PLANTS
IN URBAN AREAS AND LANDSCAPE

IMPACT OF AIRBORNE SALINITY DEPOSITION ON SHOOT GROWTH AND LEAF PHENOLOGY OF LONDON PLANE (*PLATANUS × HISPANICA* MILL. EX MÜNCHH. 'ACERIFOLIA')

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Street environmental conditions are characterised by heavy pollution which is detrimental for street trees. Especially, application of de-icing salt in streets in Central and Northern Europe causes serious damages of urban trees. Along with salt deposition in soils some amount of de-icing salt is also sprayed in the air and may be deposited on street trees' shoots. The aim of this study was to determine how the close vicinity to roads affects shoot increment and leaf phenology of London plane. Annual shoot elongation and the estimated sum of shoot length (using photographic method) of each 5 trees growing in 4 different streets was measured and leaf phenology was observed in 2008 and 2009. Additionally, the soil salinity and the shoot surface salinity was measured in spring. The results indicate that soil and shoot surface salinity depends on traffic intensity and distance of the road. Trees growing in the close vicinity to the road of low traffic and trees growing 15 m away from the road showed similar pattern in shoot salt deposition. Salt deposition on shoots in trees growing in the close proximity to a road of heavy traffic was three-fold higher. Those trees revealed very late bud swelling and late leaf shedding. Leaf yellowing did not occur, leaves turned brown and dry and were shed in late November. Moreover, trees growing in the close vicinity to the road of heavy traffic were developing late long shoots, but their estimated sum of shoot length did not increase much. This response is expected to be the consequence of buds' injuries caused by salt spray produced in roads of high vehicle speed.

Keywords: de-icing salt, electrical conductivity, salt spray, street trees, urban trees

1 Introduction

Application of de-icing salts, particularly sodium chloride (NaCl), in streets in Central and Northern Europe is a very common and efficient way to keep the appropriate traffic flow in winter. This contributes to salt deposition in street soils and affects trees growing along streets (Equiza, Calvo-Polanco, Cirelli, Señorans, Wartenbe, Saunders and Zwiazek, 2017; Ordóñez-Barona, Sabetski, Millward and Steenberg, 2018). Salt deposition in soils is the highest in the end of winter and diminishes during the growing season (Ordóñez-Barona et al., 2018). On the contrary, salt deposition in trunk, twigs, and leaves increases progressively due to abundant water up-take in the spring for new shoot formation and accompanying Na and Cl ion up-take from the soil (Cekstere, Nikodemus and Osvalde, 2008). Most of scientific papers report leaf injuries such as chlorosis and necrosis as a result of road-side salinity (Gałuszka, Migaszewski, Podlaski, Dołęgowska and Michalik, 2011), lower chlorophyll content (Equiza et al., 2017), disturbed nutrient uptake (Ordóñez-Barona et al., 2018), and decreased photosynthetic apparatus efficiency (Swoczyna, Kalaji, Pietkiewicz, Borowsk, and Zaraś-Januszkiewicz, 2010). Changed leaf anatomy (Hura, Szewczyk-Taranek Hura, Nowak and Pawłowska, 2017), diminished photosynthetic rate (Loreto, Centritto and Chartzoulakis, 2003; Hura et al., 2017) and impeded growth (Patykowski, Kołodziejek and Wala, 2018) were also observed in pot experiments.

Along with salt deposition in soils, some amount of de-icing salt is also sprayed in the air in winter (Majewski, Rogula-Kozłowska, Rozbicka, Rogula-Kopiec, Mathews and Brandyk, 2018; Rogula-Kozłowska, Majewski, Widziewicz, Rogula-Kopiec, Tytła, Mathews and Ciuka-Witrylak, 2019) and may be deposited in roadside trees' shoots (Borowski and Pstrągowska, 2010; Borowski, Pstrągowska and Swoczyna, 2014). Here, the symptoms may be different than those caused by salt up-take from the soil (Borowski et al., 2014) including dieback of shoots and buds formed in the previous

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season (Hofstra and Lumis, 1975), suppression of flowering (Hofstra and Lumis, 1975; Berkheimer and Hanson, 2006), additional buds' emergence, and tree crown deformations (Hofstra, Hall and Lumis, 1979). It was reported that airborne salinity affects foliage of evergreen gymnosperms such as Norway spruce (Zítková, Hegrová and Anděl, 2018) and may affect phenological phases (Paludan-Müller, Saxe, Pedersen and Randrup, 2002).

