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Photosynthetic apparatus efficiency of eight tree taxa as an indicator of their tolerance to urban environments

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Abstract: Urban trees, especially those growing in close proximity to roads, suffer from different kinds of stress. Most of roadside stress factors are impossible to be avoided therefore the selection of tolerant tree species and cultivars is of high importance. In our research we used the activity of photosystem II and chlorophyll relative content to monitor physiological state of 8 species and cultivars growing in urban environments in Warsaw. We compared young trees growing 2–3 m away from the road and others growing minimum 8 meters away. The experiment allowed us to indicate the most tolerant taxa to roadside conditions: *Gleditsia triacanthos*, *Pyrus calleryana* 'Chanticleer', *Platanus ×hispanica* 'Acerifolia' and *Acer campestre*. We found that *Quercus rubra* is relatively tolerant. *Tilia ×europaea* 'Pallida', *Tilia cordata* 'Greenspire' and *Ginkgo biloba* should not be planted in harmful habitats.

Additional key words: chlorophyll *a* fluorescence, Performance Index, salinity stress, street environment, urban trees.

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Introduction

Poor growth and high mortality of urban street trees is caused by a complex of environmental factors. These factors include air drought and pollution, high temperature, soil drought evoked by insufficient water accumulation near road and pavement surfaces as well as soil compaction, and finally soil pollution, especially soil salinity caused by de-icing salt (Łukasiewicz 1995; Szczepanowska 2001; Zimny 2005). Since improving trees' growth conditions is a very hard and complicated task, the selection of tree species and cultivars tolerant to severe street environments is of high importance (Łukasiewicz 1975, 1995; Bugała et al. 1984; Siewniak and Siewniak 2001; Szczepanowska 2001; Borowski and Latocha 2006). Previous laboratory and field experiments proved that our native species are mostly sensitive to soil and airborne salinity (Pracz 1990; Percival et al. 2003; Percival 2005; Marosz and Nowak 2008; Cekstere et al. 2008). Likewise, *in situ* research and observations showed leaf chloroses and necroses as well as tree crown damage in roadside trees of our native taxa (Łukasiewicz 1975; Mędrzycki 1982; Supłat

1993; Borowski 2008). This forces us to look for introduced species or even specially selected cultivars suitable for harsh streetside conditions.

London plane (*Platanus ×hispanica* Mill. ex Münchh. 'Acerifolia') and honey locust (*Gleditsia triacanthos* L.) are commonly grown as street trees in South and Western Europe as well as in the United States. Some American authors consider *Platanus ×hispanica* 'Acerifolia' to be salt sensitive contrary to *Gleditsia triacanthos* (Beckerman and Lerner 2009), however, primary observations in Poland have indicated sufficient tolerance for soil salinity of these taxa. In Warsaw they were planted in the past, but only occasionally as they had been considered frost-sensitive. Likewise, *Ginkgo* tree (*Ginkgo biloba* L.) is found to be a rarity in Poland, which is interesting in parks and gardens but not appropriate for mass plantings. Nevertheless, *Ginkgo* tree is successfully grown as a street tree in many cities in the world (Handa et al. 1997; Malinowska 1998). Callery pear (*Pyrus calleryana* Decne 'Chanticleer'), which is a novelty in Warsaw, is regarded in the USA as one of the most important tree species for street planting (Bassuk et al. 2003). Red oak (*Quercus rubra* L.) is well known as a soil and air pollution tolerant species (Seneta and Dolatowski 2007) and suitable for planting in cities (Roloff et al. 2009), however, its fitness for roadside application in Warsaw needs to be confirmed. Littleleaf linden (*Tilia cordata* Mill.) 'Greenspire' and Kaiser linden (*Tilia ×europaea* L. 'Pallida') are selected linden cultivars recommended for urban environments in North America (Bassuk et al. 2003) and as they come from Europe's native species they are widely planted in many European cities. In Warsaw they have been used only during the last 6–7 years and it is worth to test whether these cultivars are tolerant enough to roadside environments. Hedge maple (*Acer campestre* L.) is considered to be the most tolerant native species of *Acer* for urban environment conditions (Łukasiewicz 1989, 1995; Siewniak and Siewniak 2001). All these taxa have been planted in Warsaw along the streets in the last 6–7 years due to bibliography review and primary observations. They are the subject of research on the selection of the most appropriate species and cultivars for roadside planting in Warsaw where severe winters force the Metropolitan Authority of Parks, Greenery and Cleaning to use great amounts of de-icing salt on the roads.

Evaluation of trees' tolerance to unfavorable street environments *in situ* requires longstanding investigations (Supłat 1993; Borowski 2008). Nowadays, chlorophyll *a* fluorescence measurements have become an often used method for detecting plants' reactions to different kinds of stress (Robakowski et al. 2000; Percival and Fraser 2001; Hermans et al. 2003; Kalaji et al. 2004; Percival 2004; Pukacki and Kamińska-Rożek 2005; Živčák et al. 2008). It should not be considered as a measure of photosynthesis, this is given by the gross rate of carbon fixation, which is not clearly correlated with chlorophyll fluorescence under field conditions (Maxwell and Johnson 2000). Nevertheless, chlorophyll *a* fluorescence can be used to assess the efficiency of photosynthetic apparatus, especially its most sensitive component – Photosystem II (PSII), which generally express the physiological state of any photosynthetising material. This method is a rapid (up to 1 s), nondestructive, noninvasive and easy to apply technique. A measurement realised after 20–30 minutes of plant adaptation in dark allows to obtain more than 50 parameters (Kalaji and Łoboda 2009). However, researches proved that some of these measured and calculated parameters are more useful and sensitive than others in indicating the physiological state of the tested samples. "Performance Index" (PI_{abs}) (Strasser et al. 2004) seems to be the most convenient in comparative studies. It allows to detect changes in photosynthesis caused by drought and salinity stress or pathogen influence prior to visible symptoms of deterioration such as leaf chloroses and necroses or growth reduction (Christen et al. 2007; Živčák et al. 2008; Kalaji and Łoboda 2009). This index consists of three independent components: density of reaction centers per chlorophyll, probability that the absorbed photon will be trapped by reaction centers, and efficiency of electron movement into the electron transport chain beyond the Q_A (plastoquinone molecule tightly bound to PSII) (Strasser et al. 2000; Strasser et al. 2004; Kalaji and Łoboda 2009). The equipment available in the market is able to calculate automatically PI value and to display it immediately on the screen of the device. This attribute could be very advantageous for urban tree management workers for quick tests in tree maintenance practice.

