Article

Factors Influencing the Health Status of Trees in Parks and Forests of Urbanized Areas

Michał Krzyżaniak ^{*} , Dariusz Świerk and Patryk Antoszewski

Department of Landscape Architecture, Poznań University of Life Sciences, 60-637 Poznań, Poland; dariusz.swierk@up.poznan.pl (D.Ś.); patryk.j.antoszewski@gmail.com (P.A.)

* Correspondence: michal.krzyzaniak@up.poznan.pl; Tel.: +48-6-1848-7992

Abstract: This research concerns the impact of air and soil pollution on the health status of selected tree species in parks and urban forests. The analysis was carried out over a decade, which allowed for creating the best models illustrating the impact of selective factors related to air and soil pollution on the health status of small-leaved limes, maples, oaks, and chestnut trees in the city. (1) Background and Objectives: The research aimed to identify the environmental factors that have the greatest impact on the health condition of trees in urban conditions and show which species are the most resistant to pollution in urban areas. The research object was 2441 individuals of four tree species inhabiting 11 parks and urban forests in Poznań. We assessed the trees in terms of dendrometric parameters and health status. Tree-stand soils were tested for P, K, Ca, Mg, and Na content using various analytical methods. Air data were obtained from a generally accessible WIOS website. The above data were statistically analyzed using one-way ANOVA and canonical correlation analysis (CCA). Our research has shown that unfavorable environmental parameters impact the health status of trees growing in urban areas. The most significant negative impact of O₃ on the health of three out of four examined tree species was demonstrated. Other pollutants that affect the trees health include Mn (in the soil) and NO, NO₂, CO, and C₆H₆ (in the air). Oak turned out to be the most resistant species to urban pollution. The area where chestnut trees grew turned out to be the most Fe, Mn, Na, and Pb soil-polluted and air-polluted with most of the substances recorded. The permissible concentration levels were exceeded in the case of tropospheric NO_x, PM₁₀, PM_{2.5}, and Pb.

Keywords: *Tilia cordata* Mill.; *Acer platanoides* L.; *Quercus robur* L.; *Aesculus hippocastanum* L.; soil pollution; air pollution; CCA model

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1. Introduction

Urbanization is a global phenomenon. Cities are characterized by higher temperatures, greenhouse gases concentrations, and pollutants [1–3]. In contrast, O₃ concentrations are higher in rural areas due to the nature of the O₃ formation. However, the protecting vegetation thresholds may be exceeded in urban air [4].

Urban trees can minimize many of the environmental impacts of urban growth by improving the chemical and physical environment: moderating urban heat islands, improving urban hydrology and air quality, and reducing noise levels [5]. City trees can increase biodiversity and afford benefits of aesthetic, psychological, and socio-economic natures [6,7].

Cities are often characterized by high levels of pollutants from vehicular traffic. The pollution consists of gaseous pollutants and particulate matter (PM) with organic pollutants and metals [8]. Due to its adverse effect on human health, air pollution is an environmental problem of significant concern. Due to high traffic density, cities often face increased air pollutant concentrations than their surroundings [9].

Physico-chemical methods are used to monitor air quality. The number of control stations is limited to only a few per city. Besides, the mentioned methods often measure only

a few pollutants (NO_x , SO_2 , O_3). The air pollutants measurement involves dealing with a continuously varying cocktail of pollutants [9–13]. Different studies have investigated the effects of trees on pollutant concentrations. The trees can reduce concentrations of an ammonia plume by around 3–13% [14] and that forests can reduce the amount of most atmospheric pollutants [15]. Urban greenery can reduce SO_2 and O_3 concentrations by 20% [2]. Various experiments have been conducted in the last decade using vegetation to assess air and habitat pollution. Different plant species have already been used for air pollution biomonitoring. A passive biomonitoring approach is often used to evaluate urban habitat quality [11]. As trees have a large collecting surface area, the deposition velocity in woodland is three times that of adjacent grassland areas [16]. The effects of trees are not restricted to collecting particles, but is also efficient in scavenging other pollutants [2].