Street trees play essential role in mitigation of the urban heat island effect (Shashua-Bar and Hoffman, 2000), therefore, their appropriate performance in street habitats is of high importance. Good health conditions enable effective photosynthetic activity. The size of crown volume and leaf biomass are also important due to shading properties (Gillner, Korn and Roloff, 2015). Therefore, numerous researches are engaged in selection of tree species suitable for harsh urban environment. Some studies indicate that London plane is one of the best-performing tree species in urban environment in Central Europe (Dmuchowski and Badurek, 2004; Swoczyna et al., 2010). Since 2002, London plane is often planted in Warsaw as a street tree and is considered to be tolerant to urban drought and soil salinity (Dmuchowski, Baczewska, Gozdowski and Brągoszewska, 2014; Swoczyna, Kalaji, Pietkiewicz and Borowski, 2015)

The aim of this study was to determine:

1. how the magnitude of vehicle traffic and proximity to a road influences salt deposition on street trees' shoots;
2. how the salt contamination of tree crowns affects shoot increment and leaf phenology in London plane.

2 Material and methods

2.1 Plant material and location

The examined London plane trees were planted in 2003 along streets in Warsaw (52° 7′ N–52° 16′ N, 20° 55′ E–21° 2′ E), Poland. The trees were situated in 4 locations with differing proximity to a road. Rodowicza, Dolinka, and Wolska are arterial streets of heavy road traffic (2,748, 6,166 and 4,962 vehicles per hour at the morning rush hour, respectively; source: http://www.zdm.waw.pl/fileadmin/user_upload/informacje/analizy_na_drogach/Analiza_ruchu_na_drogach_2007.pdf, retrieved 2009.02.18) and high vehicle speed, and trees here were planted in the distance of 15, 8, and 3.5 m from roads, respectively. In Podskarbińska, a local street of low traffic (443 vehicles per hour, source: as above) and low car speed, trees were planted in the distance of 2.5–3 m from the road. Rodowicza and Dolinka are situated in peripheral districts, Wolska and Podskarbińska in pericentral ones. All trees grow in lawn strips. Five trees of good health condition in each site were examined.

2.2 Salinity measurements

In July 2008, soil samples at 0–20 cm depth from tree surroundings were taken for laboratory analyses and their electrical conductivity was measured using the CX-551 multifunction meter (ELMETRON Sp.j., Zabrze, Poland).

In the end of March 2011, i.e. before bud swelling, 5 living shoots from a road-side part of a tree crown and 5 shoots from an opposite side of the crown were collected from each tree (2 samples from each tree). Additionally, for shoot salinity measurements, 25 shoots from 2 trees growing in the park of the Warsaw University of Life Sciences were collected in order to assess the magnitude of overall road salt deposition. A diameter of each shoot was measured 4 cm below the apical bud. A standarised surface of every shoot was calculated as a right circular cylinder surface by multiplication of a circumference of a shoot (calculated from the measured shoot diameter) by length of 5 cm (as the cylinder height). Apical parts of every 5 shoots being a sample of the examined tree crown part were immersed in distilled water at 20 °C for the depth of 5 cm in separate beakers. After 1 hour shoots were removed and the electrical conductivity of the solutions was measured using the CX-551 multifunction meter (ELMETRON Sp.j., Zabrze, Poland). Shoot salinity was calculated as a standarised salinity index Z:

$$Z = EC/P \qquad (1)$$

where:

