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URBAN SOIL CHEMISTRY AND TREE NUTRITION UNDER THE IMPACT OF WINTER MAINTENANCE SALTS APPLICATION ON PAVEMENTS

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Abstract

Urban soil is under the influence of winter maintenance of roads and pavements using de-icing salts. Water-soluble salts (chlorides mainly) are typical of high mobility and effect on soil chemistry and plants. This study deals with the impact of de-icing salts applied to winter maintain the pavement and road surface on soil chemistry and tree nutrition. Soil chemistry was observed in the Třinec city (Czech Republic) during two winter seasons with three soil sample collection periods (December 2018; February 2019 and February 2020; 8 sampling zones – streets and parks; the sampling depths of 5-15 cm in the 0.5 to 7 m distance from pavements). The tree nutrition was studied at 5 sites where the soil samples and leaves were collected in the December 2019 (5 sampling sites and 2 sampling depths for each tree). High alkalinity of the soil resulted both from water-soluble salt content and carbonates. Winter maintenance of pavements resulted in the different increase in the soil reaction and electrical conductivity, compared Feb. 2019 and 2020. Plant nutrition was characteristic of the increased content of chlorides in one case and slight soil and leaves nutrient ratio imbalance. Compared to roads, winter maintenance of pavements performed with de-icing chemicals will not pose the hazardous environmental risk factor within the current intensity.

Keywords: electrical conductivity, soil salinity, soil reaction, plant nutrition, de-icing salts

INTRODUCTION

Urban soils are specific and may frequently be characterised by extreme chemistry in comparison with the natural soil development. The reason is, among others, enrichment with water-soluble salts of winter maintenance and with extraneous matter in the form of sedimented lime-based dust and construction residues spontaneously stored in the soil (Burgos Hernández *et al.*, 2021; Kostka *et al.*, 2019). While winter maintenance of roads is unexceptionable due to traffic safety, alternative materials can be proposed to eliminate chemical inputs into the environment in case of pavements and promenades.

The resulting predominantly alkaline soil reaction increases pH values to about 8.0 when the carbonate salt concentration is elevated, and even to about 9.0 to 9.5 in the case of increased chloride salt concentration (Equiza *et al.*, 2017; Ramakrishna and Viraraghavan, 2005). The effect of the increased salt concentration is augmented by the possible loss of the organic matter, which acts as a buffer in the exchange zone (Brady and Weil, 2002).

De-icing salts (most frequently chemical de-icing materials of chloride or acetate nature (NaCl, $CaCl_2$, $MgCl_2$, CMA) are defined by high water solubility and mobility (Ramakrishna and Viraraghavan, 2005). In the humid climate, the presence of chloride salts in the upper soil layers is rather temporary and it does not typically exceed extreme concentrations.

Their negative impact is bound mainly to antagonism of Na^+ cation with other cations on the soil sorption complex and selectivity of nutrient uptake, peptisation of the soil environment, osmotic changes in the rhizosphere and physiological unavailability of water (Czerniawska-Kusza *et al.*, 2004; Dmuchowski *et al.*, 2013; Ramoliya *et al.*, 2004).

Trees in the urban area grow under the influence of the set of stress factors. Environmental factors contribute to general urban tree stress in the sense of the multiple stress impact (Liess *et al.*, 2016) leading to nutrition imbalance, health status deterioration, accelerated aging, etc. The de-icing chloride salts application leads to osmotic stress (decrease in physiological availability of soil water) and ionic stress (chloride toxicity in the tree tissue) and also affects fungi communities in the plant-soil system (Day *et al.*, 2010).

High mobility of chlorides is associated with the transfer to plant tissues through roots and gradual transferring to leaf blade edges, resulting in chlorosis and necrosis (Fostad and Pedersen, 2000) as well as biomass reduction, lowering of increment and, in extreme cases, woody plant death (Bryson and Barker, 2002; Czerniawska-Kusza *et al.*, 2004; Dmuchowski *et al.*, 2013; Munns and Tester, 2008). The plant visual symptoms do not show only deficiency but also surplus which is in case of chlorides remarkable as local discolorations that turn into necrotic lesions and scorched leaf margins (Geilfus, 2018).

High mobility of chlorides also embarrasses direct assessment in the soil where they can be readily washed out with downward water movement. However, the spring season is even crucial due to tree phenology. Despite fast percolation in the soil, chlorides can enter to the plant tissue (Geilfus, 2018) due in spring phenological periods and start of streamflow.

Alkalisation of the soil environment of the urban area is not based solely on winter maintenance with de-icing salts, but mainly on the presence and continuous supply with alkaline compounds in the urban environment, such as the de-icing salts and lime materials from rendered plasters and the structural material of buildings.

This study focused on the selected aspects of soil chemistry in the urban area of the Třinec city (Czech Republic). From the general list of effects on the soil environment, the aim was the soil chemistry assessment in relation to winter pavement maintenance with de-icing salts in the selected parts of the city, such as streets (line areas), but also parks and inert areas where de-icers were not applied. The presented study is concerned with pavements, promenades and park footpaths, out of influence of roads producing dispersed salt aerosol. To achieve this purpose, we sampled the urban soil in the maximum distance of roads, focusing on sites where salt spray deposition was minimal. We also sampled green margin of the most frequent road to obtain reference values to be compared with the most intensive effect of the salt application on soil chemistry. According to our hypothesis, high chemical background in the form of carbonates and also the effect on the soil in the short distance were presumed.

MATERIALS AND METHODS

Study Area

Technosols (IUSS Working Group WRB, 2022) are typical of the urban area of the Třinec city, which is built in a more or less flat area of the Třinec furrow formed by Mesozoic and Tertiary flysch sediments with quaternary loess blanket, with frequently powerful sequences of anthropogenic sediments. These are created by not only locally significant dumps and heaps with redeposited topsoil, but also historically conditioned urbic debris, which are recultivated and planted in unpaved areas with herbal or woody vegetation with regard to the development of urban greenery.

Field Work, Samples Collection and Meteodata

The salinisation was investigated on two levels:

Firstly, soil salinity assessment which was evaluated in the selected sections of public spaces, namely Náměstí Míru Square (SQ1), T. G. Masaryk Square (SQ2), Dukelská Street (ST1), Jablunkovská Street - Promenade (ST2) and Koperníkova Street (ST3). To describe soil chemistry along pavements, we selected two levels of the control plots: the first one, with the least predicted salinisation: Park “at the Observatory” (C1) and Palacký Avenue (C2) – the control plot without salt input to the soil (pavement edged by curbs) and the second one, with the strongest predicted salinisation: Frýdecká St. (C3 – the green zone between pavement and frequented road) (Fig. 1). The samples were taken three consequent times:

1) prior to the beginning of the winter season, in December 2018;
2) after the winter season in the break of February and March 2019 and
3) February and March 2020.

