

Introduced plant species in the urban environment of the temperate-continental climate zone under conditions of global warming

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Global climate change stimulates migration, which increases the number of introduced plant species, as well as those with a status of rarity, so the aim of the study was to identify highly promising plants of rare and decorative species in Ukraine to overcome the negative impact of the "urban heat island". We selected 40 species of plants native to temperate and continental climates for the study: 24 species are not commonly cultivated in the Polissya and Forest-Steppe regions of Ukraine and 16 species are widespread in this area. To select plants that are effective in reducing the negative effects of the urban heat island, we determined the relative decrease in ambient temperature near the crown of plants using an Elitech RC-4 thermometer and diagnosed the photosynthetic apparatus using a Floratest fluorometer. The analysis was based on the chlorophyll fluorescence induction curve. Among the rare species, the following species proved to be the best in terms of stress resistance, photosynthetic apparatus efficiency and temperature reduction near the crown: *Acer mandshuricum*, *Aesculus pavia*, *Broussonetia papyrifera*, *Catalpa bignonioides*, *Corylus colurna*, *Fagus orientalis*, *Fagus sylvatica*, *Prunus padus*, *Tetradium daniellii*, the planting of which will reduce the negative effects of the "urban heat island". In addition, species that are not commonly cultivated in the continental climate zone have proven to be very promising for urban greening in this climate zone: *Acer pseudoplatanus*, *Acer velutinum*, *Corylus maxima* 'Atropurpurea', *Fagus sylvatica* 'Atropurpurea', *Parrotia persica*, *Phelodendron amurense*, *Platanus × hispanica*, *Prunus dulcis*, *Pterocarya pterocarpa* and *Tilia platyphyllos*. The use of rare species in urban landscaping will also help to preserve biodiversity according to the "Global Biodiversity Strategy".

Keywords: biodiversity conservation; Kautsky curve; chlorophyll fluorescence; stress resistance; rare species; urban heat island.

Introduction

Global warming in many regions of Central Europe in recent years has resulted in an increase in summer and winter temperatures, which has led to a decrease in the duration of the cold season, the number of frosty days and the severity of winters, as well as an increase in the length of the growing season (Blunden & Arndt, 2020; von Schuckman et al., 2020; Avtaeva et al., 2021; Armstrong McKay et al., 2022; Hébert et al., 2022). Such changes make it possible to test the cultivation of more thermophilic plant species in open ground conditions, the cultivation of which was questionable 30–50 years ago (Morecroft et al., 2019; Mina et al., 2021; Elmalki et al., 2022). In addition to warming, global climate change has resulted in prolonged severe droughts, which are accompanied by rising air and soil temperatures, wind erosion, lower groundwater levels, dehydration, depression, and even plant death (Lou et al., 2019; Zhang et al., 2020; Elmalki, 2022; Zhao et al., 2022; Lackóová et al., 2023). This problem is particularly acute in large megacities, where the effect of the urban heat island is most pronounced. As you know, heat islands are built-up urban areas that are 3 to 12 °C hotter than surrounding rural areas, which negatively affect the economy and public health (Jayakody et al., 2023). Another negative manifestation of global climate change is a sharp fluctuation in temperature, both a significant increase and decrease in temperature in a short period of time, which negatively affects vegetation and makes adjustments to the range of ornamental plants for green building.

Increased vegetation cover cools the ground and air, reduces the amount of CO₂ and harmful substances in the air, saturates it with O₂, increases rainwater absorption, and enhances soil protection against degradation (Önder & Akay, 2014; Chen et al., 2019; Fan et al., 2019; Gomez-Marti-

nez et al., 2021). Tree plantations have a positive impact on the local climate (Li et al., 2015; Piao et al., 2019; Li et al., 2020; Špulerová et al., 2023; Zhou et al., 2023), interacting with biogeochemical water cycles (Ellison et al., 2017). Selection of ornamental plants based on the level of CO₂ absorption (photosynthetic efficiency) and resistance to sharp temperature fluctuations will make it possible to change the range of plants for urban landscaping to mitigate the effects of the heat island, and may also contribute to the conservation of rare species. For example, the use of rare species in urban landscaping is proposed in the Global Biodiversity Strategy, the European Biodiversity Strategy and the National Strategy for State Environmental Policy of Ukraine.

Thus, changes in climate conditions require the search for plant species that are resistant to such changes, both native to Ukraine and introduced. In this regard, the aim of the study was to identify rare and ornamental species from the collection of the Fomin Botanical Garden with high photosynthetic system efficiency and potential for temperature fluctuations, with the subsequent recommendation to include these plants in the ecosystems of the urban environment to overcome the negative impact of the "urban heat island".

Materials and methods

Kyiv is located in the north of Ukraine, on the border of the Polissya and Forest-Steppe natural zones; the climate of the capital is defined as continental, with mild winters and warm summers (Rubel & Kottek, 2010). The average amount of precipitation in Kyiv is 616.9 mm per year, air humidity is about 65% in summer, and 80-90% in winter, although there is a tendency for humidity to decrease to 12% (March 2020).

The average annual temperature within the city of Kyiv has risen especially sharply in the last 10 years: in 1977 it was +7.6 °C, in 1981 +8.4 °C, in 1985 +6.2 °C, in 1990 +9.2 °C, in 1995 +8.5 °C, in 2000 +9.2 °C, in 2005 +8.7 °C, in 2010 +9.4 °C, in 2015 +10.5 °C, in 2020 +10.9 °C. Such an increase in temperature facilitates the use of plants in landscaping that previously could not withstand the winter period (www.weatheronline.co.uk).