Several studies confirm that leaf injury appearance is induced, as well as enhanced by air pollution [11,17,18]. In particular, O_3 has been identified as an agent causing injury to plant leaves [19]. Trees are exposed to environmental factors, injuries, and adverse weather conditions [20–23]. Coniferous trees are less resistant to pollution than deciduous ones (which are more often planted in the cities) [23]. Deciduous trees are more sensitive to the ozone. In contrast, coniferous trees are sensitive to the high SO_2 and NO_2 concentration in the air [24]. Salinity and plants' exposure to these conditions are manifested by visual symptoms such as the loss of the natural leaves color, necrosis, and by the shoots withering [25–28]. These conditions induce physiological drought stress.

The accumulation of heavy metals in soils and plants has been studied around the world [29–31]. The heavy metals pollution is caused by the exhaust gases emission and industry. Plants need trace amounts of some heavy metals (e.g., Fe, Mn, Zn) for proper development. However, their excessive concentrations may have a phytotoxic effect [32–35]. According to the urban gradient hypothesis, the contamination with heavy metals should decrease with distance from the city center according to the following order: center; urbanized city areas; urbanized suburban areas; agricultural areas; natural areas [36]. Increased Na, Cl, Ca, Mg, Zn and Cu and increased soil pH negatively influence the health status of small-leaved lime (*Tilia cordata* Mill.) trees growing near main roads. Additionally, increased salinity or EC caused by increased Na and Cl levels do not positively influence small-leaved lime trees, causing the phenomenon of physiological drought [37,38]. The trees of the investigated species are also relatively resistant to air pollution. It is also said that increased O_3 , NO_2 , and NO_x are significantly related to delays in horse chestnut phenology [39].

Our research aimed to determine the impact of air and soil pollution on the four most common deciduous tree species' health status in parks and urban forests in Poznań. The research covered a period of 11 years (2007–2017).

2. Materials and Methods

Poznań (52°24'30.4" N, 16°56'03.4" E) is one of the largest Polish cities in terms of area (261 km²), and population (540,000), and it is the capital of the Greater Poland Voivodeship. The city green areas form a system of green wedges and rings. It means the greenery consists of four wedges in the Warta, Bogdanka, and Cybina river valleys of the. Apart from forest areas and residential green, there are over 270 separate green facilities, including numerous parks, gardens, allotments, scientific and research parks, two zoos, and 24 cemeteries [40,41]. The study took selected municipal forests and parks of Poznań into account. These were the following (Figure 1):

We included the four most common deciduous tree species in Poznań green areas in the research: maples (*Acer platanoides* L.), small-leaved lime (*Tilia cordata* Mill.), oaks (*Quercus robur* L.), and horse chestnut (*Aesculus hippocastanum* L.). Every specimen of the examined species was considered (Table 1).

Figure 1. A map showing the location of the city of Poznan in Poland and the location of forests and parks under investigation.

Table 1. Total number of the examined specimens in different places of investigation and the number of examined specimens of each of the investigated species.

Number (Figure 1)	Park or Forest under Investigation	Total Number of Specimens	Oak	Maple	Lime	Horse Chestnut
1.	Jan Kasproicz Park	298	3	226	64	5
2.	Tadeusz Mazowiecki Park	273	1	185	50	37
3.	Czecha Housing Estate Park	270	14	235	20	1
4.	John Paul II Park	297	42	102	97	56
5.	King Boleslaw Chrobry Housing Estate Park	158	3	86	38	31
6.	Szelagowski Park (forest park)	216	6	117	40	53
7.	Marcellin Forest	175	57	85	31	2
8.	Malta Forest	74	19	36	15	4
9.	Poland's Millennium Park (forest park)	318	42	238	22	16
10.	The Home Army Park	219	2	109	60	48
11.	The Millennium Housing Estate Park	143	2	118	16	7
TOTAL		2441	191	1537	453	260