EC – was electrical conductivity of the single solution (µS/cm)

P – is the sum of standarised surfaces of 5 shoots being the single sample (cm^2)

2.3 Annual shoot elongation and estimated sum of shoot length

A photographic method described by Borowski, Pstrągowska, Sikorski, Orzechowski, and Mąkowski (2005) was used to obtain estimated sum of shoot length in each year. Five trees in every location were photographed at night-time using a digital camera and a flashgun of high light power. The obtained images showed bright and clear tree silhouettes on a dark background. The DENDRO software was used in order to calculate the estimated sum of shoot length (Borowski et al., 2005). The length of annual shoots of each 5 trees was measured after the termination of the growing season in 2008 and 2009, 20 randomly chosen shoots from around the crown from the height of 2–2.5 m above ground were selected for the measurements.

2.4 Leaf phenology

Leaf phenology was observed in 2008 and 2009. The following stages were noted when in 10% of buds occured the beginning of bud swelling, BBCH 01, and beginning of bud breaking, BBCH 07, in 90% of buds leaf expansion was completed, BBCH 19, 50% of leaves were shed, BBCH 95, and the end of leaf fall when 90% of leaves were shed, BBCH 97 (Finn, Straszewski and Peterson, 2007). The length of the growing season (LGS) was calculated as the subtraction of BBCH 97 and BBCH 01 (Matsumoto, Ohta, Irasawa and Nakamura, 2007).

