (Livesley et al., 2016; Berland et al., 2017; Rahman et al., 2020b; Ponte et al., 2021). A generalized analysis of the cooling effect of woody vegetation in 17 climatic zones proved a peak monthly temperature to be decreased to below 26°C in 83% of the cities studied worldwide (110 cities) (Li et al., 2024).

Numerous scientific studies emphasize species specificity in the processes of microclimate modification by different tree species, which is primarily due to differences in the geometry, size and light transmission of crowns, leaf surface index, and leaf morphology, wood anatomy, physiological traits of their moisture circulation (Rah-

man et al., 2015, 2019, 2020a, 2020b; Helletsgruber et al., 2020; Feng et al., 2023; Zhang & Brookhouse, 2025). On the same note, microclimatic effects can vary significantly between different species. Based on the outputs of a meta-analysis conducted by Rahman et al. (2020b), the cooling capacity can vary fourfold between different tree species. In street plantings of German cities, Rahman et al. (2020a) established that air temperature decreased an average of 2.8 °C in *Tilia cordata* crowns, and 1.9 °C in *Robinia pseudoacacia* crowns relative to open sites during the summer period; transpiration activity in *T. cordata* increased fourfold compared to *R. pseudoacacia*. In green plantings of cities in Central Europe, Helletsgruber et al. (2020) noted a decrease in average surface temperatures on hot summer days in the shaded sites of the crowns of the studied trees; *Acer platanoides*, *Aesculus hippocastanum*, *Acer platanoides* 'Globosum', *Aesculus x carnea*, *Corylus colurna*, *Platanus x hispanica* and *Tilia cordata*, with means ranging from 13.6 to 22.7 °C; *A. platanoides* 'Globosum' showed maximum cooling effect. At the same time, air cooling was observed to be maximum beneath the crowns of *T. cordata* and *C. colurna* trees. This indicates the expediency of taking into account the peculiarities of microclimatic influences of certain tree species in the construction of various types of urban plantings, especially in conditions of global warming and increasing the "heat waves" intensity.

The specifics of water use strategies by tree species affects the evapotranspirative cooling of air, as well as functionality and condition of tree species during periods of water deficit (Rahman et al., 2015; Richter et al., 2022). At the same time, the features of the water state in dendroflora species can be considered from several positions: as a factor in the development of cooling and moisturizing effects in the crown area due to transpiration (Richter et al., 2022; Feng et al., 2023), and as an indicator of physiological adaptations and the current

state of plants in response to soil-hydrological and climatic conditions of growth, in particular water or high-temperature stress (Toscano et al., 2019; Lykholat et al., 2022). Direct exposure to tree transpiration was reported to be able to provide cooling effect on atmospheric air near and within crowns by 1–8 °C (Georgi & Zafiriadis, 2006; Rahman et al., 2020b). The potential resistance of tree species to unfavorable zonal factors and manifestations of global climate change is a prerequisite for their full performance of regulatory functions.

Nowadays, increase in share of alien tree species in urban green spaces is considered to be the current global trend, and they have already become the basis of the dendroflora diversity in European cities (Schlaepfer et al., 2020; Marinšek et al., 2022). Directly in Dnipro city, the fraction of alien taxa makes up 79% (265 species and subspecies) of the dendroflora of urban green spaces (excluding our own collections and the Botanical Garden of Oles Honchar Dnipro National University) (Ivanko et al., 2024). At the same time, introduced trees are believed to be able to enrich dendroflora and perform important ecosystem services on the same level as autochthonous species (Schlaepfer et al., 2020). So, the issue of potential regulatory capabilities of introduced species and characteristics of their water state under conditions of cities in Steppe zone remains relevant, despite a significant amount of information on the role of tree stands and individual species in the formation of microclimatic parameters in the urban environment. Rational planning of urban green spaces with consideration of specific tree characteristics is crucial for implementing a strategy to adapt cities to climate change.

Materials and methods

The research was conducted in green recreational areas of the large industrial city, Dnipro (Ukraine): Taras Shevchenko Central Culture and Leisure Park (48°27'40" N, 35°04'21" E) (its right-bank part) and Ivan Starov Square (48°27'27" N, 35°03'55" E). The park and the square are located close to each other at a distance of about 240 m. The area of the park together with its island part occupies 45 hectares, and the square area is 14 hectares.

Dnipro city is located in Steppe zone with a temperate continental climate (Gorb & Duk, 2006). The climate of the Dnipropetrovsk region is often characterized by hot, dry summers and relatively cool, humid winters. Winter is characterized by unstable snow cover and periodic thaws. The average annual air temperature in the city is +8.5 °C. The territory occupied by Dnipro city belongs to the zone of unstable moisture. Here, in summer, there are constant rainless periods lasting from 20 to 40 days. The average annual precipitation is 507 mm. Despite the rather difficult climatic conditions for the growth and normal functioning of woody and shrubby vegetation, Dnipro city is characterized by significant dendrological diversity (331 species and 3 subspecies in 44 families) (Ivanko et al., 2024).