From 2007 to 2017 (in summer), we assessed the trees growing in the selected places. During the assessment, we identified the following:

1. The circumference of each tree trunk (measured at the height of 130 cm above the ground);
2. The diameter of each tree crown (as far as trees with irregular crowns are concerned, we measured two extreme, main diameter axis, and we calculated the mean value);
3. The height of each tree;
4. We evaluated the trees' health status based on the criteria assessing the tree's condition, including the tree crown, trunk, and roots [42]. The method used is a modification of the Roloff's method. It allows for a non-invasive assessment of the health status of trees. The health status of each tree was assessed according to the criteria presented in Table 2:

Table 2. Range of points for each of the criteria.

Element of Tree	Criteria	Points
1. Crown condition (C_C)	1.1. Crown structure	0–15
	1.2. Crown health condition	0–15
2. Trunk condition (C_T)	2.1. Trunk structure	0–15
	2.2. Trunk health condition	0–15
3. Roots condition (C_R)	3.1. Base of trunk and structural roots status	0–24
	3.2. Root system status (based on soil observation)	0–16

The results were calculated as the tree health status according to the formula: $C = C_C + C_T + C_R$. The last step of the assessment was to determine the trees vitality, health status and health category according to Table 3.

Table 3. Examined trees vitality, health status and category.

Points	Health Condition	Vitality Phase	Tree Health Category (Q)
100–96	very good	expansion	I
95–76	good		II
75–46	average	reduction	III
45–16	bad	stagnation	IV
15–0	very bad	resignation	V

2.1. Soil and Air Analysis

In each research object, four soil samples were collected—one at the tree of each species. Soil samples were taken for 11 years—always at a distance of approx. 3 m from the tree trunk. Soil samples from the layer of 0–20 cm were taken using Egner’s stick. The collected samples were chemically analyzed [43]. The extraction of P, K, Ca, Mg and Na was carried out in 0.03 M CH_3COOH with a quantitative 1:10 proportion of soil to extraction solution. After extraction, the following determinations were made: P—colorimetrically with ammonium vanadomolybdate; K, Ca, Na—photometrically; Mg—by ASA (Carl Zeiss-Jena apparatus). Fe, Mn, Cd, and Pb were extracted from the soil with Lindsay’s solution. Micronutrients and heavy metals were determined by the ASA method. Salinity was identified conductometrically as an electrolytic soil conductivity (EC in mS cm^{-1}), and pH—by the potentiometric method [44].

We obtained the public data of the potentially harmful substances in the air from a generally accessible WIOS website [45]. All air pollution data presented in the article are annual average data.

2.2. Statistical Analysis

To determine if there were significant differences between the calculated means, we performed a one-way ANOVA analysis at $p = 0.05$. Then, we performed a post hoc test (Tukey’s HSD test) to indicate which means were different from the others. The variables were soil and air pollution, pH, EC and health status (Q) of the studied species. The differences between soil and air pollution for species in the analyzed locations were indicated.

Based on discriminant analysis we prepared statistical analyses and models. We checked which variables may influence the health status of maples, small-leaved limes, oaks, and horse chestnut trees in the forests and parks of Poznań. The CCA analysis was used to construct the model [46]. The discriminant analysis compared the influence of different variables on tree specimens’ health status in the parks.

A stepwise progression analysis was used to find which variables had the most significant influence on the health status of small-leaved limes, maples, oaks, and horse chestnut trees in forests and parks of Poznań. We assessed all variables. The model included the variables that most contributed to the discrimination of groups based on p and F values. The process was repeated until the p -value was more significant than 0.05 for

the variable under investigation. To determine the significance limit level, we carried out a Monte Carlo permutation test. All comparisons, calculations, and graphic elements were created using Canoco for Windows (Microcomputer Power, Ithaca, NY, USA) software and Microsoft Excel spreadsheets. The following tools of Canoco software were used: Canoco for Windows v4.5, CanoDraw for Windows, and WCanolIMP.