The aim of this work was to estimate the usefulness of photosynthetic apparatus efficiency as biomarker for trees' tolerance to urban environments. In this study the Performance Index was applied to examine the condition of photosynthetic apparatus in trees of selected taxa recently planted along Warsaw streets. We expected that such measurements will help us to classify the tested taxa according to their ability to tolerate roadside stress.

Materials and methods

Material

Young trees of 8 species and cultivars were used for the experiment: *Tilia cordata* 'Greenspire', *Tilia ×europaea* 'Pallida', *Acer campestre, Quercus rubra, Gleditsia triacanthos, Pyrus calleryana* 'Chanticleer', *Platanus ×hispanica* 'Acerifolia' and *Ginkgo biloba*. The experimental material was available due to the partnership between the Department of Environmental Protection, WULS, and the Metropolitan Authority of Parks, Greenery and Cleaning conducted since 2005.

Experimental design

The young trees were planted 3–5 years prior to examination (except reference trees of *Acer campestre* – nearly 2 years before examination, in autumn 2006) in Warsaw streets. Tree pits were filled with standard soil mixture due to the planting procedures accepted by the Metropolitan Authority of Parks, Greenery and Cleaning. Roadside trees grew at 8 sites in close proximity to the road (2–3 m) in lawn strips along streets or in planting spaces of 2 to 4 m^2 surrounded by pavement surface. Reference trees had been planted at 8 sites along streets in wide lawns (the minimum distance was 8 m away from the road). During drought periods all the trees were watered once a week with an amount of 20 dm^3/tree.

Measurements of chlorophyll *a* fluorescence

The measurements were done on three terms: 16–19th June, 5–6th August and 4–5th September 2008. The experiments were carried out on randomly selected trees, 5 in each examination site. Measurements of chlorophyll *a* fluorescence and chlorophyll content were provided on the same mature leaves from crown exterior (in June, 3 and 10 replications, respectively, in August and September, 6 and 10 replications, respectively). A HandyPEA fluorimeter (Hansatech Instruments Ltd., King's Lynn, Norfolk, Great Britain) was used to measure a chlorophyll *a* fluorescence parameter Performance Index. Chlorophyll relative content was measured using the chlorophyll content meter SPAD-502 (Minolta, Osaka, Japan).

Performance Index

The Performance Index values were automatically calculated by the HandyPEA (Hansatech Instruments Ltd. 2006).

The PI is defined as:

$$PI = RC/ABS * \Phi/(1-\Phi) * \Psi/(1-\Psi)$$

or in fluorescence terms:

$$PI = (V_J/(dV/dt_0)) * (F_V/F_0) * (F_M-F_J)/(F_J-F_0)$$

where:
F_0 – minimal fluorescence,
F_J – fluorescence at 2 miliseconds,
F_M – maximal fluorescence,
F_V – variable fluorescence given by the difference F_M-F_0,
V_J – relative variable fluorescence at 2 ms or at the step J.

Soil moisture and salinity measurements, climatic data

Simultaneously to chlorophyll *a* fluorescence, the volumetric water content of soil close to the trees' root system was measured using a LB-797 moisture sensor and a LB-796 moisture sensor reader (LAB-EL Elektronika Laboratoryjna s.j., Reguły, Poland). In June the soil moisture in some locations was not recorded due to technical reasons. In July 2008, soil samples at 0–20 cm depth from the tree surroundings were taken for laboratory analyses and their electrical conductivity was measured using a CX-551 multifunction meter (ELMETRON Sp.j., Zabrze, Poland).

Climatic data were obtained from Meteorology and Climatology, Faculty of Engineering and Environmental Science, WULS –Warsaw, Poland. They were analysed using Selianinov's hydrothermal coefficient k (Skowera and Puła 2004) which was derived as:

$$k = P/0.1*T,$$

where:
P – the sum of precipitation (mm) within the decade
T – the sum of temperatures >0°C within the same decade.

A climatic diagram was created using ArcSoft PhotoStudio 5 software (Arcsoft, Inc., Fremont, CA, USA).

Statistical analysis

Student's two-sample *t*-test was performed to compare roadside trees and reference trees within each taxon using STATISTICA 8.0 software (StatSoft, Inc., Tulsa, OK, USA), as well as correlation analysis. Correlation significance was based on Zieliński and Zieliński (1987).

Results

Climatic conditions, soil moisture and salinity

During the 2008 growing season, a precipitation deficit was noticed, especially in May and June. Average monthly temperatures were reported as 14.1, 19.3, 19.7°C and 19.2°C for May, June, July and August respectively. Selianinov's hydrothermal coefficient k was below the optimal value ($1.3<k\leq1.6$) and showed dry ($0.7<k\leq1.0$) or very dry ($0.4<k\leq0.7$) conditions during the investigation period (Fig. 1).