Taras Shevchenko Central Culture and Leisure Park and Ivan Starov Square are located in the historical part of the city; their landscaping with trees and shrubs began during the initial urban development of Dnipro city. So, the modern Taras Shevchenko Central Culture and Leisure Park are located on the site of the former Prince Potemkin Garden created in 1789–1794 (Ivanko et al., 2024). Today it is an object of the Nature Reserve Fund of Ukraine, namely as a park-monument of landscape gardening art of national significance.

Research areas within Taras Shevchenko Central Culture and Leisure Park are located on a plateau in the upper third of the south-facing slope with a transition to watershed (slope of 3–4°); areas within Ivan Starov Square located on watershed are similar in soil and hydrological conditions. According to the WRB classification (IUSS Working Group WRB, 2022), the soils of the studied areas are represented by Hortic Anthrosols (Siltic, Eutric) within Taras Shevchenko Central Culture and Leisure Park, and by Hortic Anthrosols (Siltic, Eutric) in Ivan Starov Square these soils are potentially suitable for woody and shrubby vegetation growth (Didur et al., 2024).

The objects of research within the areas of the park and the square were introduced tree species widely distributed in urban green spaces of the Steppe zone of Ukraine (*Acer negundo* L., *Acer saccharum* Marshall, *Aesculus hippocastanum* L., *Ailanthus altissima* (Mill.)

Swingle, *Celtis occidentalis* L., *Fraxinus pennsylvanica* Marshall, *Gleditsia triacanthos* L., *Robinia pseudoacacia* L., *Styphnolobium japonicum* (L.) Schott, *Ulmus pumila* L.), and those quite occasionally represented in the species composition of dendroflora in parks and squares (*Gymnocladus dioica* (L.) K. Koch, *Quercus rubra* L.). Specific names of the trees were presented using the modern POWO database. For the study, by 1 specimen of each tree species was selected without signs of diseases, crown and trunk damage in the same age group (from 40 to 50 years).

Microclimatic measurements beneath the tree crowns (temperature, relative humidity, topsoil temperature and humidity) and leaf sampling to determine Relative Water Content (RWC) and Water Deficit (WD) were carried out during the growing season (June to August) of 2023, once a week. Additionally, studies were conducted on the hottest possible days (13.06.2023, 26.07.2023 and 06.08.2023). Microclimatic measurements were carried out from 06.00 a.m. to 06.00 p.m. beneath the canopies of trees in the cardinal directions in triplicate. Leaf samples were taken in the morning (6–7 a.m.), noon (12 a.m. – 01 p.m.), and evening (05–06 p.m.) of the middle part of the crown in quadruplicate.

Soil moisture was measured with the MG–44 device (Ukraine) at a depth of 0–10 cm. The soil temperature in a layer of 5–10 cm was measured with a digital thermometer TC–3M (Ukraine). The temperature and relative humidity of atmospheric air at an altitude of 1.3 m were measured using a temperature and humidity recorder HUATO HE–173 (China).

Being classical physiological indicators that characterize the plant water state, Relative Water Content (RWC) and Water Deficit (WD) in tree leaves were determined by die-cutting. The mass of fresh, turgid and dry leaf tissue was measured. From the tree leaves, the discs were cut out (with a 1 cm-diameter punch), which were weighed in stages: Fresh Weight (FW) – fresh mass of the leaf immediately after harvest; Turgid Weight (TW) – mass after complete saturation with water; Dry Weight (DW) – mass after drying to a constant weight.

Relative Water Content (RWC, %):

$$RWC = \frac{FD - DW}{DW} * 100\%$$

Water deficit (WD, %):

$$WD = 100\% - \frac{FD - DW}{TW - DW} * 100\%$$

Statistical calculations performed using a Language and Environment for Statistical Computing R (R Core Team, 2020). R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org.

Results

Information on time in the diurnal aspect, day-to-day differences, and the influence of tree species were able to explain 66% of the variability in air temperature in the crown projection area during daylight hours (Table 1).

The lowest average air temperature was 28.3 ± 0.9 °C, and the highest was 30.3 ± 1.0 °C. The highest air temperature was observed beneath the canopy of such tree species as *Acer negundo* L., *Gleditsia triacanthos* L., *Styphnolobium japonicum* (L.) Schott, and the lowest was observed beneath the canopy *Acer saccharum* Marshall, *Ulmus pumila* L., *Celtis occidentalis* L. (Fig. 1).

The factors studied were able to explain 79% of the variability of relative humidity in the undercanopy space of the species studied. Humidity ranged from 47.2 ± 1.8% to 51.2 ± 1.6%. The highest values of relative air humidity were observed beneath the canopies of *Fraxinus pennsylvanica* Marshall, *Ailanthus altissima* (Mill.) Swingle, *Aesculus hippocastanum* L., and the smallest ones were beneath the canopy of *Gleditsia triacanthos* L., *Styphnolobium japonicum* (L.) Schott, *Acer negundo* L. Information on time in the diurnal aspect, day-to-day differences, and the influence of tree species were able to explain 67% of the variability in soil temperature beneath the tree canopies. The lowest average soil temperature was 22.3 ± 0.6 °C, and the highest was 26.0 ± 0.9 °C. The greatest values of soil temperature were observed beneath the canopies of *Styphnolobium japonicum* (L.) Schott, *Gymnocladus dioica* (L.) K. Koch, *Aesculus hippocastanum*

L., and the lowest ones were observed beneath the canopies of *Ulmus pumila* L., *Celtis occidentalis* L., *Quercus rubra* L. (Fig. 2).