This part of the study was based on the repetitive collection of the soil samples for the determination of the soil reaction active (pH/H_2O) and potential exchange (pH/KCl), the concentration of water-soluble salts, respectively electrical conductivity and carbonate content.

The soil samples were taken from the depth of 5–15 cm, under a continuous layer of grass turf. In the case of the linear character localities (ST1-ST3, C1-C3), the samples were taken from the transects with the distance of 30 m (ST1 – 5 transects; ST2 – 6 transects; ST3 – 3 transects; C1 – 2 transects; C2 – 3 transects and C3 – 5 transects depending of the studied zone length), perpendicular to the longitudinal axis of the streets at the distance of

1: *The biased sampling zones of the soil samples for soil chemistry evaluation, resp. salinisation of the soil and investigated trees positions*

0.5 m and 1 m from the edge of the pavement – in the case of ST2 and C1 on both sides and in the case of ST1 and ST3 on one side, because of the curb of the pavement or the transverse slope, which meant the drainage of surface water from the pavement in only one direction. Squares (SQ1 and SQ2) were sampled along perimeter from four sampling sites organized in cross and from central point in centripetal direction from pavement, in distance of 0.5 and 1.0 m from the pavement. As SQ1 internal area was grassed, the plot was sampled also in centre of the sqare ((7 m from pavement). C2 was sampled in the distances of 0.5; 1; 1.5 and 2 m from the road. A total of 226 soil samples from 8 localities were collected (80 samples in 2019 and 73 samples in 2018 and 2020 when C2 was not sampled).

Secondly, soil salinity was assessed below 5 trees to investigate soil chemistry and tree nutrition status (Tab. I). The tree 4 was selected as the control in the sense of maximal effect under the direct influence of the frequented road – 3 m far from the road edge (Cmax) and 5 were selected as the control in the sense of minimal effect, placed in the centre of the park with the assumption of the least affected soil chemistry (Cmin). The soil samples (34 in total) were collected in four directions (N/S/E/W) under the tree crown projection from two depths: 5–10 and 20–25 cm. As tree 3 grew narrowly between road and pavement, we were able to sample the soil only with one repetition. Leave samples (5 in total) were collected from the upper third of the crown (exposed to the sun). One sample was composed of 50 leaves collected from 5 different branches. The sampling process was performed prior to leave senescence (September 2020). This part of the study was focused on the assessment of the wide spectrum of factors: soil reaction, nutrient content, cation exchange capacity, electrical conductivity, organic carbon, chlorides, carbonates and sulphates contents and for nutrient contents in assimilation apparatus.

I: *Location of study trees.*

Tree No.	Street	Street code	Taxon	GPS (N)	GPS (E)
1	Jablunkovská St.	ST2	Tilia cordata	49°40´32,1´´	18°40´28,5´´
2	Náměstí Míru Sq.	SQ1	Magnolia x loebneri	49°40´44,7´´	18°40´1,5´´
3	Koperníkova St.	ST3	Tilia cordata	49°40´9,1´´	18°40´20,4´´
4 (Cmax)	Jablunkovská St.	ST2	Acer pseudoplatanus	49°39´56,3´´	18°41´7,1´´
5 (Cmin)	Jablunkovská St.	ST2	Tilia cordata	49°40´1,0´´	18°41´4,2´´

Precipitation sums were collected in periods of November-March (salt accumulations due to winter maintenance) and March–November (salt leaching) within monitoring years. The data were considered as a supplementary information allowing interpretations of changes in soil chemistry. The data were collected as daily values from meteorological station Ropice (station code O1ROPI01, Czech Hydrometeorological Institute), 10 km far from Třinec city centre, downloaded from chmi.cz on 2nd December 2024.

Laboratory Analysis and Data Processing

All laboratory procedures of soil were adjusted for fine earth fractions I (fraction size max. 2 mm) with a dry matter content of 100%, except of oxidizable organic carbon (Cox) and total nitrogen (Nt) which were adjusted for soil powder prepared from 5 g of the fine earth fraction I by milling to fraction of 0.25 mm (Zbíral *et al.*, 2011).

The soil reaction was determined as active (pH/H_2O) and potential (pH/KCl) using a pH meter with a combined glass electrode (soil/H_2O, resp. 1M KCl = 1/2.5) (Zbíral, 2002). For purposes of a more detailed assessment of the alterations in the hydrogen ion content at their low concentration at high pH values, the soil reaction was also expressed in the mass concentration of H^+ ions contained in the soil solution, denoted $C(H^+)$ [mmol/l] by means of the relation $C(H^+) = 10^{-pH} \times 1.008 \times 1{,}000{,}000$ [mmol/l], where $C(H^+)$ is the concentration of hydrogen ions in the water or potassium chloride leachate; pH is the soil reaction in water or potassium chloride leachate; 1.008 is the atomic mass of hydrogen; 1,000,000 is the conversion to mmol. $C(H^+)$ values for the content in water and potassium chloride were applied to determine the difference between the active and potentially exchangeable soil reaction values using the formula Delta (pH) = $C(H^+)^{KCl} - C(H^+)_{H_2O}$ [mmol/l], where $C(H^+)_{KCl}$ and $C(H^+)_{H_2O}$ are the concentrations of hydrogen ions in the leachate in water and potassium chloride, respectively. The electrical conductivity (EC) for expressing the soil salinity was determined according to (Rhoades *et al.*, 1999). The results were recalculated for the current water temperature during the measurement (f = 1.112). The content of $CaCO_3$, resp. carbonates, was determined volumetrically with Jank's calcimeter by decomposing 20 g of the sample with 12.5% HCl, expressed in %.