During the same period, soil moisture measurements revealed that the water content in the root area was insufficient and far from the optimum values (15–25%). Moreover, in some cases volumetric water content was below 10% (Fig. 2).

Soil salinity, based on electrical conductivity measurements, was distinctly higher in close proximity to

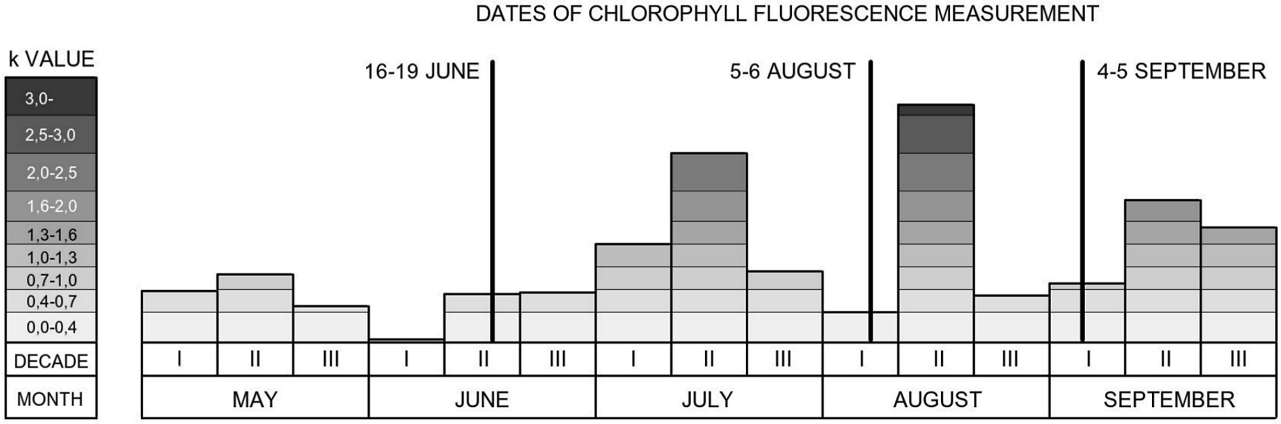

Fig. 1. Selianinov's hydrothermal coefficient k = P/0.1*T values of selected months in 2008 divided into decades and dates of chlorophyll *a* fluorescence measurements

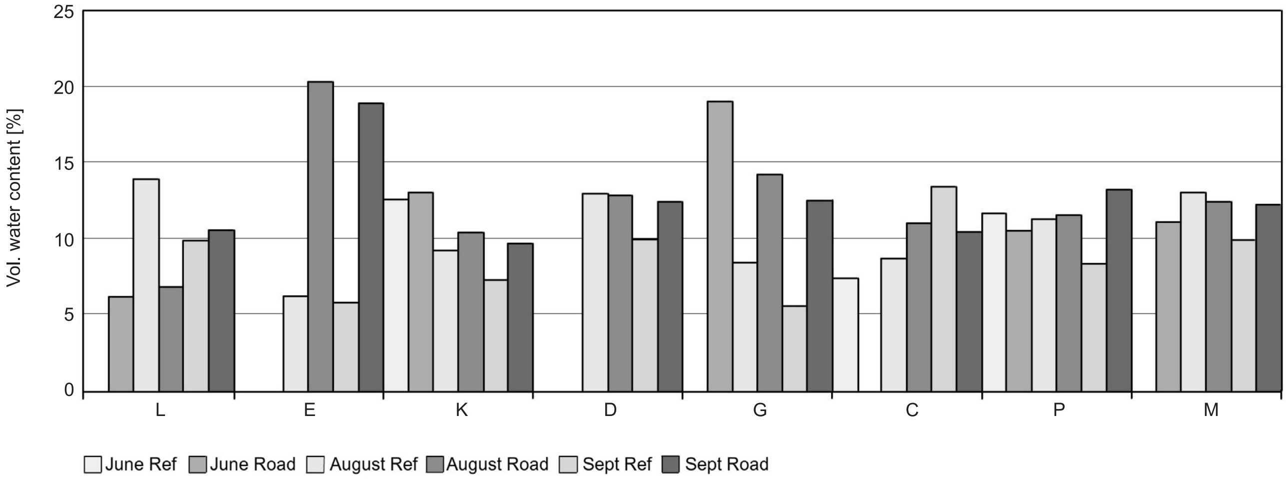

Fig. 2. Average values of soil moisture in 2008 (N=5)

Abbreviations: L – *Tilia cordata* 'Greenspire', E – *Tilia ×europaea* 'Pallida', K – *Acer campestre*, D – *Quercus rubra*, G – *Gleditsia triacanthos*., C – *Pyrus calleryana* 'Chanticleer', P – *Platanus ×hispanica* 'Acerifolia', M – *Ginkgo biloba*. Ref – reference trees, Road – roadside trees

the road at all the tested sites than in lawns where the reference trees grew. Likewise, pH showed higher values in the roadside locations (Table 1).

Chlorophyll *a* fluorescence and chlorophyll relative content

The experiment showed some differences in photosynthetic efficiency based on Performance Index measurements between roadside trees and reference trees. In two species: *Platanus ×hispanica* 'Acerifolia' and *Acer campestre* the differences were highly significant indicating stronger vitality in roadside trees. In *Gleditsia triacanthos* the significant differences did not occur. In other taxa the differences appeared or not depending on the date of examination. Roadside trees of *Pyrus calleryana* 'Chanticleer' revealed significantly higher values of PI in August and September, contrary to *Quercus rubra, Tilia ×europaea* 'Pallida' and *Tilia cordata* 'Greenspire'. The significantly lower PI values in roadside trees showed only *Tilia cordata* 'Greenspire' and *Ginkgo biloba* in September (Table 2, Fig. 3, 4, 5).