Trees of different species were able to lower the soil temperature compared to the air temperature by 2.1–3.2%. *Fraxinus pennsylvani-*

ca, *Acer saccharum*, *Aesculus hippocastanum* had the most influence on reducing of soil temperature, and *Ailanthus altissima*, *Robinia pseudoacacia*, *Styphnolobium japonicum* had the smallest effect.

Table 1

Assessment of General Linear Models on the impact of date, time, and tree species on climatic variables ('*' indicates a statistically significant difference from the reference level of the corresponding predictor)

Predictor	Air temperature		Air humidity		Soil temperature		Soil water content	
	F(15, 524) = 70.76, P < 0.001, R _{adj} ² = 0.66	F(15, 524) = 133.87, P < 0.001, R _{adj} ² = 0.79	F(15, 524) = 75.12, P < 0.001, R _{adj} ² = 0.67	F(15, 524) = 125.93, P < 0.001, R _{adj} ² = 0.78				
Date ¹	13.06.23	-1.39 ± 0.06*	1.38 ± 0.05*	-1.50 ± 0.06*	1.36 ± 0.05*			
	26.07.23	-0.53 ± 0.06*	0.52 ± 0.05*	-0.05 ± 0.06	-0.65 ± 0.05*			
Time ²	Midday	0.25 ± 0.06*	-0.15 ± 0.05*	-0.22 ± 0.06*	0.04 ± 0.05			
	Morning	-1.07 ± 0.06*	1.35 ± 0.05*	-0.93 ± 0.06*	0.08 ± 0.05			
Species ³	<i>A. saccharum</i>	-0.08 ± 0.12	-0.15 ± 0.10	-0.37 ± 0.12*	-0.23 ± 0.10*			
	<i>U. pumila</i>	-0.08 ± 0.12	-0.18 ± 0.10	-0.73 ± 0.12*	0.19 ± 0.10			
	<i>C. occidentalis</i>	-0.07 ± 0.12	-0.10 ± 0.10	-0.64 ± 0.12*	-0.18 ± 0.10			
	<i>G. triacanthos</i>	0.19 ± 0.12	-0.36 ± 0.10*	-0.35 ± 0.12*	-0.54 ± 0.10*			
	<i>S. japonicum</i>	0.26 ± 0.12*	-0.21 ± 0.10*	-0.28 ± 0.12*	0.04 ± 0.10			
	<i>F. pennsylvanica</i>	0.13 ± 0.12	-0.09 ± 0.10	-0.33 ± 0.12*	-0.24 ± 0.10*			
	<i>R. pseudoacacia</i>	0.11 ± 0.12	-0.21 ± 0.10*	-0.36 ± 0.12*	0.16 ± 0.10			
	<i>Q. rubra</i>	-0.05 ± 0.12	-0.13 ± 0.10	-0.42 ± 0.12*	0.47 ± 0.10*			
	<i>A. altissima</i>	0.06 ± 0.12	-0.02 ± 0.10	-0.42 ± 0.12*	0.43 ± 0.10*			
	<i>G. dioica</i>	0.03 ± 0.12	-0.11 ± 0.10	-0.07 ± 0.12	-0.15 ± 0.10			
	<i>A. negundo</i>	0.16 ± 0.12	-0.21 ± 0.10*	-0.41 ± 0.12*	-0.17 ± 0.10			

Notes: 1 – 06.08.23 is the reference value for the Date predictor; 2 – evening is the reference value for the time predictor; 3 – *A. hippocastanum* is the reference value for the species predictor.