The hydrolytic acidity was determined according to (Adams and Evans, 1990). Available nutrients were detected from Mehlich II leaching by atomic adsorption spectrophotometry (Mehlich, 1978). The phosphorus content (P) was identified according to Olsen (Olsen *et al.*, 1954) due to alkaline soil chemistry and phosphorus fixation in forms unavailable when using Mehlich II leachate. The determination of potassium (K^+) and sodium (Na^+) was carried out from Mehlich II soil leachate, where a characteristic quantum is emitted after thermal excitation of the potassium and sodium atoms in the acetylene-air flame. The intensity of characteristic radiation is proportional to the potassium concentration. The calcium (Ca^{2+}) and magnesium (Mg^{2+}) contents were determined by acetylene-air flame atomic absorption spectrophotometry after dilution of Mehlich II leachate. Interference is removed by addition of lanthanum excess. Signal evaluation was performed by the calibration curve method and nutrient concentrations were calculated by summation method (Zbíral, 2002). Oxidizable organic carbon (C_{ox}) was determined by oxidation with a chromosulphuric acid spectrophotometrically (Zbíral *et al.*, 2011). Total nitrogen determination (N_t) was carried out by the Kjeldahl method (Kirk, 1950). Sulphur contained in the sulphate form (S-/$SO_4/^{2-}$) was determined after extraction with water (Zbíral, 2002), total sulphur (Stot) was ascertained in the leachate in diluted hydrochloric acid according to Regulation EC (2003/2003) of the European Parliament and of the Council.

Chloride concentration was assessed from water solution (either soil or plant biomass), followed by IC (Ion Chromatography) method (Zbíral, 2014). The nutrient contents in biomass were assessed after mineralization in 96% sulphuric acid and 35% hydrogen peroxide: P spectrophotometrically, Ca and Mg using FAAS and K using FAES (Zbíral, 2014).

Exchangeable sodium percentage (ESP) was calculated as the molar percentage proportion of sodium in total *CEC*. The sodium adsorption ratio was calculated using equation SAR = $Na^+/[\mathrm{sqrt}(Ca^{2+} + Mg^{2+})/2]$ where Na^+, Ca^{2+} and Mg^{2+} are molar concentrations of ions within *CEC*.

Data processing: Parametrical ANOVA and post-hoc Tukey HSD test were performed at the significance level α = 0.05 in Statistica Cz 12 software with graphical outputs. Correlation analysis was performed for samples subset of February 2020 in R Studio software, version 1.2.153 using correlation coefficient R = 0.211 with the number of repetitions n = 73 and the significance level $\alpha = 0.05$. Variability of variables in histograms was expressed by means of the standard deviation (SD).

RESULTS

Soil Chemistry in Streets and Squares

Soil chemistry in the urban area was differentiated according to the studied localities (Fig. 2), sampling sites and sampling times. The prevailing soil reaction was slightly alkaline, less neutral, and mild to strongly (rarely very strongly) alkaline (Fig. 2a). The control plot with the highest presumed salinisation (C3) was substantially affected by salts with the origin related to roads. Contrarily, soil chemistry along the footpaths was lower in pH, as well as in electrical conductivity which was generally more than four times lower (Fig. 2b). The carbonate contents (Fig. 2c) were the lowest at the control plots and increased on the squares (SQ1 and SQ2). Generally, the footpaths maintenance did not affect soil chemistry in as such high influence as road maintenance. The C1 and C2 plots with the least affected soil chemistry showed the lowest values of pH, as well as of EC. Increased alkalinity was more typical of pH/H_2O, which reflects the nature free hydrogen ions; pH/KCl was less variable in time and space (Tab. II).

The temporal changes in soil chemistry are shown in Tab. II and Fig. 3. Lower values of pH, as well as of EC were recognized at the control plots C1 and C2. Compared with December 2018, the soil reaction was higher at the sites with the salts application in Feb. 2019 in the instance of both pH/H_2O as well as pH/KCl and in Feb. 2020 only in the case of pH/KCl. The soil reaction values also decreased with the distance from the pathways. The lowest values were in the December 2018 at the distance of 0.5 m, which was statistically significant compared with the spring 2019 and narrowly non-significant compared with the spring 2020. In the distance of 1 m the differences were less notable, however they evinced the similar trend.

The exchangeable soil reaction showed the increasing trend and less noticeable distance differences (Fig. 3). The active soil reaction reached moderately alkaline zones (the criteria ranges between 8.0 and 8.5 according to Vavříček and Kučera, 2024) especially in February 2019 in the distance of 0.5 m from the pathway edge. In the control sections without the salt application, pH/H_2O was ca. 0.15–0.30 lower and evinced the different trend, especially at the distance of 1 m – one that was also recorded in the instance of pH/KCl at both distances and treatments (cf. Fig. 3a and 3b).