We selected 40 plant species for the study, most of which have undergone long-term trials in the Fomin Botanical Garden (70–180 years). Among the selected species, there were 24 species originating from temperate and continental climates, which are rarely cultivated in the Polissya and Forest-Steppe zones of Ukraine (*Acer mandshuricum* Maxim., *A. velutinum* Boiss., *Aesculus pavia* L., *Aralia elata* (Miq.) Seem., *Broussonetia papyrifera* (L.) L'Hér. ex Vent., *Castanea sativa* Mill., *Catalpa bignonioides* Walter, *Catalpa fargesii* Bureau, *Cercis canadensis* L., *Cotinus coggygria* Scop., *Cotinus coggygria* Scop. 'Royal Purple', *Fagus orientalis* Lipsky, *Ginkgo biloba* L., *Juglans nigra* L., *Liriodendron chinense* (Hemsl.) Sarg., *Parrotia persica* C. A. Mey., *Paulownia tomentosa* Steud., *Platanus × hispanica* Mill. Ex Münchh., *Platycarya strobilacea*

Siebold & Zucc., *Prunus dulcis* (Mill.) D. A. Webb., *Pterocarya pterocarpa* Kunth ex I. Iljinsk., *Styphnolobium japonicum* (L.) Schott, *Tetradium daniellii* (Benn.) T. G. Hartley, *Zizyphus jujuba* Mill.).

There were also 16 species originating from temperate and continental climates, widespread in mass culture in the Polissya and Forest-Steppe zones of Ukraine (*Acer pseudoplatanus* L., *Acer saccharinum* L., *Aesculus × carnea* Zeyh., *Aesculus hippocastanum* L., *Berberis vulgaris* L. 'Atropurpurea', *Corylus colurna* L., *Corylus maxima* Mill. 'Atropurpurea', *Fagus sylvatica* L., *Fagus sylvatica* 'Atropurpurea' L., *Phelodendron amurense* Rupr., *Prunus padus* L., *Quercus rubra* L., *Robinia pseudoacacia* L., *Robinia viscosa* Vent., *Tilia europea* L., *Tilia platyphyllos* Scop.).

The species were characterised by high decorativeness, dense, mostly spreading crown. Since the efficient use of the territory is particularly important in urban landscaping, the species we selected were divided into three groups: large trees (10–50 m in height), medium-sized trees (up to 10 m) and shrubs. Among the selected species, 21 are rare or endangered. The degree of rarity of the plant species was determined according to the IUCN Red list (2022). Heliophilicity is described according to Kolisnichenko (2004) (Table 1).

Table 1
General characteristics of the studied species

Species	Origin	Height_m	H/ph	Rare-ness
<i>Acer mandshuricum</i>	South of the Far East of Russia, Korea, China	20(40)	Sh	LC
<i>A. pseudoplatanus</i>	Central and Western Europe, Western Asia	40	Sh	–
<i>A. saccharinum</i>	Central and Eastern USA, southern Canada	40	L	–
<i>A. velutinum</i>	Caucasus, Northern Iran	40	Sh	–
<i>Aesculus × carnea</i>	hybrid	20	L	–
<i>A. hippocastanum</i>	Balkans, Greece, Albania, Bulgaria	25	L	VU
<i>A. pavia</i>	North America	12	L	LC
<i>Aralia elata</i>	Far East of Russia, China, Korea, Japan	3-7 (12)	Sh	LC
<i>Berberis vulgaris</i> 'Atropurpurea'	Europe, Turkey, Iran	3	L	–
<i>Broussonetia papyrifera</i>	East and Southeast Asia	12	L	LC
<i>Castanea sativa</i>	Southern Europe, North America, Asia Minor	40	L	LC
<i>Catalpa bignonioides</i>	North America	15(20)	L	DD
<i>C. fargesii</i>	Southwest China	30	L	–
<i>Cercis canadensis</i>	North America	10(12)	L	LC
<i>Corylus colurna</i>	Southeast Europe, Asia Minor	30(50)	Sh	LC
<i>C. maxima</i> 'Atropurpurea'	Southeast Europe, Asia Minor	5	Sh	DD
<i>Cotinus coggygria</i>	From Europe to China	2-3 (10)	L	LC
<i>C. coggygria</i> 'Royal Purple'	sort	2-3 (10)	L	–
<i>Fagus orientalis</i>	Crimea, Caucasus, Balkans, Asia Minor	50	Sh	LC
<i>F. sylvatica</i>	Western Europe	30(50)	Sh	LC
<i>F. sylvatica</i> 'Atropurpurea'	sort	30(50)	Sh	–
<i>Ginkgo biloba</i>	China	40	L	EN
<i>Juglans nigra</i>	North America	50	L	LC
<i>Liriodendron chinense</i>	Southeast Asia (South China, Vietnam)	15	L	NT
<i>Parrotia persica</i>	Caucasus, Iran	25	Sh	–
<i>Paulownia tomentosa</i>	China	15(20)	L	–
<i>Phelodendron amurense</i>	Far East of Russia, China, Korea	30	Sh	–
<i>Platanus × hispanica</i>	hybrid	35(40)	L	–
<i>Platycarya strobilacea</i>	North America	10(12)	L	–
<i>Prunus dulcis</i>	Mediterranean, Asia Minor and Central Asia	4-6 (8)	L	–
<i>P. padus</i>	Eurasia	20	Sh	LC
<i>Pterocarya pterocarpa</i>	Caucasus Turkey, Iran	30	L	–
<i>Quercus rubra</i>	East of North America	25	L	LC
<i>Robinia pseudoacacia</i>	North America	25	L	LC
<i>R. viscosa</i>	North America	10(12)	L	–
<i>Styphnolobium japonicum</i>	Japan, China, Korea	25	L	–
<i>Tetradium daniellii</i>	South China, Korea	5-10	L	LC
<i>Tilia × europea</i>	Europe	20	L	–
<i>T. platyphyllos</i>	Europe, Turkey	35	L	–
<i>Zizyphus jujuba</i>	Mediterranean, Southern and Eastern Asia	9	L	LC

Notes: H/ph – heliophilicity, L – light-loving, Sh – shade tolerant, EN – endangered, VU – vulnerable, NT – near threatened, LC – least concern, DD – data deficient.