3. Results

Horse chestnut trees were characterized by the worst health status, as our research indicates (Table 4). The soil collected from the areas inhabited by this species was characterized by the lowest values of Ca concentrations, which were, on average, 3609.73 mg dm⁻³. Moreover, in the soil where chestnut trees grew, we determined the highest amounts of Mn, Na and Pb at the lowest pH compared to other studied species' locations. The analysis included all partial values, from which we calculated the means from Tables 2 and 3. We calculated the best mean Q value (health status) for small-leaved lime trees, which was 3.34. The soil collected from lime areas in parks was characterized by the lowest Na level and the most alkaline pH.

Table 4. Minimum, maximum, average values, and standard deviations for the tested parameters in soil (Q—trees' health condition).

		P	K	Ca	Mg	Soil (mg dm ⁻³)		Na	Cd	Pb	pH	EC	Q
small-leaved lime (n = 121)	min	8.15	48.50	1930.55	109.35	29.50	8.15	10.05	0.42	3.08	7.25	0.10	2.60
	max	85.24	226.95	8181.03	403.73	136.16	41.79	40.47	0.68	13.70	10.46	0.32	3.86
	SD	24.60	49.40	1766.07	65.90	30.00	10.83	7.92	0.06	2.52	0.75	0.06	0.33
	mean	33.84 a	114.46 a	4837.72 a	194.90 a	68.46 a	18.32 a	16.90 a	0.51 a	7.39 a	8.38 a	0.17 a	3.34 a
Oak (n = 121)	min	9.32	48.13	1824.65	106.23	37.28	5.48	10.01	0.19	4.38	5.58	0.10	2.35
	max	72.73	210.26	11,755.78	441.52	134.21	41.57	51.86	0.95	16.02	9.71	0.47	4.00
	SD	21.71	44.83	3004.63	88.80	24.97	9.98	12.99	0.19	3.18	0.66	0.12	0.48
	mean	33.42 a	122.65 b	4741.01 a	230.87 b	75.64 b	20.85 a	22.36 b	0.49 a	9.43 a	7.72 b	0.19 b	3.24 a
Maple (n = 121)	min	8.22	46.02	1853.11	94.56	21.99	7.12	9.87	0.18	2.65	7.03	0.09	2.45
	max	78.47	197.96	7344.20	343.77	134.78	40.84	63.23	0.83	17.75	8.91	0.22	3.89
	SD	21.65	37.99	1695.95	52.38	29.16	11.66	17.39	0.16	3.63	0.42	0.04	0.34
	mean	30.73 b	107.75 a	4469.64 a	189.87 a	69.90 a	19.86 a	22.92 b	0.45 a	8.69 a	8.00 b	0.14 a	3.28 a
Horse Chestnut (n = 121)	min	5.80	32.45	1224.60	132.95	39.56	6.34	9.15	0.24	3.29	5.81	0.08	1.80
	max	117.49	218.76	5778.51	318.49	152.77	40.52	71.16	0.60	25.86	8.72	0.26	3.50
	SD	31.00	59.08	1391.34	47.63	28.32	10.46	21.60	0.09	7.66	0.77	0.06	0.39
	mean	31.69 b	108.11 a	3609.73 b	201.21 a	83.20 c	21.44 b	26.73 c	0.34 b	12.39 b	7.56 c	0.15 a	2.87 b

a, b, c—the statistical differences for means, consistent with the applied statistical tests in the trees species groups.

The table below shows the permissible levels for air pollution (Table 5) and that the most polluted areas are the areas with horse chestnut trees (Table 6). The one-way ANOVA and Tukey's test clearly showed that all the tested substances in the air in the areas where the chestnut tree grew occurred in the highest concentration. These were statistically significant differences. The air pollution could have had an impact on the health status of the horse chestnut trees. For the remaining species, we did not find significant differences between health status and air pollution.

Table 5. Maximum permissible air pollution levels, considering humans and plants protection (μg m⁻³) [47–50].