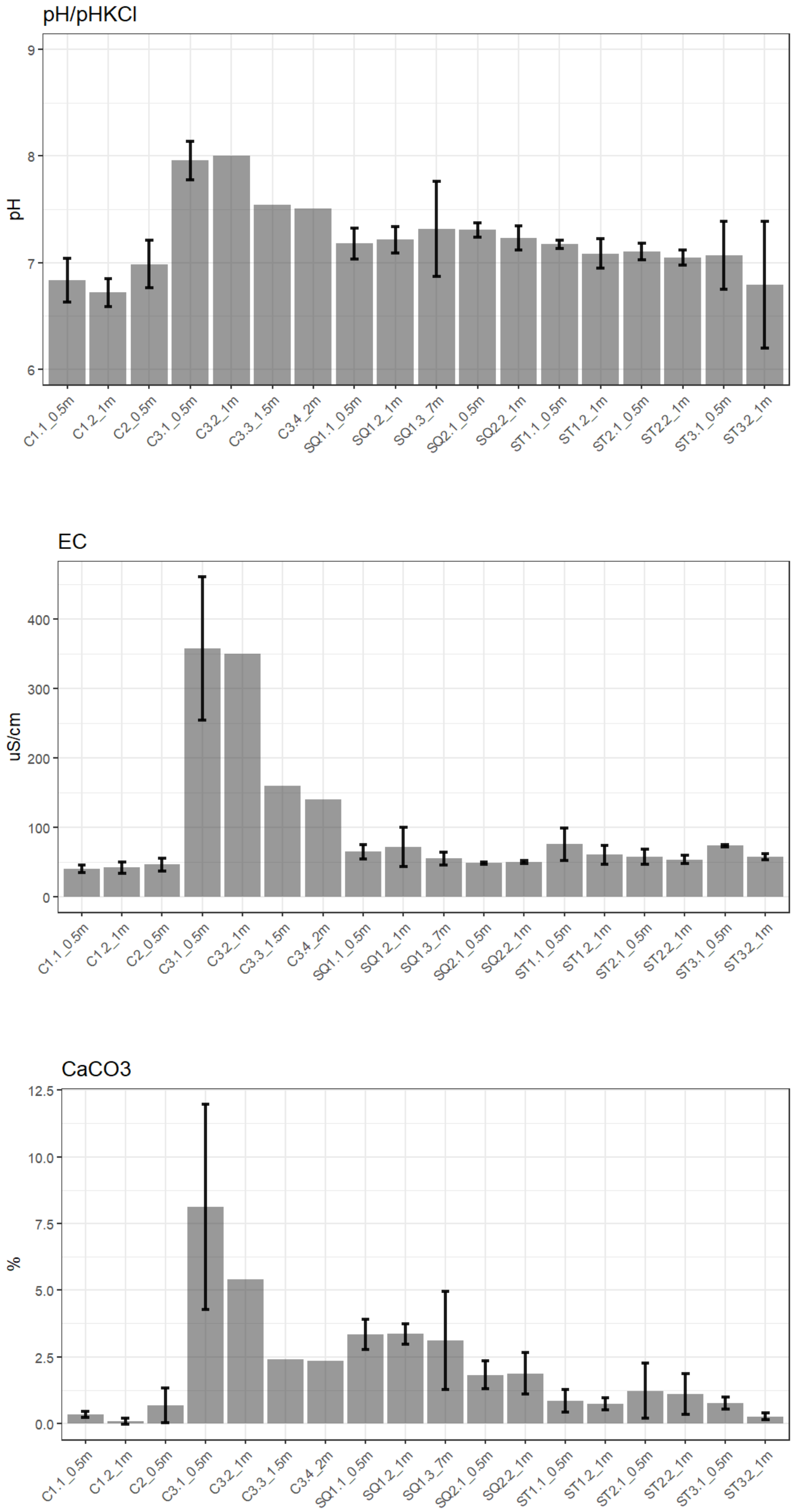
Of the three monitored periods, the salt concentration expressed by EC was the highest in the spring 2020, but with no statistically significant difference. In particular, at the distance of 0.5 m from pavements, the significant increase was evident, which was not recorded in the previous year. In the preceding monitored time period, the pre-season and post-season salinity values were relatively close, which can no longer be said about sampling in Feb. 2020. The systematically higher values of EC values were also found out in the control sections without the application of salts.

The value of pH/KCl increased less or remained unchanged during winter 2018/2019. It ranged from the area of neutral to slightly alkaline soil reaction (with values of the criteria 6.0–7.0 for neutral and 7.0–7.5 for slightly alkaline according to Vavříček and Kučera, 2024), where these differences demonstrated the cation exchange given by the reduction of hydrogen ion concentration in the soil solution both in relation to their washing off and in connection with their transition to the soil sorption complex. The soil reaction values during the winter increased by about 0.3 in the case of pH/H_2O and by 0.1 to 0.2 in the case of pH/KCl and the alterations in soil chemistry thus mainly affected the soil solution, less the soil sorption complex.

Soil Chemistry under Trees and Tree Nutrition

The soil reaction ranged from neutral to slightly alkaline at the depth of 5–10 cm, but mostly slightly alkaline (higher values) at the depth of 20–25 cm (Tab. III). The values for both active and potential reactions were higher in the deeper horizons. This state also corresponds to the increase in the concentration of the sum of base cations with the depth, of which the most represented was calcium in a very high concentration exceeding on average four times (but also eleven times at the maple site in the main rooting zone) the upper limit of the norm for very high saturation with this element. Magnesium was contained in high to very high concentration at the lowest concentration at the control site, where the values are still at an extremely high level. Potassium was contained in high to very high concentrations, which can be considered a favourable condition with regard to its importance for resistance to climatic extremes of drought or low temperatures. Its content was extremely high at the locality 4 with maple, which can be perceived as extreme in all respects as well as the locality 2 with magnolia at Náměstí Míru Sq.

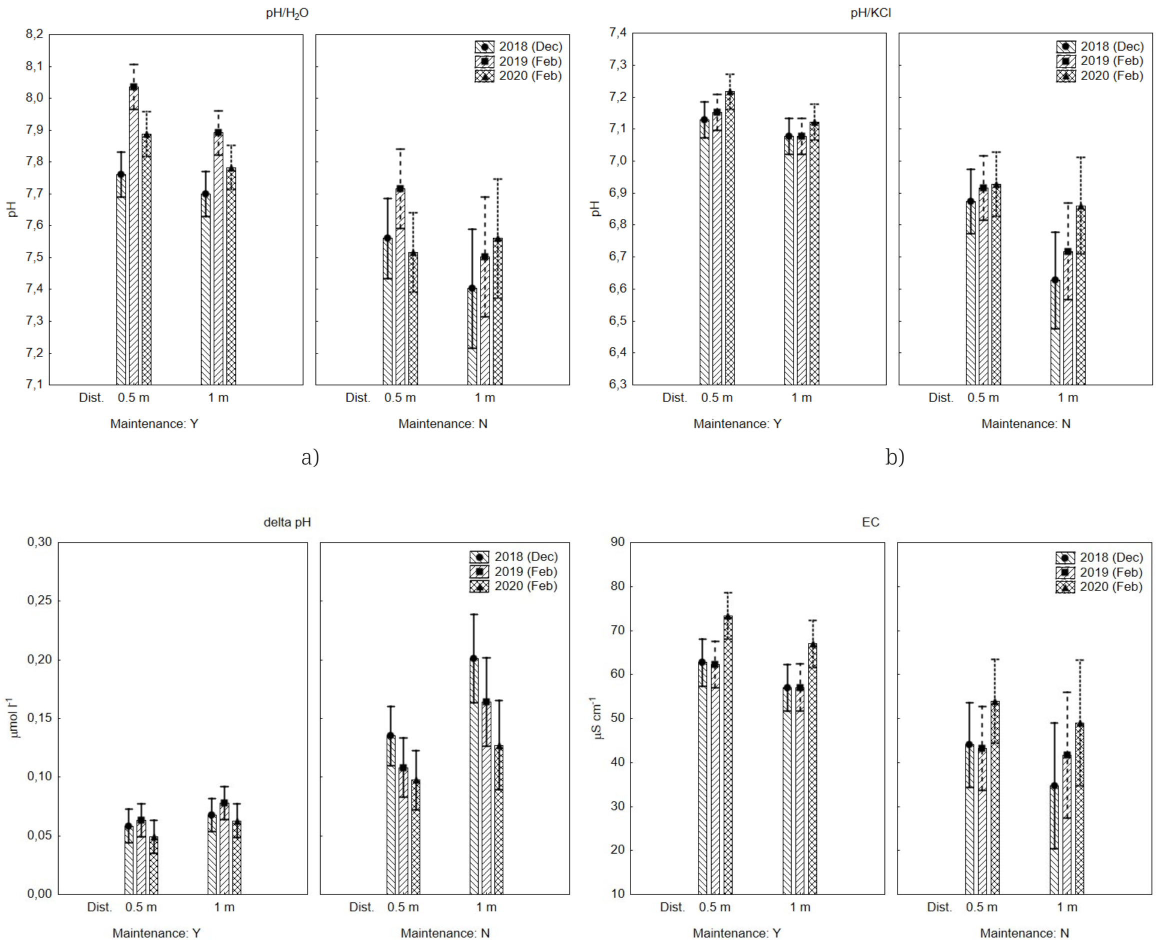
The soil sorption complex was fully saturated at all the localities (Tab. III). Full saturation of the sorption complex corresponds to the high pH values and thus also low values of hydrolytic acidity (H^+ content, resulting from differences between 100 % and actual percentage of BS), in which hydrogen cations are present in minority within alkaline soil reactions as carriers of soil acidity and thus aluminium, whose concentrations are mostly below the analytical detection limit.