One of the parameters for selecting plants effective in reducing the negative effects of the "urban heat island" is the relative decrease in ambient temperature. Therefore, the temperature was measured within the crown of trees and shrubs (n = 6 for each species) at a height of 1.5 m from ground level. The relative temperature decrease was calculated by subtracting the average temperature within the crown from the average temperature measured in the open space. Measurements were made using an Elitech RC-4 thermologger (UK) in sunny, windless, warm weather (the average air temperature in the open space was 28.16 ± 0.26 °C).

When selecting plants, it is important to take into account not only the efficiency of photosynthesis, the release of O₂ and the absorption of CO₂ but also the resistance of plants to the influence of negative environmental

factors. We studied the effect of negative temperature stressors on the state of the photosynthetic apparatus in mid-September, when a sharp decrease in daytime temperature from 26 to 8 °C began, followed by a temperature increase to 28 °C within a week. We used the optical properties of chlorophyll as a source of information for rapid diagnostics of plant cells, since under the influence of external factors, photosynthetic membranes are one of the first to be damaged (Ashraf & Harris, 2013). Also, the efficiency of photosynthetic processes indirectly indicates a better CO₂ absorption. The diagnostics of the photosynthetic apparatus was carried out using a fluorometer "Floratest" (Ukraine). Leaves for measurement were simultaneously sampled from the annual vegetative growth of lower third of the crown on the south side for all plants. Dark adaptation before measure-

ment was ten minutes; the time of each measurement was 240 seconds. The analysis was based on the chlorophyll fluorescence induction curve (Krause & Weis, 1991; Strasser et al., 2004, Romanov et al., 2009), which was calculated according to the following formulas:

$K_1 = (F_m - F_0)/F_m$ is an indicator of the efficiency of the light phase of photochemical reactions (Krause & Weis, 1991);

$K_2 = (F_m - F_{St})/F_m$ is the efficiency factor of dark photosynthetic processes (Strasser et al., 2004);

$K_3 = (F_{max2} - F_{St})/F_{St}$ is a viability indicator sensitive to exogenous factors; a decrease in K_3 values indicates a decrease in the potential activity of the plant photosynthetic apparatus, and also corresponds to a correlation with the intensity of dark carbon dioxide fixation (Stürbet & Govindjee, 2011);

$K_{pl} = (F_{pl} - F_0)/(F_m - F_0)$ is an indicator of the probable presence of the disease, the lower this indicator, the more resistant the plant (Strasser et al., 2004);

$F_v = F_m - F_0$ is an indicator of photochemical redox processes, characterising the activity of the initial stages of photosynthesis; it decreases as environmental conditions deviate from the temperature optimum (Krause & Weis, 1991). The data were analyzed by Prism Graphpad 6 (GraphPad Company, San Diego, USA, 2014). The values for different groups were compared by ANOVA followed by Tukey's multiple comparison test with Bonferroni adjustment.

Results

Among the studied large trees (10–50 m in height), the efficiency of the light phase of photochemical reactions and dark photosynthetic pro-

cesses was high in the following plant species: *Acer pseudoplatanus*, *Acer saccharinum*, *Acer velutinum*, *Catalpa bignonioides*, *Catalpa fargesii*, *Corylus colurna*, *Fagus orientalis*, *Fagus sylvatica* 'Atropurpurea', *Parrotia persica*, *Paulownia tomentosa*, *Phelodendron amurense*, *Platanus × hispanica*, *Prunus padus*, *Pterocarya pterocarpa*, *Robinia pseudoacacia* and *Tilia platyphyllos* (Fig. 1, 2).

Normally, the value of K_2 is > 0.6 . The following species (*Aesculus × carnea*, *Aesculus hippocastanum*, *Castanea sativa*, *Ginkgo biloba*, *Juglans nigra*, *Liriodendron chinense*, *Quercus rubra*, *Styphnolobium japonicum* and *Tilia × europea*) showed lower rates of the dark phase of photosynthesis compared to other studied species. However, only *Aesculus × carnea* and *Aesculus hippocastanum* had K_2 below 0.6 (Fig. 2).

Also, species that showed high efficiency of the light and dark phases of photochemical processes have high values of the K_3 criterion, which indirectly indicates the high viability of these plants, and also have low K_{pl} indicators, which indicates increased stress resistance of these plants (Table 2). High F_v values indicate that these plants did not react negatively to the sharp temperature drops that occurred during September (daytime temperature dropped from 26 to 8 °C within a week), which also indicates plant resistance. Only *Catalpa fargesii*, *Platanus × hispanica* and *Paulownia tomentosa* among the above species had lower F_v values and thus showed an average level of cold resistance. At the same time, *Juglans nigra*, *Quercus rubra*, *Styphnolobium japonicum* and *Tilia × europea* had average indicators of relative stress resistance, and *Aesculus × carnea*, *Aesculus hippocastanum*, *Castanea sativa*, *Ginkgo biloba*, *Liriodendron chinense* had lower K_3 and F_v values, which indirectly indicates an increase in destructive processes due to the action of exogenous factors (Table 2).