The relative chlorophyll content was significantly higher in roadside trees of all taxa except *Ginkgo biloba* (in August and September) and *Tilia cordata* 'Greenspire'. These two species showed significantly lower relative chlorophyll content in roadside trees in August (*Ginkgo biloba*) and September (*Tilia cordata* 'Greenspire' and *Ginkgo biloba*) (Table 3, Fig. 3, 4, 5).

Discussion

Higher salinity expressed by EC and higher pH values as occurred in this experiment are undoubtly one of the most recognizable factors which evoke street tree decline (Supłat 1993; Wrochna 2007). Soil salinity reduces water uptake and, by increase of pH, nutrients uptake. Consequently ion balance in plants is disturbed (Grattan and Grieve 1999). This results the decrease of growth, health, decorative value (Marosz 2004; Marosz and Nowak 2008; Borowski 2008) and, ultimately, death of many trees and shrubs grown in the close proximity to roads.

Table 1. Soil electrical conductivity and pH of examined sites (July 2008)

Species/cultivar	Symbol	Electrical conductivity [mS/cm]		pH	
		Ref	Road	Ref	Road
Tilia cordata 'Greenspire'	L	0.609	1.266	7.13	8.05
Tilia ×europaea 'Pallida'	E	0.714	1.722	7.21	7.64
Acer campestre	K	0.660	1.004	7.05	7.80
Quercus rubra	D	0.795	1.026	7.30	7.68
Gleditsia triacanthos	G	0.648	1.491	7.36	7.57
Pyrus calleryana 'Chanticleer'	C	0.723	1.146	7.11	7.63
Platanus ×hisp. 'Acerifolia'	P	0.648	1.089	7.26	7.62
Ginkgo biloba	M	0.675	1.506	7.32	7.81

Abbreviations: Ref – reference trees, Road – roadside trees

In addition, soil moisture measurements taken simultanously have indicated insufficient water content in the root area. While optimum is 15–25% volumetric water content, in some cases water content was reduced below 10%. Therefore the influence of water stress is expected to be of significant importance for the condition of the examined trees. Nevertheless, it should be considered as a constant element of the urban environment because of the great scale of such agglomeration like Warsaw, where there are about 1000 trees planted every year. Technical and financial limitations do not provide for comfortable water conditions for most of the newly planted trees. However, our results showed that there is no signifi-

Table 2. Differences in Performance Index (PI) between reference trees (Ref) and roadside trees (Road) based on Student's *t*-test. The *t* statistic was calculated for equal or unequal variances according to F value. Numbers given in bold indicate significantly higher means and test statistics at p = 0.05

Taxon/Date		Means		t-test			N	N	Std deviation		F test	
		Ref	Road	t	df	p	Ref	Road	Ref	Road	F	p
L	June	0.970	**1.631**	**–3.387**	**28**	**0.00211**	15	15	0.503	0.564	1.256	0.67554
	August	2.229	2.434	–0.642	34.300	0.52519	27	28	0.578	1.583	7.502	0.00000
	September	**2.896**	2.194	**2.510**	**52**	**0.01522**	24	30	1.035	1.010	1.051	0.88791
E	June	1.063	**1.592**	**–2.426**	**28**	**0.02196**	15	15	0.440	0.721	2.679	0.07557
	August	1.797	1.733	0.339	52	0.73598	25	29	0.633	0.749	1.397	0.40867
	September	1.991	1.945	0.185	55	0.85380	28	29	1.027	0.835	1.513	0.28212
K	June	1.396	**3.438**	**–6.527**	**21.251**	**0.00000**	15	15	0.566	1.072	3.583	0.02300
	August	1.265	**4.287**	**–13.383**	**42.694**	**0.00000**	30	28	0.605	1.043	2.973	0.00493
	September	1.659	**3.776**	**–8.119**	**56**	**0.00000**	29	29	0.929	1.052	1.283	0.51427
D	June	0.942	**1.972**	**–2.820**	**17.695**	**0.01148**	15	15	0.487	1.327	7.444	0.00058
	August	2.417	2.404	0.029	51	0.97724	28	25	1.534	1.552	1.025	0.94543
	September	3.248	3.650	–0.633	57	0.52952	30	29	2.290	2.590	1.279	0.51344
G	June	2.465	3.400	–1.835	28	0.07720	15	15	1.602	1.152	1.934	0.22952
	August	4.706	4.240	1.009	52	0.31748	27	27	1.850	1.525	1.473	0.32987
	September	4.752	4.317	1.032	56	0.30633	30	28	1.339	1.843	1.894	0.09474
C	June	2.891	3.448	–1.404	28	0.17131	15	15	0.957	1.201	1.577	0.40425
	August	2.831	**3.918**	**–5.439**	**55**	**0.00000**	28	29	0.754	0.755	1.003	0.99651
	September	3.389	**4.393**	**–2.623**	**57**	**0.01115**	29	30	1.186	1.701	2.057	0.05985
P	June	1.519	**2.849**	**–4.595**	**20.955**	**0.00016**	15	15	0.514	0.996	3.760	0.01856
	August	1.680	**3.091**	**–5.258**	**30.897**	**0.00001**	29	25	0.514	1.254	5.954	0.00001
	September	1.854	**4.427**	**–7.116**	**39.122**	**0.00000**	30	30	0.774	1.823	5.550	0.00001
M	June	0.953	0.760	1.217	28	0.23377	15	15	0.355	0.500	1.983	0.21247
	August	2.265	2.022	0.425	34.539	0.67313	30	27	1.183	2.748	5.393	0.00003
	September	**2.986**	1.569	**4.073**	**55**	**0.00015**	28	29	1.185	1.425	1.447	0.34051