2: *Exchangeable soil reaction (a), electrical conductivity (b) and carbonate content (c) in the soils of the studied localities at the sampling distances, ascertained in February 2019*

II: *Means and standard deviations of soil properties in the different distances and in three sampling times grouped according to either applied (Y – SQ1; SQ2; ST1; ST2 and ST3) or non-applied (N – C1 and C2) salts.*

Sampling time	Distance	Salt application	pH/H_2O		pH/KCl		delta pH [mmol/l]		EC [mS/cm]	
			mean	sd	mean	sd	mean	sd	mean	sd
Dec 2018	0.5 m	Y	7.76	0.13	7.13	0.10	0.06	0.01	62.7	14.70
		N	7.56	0.24	6.87	0.26	0.14	0.12	44.0	9.28
	1 m	Y	7.70	0.18	7.08	0.15	0.07	0.03	57.0	7.72
		N	7.40	0.11	6.63	0.09	0.20	0.04	34.7	1.51
Feb 2019	0.5 m	Y	8.04	0.19	7.15	0.11	0.06	0.02	62.3	15.53
		N	7.72	0.23	6.92	0.16	0.11	0.04	43.2	7.76
	1 m	Y	7.89	0.16	7.08	0.17	0.08	0.04	57.0	13.16
		N	7.50	0.04	6.72	0.07	0.16	0.03	41.7	7.09
Feb 2020	0.5 m	Y	7.89	0.18	7.22	0.12	0.05	0.01	73.3	17.96
		N	7.52	0.18	6.93	0.19	0.10	0.05	54.0	16.28
	1 m	Y	7.78	0.25	7.12	0.17	0.06	0.03	67.0	17.41
		N	7.56	0.18	6.86	0.22	0.13	0.06	49.0	9.69



3: *Soil reaction active (a) and exchangeable (b), difference of pH/H_2O and pH/KCl (c) and electrical conductivity (d) in the distances of 0.5 and 1.5 m from the pathway edges, sampled in three periods and grouped by maintenance (Y – plots with the application of de-icing salts; N – plots without the application of de-icing salts)*

III: *Soil reaction (pH/H_2O and pH/KCl), nutrient (P, Mg, Ca, K and Na) content, cation exchange capacity (CEC) and base saturation (BS) at the study plots under the trees, when n = 4 (N/S/W/E) for each soil sampling depth*

tree No. / locality (species)	sampl.	pH/H_2O		pH/KCl		P		Mg		Ca		K		Na		CEC		BS	
	depth									mg/kg						mmolchekv/kg		%	
	cm	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
1 / Jablunkovská st.	5–10	7.23	0.3	6.66	0.3	42	20.5	418	31	3345	498	148	70	108	122	221	30	94.5	2.5
Tilia cordata	20–25	7.76	0.0	7.09	0.1	18	10.5	459	111	3540	1986	87	22	46	45	225	103	93.8	8.0
2 / Nám. míru sq.	5–10	8.17	0.0	7.62	0.0	49	17.7	706	176	7727	623	227	25	42	23	451	22	100.0	0.0
Magnolia x loebneri	20–25	8.17	0.1	7.59	0.0	46	14.6	693	131	5301	1275	198	27	86	39	330	74	100.0	0.0
3 / Koperníkova st.	5–10	7.61	0.2	6.92	0.2	26	12.1	547	132	4807	2128	192	66	65	38	302	117	96.2	1.9
Tilia cordata	20–25	8.02	0.1	7.25	0.1	14	5.7	548	109	5335	1320	131	23	64	33	320	72	99.1	0.4
4 / Jablunkovská st. (Cmax)	5–10	7.82	-	7.27	-	42	-	684	-	8552	-	676	-	128	-	515	-	98.3	-
Acer pseudoplatanus	20–25	8.14	-	7.45	-	35	-	841	-	11590	-	452	-	218	-	669	-	100.0	-
5 / Jablunkovská st. (Cmin)	5–10	6.53	0.3	5.90	0.4	17	3.5	243	8	2402	518	95	32	43	24	172	23	83.4	4.2
Tilia cordata	20–25	7.00	0.6	6.22	0.6	11	5.4	218	37	2493	963	96	29	51	57	167	43	86.8	5.4