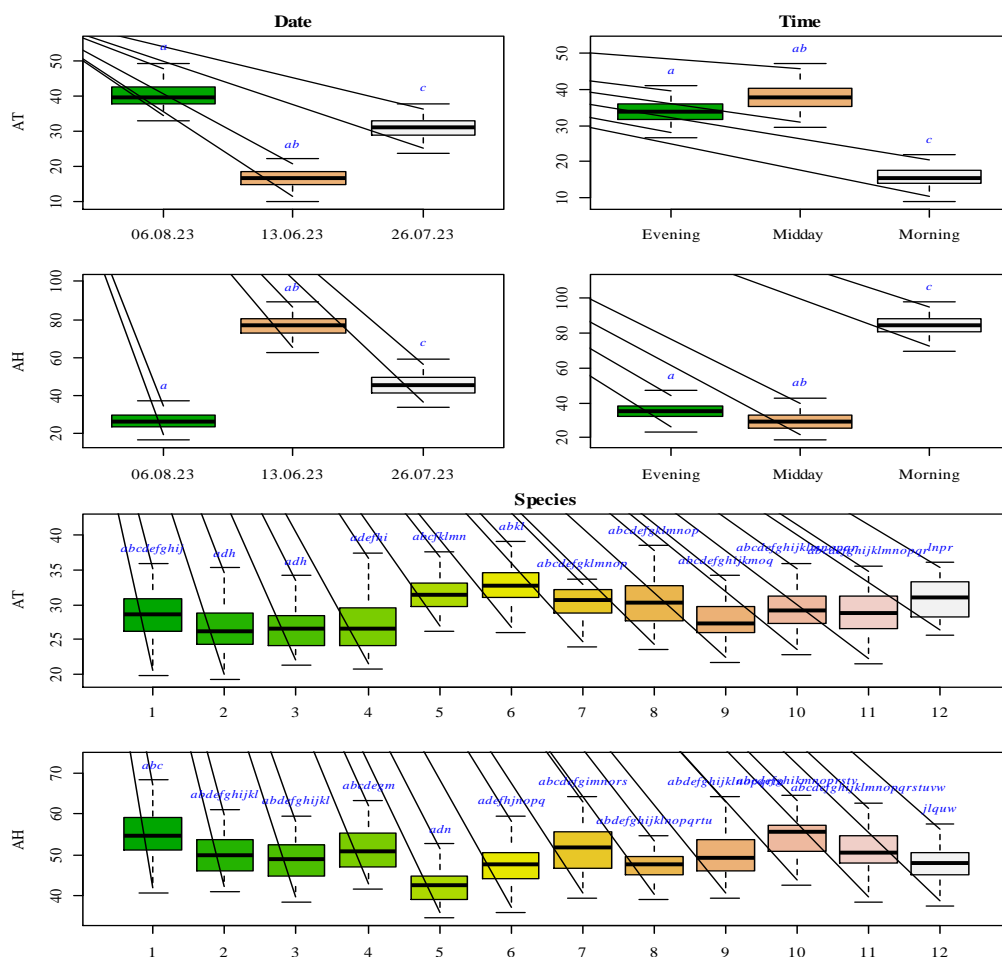


Fig. 1. Boxplot of the variability of air temperature (AT, °C) and air humidity (AH, %) depending on the date, time, and trees species: the box plot displays the interquartile range, which encompasses the first quartile (Q₁, 25%) and the third quartile (Q₃, 75%), with the median (Q₂, 50%) represented by the line within the box; the whiskers indicate the minimum and maximum values that are not classified as outliers; according to the Tukey test, identical letters denote levels of factors statistically indistinguishable at a significance level of P < 0.05, while differing letters indicate levels of factors statistically significantly different; species: 1 – *Aesculus hippocastanum* L., 2 – *Acer saccharum* Marshall, 3 – *Ulmus pumila* L., 4 – *Celtis occidentalis* L., 5 – *Gleditsia triacanthos* L., 6 – *Styphnolobium japonicum* (L.) Schott, 7 – *Fraxinus pennsylvanica* Marshall, 8 – *Robinia pseudoacacia* L., 9 – *Quercus rubra* L., 10 – *Ailanthus altissima* (Mill.) Swingle, 11 – *Gymnocladus dioica* (L.) K. Koch, 12 – *Acer negundo* L.