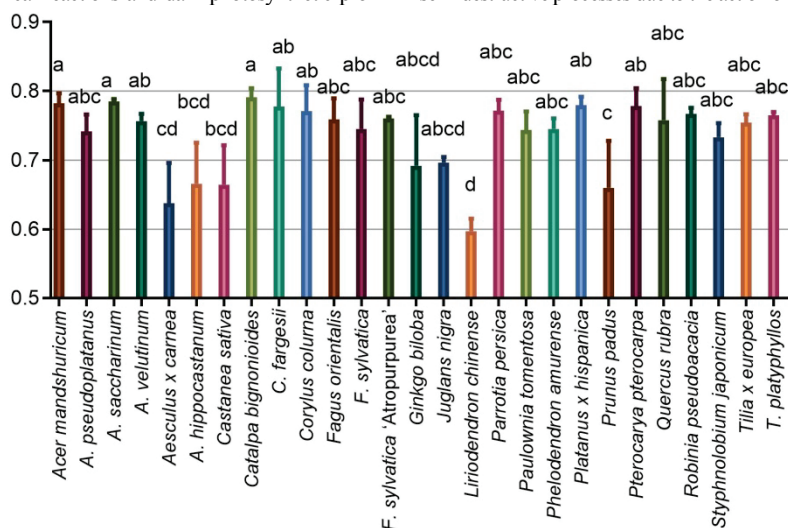


Fig. 1. Indicator of fluorescence K_1 of large trees (10–50 m): $x \pm SD$, $n = 12$; different letters indicate significant differences inside the parameter ($P < 0.05$) according to the results of Tukey's multiple comparison test with Bonferroni adjustment

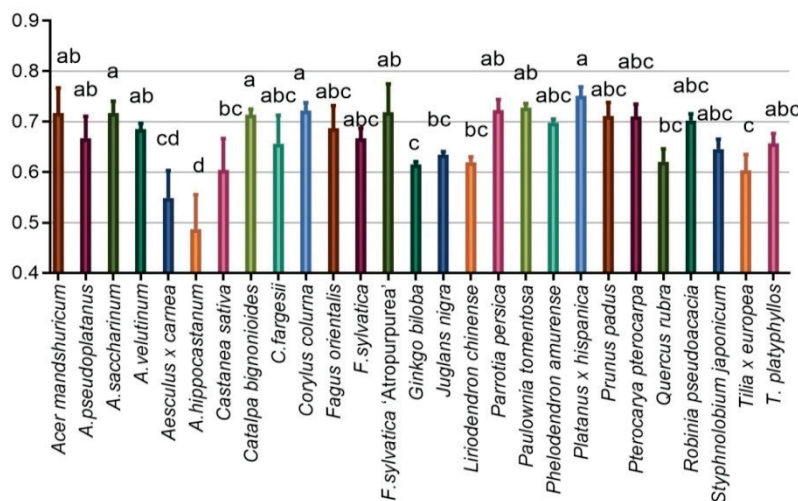


Fig. 2. Indicator of fluorescence K_2 of large trees (10–50 m): $x \pm SD$, $n = 12$; different letters indicate significant differences inside the parameter ($P < 0.05$) according to the results of Tukey's multiple comparison test with Bonferroni adjustment

Table 2

Indicators of the state of the photosynthetic system of large trees (10–50 m) ($x \pm SD$, $n = 12$)