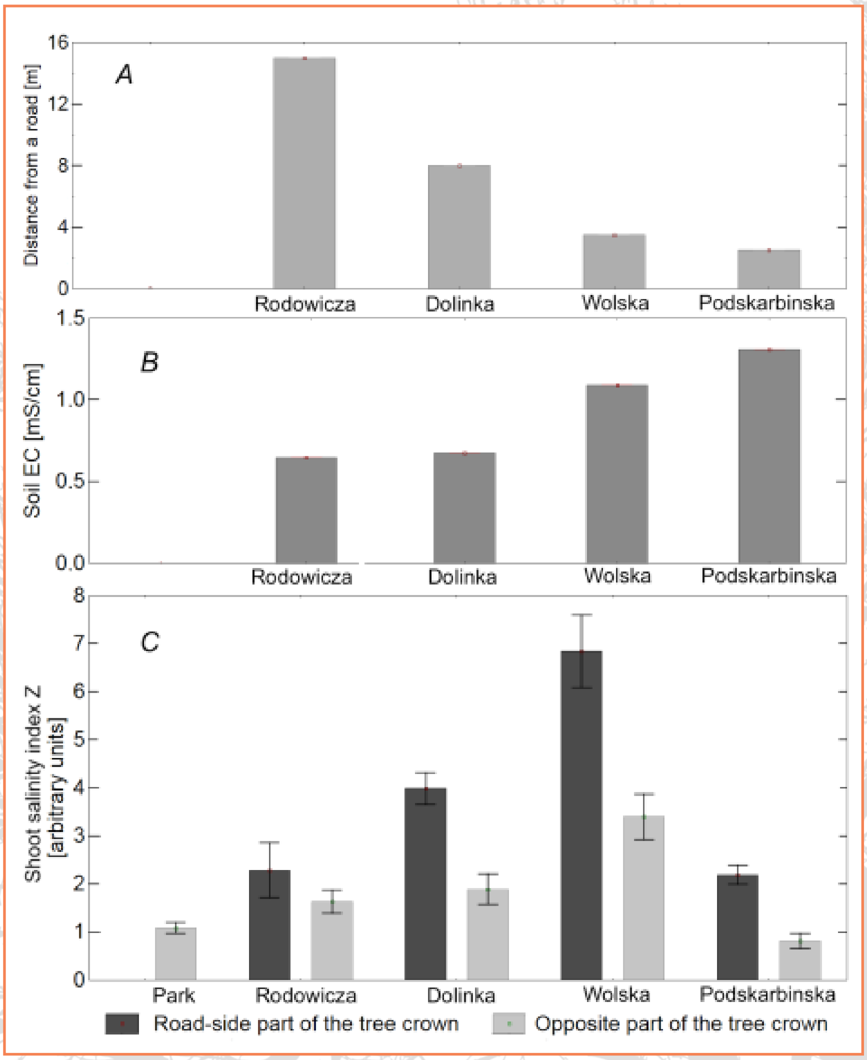
2.5 Statistical Analysis

One-way ANOVA was used to compare leaf phenology and shoot increments between 4 locations, as well as for shoot salinity comparison. For all comparisons STATISTICA version 13.0 software (TIBCO Software Inc. (2017), http://statistica.io., USA) was used.

3 Results and discussion

Salt deposition in road-side soils depends on the distance from a road, but also on the magnitude of road traffic (Blomqvist and Johansson, 1999). In our research, salt deposition in street soils depended on the distance of the road (Figure 1A and B). The farther the samples were collected the lower soil salinity was measured. The soil in Dolinka (8 m from a road) had similar EC to the soil in Rodowicza. This is consistent to Marosz (2011) who found that contamination with de-icing salt reaches up to 7 m or rarely 8 m far from a landscape road characterised by heavy road traffic.

Soil samples from Wolska and Podskarbińska were collected nearly from the same distance from a road edge adequately to the position of tree trunks. Lower EC in Wolska (a street of high road traffic) than in Podskarbińska (a street of low road traffic) suggests the different way of salt deposition in soil. In fact, streets of high road traffic were simultaneously of higher vehicle speed due to longer distances between neighbouring crossings, and Podskarbińska, the street of low road traffic, was of lower vehicle speed. In the streets of higher vehicle speed diluted de-icing salts are moved with the traffic-raised wind as aerosol farther and deposited in soil at distant locations (Hofstra



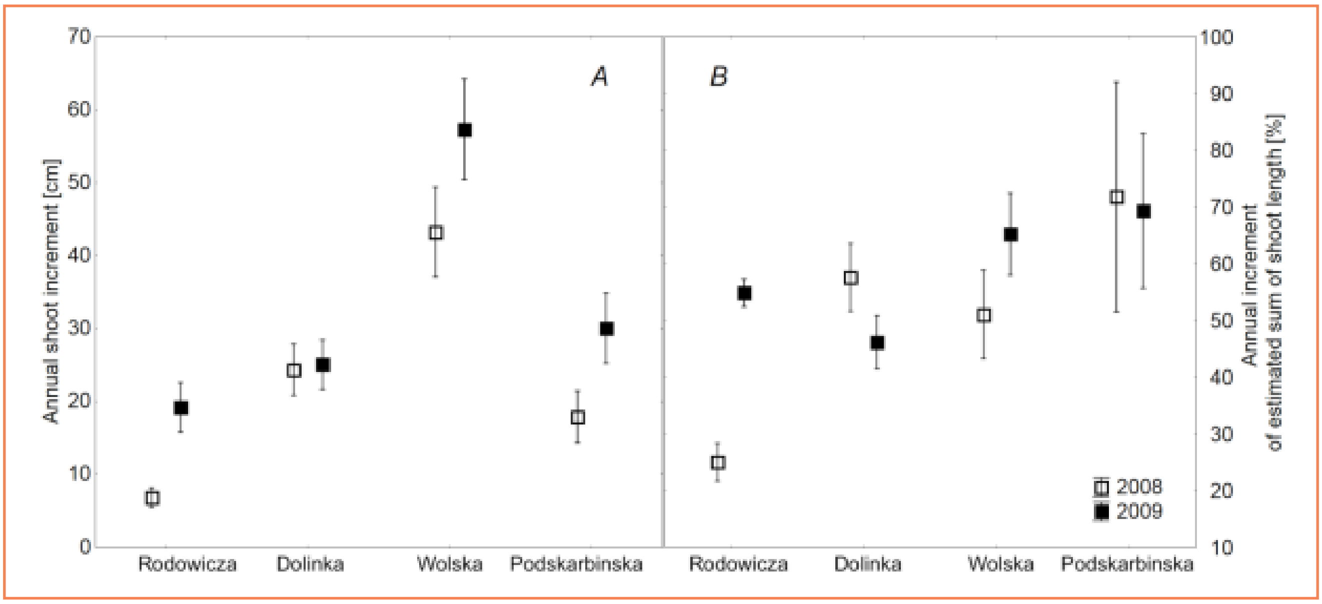
■ **Figurere 1:** Distance from a road where examined trees were planted (A), soil *EC* in examined locations (B), and standardised shoot salinity index *Z* calculated as a ratio of *EC* of diluted salt spray from shoots divided by standarised area of shoot surface (C)
Source: author's own work