	SO ₂	NO ₂	NO _x	CO	PM ₁₀ Yearly	PM _{2.5}	C ₆ H ₆	Pb	O ₃ 8 h
National levels	20	40	30	10,000	40	20	5	0.5	120
EU levels	20	40	-	-	40	25	5	0.5	120
Switzerland	30	30	-	8000	20	-	-	-	-
USA levels	79	100	-	-	50	15	-	-	160
WHO levels	20	40	-	-	20	10	1.7	0.5	100

The study also checked how the tested pollutants in soil and air affect each other and the analyzed trees' health status. For this purpose, we performed Pearson's correlation analysis (Table 7). A strong negative correlation was demonstrated between the health of trees and tropospheric ozone, benzene, PM_{2.5}, CO, NO_x, NO₂, and Mn. This

may indicate that these substances may deteriorate the health of the studied trees. Most airborne substances can act synergistically with each other. This fact may influence the more substantial effect of pollutants on living organisms (the phenomenon of synergistic influence of harmful substances). For the parameters measured in the soil, no interaction was found concerning each other in most cases. However, we noted very high positive correlations between Mn–P, Mn–Fe, and EC–Ca.

Table 6. Minimum, maximum, average values and standard deviations for the air pollution ($\mu\text{g m}^{-3}$) [45].

		Air									
		SO ₂	NO ₂	NO _x	NO	CO Yearly	PM ₁₀	PM _{2.5}	C ₆ H ₆	Pb	O ₃ 8 h
<i>small-leaved lime</i>	min	1.41	13.22	17.41	3.41	174.01	13.89	16.95	0.79	0.00	31.78
	max	6.29	35.61	62.12	16.60	613.07	92.61	48.96	2.45	5.40	69.31
	SD	1.28	6.16	10.77	3.31	98.53	14.83	6.78	0.35	1.34	9.45
	mean	3.95 a	23.28 a	36.82 a	8.63 a	365.78 a	36.63 a	29.48 a	1.47 a	1.90 a	46.23 a
<i>oak</i>	min	1.59	14.05	20.36	3.97	194.06	16.06	14.87	0.69	0.00	26.09
	max	7.68	39.59	69.08	18.46	614.92	87.87	55.49	2.77	6.12	77.70
	SD	1.37	6.79	11.59	3.47	107.71	16.08	9.36	0.47	1.51	13.62
	mean	4.07 a	24.22 a	38.20 a	8.91 a	381.02 a	38.42 a	31.18 a	1.56 a	2.02 a	48.88 a
<i>maple</i>	min	1.32	12.42	16.85	3.26	168.40	12.95	16.51	0.77	0.00	29.65
	max	6.39	33.43	57.65	16.12	556.66	85.36	51.79	2.59	5.71	73.97
	SD	1.24	5.59	9.75	3.07	92.23	15.18	7.02	0.36	1.40	9.74
	mean	4.01 a	23.99 a	37.89 a	8.84 a	377.67 a	38.01 a	30.58 a	1.53 a	1.97 a	47.95 a
<i>horsechestnut</i>	min	1.73	16.41	22.75	4.32	227.33	17.00	22.31	1.03	0.00	37.95
	max	6.72	42.11	65.44	18.30	700.55	111.19	67.46	3.37	7.44	95.42
	SD	1.14	6.05	9.73	2.99	112.28	20.63	8.33	0.43	1.72	11.41
	mean	4.40 b	29.51 b	46.34 b	10.70 b	467.32 b	47.79 b	37.76 b	1.88 a	2.44 b	59.21 b

a, b, c—the statistical differences for means, consistent with the applied statistical tests in the trees species groups.

Table 7. Pearson’s correlation for all tested variables (the level of correlation was determined based on the Guilford classification).