Abbreviations: L – *Tilia cordata* 'Greenspire', E – *Tilia ×europaea* 'Pallida', K – *Acer campestre*, D – *Quercus rubra*, G – *Gleditsia triacanthos*, C – *Pyrus calleryana* 'Chanticleer', P – *Platanus ×hispanica* 'Acerifolia', M – *Ginkgo biloba*

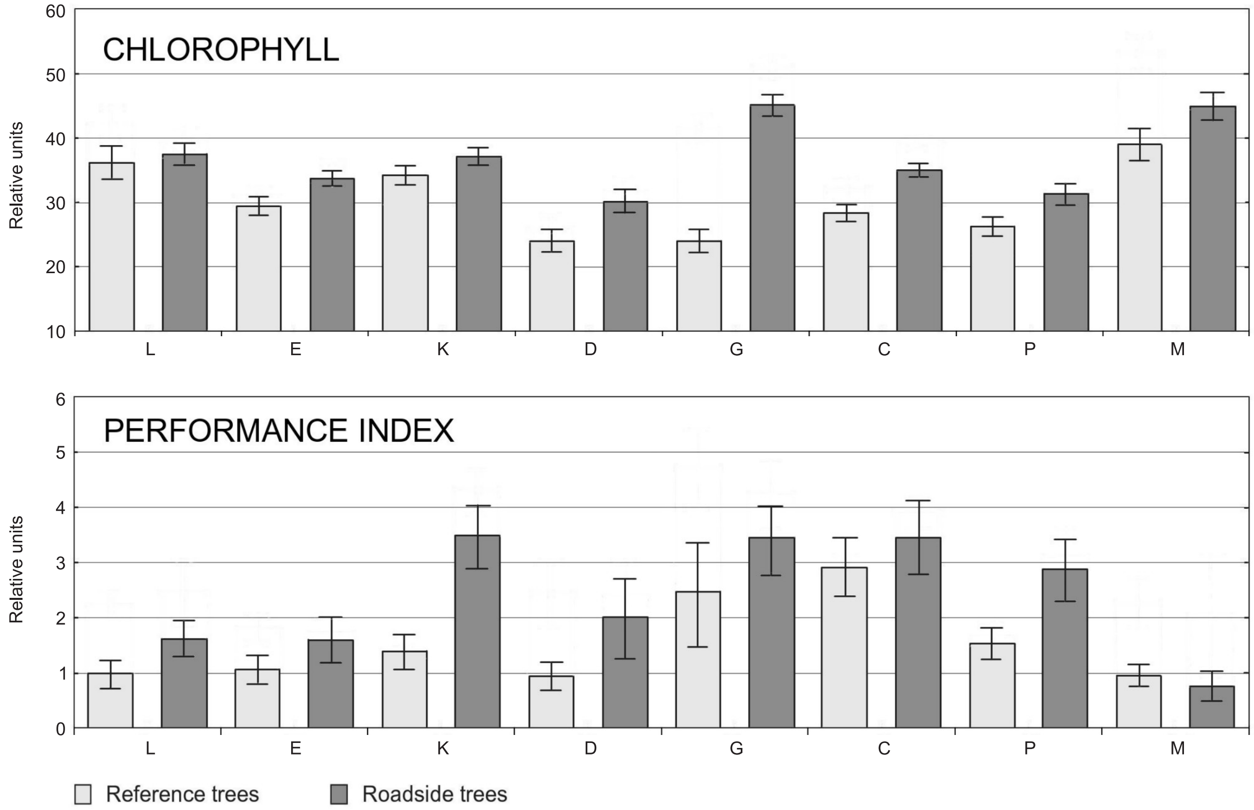

Fig. 3. Mean values of relative chlorophyll content and Performance Index (PI) in June 2008
Abbreviations: L – *Tilia cordata* 'Greenspire', E – *Tilia ×europaea* 'Pallida', K – *Acer campestre*, D – *Quercus rubra*, G – *Gleditsia triacanthos*, C – *Pyrus calleryana* 'Chanticleer', P – *Platanus ×hispanica* 'Acerifolia', M – *Ginkgo biloba*. Whiskers show confidence levels