et al., 1979). Therefore, their concentration in the soil adjacent to the road may be lower compared to roads where splashing or spraying of diluted salts do not penetrate far.

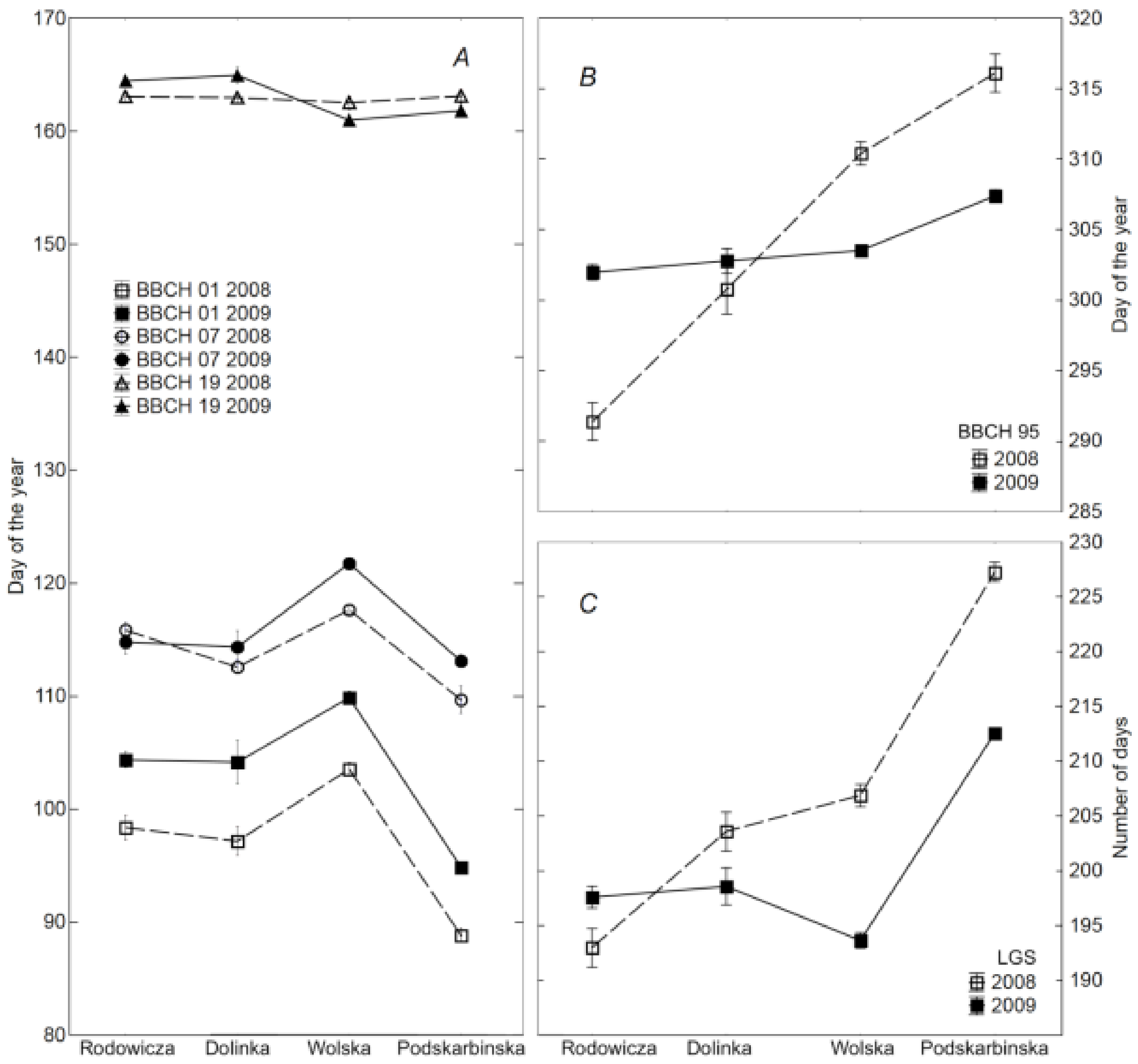
On the contrary, salt deposition on shoots of trees growing along two high-speed roads, Wolska and Dolinka, was higher than in Podskarbińska (Figure 1C). Road-side part of the crowns in Podskarbińska revealed higher EC while the opposite part of the crowns showed EC similar to park trees. This confirms the above mentioned suggestion that in quiet streets de-icing salt dispersion is low. In Rodowicza, at the distance of 15 m, salt deposition on road-side shoots was as high as in Podskarbińska. Moreover, salt deposition in the opposite part of the crowns in Rodowicza was still higher than in the opposite part of the crowns in Podskarbińska and in park trees. Some authors underline that wind exposure and prevailing direction may shift salt deposition on road-side trees and shrubs (Hofstra et al., 1979; Berkheimer and Hanson, 2006). In Central Poland, west, southwest and northwest winds predominate and trees in Rodowicza planted on the east side of the street were the most exposed ones to winds. Trees in Wolska and Dolinka grew on the south and north side, respectively. Nevertheless, in each examined site salt deposition on the opposite side of tree crowns was approximately twice as low as on the road-side shoots. This indicates that not only simply a distance from a road affects salt deposition, but also filtering capacity of numerous twigs and branches in the crown as ascertained by Beckett, Freer-Smith, and Taylor (2001). Weerakkody, Dover, Mitchell and Reiling (2018) found that particular matter deposition depends on density of plant organs so it is obvious that crowns themselves acted as filters to some extent and farther situated shoots captured less salt microparticles.