	P	K	Ca	Mg	Fe	Mn	Na	Cd	Pb	pH	EC	SO ₂	NO ₂	NO _x	NO	CO	PM ₁₀	PM _{2.5}	C ₆ H ₆	Cd	B(a)P	O ₃
K	−0.22	1.00																				
Ca	−0.52	0.29	1.00																			
Mg	−0.38	0.67	0.37	1.00																		
Fe	0.58	−0.09	−0.63	0.13	1.00																	
Mn	0.71	−0.12	−0.55	−0.03	0.73	1.00																
Na	−0.34	0.54	0.44	0.35	−0.39	−0.26	1.00															
Cd	0.21	0.11	0.39	0.22	0.05	0.13	−0.16	1.00														
Pb	0.07	0.36	0.05	0.20	0.15	0.02	0.34	−0.08	1.00													
pH	0.10	−0.03	0.14	−0.24	−0.15	−0.06	−0.07	0.17	−0.14	1.00												
EC	−0.36	0.54	0.80	0.59	−0.38	−0.32	0.66	0.40	0.32	0.02	1.00											
SO ₂	0.07	−0.09	−0.01	−0.04	0.07	0.09	0.07	−0.08	0.04	−0.05	0.01	1.00										
NO ₂	0.08	−0.13	0.03	0.03	0.23	0.17	0.29	−0.18	0.14	0.02	0.14	0.37	1.00									
NO _x	0.12	−0.14	0.03	0.01	0.20	0.21	0.31	−0.16	0.15	0.04	0.14	0.38	0.95	1.00								
NO	0.16	−0.15	0.04	−0.03	0.14	0.25	0.28	−0.10	0.13	0.08	0.13	0.32	0.77	0.91	1.00							
CO	0.02	−0.10	0.03	0.07	0.23	0.10	0.26	−0.18	0.14	0.01	0.14	0.31	0.88	0.83	0.61	1.00						
PM ₁₀	−0.07	−0.03	0.01	0.09	0.17	−0.03	0.13	−0.14	0.08	−0.04	0.08	0.52	0.54	0.42	0.16	0.55	1.00					
PM _{2.5}	0.13	−0.12	−0.05	0.01	0.26	0.19	0.12	−0.17	0.05	−0.02	−0.01	0.58	0.81	0.75	0.55	0.71	0.64	1.00				
C ₆ H ₆	0.14	−0.10	−0.04	0.02	0.27	0.19	0.12	−0.15	0.06	0.03	0.00	0.55	0.79	0.73	0.55	0.71	0.60	0.97	1.00			
Cd	0.04	−0.05	−0.03	−0.01	0.09	0.06	0.04	−0.08	0.01	−0.06	−0.01	0.72	0.40	0.33	0.15	0.29	0.59	0.71	0.68	1.00		
B(a)P	0.03	−0.03	−0.01	0.00	0.06	0.04	0.03	−0.04	0.01	−0.01	0.00	−0.50	0.05	0.05	0.08	0.14	−0.30	−0.24	−0.24	−0.79	1.00	
O ₃	0.15	−0.13	−0.06	0.01	0.29	0.20	0.13	−0.19	0.05	−0.03	−0.02	0.27	0.79	0.76	0.61	0.74	0.44	0.85	0.82	0.28	0.20	1.00
Q	−0.46	0.12	0.05	−0.03	−0.31	−0.71	−0.14	0.17	−0.07	−0.05	0.00	−0.30	−0.81	−0.78	−0.64	−0.75	−0.44	−0.87	−0.87	−0.30	−0.19	−0.95

Colors represent the following: light orange—high negative correlation, orange—very high negative correlation, light green—high positive correlation, green—very high positive correlation.

The performed CCA analysis confirms the relationship between the studied trees’ health status in city parks and the analyzed chemical parameters in soil and air. In three out of four analyzed cases, tropospheric ozone might have been a factor that harmed the health of trees in the city, which concerned small-leaved lime, maple, and horse chestnut trees. Only in the oak’s case did we not find any factors that could adversely affect the

health condition. Apart from O_3 , environmental variables that could negatively affect the health of trees included: CO and NO_x in the air, as well as Mn, Cd, Fe, and alkaline soil reaction in the case of small-leaved lime trees; soil Mn in the case of maple trees; NO_x and C_6H_6 in the air and Mn in the soil in the case of horse chestnut trees (Figure 2, Table 8). Some elements marked in soil may have a positive effect on the development of trees. This group includes Mg, K, and Ca, i.e., elements that perform physiological functions in plants.