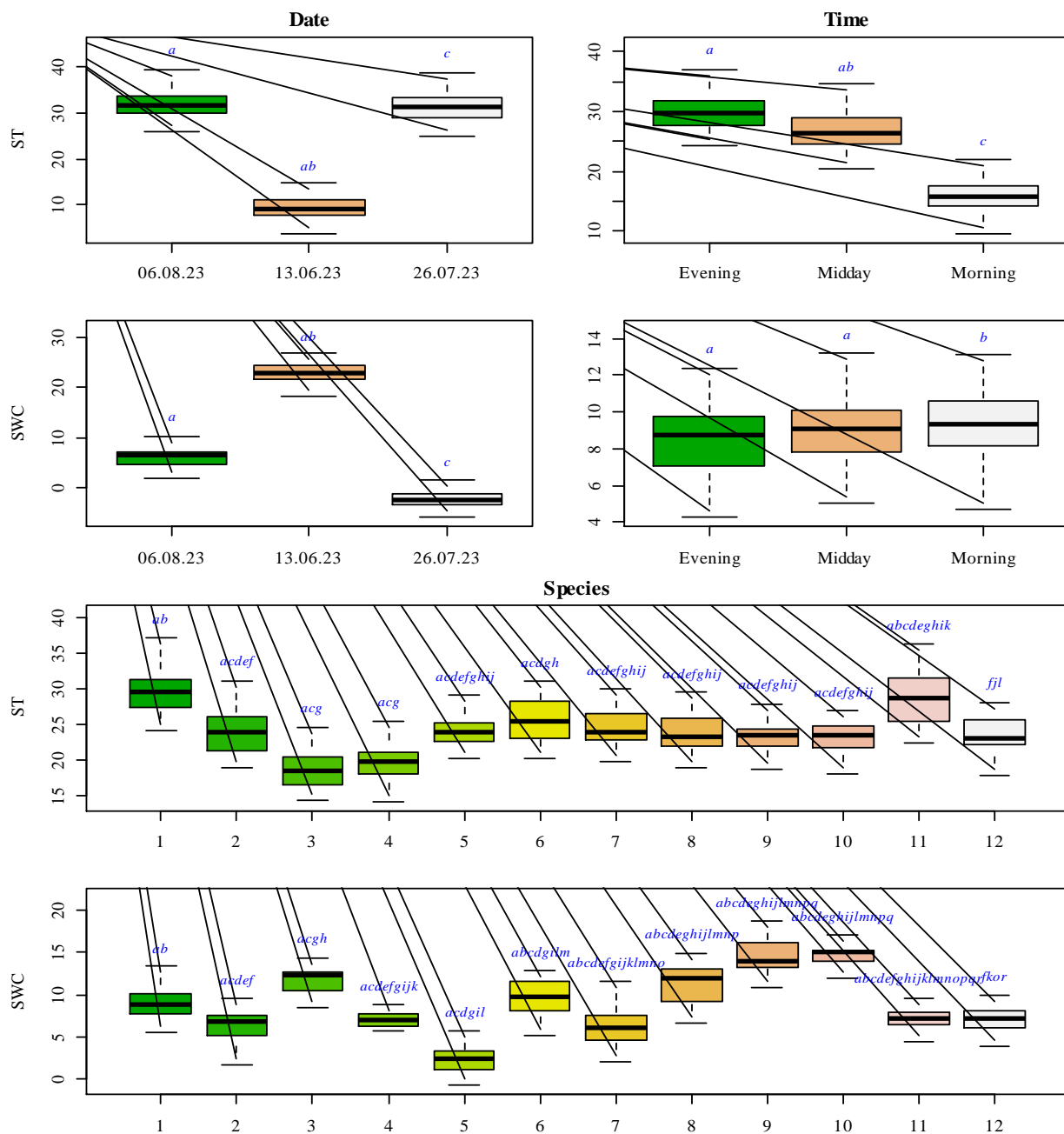


Fig. 2. Boxplot of the variability of soil temperature (ST, °C) and soil water content (SWC, %) depending on the date, time, and tree species: the box plot displays the interquartile range, which encompasses the first quartile (Q₁, 25%) and the third quartile (Q₃, 75%), with the median (Q₂, 50%) represented by the line within the box; the whiskers indicate the minimum and maximum values not classified as outliers; according to the Tukey test, identical letters denote levels of factors statistically indistinguishable at a significance level of P < 0.05, while differing letters indicate levels of factors that are statistically significantly different; species: 1 – *Aesculus hippocastanum* L., 2 – *Acer saccharum* Marshall, 3 – *Ulmus pumila* L., 4 – *Celtis occidentalis* L., 5 – *Gleditsia triacanthos* L., 6 – *Styphnolobium japonicum* (L.) Schott, 7 – *Fraxinus pennsylvanica* Marshall, 8 – *Robinia pseudoacacia* L., 9 – *Quercus rubra* L., 10 – *Ailanthus altissima* (Mill.) Swingle, 11 – *Gymnocladus dioica* (L.) K. Koch, 12 – *Acer negundo* L.

The factors studied were able to explain 78% of the variability in soil water content. Soil water content ranged from $6.7 \pm 0.5\%$ to $11.0 \pm 0.6\%$. The largest values of soil water content were observed beneath the canopies of such tree species as *Ulmus pumila*, *Ailanthus altissima*, *Quercus rubra*, and the smallest ones were observed beneath the canopies of *Gleditsia triacanthos*, *Fraxinus pennsylvanica*, *Acer saccharum* trees.

Information on time in the diurnal aspect, day-to-day differences, and the influence of tree species were able to explain 86% of the variability in relative water content in the tree leaves (Table 2).

The lowest average relative water content was $58.4 \pm 0.8\%$, and the highest one was $76.3 \pm 0.5\%$. The greatest relative water content was observed in the leaves of *Styphnolobium japonicum*, *Acer negundo*, *Ailanthus altissima*, and the smallest one was in leaves of

Quercus rubra, *Aesculus hippocastanum*, *Gleditsia triacanthos* (Fig. 3). Information on time in the diurnal aspect, day-to-day differences, and the influence of tree species were able to explain 73% of the water deficit variability in tree leaves. The lowest average water deficit was $11.2 \pm 1.2\%$, and the highest was $24.2 \pm 0.8\%$. The greatest water deficit was observed in the leaves of *Fraxinus pennsylvanica*, *Aesculus hippocastanum*, *Gymnocladus dioica*, and the smallest one was in the leaves of *Styphnolobium japonicum*, *Celtis occidentalis*, *Ulmus pumila*.

Discriminant analysis was performed based on environment parameters beneath the canopy of tree species and physiological traits of their leaves. On the outputs, a matrix of Mahalanobis distances between tree species was obtained, and cluster analysis was performed (Fig. 4).