Species	Indicators of fluorescence		
	K_3	K_{pi}	F_v in relative fluorescence units (RFU)
<i>Acer mandshuricum</i>	2.45 ± 0.69 ^{ab}	0.12 ± 0.01 ^{bc}	1835 ± 275 ^a
<i>A. pseudoplatanus</i>	1.84 ± 0.36 ^{bcd}	0.11 ± 0.01 ^{bc}	1333 ± 130 ^{abc}
<i>A. saccharinum</i>	2.21 ± 0.23 ^{ab}	0.08 ± 0.02 ^c	1520 ± 55 ^{ab}
<i>A. velutinum</i>	2.33 ± 0.18 ^{ab}	0.10 ± 0.02 ^{bc}	1179 ± 65 ^{abcd}
<i>Aesculus × carnea</i>	1.17 ± 0.27 ^c	0.12 ± 0.03 ^{bc}	720 ± 267 ^{cd}
<i>A. hippocastanum</i>	1.17 ± 0.24 ^c	0.16 ± 0.03 ^{bc}	1013 ± 295 ^{bcd}
<i>Castanea sativa</i>	1.45 ± 0.44 ^{bc}	0.31 ± 0.16 ^{ab}	608 ± 222 ^d
<i>Catalpa bignonioides</i>	2.52 ± 0.10 ^{ab}	0.09 ± 0.02 ^{bc}	1301 ± 222 ^{abcd}
<i>C. fargesii</i>	1.95 ± 0.40 ^{abc}	0.09 ± 0.00 ^{bc}	1088 ± 461 ^{abcd}
<i>Corylus colurna</i>	2.53 ± 0.24 ^{ab}	0.13 ± 0.02 ^{bc}	1349 ± 318 ^{abc}
<i>Fagus orientalis</i>	2.21 ± 0.44 ^{ab}	0.10 ± 0.02 ^{bc}	1136 ± 169 ^{abcd}
<i>F. sylvatica</i>	2.12 ± 0.18 ^{ab}	0.10 ± 0.04 ^{bc}	1317 ± 241 ^{abc}
<i>F. sylvatica 'Atropurpurea'</i>	2.65 ± 0.57 ^{ab}	0.09 ± 0.02 ^{bc}	1419 ± 33 ^{abc}
<i>Ginkgo biloba</i>	1.31 ± 0.11 ^c	0.29 ± 0.14 ^{abc}	1029 ± 490 ^{bcd}
<i>Juglans nigra</i>	1.75 ± 0.07 ^{bc}	0.15 ± 0.04 ^{bc}	1077 ± 37 ^{abcd}
<i>Liriodendron chinense</i>	1.82 ± 0.17 ^{bc}	0.42 ± 0.24 ^a	544 ± 42 ^d
<i>Parrotia persica</i>	2.38 ± 0.30 ^{abc}	0.16 ± 0.07 ^{bc}	1819 ± 263 ^a
<i>Paulownia tomentosa</i>	2.42 ± 0.11 ^{ab}	0.17 ± 0.08 ^{bc}	976 ± 55 ^{bcd}
<i>Phelodendron amurense</i>	2.08 ± 0.04 ^{abc}	0.12 ± 0.01 ^{bc}	1520 ± 23 ^{ab}
<i>Platanus × hispanica</i>	2.85 ± 0.40 ^a	0.09 ± 0.01 ^c	1091 ± 153 ^{abcd}
<i>Prunus padus</i>	2.41 ± 0.33 ^{ab}	0.16 ± 0.06 ^{bc}	1012 ± 199 ^{bcd}
<i>Pterocarya pterocarpa</i>	2.23 ± 0.28 ^{ab}	0.10 ± 0.02 ^{bc}	1189 ± 321 ^{abcd}
<i>Quercus rubra</i>	1.61 ± 0.21 ^{bc}	0.12 ± 0.06 ^{bc}	1269 ± 406 ^{abcd}
<i>Robinia pseudoacacia</i>	2.29 ± 0.13 ^{ab}	0.11 ± 0.04 ^{bc}	1920 ± 91 ^a
<i>Styphnolobium japonicum</i>	1.59 ± 0.05 ^{bc}	0.22 ± 0.05 ^{abc}	1035 ± 160 ^{bcd}
<i>Tilia × europea</i>	1.47 ± 0.12 ^c	0.10 ± 0.02 ^{bc}	1413 ± 217 ^{ab}
<i>T. platyphyllos</i>	1.89 ± 0.14 ^{bc}	0.11 ± 0.01 ^{bc}	1461 ± 185 ^{ab}

Notes: different letters indicate significant differences inside the parameter ($P < 0.05$) according to the results of Tukey's multiple comparison test with Bonferroni adjustment.

Among the low trees (up to 10 m), the highest efficiency of the photosynthetic system at all levels was found in representatives of the following species: *Aesculus pavia*, *Broussonetia papyrifera*, *Prunus dulcis* and *Tetradium daniellii* (Fig. 3). All these species also had a high rate of viability. Resistance to a sharp decrease in temperature was high in *Aesculus pavia* and *Broussonetia papyrifera*, and medium in *Prunus dulcis* and *Tetradium daniellii*. Representatives of the *Aralia elata* and *Ziziphus jujuba* species have average values of the measured indicators. However, *Aralia elata* has a high coefficient of cold resistance (Table 3). Species such as: *Cercis canadensis*, *Platycarya strobilacea* and *Robinia viscosa* had the lowest resistance coefficients K_3 and F_v , as well as elevated K_{pi} values, which may indicate the presence of infection in the leaves, which may have been the reason for the reduction in the efficiency of the photosynthetic system. The absence of a significant difference between species in term of K_{pi} is associated with large standard deviation within a species, since the studied plants probably included both healthy plants and plants with initial undetected stages of diseases.

Table 3

Indicators of the state of the photosynthetic system of trees up to 10 m tall ($x \pm SD$, $n = 12$)

Species	Indicators of fluorescence		
	K_3	K_{pi}	F_v in relative fluorescence units (RFU)
<i>Aesculus pavia</i>	2.23 ± 0.27 ^{ab}	0.12 ± 0.02 ^a	1674 ± 64 ^{ab}
<i>Aralia elata</i>	1.77 ± 0.17 ^{bc}	0.12 ± 0.02 ^a	1717 ± 344 ^a
<i>Broussonetia papyrifera</i>	1.85 ± 0.36 ^{bc}	0.09 ± 0.01 ^a	1621 ± 333 ^{abc}
<i>Cercis canadensis</i>	1.34 ± 0.20 ^c	0.29 ± 0.17 ^a	837 ± 104 ^d
<i>Platycarya strobilacea</i>	1.27 ± 0.45 ^c	0.33 ± 0.17 ^a	832 ± 239 ^d
<i>Prunus dulcis</i>	2.27 ± 0.29 ^{ab}	0.07 ± 0.02 ^a	1115 ± 112 ^{cd}
<i>Robinia viscosa</i>	1.24 ± 0.40 ^c	0.23 ± 0.13 ^a	875 ± 265 ^d
<i>Tetradium daniellii</i>	2.75 ± 0.29 ^a	0.09 ± 0.02 ^a	1068 ± 140 ^d
<i>Ziziphus jujuba</i>	1.72 ± 0.05 ^{bc}	0.10 ± 0.03 ^a	1189 ± 104 ^{bcd}

Notes: see Table 2.