IV: *Soil chemistry at the study plots under the trees, when n = 4 (N/S/W/E) for each soil sampling depth. ESP – exchangeable sodium percentage; SAR – sodium adsorption ratio; Cox – oxidizable carbon; EC – electrical conductivity; $CaCO_3$, Stot, S-$(SO_4)^{2-}$ and Cl^- – chemical compound contents*

tree No./locality (species)	sampl.	ESP		SAR		Cox		EC		$CaCO_3$		S_{tot}		S-$(SO_4)^{2-}$		Cl^-	
	depth	%				%		μS/cm		%		mg/kg		mg/kg		mg/kg	
	cm	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
1 / Jablunkovská st.	5–10	1.90	1.9	0.44	0.5	3.77	0.2	62.61	13.3	0.38	0.4	657.5	0.0	11.9	0.5	45.5	7.4
Tilia cordata	20–25	1.04	0.8	0.20	0.2	2.50	0.1	54.51	1.7	0.68	0.1	525.0	0.1	11.8	1.7	31.5	4.9
2 / Nám. míru sq.	5–10	0.40	0.2	0.12	0.1	3.16	0.2	70.72	6.2	2.12	0.4	685.0	0.0	16.9	3.3	61.8	11.1
Magnolia x loebneri	20–25	1.17	0.5	0.30	0.1	2.50	0.3	65.67	4.8	1.07	0.5	615.0	0.2	15.8	0.3	65.6	2.9
3 / Koperníkova st.	5–10	0.94	0.5	0.23	0.1	3.58	0.9	70.06	17.5	0.89	1.1	1316.7	0.2	17.4	4.0	83.8	13.4
Tilia cordata	20–25	0.84	0.4	0.22	0.1	2.19	0.2	65.03	2.4	1.07	0.6	1050.0	0.2	16.5	3.6	76.4	15.7
4 / Jablunkovská st. (Cmax)	5–10	1.08	-	0.35	-	3.89	-	92.39	-	3.70	-	1520.0	-	18.5	-	71.9	-
Acer pseudoplatanus	20–25	1.42	-	0.52	-	2.82	-	85.79	-	2.65	-	1680.0	-	22.2	-	68.8	-
5 / Jablunkovská st. (Cmin)	5–10	1.02	0.4	0.21	0.1	3.58	0.3	49.80	9.5	0.03	0.0	1222.5	0.3	12.3	0.8	54.3	13.4
Tilia cordata	20-25	1.12	0.9	0.23	0.2	2.52	0.2	36.11	12.3	0.17	0.3	885.0	0.4	9.6	1.2	46.4	6.5

V: *Chlorides and nutrient contents and ratios in assimilation apparatus of the trees at the study plots, when n = 1*

tree No. / locality	species	N	P	K	Ca	Mg	S	Cl^-	Ca/Mg	K/Mg
		%			g/kg			mg/kg		
1 / Jablunkovská st.	Tilia cordata	2.23	2.06	10.40	14.10	4.24	1.64	1 140	3.3	2.5
2 / Nám. míru sq.	Magnolia × loebneri	1.73	1.76	4.16	12.90	7.05	1.24	15 300	1.8	0.6
3 / Koperníkova st.	Tilia cordata	1.79	2.56	13.10	11.90	4.13	1.64	4 210	2.9	3.2
4 / Jablunkovská st. (Cmax)	Acer pseudoplatanus	2.40	1.58	8.29	11.60	2.61	1.59	4 220	4.4	3.2
5 / Jablunkovská st. (Cmin)	Tilia cordata	2.39	2.00	11.40	11.30	2.26	1.81	1 430	5.0	5.0

The high base saturation results mainly from the high calcium content to the slight detriment of potassium. The phosphorus content ranged from very low to low concentrations and the content followed the organic matter content (correlation coefficient of two-tailed Pearson's coefficient was 0.307, compared with critical value of 0.296 for n = 34). Sodium, the presence of which was one of the partial hypotheses of the study, was also included in the increased concentration. Nevertheless, despite the increased sodium content, its relative content was not significant with respect to other cations and sodium did not play a key role in the soil sorption complex.

The soils were moderately humus-rich at both sampling depths (Tab. IV), which can be considered as a property mitigating the negative impact of chemical-based stress factors. Carbonates were present in the lower average concentration in most localities (e.g. below 3.0 according to Vavříček, Kučera, 2024) except of tree 4 with medial levels of $CaCO_3$ content. Sulphates were present in the medium concentration.

Of the study localities, the localities 2 - Náměstí Míru Sq. (Magnolia) and 4 - Jablunkovská St. (Cmax), which is close to the busy road and in which the soil evinced the highest sodium concentrations and at the same time the highest salinity, were extreme when assessing the soil parameters. The electrical conductivity was at the highest level in the range of high salinity with a limit of 60 mS/cm according to Pokorný and Šarapatka (2003). High salinity was also identified at other localities, with the exception of the control plots where the values were in the range of slightly increased salt concentrations.

The nutritional characteristics of trees were distinguished by the normal nutritional status (cf. Vavříček, Kučera, 2023) with a few exceptions (Tab. V). The trees no. 1, 3 and 5 were nutritionally optimally provided. The Ca and Mg contents in leaves of the trees no. 1 and 2 and lower of nitrogen of the tree no. 3 were enhanced (with lower limit for suitable nutrient content level of 2.3 %), which however did not caused visual symptoms on leaves. The potassium content was lower on trees 2 and 4. The chlorides content was the highest in the case of the tree 2 (magnolia) where we also detected the lowest K/Mg ratio. The sulphur content was on levels of the optimal nutrition status (Vavříček, Kučera, 2024).

DISCUSSION

Soil Chemistry in Streets and Squares

In the study, the soil environment in the selected sections of the city (outside the exposed zones immediately adjacent to the road) appears to be relatively stable due to its chemistry. With an unchangeable load and constant sources that condition the chemical properties of soils, a slightly fluctuating but upward trend in the development of pH, which might be shifted to zones of strongly alkaline soil reaction. These results are consistent with a number of studies focusing on urban soil (Cekstere *et al.*, 2008; Gałuszka *et al.*, 2011; Kostka *et al.*, 2019) in the areas of intensive winter maintenance management. Concurrently, the naturally acidifying mechanisms, of which there are many in the soil environment (Delbecque *et al.*, 2022) and which would result in the decrease in pH, already encounter the stabilising mechanism of soil chemistry in the form of a carbonate buffer zone (Bache, 2006).

Comparing autumn and spring values, both the active, as well as exchangeable soil reaction showed increasing trend within the three sampling periods and less noticeable space differences (Fig. 3). In the instance of pH/KCl less dynamics and space variability was observed, as well as increased permanency of soil chemistry due to soil buffer capacity and specific duration of cation exchange (Zhang *et al.*, 2023). Fig. 3c indicates smaller differences in the values of both types of the H^+ concentrations (delta pH) in the instance of the localities with the application of salts than without it. Chemistry water leachates shows greater differences in the values of both types of pH at lower concentrations of alkalising components. This is due to the fact that the alkaline components (base cations with a displacing effect for acidic H^+ ions) gradually pass from the soil solution to the soil sorption complex in saline soils and therefore the values of these two types of soil reactions also approach (Brady and Weil, 2002; White, 2006).