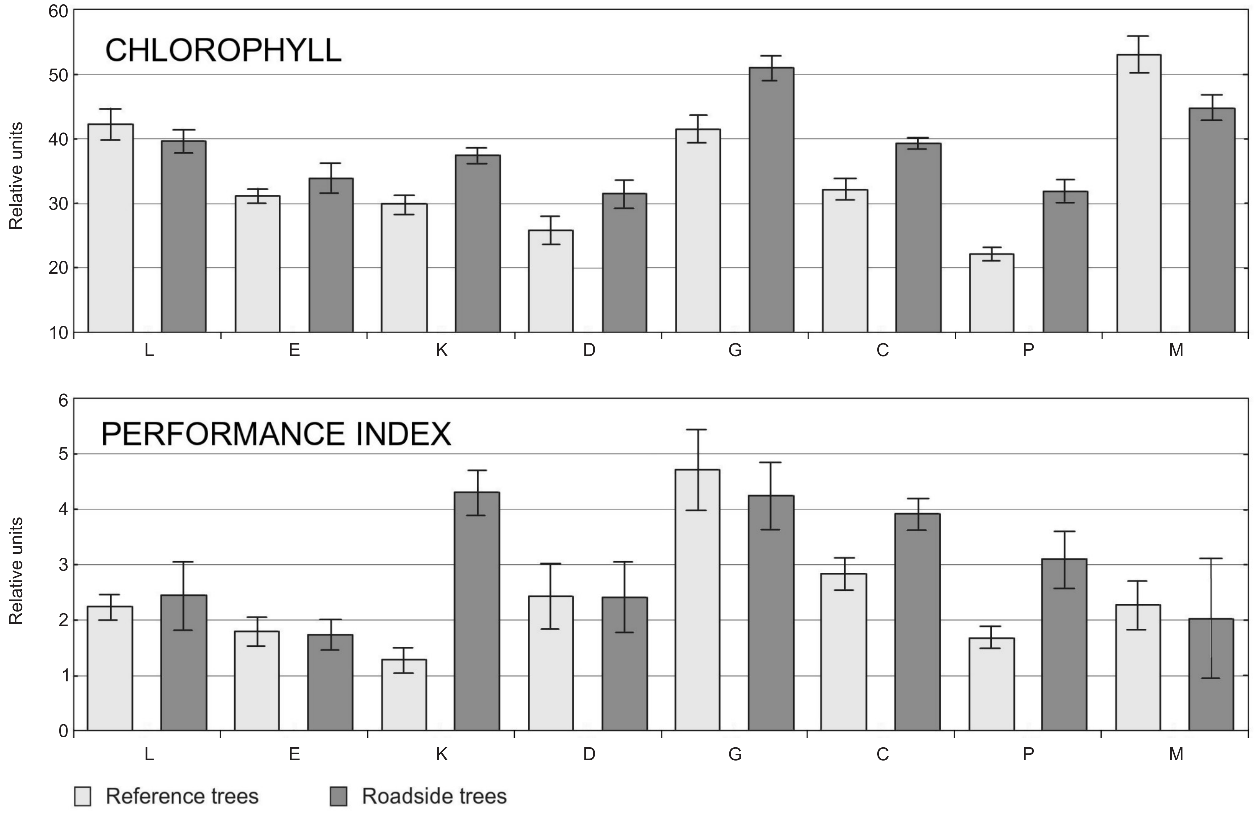

Fig. 4. Mean values of relative chlorophyll content and Performance Index (PI) in August 2008
Abbreviations: L – *Tilia cordata* 'Greenspire', E – *Tilia ×europaea* 'Pallida', K – *Acer campestre*, D – *Quercus rubra*, G – *Gleditsia triacanthos*, C – *Pyrus calleryana* 'Chanticleer', P – *Platanus ×hispanica* 'Acerifolia', M – *Ginkgo biloba*. Whiskers show confidence levels

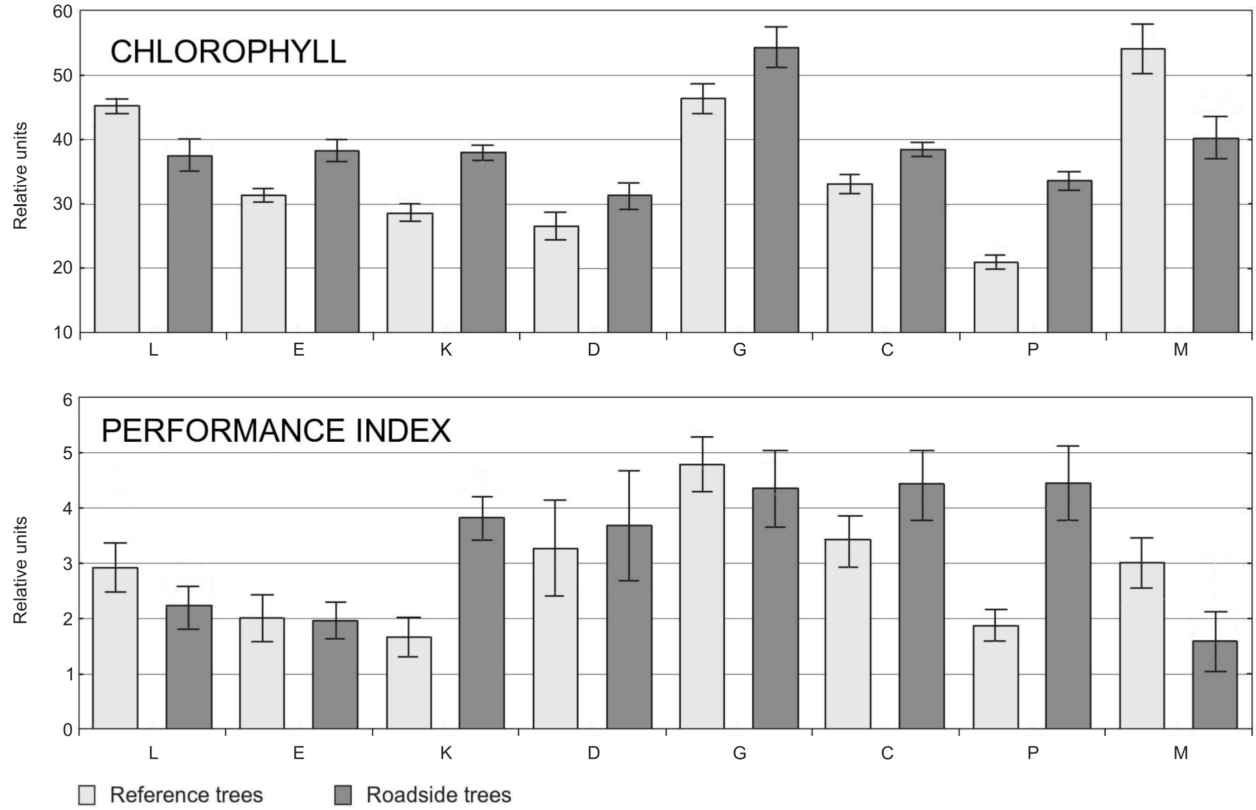

Fig. 5. Mean values of relative chlorophyll content and Performance Index (PI) in September 2008
Abbreviations: L – *Tilia cordata* 'Greenspire', E – *Tilia ×europaea* 'Pallida', K – *Acer campestre*, D – *Quercus rubra*, G – *Gleditsia triacanthos*, C – *Pyrus calleryana* 'Chanticleer', P – *Platanus ×hispanica* 'Acerifolia', M – *Ginkgo biloba*. Whiskers show confidence levels

cant relationship between the relative chlorophyll content or the fluorescence parameters and the soil moisture measured simultaneously during the whole period of investigation (data not shown). This indicates that not only water deficiency in soil affected the photosynthetic efficiency of tested trees.