Among the investigated shrubs, *Corylus maxima* 'Atropurpurea' showed the best result for all measured parameters, while *Cotinus coggygria* showed the worst result, which is associated with a high K_{pi} value in these plants, which indicates a possible plant disease and low cold resis-

tance (Fig. 4, Table 4). *Berberis vulgaris* 'Atropurpurea' and *Cotinus coggygria* 'Royal Purple' had intermediate characteristics. However, the K_2 index in *Cotinus coggygria* 'Royal Purple' was the lowest among the studied species, the value was > 0.6 , which is considered to be normal for this index.

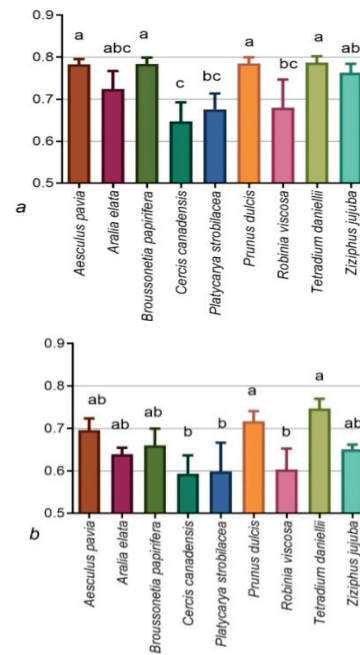


Fig. 3. Indicators of fluorescence K_1 (a) and K_2 (b) of trees up to 10 m tall: $x \pm SD$, $n = 12$; different letters indicate significant differences inside the parameter ($P < 0.05$) according to the results of the Tukey multiple comparison test with Bonferroni adjustment

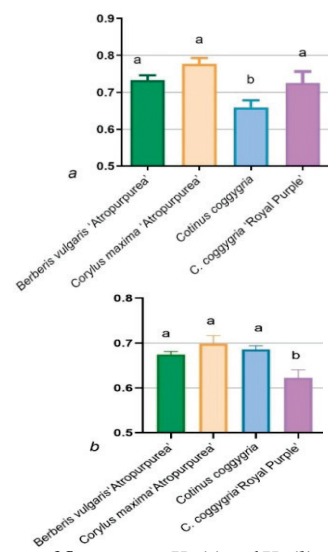


Fig. 4. Indicators of fluorescence K_1 (a) and K_2 (b) of shrub leaves: $x \pm SD$, $n = 12$; different letters indicate significant differences inside the parameter ($P < 0.05$) according to the results of Tukey's multiple comparison test with Bonferroni adjustment

Table 4

Indicators of the state of the photosynthetic system of shrub leaves ($x \pm SD$, $n = 12$)

Species	Indicators of fluorescence		
	K_3	K_{pi}	F_v in relative fluorescence units (RFU)
<i>Berberis vulgaris</i> 'Atropurpurea'	1.93 ± 0.10 ^a	0.12 ± 0.01 ^b	1512 ± 57 ^b
<i>Corylus maxima</i> 'Atropurpurea'	2.24 ± 0.18 ^a	0.14 ± 0.01 ^b	2091 ± 120 ^a
<i>Cotinus coggygria</i>	2.00 ± 0.10 ^a	0.40 ± 0.10 ^a	917 ± 24 ^d
<i>C. coggygria</i> 'Royal Purple'	1.90 ± 0.19 ^a	0.18 ± 0.12 ^{ab}	1200 ± 85 ^c

Notes: see Table 2.

The lowest F_v value in *Cotinus coggygia* also indicates low resistance to sharp temperature fluctuations.

For more effective analysis, all fluorescence indicators and the average value of the temperature decrease near the crown are presented in Table 5. In the open space, the average daytime temperature was 28 ± 0.2 °C (Table 5).

Table 5

Efficiency of the photosynthetic system, stress tolerance and efficiency to reduce environmental temperature ($\bar{x} \pm SD$, $n = 6$) of species originating from temperate and continental climate zones