In the study monitoring the impact of winter road maintenance in the Krakow city (Poland) (Kostka *et al.*, 2019), the decrease in the pH values was ascertained in some cases. The authors attribute the alterations in the soil reaction values to a number of factors, among which de-icing salts use was not

VI: *Precipitation sums within monitoring periods, separately for seasons without salt application (March-November) and with salt application (November-March)*

Year	March-November	November-March
2018	521	
		227
2019	759	
		242
2020		

a major source of salinity. The outcomes of the cited authors agree with ours findings regarding sources of undesirable soil conditions increasing risk of trees withering. At the same time, the observed level of salinity in our study does not need to be considered hazardous with regard to growing tree species when the lower limit of the risk resulting from increased soil salinity for sensitive plants commences at 500 ms/cm (Lech *et al*., 2016). This particular EC expressing salt concentration was achieved merely on the area C3 immediately adjacent to the road, but on no area along the pavement, out of reach of road traffic.

In a slightly alkaline and higher soil reaction, not only the lacking H^+ hydrogen cation but also the hydroxyl anions OH^- which prevail at pH > 7 contribute to the values to some extent. At the same time, remaining fixed hydrogen ions did not directly exchange within cation exchange during the winter season, therefore, pH/KCl was also more or less unchanged when compared to December 2018-spring 2019 while pH/H_2O was more variable. Thus, during the winter, the base cations remained in the soil without further washing off but without cation exchange. Thus the soil chemistry changed on the level of soil solution rather than on the level of the soil sorption complex.

In case of saline soil, the direct washing management presupposes much higher water leaching volumes (Xiaoqing *et al*., 2014; Yin *et al*., 2022) compared with precipitations rates during our monitoring seasons (Tab. VI). Regarding the periods of November–March (winter season) vs. March–November (remaining seasons), both play different role in salt concentration dynamics. The EC was the highest in 2020 (Fig. 3d) despite the winter 2019/2020 precipitation rates were about 15 mm higher than preceding year and precipitation rates in summer 2019 were about more than 230 mm higher than in 2018. However, the increased precipitation rates did not lead to more intensive washing effect after the winter maintenance season finished.

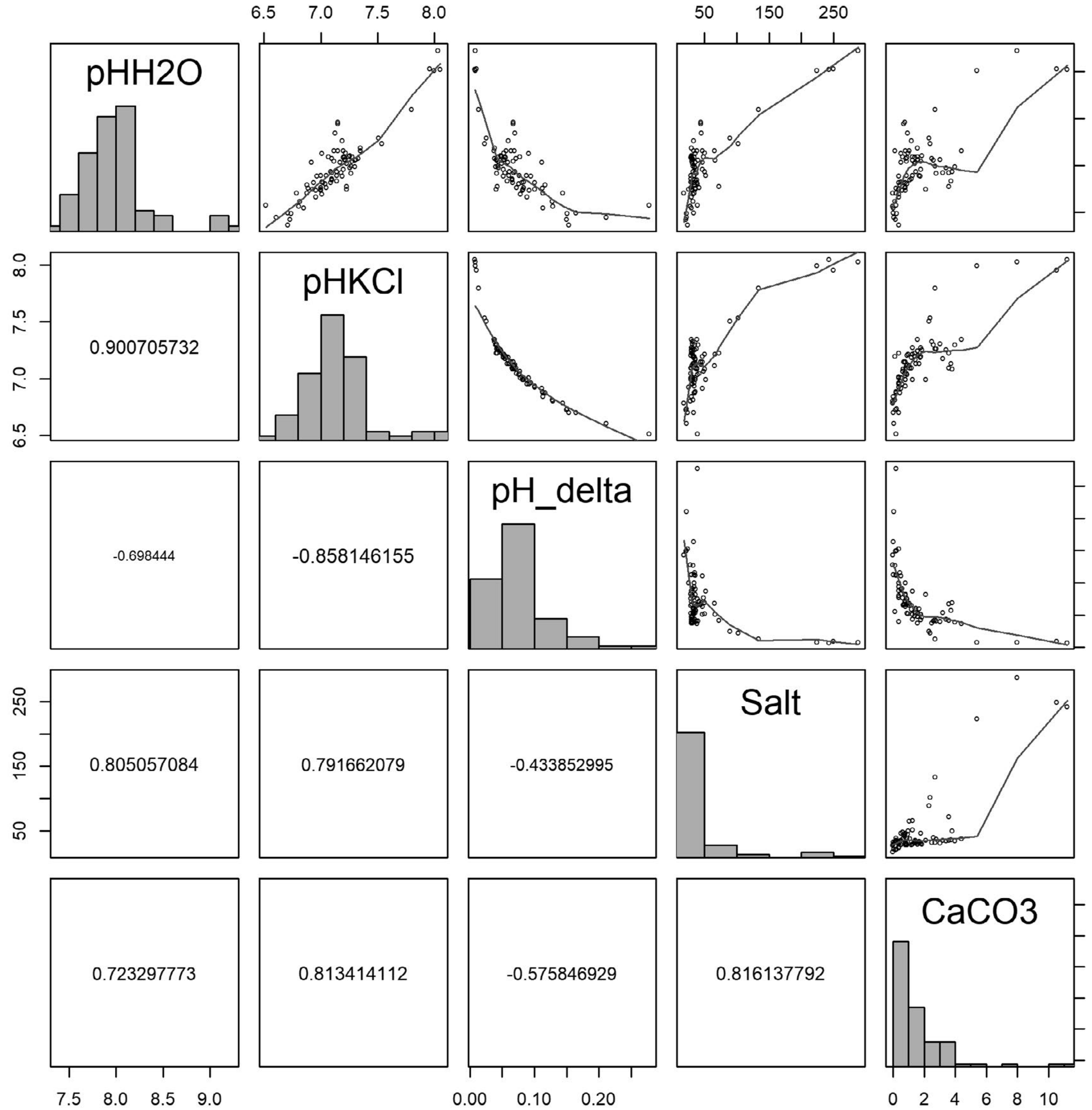
The relationship of soil reaction resulting from either water-soluble salt or carbonate concentrations is also linked with the chemical and physico-chemical conditions of the soil environment in connection with the common ion effect process (Brady and Weil, 2002) and de facto from a possible temporary increase in the concentration of NaCl salts. This, due to the high solubility of the chlorides, especially during the winter of the rather humid nature, entails the suppression of the degree of dissociation of the weak base by adding as strong electrolyte as sodium chloride, while weak sodium hydroxide is formed by the cleavage of NaCl when the OH^- ions dominate. It is reflected in the rapid increase in the active soil reaction, but also a low concentration of the chlorides in the soil solution. In addition, due to the increased content of carbonates in the soil (Fig. 2c), the transition of chloride form of sodium into carbonate and sulphate, water-insoluble and less-soluble form, respectively can be assumed (Craul, 1992).