Table 2

Assessment of General Linear Models on the impact of date, time, tree species, air temperature, air humidity, soil temperature, and soil water content on relative water content and water deficit in the tree leaves (** indicates a statistically significant difference from the reference level of the corresponding predictor)

Predictor	Relative water content $F(19, 520) = 179.75$, $P < 0.001$, $R_{adj}^2 = 0.86$		Water deficit $F(19, 520) = 76.29$, $P < 0.001$, $R_{adj}^2 = 0.73$	
Date ¹	13.06.2023	0.07 ± 0.10	0.05 ± 0.14	
	26.07.2023	0.20 ± 0.06*	-0.55 ± 0.08*	
Time ²	midday	-0.15 ± 0.05*	0.72 ± 0.06*	
	morning	-0.13 ± 0.08	-0.43 ± 0.11*	
Species ³	<i>A. saccharum</i>	0.55 ± 0.09*	-1.09 ± 0.12*	
	<i>U. pumila</i>	0.77 ± 0.09*	-0.95 ± 0.12*	
	<i>C. occidentalis</i>	0.16 ± 0.09	-1.23 ± 0.12*	
	<i>G. triacanthos</i>	0.29 ± 0.09*	-0.95 ± 0.13*	
	<i>S. japonicum</i>	1.59 ± 0.09*	-1.40 ± 0.12*	
	<i>F. pennsylvanica</i>	0.33 ± 0.09*	-0.51 ± 0.12*	
	<i>R. pseudoacacia</i>	0.97 ± 0.09*	-0.85 ± 0.12*	
	<i>Q. rubra</i>	-0.80 ± 0.09*	-0.54 ± 0.12*	
	<i>A. altissima</i>	2.08 ± 0.09*	-0.51 ± 0.12*	
	<i>G. dioica</i>	0.74 ± 0.09*	0.27 ± 0.12*	
	<i>A. negundo</i>	2.15 ± 0.09*	-0.98 ± 0.12*	
	Environment	air temperature	-0.06 ± 0.03	0.06 ± 0.04
predic-	air humidity	0.07 ± 0.04	0.00 ± 0.05	
tors	soiltemperature	-0.16 ± 0.03*	0.25 ± 0.04*	
	soilwatercontent	0.19 ± 0.04*	-0.17 ± 0.05*	

Notes: 1 – 06.08.2023 is the reference value for the date predictor; 2 – evening is the reference value for the time predictor; 3 – *A. hippocastanum* is the reference value for the Species predictor.