Species	EPhS	Stress resistance	Δt °C
Trees (10–50 m)			
<i>Acer mandshuricum</i>	***	***	2.33 ± 0.19^d
<i>A. pseudoplatanus</i>	***	***	3.45 ± 0.37^c
<i>A. saccharinum</i>	***	***	2.15 ± 0.61^f
<i>A. velutinum</i>	***	***	3.81 ± 0.56^{ab}
<i>Aesculus hippocastanum</i>	*	**	0.86 ± 0.35^g
<i>A. × carnea</i>	*	*	2.96 ± 0.41^{dk}
<i>Castanea sativa</i>	*	*	2.06 ± 0.38^g
<i>Catalpa bignonioides</i>	***	***	3.46 ± 0.54^{bc}
<i>C. fargesii</i>	***	**	3.39 ± 0.05^{bc}
<i>Corylus colurna</i>	***	***	3.35 ± 0.25^c
<i>Fagus sylvatica</i> ‘Atropurpurea’	***	***	3.36 ± 0.26^{bc}
<i>F. sylvatica</i>	***	***	4.06 ± 0.23^a
<i>F. orientalis</i>	***	***	3.56 ± 0.21^b
<i>Ginkgo biloba</i>	*	*	1.96 ± 0.18^f
<i>Juglans nigra</i>	*	**	3.78 ± 0.20^{ab}
<i>Liriodendron chinense</i>	*	*	2.75 ± 0.20^{dk}
<i>Parrotia persica</i>	***	***	3.26 ± 0.26^c
<i>Paulownia tomentosa</i>	***	**	2.66 ± 0.29^{dk}
<i>Phelodendron amurense</i>	***	***	2.89 ± 0.23^{cd}
<i>Platanus × hispanica</i>	***	***	3.79 ± 0.16^{dk}
<i>Prunus padus</i>	**	***	0.59 ± 0.36^g
<i>Pterocarya pterocarpa</i>	***	***	3.45 ± 0.23^{bc}
<i>Quercus rubra</i>	**	**	3.39 ± 0.23^c
<i>Robinia pseudoacacia</i>	***	***	2.76 ± 0.22^{dk}
<i>Styphnolobium japonicum</i>	**	**	3.23 ± 0.16^c
<i>Tilia × europea</i>	**	**	3.49 ± 0.30^{bc}
<i>T. platyphyllos</i>	***	***	3.93 ± 0.16^{ab}
Trees up to 10 m			
<i>Aesculus pavia</i>	***	***	3.26 ± 0.34^b
<i>Aralia elata</i>	**	**	1.73 ± 0.29^e
<i>Broussonetia papyrifera</i>	***	***	2.30 ± 0.15^{cd}
<i>Cercis canadensis</i>	**	*	3.16 ± 0.34^b
<i>Platycarya strobilacea</i>	**	*	2.55 ± 0.25^c
<i>Prunus dulcis</i>	***	***	3.66 ± 0.31^a
<i>Robinia viscosa</i>	**	*	2.07 ± 0.22^{dk}
<i>Tetradium daniellii</i>	***	***	2.03 ± 0.20^{dk}
<i>Ziziphus jujuba</i>	**	**	3.27 ± 0.23^b
Shrubs			
<i>Berberis vulgaris</i> ‘Atropurpurea’	**	**	2.66 ± 0.37^c
<i>Corylus maxima</i> ‘Atropurpurea’	***	***	3.15 ± 0.25^b
<i>Cotinus coggygia</i>	**	*	3.65 ± 0.13^a
<i>C. coggygia</i> ‘Royal Purple’	**	**	2.96 ± 0.26^{bc}

Notes: * – low indicators, ** – average indicators, *** – high indicators; the efficiency of the photosynthetic system (EPhS) was determined on the basis of K_1 and K_2 coefficients; stress resistance is a relative indicator determined on the basis of K_3 , K_{pi} and F_v coefficients; Δt °C – temperature drop in the open space and near the crown; different letters indicate significant differences inside the group of plants ($P < 0.05$) according to the results of Tukey’s multiple comparison test with Bonferroni adjustment.

Comparatively less effective temperature reduction near the tree crown was observed in such tall trees as *Prunus padus*, *Aesculus hippocastanum*, *Ginkgo biloba*, *Castanea sativa*, *Acer saccharinum* and *Acer mandshuricum*. A small decrease in temperature was detected within the crown of the following trees up to 10 m: *Prunus dulcis*, *Tetradium daniellii*, *Robinia viscosa* and *Aralia elata*.

Discussion

Plants in urbanised environments are exposed to daily abiotic stresses: very intense or insufficient sunlight, water or mineral deficiencies, high and low temperatures, heavy metal toxicity and air pollution cause a harm-

ful effect on the photosynthetic apparatus (Murata et al., 2007). Chlorophyll fluorescence analysis is one of the most powerful and widely used methods for studying the impact of stress on photosynthesis (Guidi et al., 2019; Lewu et al., 2020; Pantazi et al., 2020). Numerous studies of the photosynthetic system, conducted mainly on agricultural plants or their fruits (Zhong & Wang, 2019; Lewu et al., 2020; Pantazi et al., 2020), have confirmed the effectiveness of fluorescence analysis in determine the adaptation of plants not only to sudden changes in temperature, but also to the influence of such stressors as acidification, salinity and dehydration (Shavanova et al., 2013). Since all the plants we studied grow in the limited area of the botanical garden, they all have the same low level of air and soil pollution, watering, identical light intensity and temperature conditions. Accordingly, the sharp drop in temperature, after which the state of the photosynthetic apparatus was measured, was considered a stress factor that had a negative impact on plants.

The first important parameter derived from the Kautsky curve was the F_v/F_m ratio, which is a key parameter for detecting stress-induced photoinhibition of PSII (Krause & Weis, 1991). F_v/F_m values usually range between 0.75 and 0.85 (Guidi et al., 2019). Krause & Weis (1991) showed that K_1 significantly decreases at low temperature. Trees of species such as: *Aesculus × carnea*, *Aesculus hippocastanum*, *Castanea sativa*, *Liriodendron chinense* and *Prunus padus* showed relatively lower efficiency of the light phase of photochemical reactions, which may be a consequence of reduced resistance to temperature stress.

It is now known that environmental stresses affect the repair mechanism of PSII rather than induce the photodamage process itself (Kangasjärvi et al., 2012; Nishiyama & Murata, 2014). Photoinhibition of PSII is a mechanism by which plants limit photodamage to PSII but also preserve PSI, which is not equipped with its own repair mechanisms (Järvi et al., 2015). Therefore, PSI is less likely to be damaged due to a very efficient photoprotection mechanism (Gururani et al., 2015). It is the species *Aesculus × carnea* and *Aesculus hippocastanum* that showed a low level of PSI efficiency, and *Castanea sativa* and *Liriodendron chinense* were on the border of the normal range of this indicator, which may be a consequence of PSII damage and, accordingly, a reduced PSI protection. We obtained a similar dependence for trees up to 10 m in height: low values of both K_1 and K_2 in *Cercis canadensis*, *Platycarya strobilacea* and *Robinia viscosa*. According to the literature data, diseased plants also have a decrease in the fluorescence factor K_2 , which characterises the efficiency of dark photosynthetic processes and, above all, ribulose-bisphosphate carboxylase activity – the main enzyme of the Calvin cycle.