The relative chlorophyll content allows to evaluate leaf chlorophyll concentration (Loh et al. 2002). It is useful only in comparative studies within a species or a cultivar as the relationship between SPAD measurements and extractable chlorophyll concentration had species-specific characteristics (Loh et al. 2002; Samsone et al. 2007). Nevertheless, the noticeably lower relative chlorophyll content than expected indicates some disturbances in the availability of nitrogen or other nutrients in many trees (Turner and Jund 1994; Peryea and Kammereck 1997; Rubio-Covarrubias 2009). In our research the significantly lower relative chlorophyll content in reference trees might be the reason for weak photosynthetic efficiency in some studied taxa growing away from the street (Table 4).

Performance Index of photosystem II (PI) is considered to be a more sensitive indicator than other measured or/and calculated chlorophyll *a* fluorescence parameters, especially *in situ* (Christen at al. 2007; Naumann et al. 2008) and it is able to differentiate clearly plants exhibiting better or worse photosynthetic efficiency (Hermans et al. 2003). In our experiment the PI did not reveal significantly worse values due to the close proximity to the road, exept *Tilia cordata* 'Greenspire' and *Ginkgo biloba* in September. Although, the Performance Index comparison between the taxa is debatable, poor performance of both linden taxa and *Ginkgo* roadside trees should be noticed. In the roadside trees of both linden cultivars margin chloroses and necroses referring to salinity stress were observed (Marosz and Nowak 2008). Such injuries also appeared in new leaves and shoots which emerged in the late summer. *Tilia cordata* 'Greenspire' and *Tilia ×europaea* 'Pallida' are cultivars selected for urban planting, however, their reactions to harsh street environment conditions were similar to those noticed in other linden taxa (Supłat 1993; Borowski 2008). In our opinion linden taxa planting in close proximity to a road should be avoided.

Likewise, in *Ginkgo biloba* about 40% of the roadside trees revealed margin chloroses and necroses in August. This corresponds with permanently low performance of photosystem II in the roadside *Ginkgo* trees. Although *Ginkgo* is considered to be a good species for street planting (Handa et al. 1997; Bassuk et al. 2003), we believe that this species should not be planted in close proximity to the road in our climate where a great amount of salt is used for road de-icing.

Many observations indicate that *Quercus rubra* exhibits fair tolerance to urban street environments

Table 3. Differences in relative chlorophyll content between reference trees (Ref) and roadside trees (Road) based on Student's *t*-test. The *t* statistic was calculated for equal or unequal variances according to F value. Numbers given in bold indicate significantly higher means and test statistics at p = 0.05

Taxon/Date		Means		t-test			N	N	Std deviation		F test	
		Ref	Road	t	df	p	Ref	Road	Ref	Road	F	p
L	June	36.004	37.187	–0.809	77.553	0.42126	45	45	8.109	5.518	2.160	0.01211
	August	42.240	39.652	1.773	98	0.07936	50	50	8.157	6.325	1.663	0.07810
	September	**45.162**	37.492	**5.626**	**73.254**	**0.00000**	50	50	4.412	8.572	3.776	0.00001
E	June	29.438	**33.467**	**–4.714**	**88**	**0.00001**	45	45	3.951	4.154	1.106	0.74063
	August	31.128	**33.866**	**–2.169**	**73.437**	**0.03328**	50	50	4.098	7.928	3.743	0.00001
	September	31.328	**38.182**	**–6.350**	**76.997**	**0.00000**	50	50	3.730	6.659	3.187	0.00008
K	June	33.833	**36.944**	**–3.221**	**88**	**0.00179**	45	45	5.096	4.001	1.622	0.11238
	August	29.816	**37.400**	**–8.174**	**98**	**0.00000**	50	50	5.217	3.979	1.719	0.06075
	September	28.616	**37.934**	**–10.495**	**98**	**0.00000**	50	50	4.876	3.955	1.520	0.14608
D	June	23.791	**30.211**	**–5.157**	**88**	**0.00000**	45	45	6.139	5.662	1.175	0.59412
	August	25.728	**31.438**	**–3.683**	**98**	**0.00038**	50	50	7.496	7.998	1.138	0.65202
	September	26.574	**31.202**	**–3.214**	**98**	**0.00177**	50	50	7.297	7.100	1.056	0.84828
G	June	24.091	**45.356**	**–17.622**	**88**	**0.00000**	45	45	5.666	5.782	1.041	0.89343
	August	41.482	**50.932**	**–6.688**	**98**	**0.00000**	50	50	7.480	6.624	1.275	0.39801
	September	46.144	**54.364**	**–4.221**	**98**	**0.00005**	50	50	8.592	10.762	1.569	0.11826
C	June	28.224	**35.207**	**–8.435**	**73.765**	**0.00000**	45	45	4.711	2.940	2.567	0.00226
	August	32.128	**39.302**	**–7.803**	**73.119**	**0.00000**	50	50	5.784	2.967	3.800	0.00001
	September	33.042	**38.372**	**–5.864**	**87.661**	**0.00000**	50	50	5.268	3.683	2.046	0.01361
P	June	26.256	**31.169**	**–4.501**	**88**	**0.00002**	45	45	4.440	5.824	1.720	0.07530
	August	22.102	**31.894**	**–9.873**	**82.740**	**0.00000**	50	50	3.746	5.929	2.505	0.00166
	September	20.990	**33.494**	**–14.136**	**86.214**	**0.00000**	50	50	3.511	5.176	2.173	0.00758
M	June	39.116	**45.173**	**–3.749**	**88**	**0.00032**	45	45	8.248	7.033	1.375	0.29411
	August	**53.054**	44.830	**4.763**	**89.523**	**0.00001**	50	50	9.872	7.183	1.889	0.02804
	September	**53.974**	40.144	**5.641**	**98**	**0.00000**	50	50	13.270	11.154	1.415	0.22750