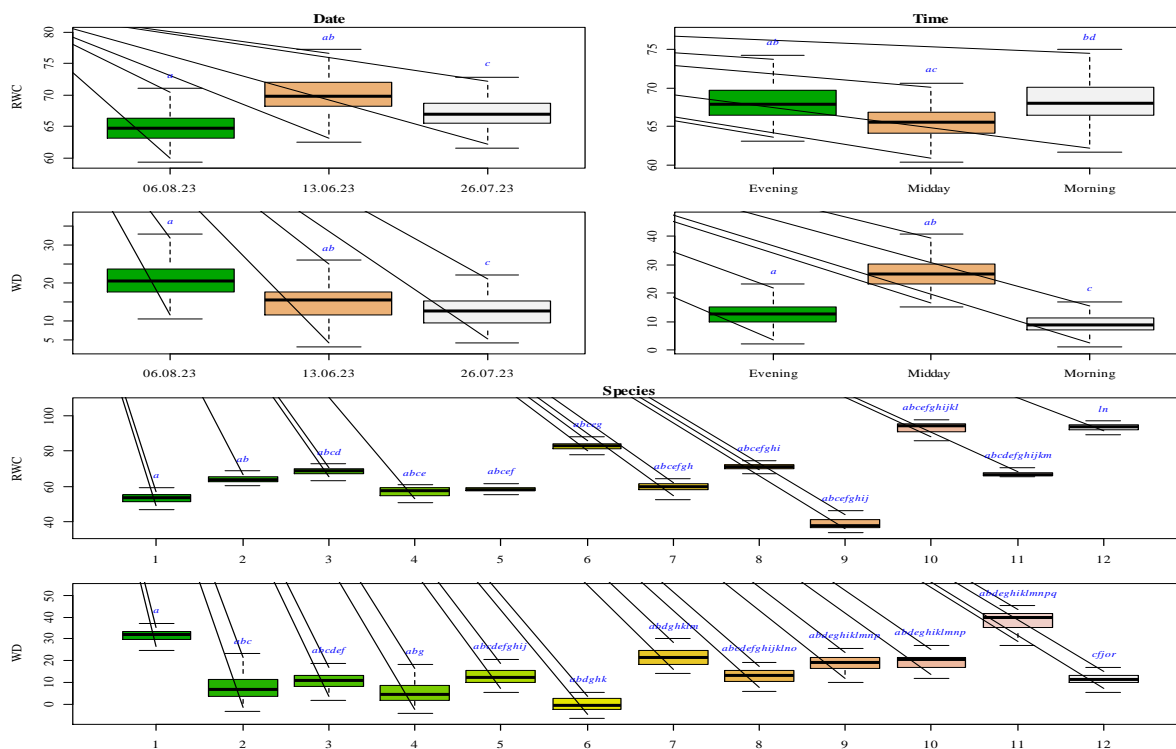


Fig. 3. Boxplot of the variability of relative water content (RWC, %) and water deficit (WD, %) depending on the date, time, and tree species with air temperature, air humidity, soil temperature, and soil water content as covariates: the box plot displays the interquartile range, which encompasses the first quartile (Q₁, 25%) and the third quartile (Q₃, 75%), with the median (Q₂, 50%) represented by the line within the box; the whiskers indicate the minimum and maximum values not classified as outliers; according to the Tukey test, identical letters denote levels of factors statistically indistinguishable at a significance level of $P < 0.05$, while differing letters indicate levels of factors statistically significantly different; species: 1 – *Aesculus hippocastanum* L., 2 – *Acer saccharum* Marshall, 3 – *Ulmus pumila* L., 4 – *Celtis occidentalis* L., 5 – *Gleditsia triacanthos* L., 6 – *Styphnolobium japonicum* (L.) Schott, 7 – *Fraxinus pennsylvanica* Marshall, 8 – *Robinia pseudoacacia* L., 9 – *Quercus rubra* L., 10 – *Ailanthus altissima* (Mill.) Swingle, 11 – *Gymnocladus dioica* (L.) K. Koch, 12 – *Acer negundo* L.

As the analysis outputs, 4 homogeneous groups of trees were identified. Cluster 3 was distinguished from the other clusters in higher air temperature (Planned comparison $F = 3.7$, $P = 0.05$), while difference between other clusters was not found (Planned comparison $F =$

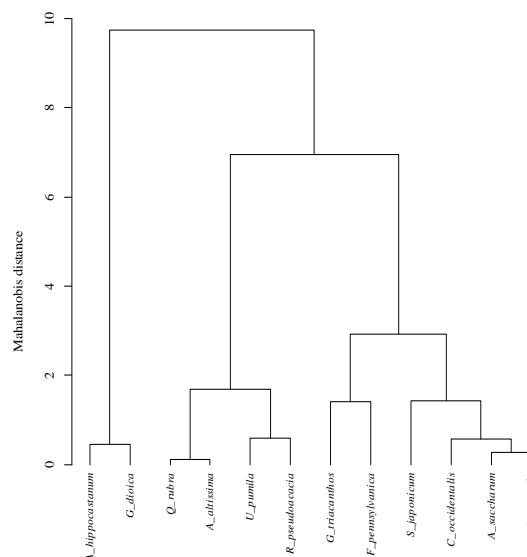


Fig. 4. Cluster analysis of tree species based on their water properties and their impact on the phytoclimatic regime of air and soil (using Mahalanobis distance and Ward's method): Cluster 1: *Aesculus hippocastanum* L. and *Gymnocladus dioica* (L.) K. Koch; Cluster 2: *Ailanthus altissima* (Mill.) Swingle, *Quercus rubra* L., *Robinia pseudoacacia* L. and *Ulmus pumila* L.; Cluster 3: *Fraxinus pennsylvanica* Marshall, *Gleditsia triacanthos* L. and *Styphnolobium japonicum* (L.) Schott; Cluster 4: *Acer negundo* L., *Acer saccharum* Marshall. and *Celtis occidentalis* L. *Styphnolobium japonicum* (L.) Schott

1.6, $P = 0.27$). Cluster 3 was distinguished from all others in lower humidity (Planned comparison $F = 4.1$, $P = 0.04$), and Cluster 1 was characterized by the highest level of this indicator (Planned comparison $F = 4.7$, $P = 0.03$). Clusters 2 and 3 had intermediate indicators of

air humidity and were not different in this indicator (Planned comparison $F = 0.4$, $P = 0.54$). The soil temperature beneath the canopy of Cluster 1 trees was the highest (Planned comparison $F = 32.6$, $P < 0.001$). Other clusters were not different in this indicator (Planned comparison $F = 0.2$, $P = 0.65$). In terms of soil moisture beneath the canopy of trees, the clusters differed statistically significantly ($F = 248.8$, $P < 0.001$). According to the level of soil moisture beneath the canopy of trees, the clusters can be ordered as follows (from highest level to lowest): Cluster 2 → Cluster 1 → Cluster 4 → Cluster 3.

Discussion

The ability of urban trees to change the microclimate is a key factor in enhancing the resistance of cities to climate change. The results of the conducted research confirmed important role of urban trees in microclimate regulation within urbanized areas. Beneath the crowns of the trees studied air temperature was found to be significantly lower, and relative humidity was found to be higher compared to open sites. This is consistent with data from other authors who note that the temperature beneath the tree canopy could drop by 1–8°C, and humidity could increase by 5–15% (Souch & Souch, 1993; Feng et al., 2023, Abdili et al., 2024). Such mitigating effects are extremely important for large industrial cities situated in Steppe zone of Ukraine, where long rainless periods up to 40 days are observed in summer. The results obtained confirm that green spaces are highly effective natural mechanisms to cool the environment; it is of direct importance for reducing heat stress in the human population.

Indicators of leaf water status (RWC and WD) showed significant interspecific differences in the ability of trees to control water balance under stressful conditions. The trees of black locust (*R. pseudo-acacia*) were characterized by lower WD values; it indicated its ability to reduce transpiration losses due to stomatal closure during drought. Similar patterns have been described by other researchers (Pepe et al. 2022). This indicates the need for careful selection of plant species for urban green spaces, depending on climatic conditions. Thus, tree species have distinct transpiration and water balance strategies, which is crucial for their use in urban landscaping.