Today, methods based on measuring the intensity of chlorophyll fluorescence are often used to determine the extreme impact of environmental factors, including changes in temperature and water regime, and environmental pollution by chemicals. At the same time, the effectiveness of using these methods for rapid diagnosis of viral, bacterial and fungal plant diseases has been proven (Shavanova et al., 2013). The advantage of such methods, compared to traditional electron and immunofluorescence microscopy, ELISA and serological tests, is the ability to detect small changes in this indicator without damaging plant tissues, the cheapness and speed of the method, as well as the ability to assess the condition of plants in field. One of these indicators is the K_{pi} coefficient, which characterises the relative number of inactive reaction centres in relation to the total number of reaction centres, and is defined as a test indicator of high adaptability. The value of the K_{pi} plateau on the Kautsky curve can be used as a test for the early selection of plants resistant to the influence of a complex of environmental factors (Shavanova et al., 2013). High values of the K_{pi} coefficient in *Castanea sativa*, *Ginkgo biloba*, *Liriodendron chinense*, *Styphnolobium japonicum*, *Cercis canadensis*, *Platycarya strobilacea*, *Robinia viscosa* and *Cotinus coggygia* are accompanied by low values of the F_v index, which indicates an increase in destructive processes due to the action of exogenous factors, in particular, sudden changes in temperature and cold. All species (except *Robinia viscosa*) that had high values of the K_{pi} coefficient, and low F_v values are not common in culture in the Polissia and Forest-Steppe regions of Ukraine. It is possible that the low temperatures of this area are one of the limiting factors of distribution. Also, high values of the K_{pi} coefficient in all studied species may indicate the presence of an undetected viral, bacterial or fungal infection in the leaves of the studied plants, which in turn could be accompanied by a decrease in the

efficiency of the photosynthetic system and a general decrease in viability and stress tolerance. If we compare the species within the genus, we can say that among the studied representatives of the genus *Acer*, the highest indicators of photosynthetic activity and viability were found in *Acer saccharinum*, among the genus *Aesculus* – in *Aesculus pavia*, among the genus *Catalpa* – in *Catalpa bignonioides*, among the genus *Fagus* v *Fagus sylvatica* 'Atropurpurea', among the genus *Tilia* – *Tilia platyphyllos*; *Robinia pseudoacacia* is more resistant to negative factors than *Robinia viscosa*; *Prunus dulcis* – than *Prunus padus* and *Cotinus coggygria* 'Royal Purple' – than *Cotinus coggygria*.

According to the summarized data (Table 5), the following species of shade-tolerant tall trees can be recommended for urban greening: *Acer mandshuricum*, *Acer pseudoplatanus*, *Acer velutinum*, *Corylus colurna*, *Fagus orientalis*, *Fagus sylvatica*, *Fagus sylvatica* 'Atropurpurea', *Parrotia persica*, *Phelodendron amurense*; and among light-loving plants: *Catalpa bignonioides*, *Platanus* × *hispanica*, *Pterocarya pterocarpa*, *Robinia pseudoacacia* and *Tilia platyphyllos*. Also, most of these plants are rare species, which in turn will help preserve biodiversity.

It is important to note that some species listed in the Red Book have been successfully introduced in new territories for them. In particular *R. pseudoacacia* (widespread in 42 regions of Europe) and *Quercus rubra* (in 34 regions) are recognized as an invasive species in many countries of the world (Burda & Koniakin, 2019; Nicolescu et al., 2020). On the other hand, *R. pseudoacacia* has ecological, social and economic significance for many countries (Nicolescu et al., 2020). Therefore, although these two species showed high efficiency of the photosynthetic system, it is necessary to take these nuances into account when planning landscaping, even megacities, where the spread of plants is under relative control.

Among the low trees, the most intense temperature decrease was observed near representatives of the following species: *Aesculus pavia*, *Broussonetia papyrifera*, *Cercis canadensis* and *Ziziphus jujuba*, as well as near all shrubs except *Berberis vulgaris* 'Atropurpurea' (Table 5). Based on summary data, the species *Platycarya strobilacea* and *Robinia viscosa*, which were characterized by relatively low all measurements for all indicators, were the least promising for greening among low-growing trees (Table 5). *Aesculus pavia*, *Broussonetia papyrifera* and *Tetradium danielii* were the most interesting for urban landscape design among this group of plants, which were characterised by high stress resistance and efficiency of the photosynthetic system, significantly reduced temperature, and are also rare plants, which is an additional reason to recommend these species for planting in cities. *Prunus padus* is also a rare species and stress-resistant, as is *Prunus dulcis*, but these species are less effective in reducing temperature.

All the studied shrubs can be called promising for cultivation in urban environment due to the efficiency of the photosynthetic system and indirect reduction of carbon dioxide in the air, lowering the temperature in the middle tiers of vegetation and stress resistance (Table 5). The species *Cotinus coggygria* showed the lowest stress resistance, which may be related to the detected potential viral infection of the studied plants. *Corylus maxima* 'Atropurpurea' was the best performer.

It was also found that among all studied species, the photosynthetic system of shade-tolerant plants was more efficient and resistant to the influence of exogenous factors, than that of light-loving plants.

Conclusion

Thus, among the studied plant species, 10 rare species and 10 species not listed in the Red Data Book, but mainly not widely cultivated in the Polissia and Forest-Steppe regions of Ukraine, were found to be potentially effective in reducing the negative effects of the "urban heat island". Therefore, these species can be recommended for use in urban greening, particularly in the temperate and continental climate zone.

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