Abbreviations: L – *Tilia cordata* 'Greenspire', E – *Tilia ×europaea* 'Pallida', K – *Acer campestre,* D – *Quercus rubra,* G – *Gleditsia triacanthos,* C – *Pyrus calleryana* 'Chanticleer', P – *Platanus ×hispanica* 'Acerifolia', M – *Ginkgo biloba*

Table 4. Pearson's correlation coefficient r for the relationship between PI and relative chlorophyll content for each species/cultivar on succeeding dates and during the whole period of experiment

Date	L	E	K	D	G	C	P	M
June	0.55*	0.83**	0.34	0.86**	0.55*	0.13	0.43	0.65*
August	0.48	0.41	0.59*	0.82**	–0.57*	0.82**	0.78**	0.81**
September	0.85**	0.22	0.77**	0.58*	0.36	0.73**	0.97**	0.40
2008	0.68**	0.50**	0.56**	0.63**	0.51**	0.60**	0.73**	0.58**

Abbreviations: L – *Tilia cordata,* 'Greenspire', E – *Tilia ×europaea* 'Pallida', K – *Acer campestre,* D – *Quercus rubra,* G – *Gleditsia triacanthos,* C – *Pyrus calleryana* 'Chanticleer', P – *Platanus ×hispanica* 'Acerifolia', M – *Ginkgo biloba,* *indicates signifficant correlation at $P < 0.05$, **indicates signifficant correlation at $P < 0.01$, N=10 for the succeeding dates and N=30 for the whole period (for this test mean values of PI and chlorophyll content of each tree were used)

(Siewniak and Siewniak 2001; Bassuk et al. 2003; Borowski and Latocha 2006). Pracz (1990) ascertained wide variation in salt tolerance in *Quercus rubra*. According to Percival (2005) it is more salt tolerant than *Q. robur*, but more sensitive to heat and herbicides. In our investigation the condition of the photosynthetic apparatus of all *Quercus rubra* trees was very poor in the beginning of the growing season but recovered steadily. In the beginning of September this species approached the taxa of the higher photosynthetic efficiency.

The most favorable values of Performance Index were shown in *Gleditsia triacanthos*, *Pyrus calleryana* 'Chanticleer', *Platanus ×hispanica* 'Acerifolia' and *Acer campestre*. Close proximity to the road did not reduce the efficiency of their photosynthetic apparatus. In our opinion higher PI values may indicate the adjustment ability of these taxa to the specific roadside conditions. Similar reactions in the face of stress factors were observed by Bussotti et al. (2007). In the roadside trees of these taxa no visible signs of stress reaction, i.e. leaf chlorosis or necrosis, were noticed, including *Acer campestre*, although Percival et al. (2003) indicated that this species is sensitive to salt stress. This confirms opinions presented by Łukasiewicz (1995), Siewniak and Siewniak (2001), Bassuk et al. (2003), Borowski and Latocha (2006) related to urban environment tolerance of the above-mentioned species. Roloff et al. (2009) classified these four taxa as suitable or very suitable for urban habitats in view of climate change.

The lower photosynthetic efficiency in *Pyrus calleryana* 'Chanticleer', *Platanus ×hispanica* 'Acerifolia' and *Acer campestre* trees growing away from the road indicates some disturbances in their vitality. All the examined trees were planted in comparable way in standard soil mixture and similarly cared for. Nevertheless their growing conditions might have changed during the growing period. Variations in nutrition availability might be one of the influencing factors, as well as other effects like freezing, drought or even human negligences in care and maintenance. To find out the reasons responsible for any disturbances in the physiological state of these plants, further analyses of nutrients and water content in the soil and the plants, as well as on site morfological observations are needed.

Our experiment showed the usefulness of chlorophyll *a* fluorescence as a rapid and convenient method for evaluation of city trees' condition. However, this method can indicate only the physiological state of plants growing under certain growth conditions. Thus, it should be considered as a preliminary test in stress detection (Hermans et al. 2003). In the case of alarming values of chlorophyll *a* fluorescence parameters, obtained results would be the first step to undertake further investigations on the causes of any disturbances in the tree's physiological state. This would further allow for the formulation of guidelines for tree care and maintenance.

Nevertheless, our experiment allowed us to distinguish the species most tolerant to urban environment stress: *Gleditsia triacanthos, Pyrus calleryana* 'Chanticleer', *Platanus ×hispanica* 'Acerifolia' and *Acer campestre. Quercus rubra* proved to be relatively tolerant. *Tilia ×europaea* 'Pallida', *Tilia cordata* 'Greenspire' and *Ginkgo biloba* showed worse tolerance compared to other studied taxa.

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