Microclimatic measurements revealed not only a decrease in air temperature, but also a stabilization of soil temperature within the crown projection area. In shaded sites, the soil temperature was lower, and its humidity was higher than that in open sites. Similar findings were provided by Armson et al. (2013), where the combination of tree shade and the presence of grass cover reduced significantly soil surface evaporation. This suggests that urban trees not only affect the air microclimate, but also enhance the soil water regime, which is especially important in the sites covered with compacted soils with reduced natural infiltration capacity.

In addition to influencing the air microclimate, trees significantly affect the soil water state. Our findings showed a stabilization in humidity and a decrease in topsoil temperature beneath the crowns of trees. This correlates with the results of Armson et al. (2013), where shading was found to reduce a topsoil evaporation and also to promote moisture infiltration. Similar patterns were established by Kokila et al. (2024), where the trees in urban environments were proven not only to cool the environment, but also to reduce surface runoff, thereby enhancing the stability of the hydrological cycle. The mechanism of these processes is explained by a combination of shading, precipitation interception by crowns, and the contribution of root systems to improving the infiltration capacity of compacted urban soils.

Statistical analysis confirmed significant interspecific differences in terms of a complex of microclimatic and physiological parameters. GLM models demonstrated tree species to respond differently to changing of climatic conditions, and clustering allowed groups to be distinguished with similar adaptive characteristics. Such approach provides benefits for planning urban green spaces, as it allows tree species with complementary properties to be combined.

The practical value of the results obtained lies in the development of scientifically based recommendations for landscaping cities in the Steppe zone of Ukraine. Taking into account the fact that a single mature tree specimen can evaporate more than 100 liters of water per

day, the role of trees in maintaining the local water balance is extremely important. A combination of species that have high transpiration activity (*T. cordata*, *A. hippocastanum*) with drought-resistant species (*R. pseudoacacia*, *G. triacanthos*) allows a balance to be achieved between the cooling effect and the rational use of water resources. A similar approach was already introduced in the world practice to create sustainable green urban infrastructure (Feng et al., 2023). This is especially important in the conditions of Ukraine, since the projected increase in the frequency of heat waves in the coming decades may complicate significantly living conditions in large cities.

The findings were also consistent with current trends in urban ecology, which consider green spaces to be not only an aesthetic or recreational element, but also as a critical component of ecological infrastructure providing a wide-range of ecosystem services (Livesley et al., 2016; Feng et al., 2023). It is important to emphasize that these functions cannot be completely replaced by technical means without significant costs. The use of air conditioning or irrigation systems in cities requires a significantly higher energy and financial cost compared to the natural cooling and moisturizing effect of trees. Therefore, the results of our research are of practical importance for generation sustainable urban development strategies aimed at integrating green infrastructures into urban space planning.

Overall, the research confirmed urban trees to be a key element of the green infrastructure framework; they ensure a change in the microclimatic parameters of the near-ground air, a decrease in surface runoff and an increase in soil infiltration capacity (Livesley et al., 2016; Abdili, et al., 2024). Characterized by a combination of high temperatures and unstable humidity, conditions of Steppe zone of Ukraine make this function particularly relevant. At the same time, the findings obtained demonstrated that not all species were equally effective in performing such functions; this fact requires a reasonable approach to the choice of plant species for landscaping. Further research shall be conducted on long-term monitoring of the impact of climate change on the water balance and microclimatic functions of trees, as well as on the development of models for predicting the effectiveness of different species in prospective climate change scenarios. Taking into account the species specifics will increase the ecological sustainability of urbanized systems and contribute to creating a comfortable environment for urban residents.

Conclusion

Research on the influence of tree crowns of introduced species has shown that urban tree stands affected significantly the microclimatic parameters of air and soil. The air temperature was lower (28.3–30.3 °C), while the relative humidity was higher (47.2–51.2%) beneath the canopies of trees compared to open sites. In the topsoil layer, temperature decreased from 26.0 ± 0.9 °C in open sites to 22.3 ± 0.6 °C in shaded sites, while there was an increase in its humidity 6.7–11.0%. The leaf physiological traits confirmed interspecific differences in the water state of introduced tree species in urban plantings of Steppe zone. The Relative Water Content (RWC) ranged from $58.4 \pm 0.8\%$ to $76.3 \pm 0.5\%$, while the Water Deficit (WD) ranged from $11.2 \pm 1.2\%$ to $24.2 \pm 0.8\%$. This indicates the different adaptive capacity of tree species to arid conditions, which is important criterion for selecting tree species in the creation of green infrastructure. According to the GLM analysis, significant interspecific differences were established in the complex of microclimatic and physiological parameters. The cluster analysis allowed us to distinguish groups of tree species by their stability and phytoclimatic effects, which indicates the feasibility of their combined use to improve the ecological stability of green spaces. The practical significance of the research lies in the scientifically based selection of tree species for landscaping cities in Steppe zone of Ukraine in order to increase their resistance to climate change.

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