According to the principle of ratio law (White, 2006), the balance between the concentration of ions in the soil solution and the soil sorption complex is constantly balanced, where the rhythm of maintaining of this balance is determined primarily by changes in the soil solution to which the soil sorption complex reacts. So, pH/KCl was less variable and for this reason the differences between pH/H_2O and pH/KCl were (temporarily) blurred in the spring 2019.

The presumed decrease in the biological activity of both soil microbiota and especially vegetation in winter are also factors reducing the intensity of pH decrease in connection with the decrease in the production of acidic soil components (organic acids or carbonic acid), of nutrient uptake by plants, respectively (Yan *et al*., 1996). The fact that was linked to the salt concentration values in the soil was not of the less importance.

Fig. 4 shows the relations between the soil parameters being monitored. The plots demonstrate the aforementioned premise that the difference in the values of the various types of the soil reaction was mainly due to changes in pH/H_2O (the correlation coefficient R for pH/H_2O vs. delta pH was lower than for pH/KCl vs. delta pH). The water-soluble salts expressed via EC influenced the soil solution more (cf. Salt vs. pH/H_2O, where the Pearson correlation coefficient was higher than salt vs. pH/KCl), albeit negligibly due to the generally low salinity of the soil. Conversely, water-insoluble carbonates more corresponded with pH/KCl from the aspect of soil chemistry and thus they reflected more distinctively in its values (R is 0.8134) than in pH/H_2O values (R is 0.7233).

Each winter season was specific by its influence on the soil environment in a two-way process. Firstly, in the sense of the tendency to increase the soil reaction values due to (1) absence of acidifying effects of vegetation, (2) reduction of metabolic processes in the soil, (3) winter maintenance management of pavements with road water-soluble chloride salts. And secondly, in the sense of a tendency to decrease soil reaction values due to increased soil moisture and more intensive washing regime, which co-determines the dynamics of changes in the soil solution and soil sorption complex. Soil



4: *The scatter plot and the correlation coefficient values – the correlation analysis results for the selected parameters, ascertained from the samples taken in February 2019*

chemistry in the monitored period underwent changes indicating the rather alkalizing effect of the selected management strategy of winter pavement maintenance. Unlike roads (Shannon *et al.* 2020), alternatives in terms of seeking for winter maintenance technologies with the lower impact on the natural environment of the city – especially on vegetation of tree species.

Soil Chemistry under Trees and Tree Nutrition

Soil chemistry at the sites of the surveyed trees indicated a similar situation as in the instance of the sampling along pavements. Regarding chemical soil properties (Tab. III; Tab. IV), the control area 5 (Cmin) can be perceived as a suitably selected reference area, which represents a site-friendly environment for linden trees. Neutral and even slightly acidic soil reactions, soil organic carbon content and the most balanced nutrient content indicated site suitable conditions for tree prosperity. At the same time, soil properties were balanced in both depths and it is possible to infer uniform deeper rooting.

The nutritional status of the monitored trees reached a normal state, with a few exceptions. These were the tree no. 1 and 2 for the slightly increased Ca and Mg content (Tab. V). The antagonistic intake, especially for the tree no. 2, cannot be excluded with respect to potassium, the content of which was lower in the ratio K/Mg, precisely due to the low total content of K, which uptake can be blocked (Xie *et al.*, 2021) – cf. with unlimited potassium content in the soil (Tab. III). The K content was also lower in the maple leaves (Cmax, tree 4), but the K/Mg ratio remained optimal with regard to the reduced Mg intake.

The content of chlorides in the assimilation apparatus was the highest in the instance of Náměstí Míru Sq. (*Magnolia x loebneri*). The reference critical values of the chloride content in the assimilation apparatus, accompanied by visual symptoms were reported in Riga city, Latvia, for *Tilia x vulgaris* by (Cekstere et al., 2008). In the case of linden sites in our study, neither were the stated values exceeded by the authors, nor were visual symptoms recorded, which may be perceived as consistent with the results of the researchers.

In the soil of the locality 2, the Cl^- concentration values were comparable with other localities. Nonetheless, with regard to mobility of chlorides the increased input is evident even at their low concentrations in the soil at the time of sampling, and it might have occurred before they were washed out of the soil, i.e. in the spring during the ongoing tree transpiration. These conclusions were also reported by Cekstere *et al*. (2008) or White and Broadley (2001), where the dynamics of mobility, especially chlorides, was significantly dependent on both plant uptake but also washing depending on the course of the weather throughout the year.

Therefore, the particular magnolia site represents an example of the synergistic effect of unfavourable soil chemistry with the simultaneous action of several factors. In addition to chloride inputs into biomass, the low K/Mg ratio reduces the individual's resistance to climatic stresses. Resistance based on the potassium nutrition status to frost damage was researched a few decades ago (Grewal and Singh, 1980; Karimi, 2017), with the risk of frost damage increasing significantly in connection with the reduced K intake. Similarly, the instances of accelerated senescence of the assimilation apparatus have also been reported (Allu *et al*., 2014; Gałuszka *et al*., 2011).

CONCLUSION

The soil reaction in the investigated localities was mainly neutral to slightly alkaline (rarely with increased alkalinity), with the low to slightly increased content of water-soluble salts expressed via EC and at least with the minimal content of carbonates. The soil reaction was slightly spatially and temporally variable.

The nutritional status of the tree species was not fundamentally impaired in our study with regard to the overall mild soil salinity along the pavements, especially in comparison with the zones along the roads. The increased concentration of chlorides in the assimilation apparatus was demonstrated in one case of soil surrounding Acer pseudoplatanus; the values were assessed as being below the limit in others.

However, the discussion on the complex effect of stress factors on the tree at the particular site showed that the absolute values of the monitored parameters are merely a partial indicator of vitality and tree prospects at the site.

On the basis of the results obtained, it can be assumed that winter maintenance by de-icing chemicals will not pose an environmental risk factor within the current intensity in case of pathways, compared to roads.

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