Salt deposition on shoots and buds is harmful for trees and shrubs growing along roads (Hofstra et al., 1979; Borowski et al., 2014; Swoczyna and Latocha, 2016). According to visual assessment of examined trees, the most severe injuries were observed in Wolska and Dolinka. Numerous buds did not develop and shoots partially died down. Affected branches developed new shoots and leaves later from dormant or adventitious buds. There were no evident differences between road-side and opposite parts of tree crowns according to visual assessment, however, lost shoots were not counted and such comparison was not performed. Reaction of trees to abundant shoot dieback was illustrated by annual shoots' measurements. In severely affected planes in Wolska, new shoots developing from adventitious buds revealed high vitality and their length was untypically great (Figure 2A). This is consistent with Puijalon, Piola, and Bornette (2008) reporting shifted regeneration ability in stressed plants.

Formation of long shoots did not cause the increase of digitally estimated sum of shoot length (Figure 2B). Dead dry shoots were partially dropped down and thus the increase of shoot number in Wolska did not differ from other locations. In many species, died shoots



■ **Figurere 2:** Annual shoot increments [cm] in London plane growing in 4 locations (A), means, whiskers indicate confidence level at $p = 0.05$, $N = 100$; annual increment of estimated sum of shoots (B), means, whiskers indicate *SD*, $N = 5$
Source: author's own work



Figurere 3: Phenological stages of bud and leaf development, beginning of bud swelling, BBCH 01, bud breaking, BBCH 07, leaf expansion completed, BBCH 19 (A); 50% of leaves shed, BBCH 95 (B); length of growing season, LGS (C); means, whiskers indicate *SE*
Source: author's own work

are not removed by the tree itself. Then, formation of bundles of old and new shoots developing at the base of older branches is observed (Hofstra et al., 1979; Borowski and Pstrągowska, 2010).

Previous research indicates late bud breaking as a typical consequence of salt injuries in trees and shrubs (Hofstra et al., 1979). Reports describing injuries due to salt deposition on shoots are rather sparse and discuss both marine aerosol (in seashore habitats) and de-icing salts (in the proximity to roads) effects. Paludan-Müller et al. (2002) showed that salt solution application to bark evoked 4–6 day delay in bud breaking in *Tilia cordata* and 8 day delay in *Acer pseudoplatanus* and *Fagus sylvatica*, however, salt application to buds did not influenced bud break timing. Jonsson (2006) in *in situ* research indicated that the delay in bud development is connected with high chloride concentration in leaf primordia in buds. This impeded water accumulation and then primordia remained stagnant till mid-May. Shifted chloride concentration and unsuccessful water accumulation in leaf primordia led to bud necrosis.

In our research, the latest bud swelling and breaking was observed in Wolska, but the last stage of spring development was nearly of the same timing as in other locations in 2008 and slightly earlier in 2009 (Figure 3A). This indicates that after the delay in bud development in April, leaf development was vigorous and terminated on time. Contrary to Paludan-Müller et al. (2002) and Jonsson (2006), no visible symptoms of leaf injuries were observed in Wolska. Both new shoots and leaves were of good conditions. Leaf shedding phase in Wolska appeared simultaneously with leaf shedding in Dolinka and Rodowicza in 2008 and 8 days later in 2009 (Figure 3B). In all streets, leaf shedding was preceded by leaf yellowing, except of Wolska where only green leaves were shed. Although trees in Wolska started vegetation with ca. 5 day delay, the length of the growing season there was not shortened (Figure 3C).

According to former research, London plane seems to be very tolerant to urban environments (Dmuchowski et al., 2014; Swoczyna et al., 2015) in Poland. The results of this research reveal that road-side salinity in the city affects growth and physiological processes in young London plane trees leading to disturbances in phenological behaviour. Salt contamination of shoots and buds may result in dieback of particular organs. But in general, trees maintain good vitality and are able to acclimate to urban conditions. The pattern of habitat conditions in urban streets is more complex and depends on street characteristics (wide or narrow), built environment (dense or scattered), magnitude of road traffic (high or low), soil conditions (tree pits or lawns), wind exposure and many other factors. Evaluating species only based on e.g. their ability to accumulation of sodium and chloride ions or on growth pattern does not give the complex information. In order to evaluate woody species ability to cope with urban environmental conditions, the examined species should experience different sites and their behaviour should be evaluated comprehensively.

4 Conclusions

1. In urban habitats, salt contamination at harmful levels may concentrate mostly in soil, but also on tree shoots and branches, depending on street characteristics.
2. Higher de-icing salt deposition on road-side shoots than on opposite-side shoots indicates both the depletion of salt aerosol deposition along with the distance from a road and filtering capacity of twigs and branches in tree crowns.
3. High salt deposition on shoots in trees growing along arterial streets indicates the important effect of vehicle speed on salt dispersion and tree crowns' contamination.
4. Shoot deposition of de-icing salt may lead to shoot and bud dieback and secondary growth from dormant or adventitious buds may not compensate for the lost of injured organs.
5. Extended length of the growing season in trees in a local street despite the highest soil salinity should be explained as an effect of the urban heat island because of its location in proximity to the downtown area. Simultaneously, this confirms relatively high resistance of London plane to soil salinity.
6. London plane seems to be a species of high vitality and ability to cope also with salt deposition on shoots.

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