Figure 2. CCA analysis—relationships between the analyzed greenery locations (1–11) and the levels of the studied parameters in soil (green axes) and air (red axes): (A) small-leaved lime ($n = 121$); (B) oak ($n = 121$); (C) maple ($n = 121$); (D) horse chestnut ($n = 121$).

Table 8. Statistical parameters for the CCA analysis.

Parameter	<i>p</i> -Value	F-Value	%EXPL.	Parameter	<i>p</i> -Value	F-Value	%EXPL.
Small-Leaved Lime (A)				Oak (B)			
Q	0.001	17.266	10.71	Q	0.001	10.562	14.51
P	0.001	17.149	10.36	P	0.001	9.411	10.55
O_3	0.001	15.931	10.12	Mn	0.001	9.213	9.55
NO	0.001	14.594	9.23	K	0.001	8.963	8.36
K	0.002	13.251	8.57	Na	0.001	7.119	8.21
pH	0.001	12.633	8.09	Ca	0.001	6.452	8.01
Cd	0.004	10.362	7.23	Mg	0.003	5.998	7.41
Fe	0.007	10.355	7.12	Fe	0.005	4.415	6.26
Mg	0.008	8.441	6.89	pH	0.013	3.125	6.07
Na	0.010	8.237	5.22	Pb	0.029	2.961	5.16
CO	0.014	7.888	5.01				
Mn	0.024	5.214	4.93				
PM ₁₀	0.037	4.412	3.78				
Maple (C)				Horse Chestnut (D)			
Q	0.001	12.963	15.02	Q	0.001	9.266	9.53
O_3	0.001	10.232	12.56	O_3	0.001	9.127	9.22
Mn	0.001	8.265	11.12	C_6H_6	0.001	8.964	8.36
K	0.001	7.371	10.26	NO_2	0.001	8.691	8.08
EC	0.002	5.996	9.36	Mn	0.001	8.424	7.26
Ca	0.002	4.503	8.95	P	0.001	7.591	6.99
Cd	0.008	4.334	7.51	NO	0.001	7.444	6.50
P	0.017	3.191	6.02	pH	0.001	7.071	6.02
pH	0.050	2.063	4.69	K	0.002	6.526	5.23
				Ca	0.002	6.025	5.23
				Na	0.009	4.266	5.09
				Mg	0.011	4.077	4.99

4. Discussion

4.1. Soil Analysis

The urbanized areas' soils are changed by human activity. They have unfavorable properties for the growth, development, and appearance of the dendroflora. Transformations of these soils involve many variables concerning their physical and chemical properties [51–53]. For these reasons, the conditions for the trees' growth in the city are not the best [54,55].

Our research showed that the soils' alkalization was an essential problem in Poznań. In the locations of deciduous trees we studied, the pH ranged from 7.56 (in chestnut trees stands) to 8.38 (in small-leaved lime trees stands). Other researchers reported the excessive calcium content problem in Poznań as well [56]. The accumulation of calcium cations may be caused by the burning of solid fuels and the presence of debris in the soil [57]. Importantly, alkalization may have a more negative effect on plant health than salinity [58]. Soil alkalization was confirmed by Bosiacki et al. [59]. Studies conducted in Greece and China also confirmed the high pH level of urban soils [60,61]. The research conducted in Poland showed that alkalization decreased with the distance from roads [62,63].

There were standard amounts of soil magnesium at lime and horse chestnut trees sites, i.e., on average $194.90 \text{ mg dm}^{-3}$ and $201.21 \text{ mg dm}^{-3}$, respectively. Much higher magnesium content was observed in *Quercus* stands— $230.87 \text{ mg dm}^{-3}$ on average, while in *Acer* stands, the average content of this component was $189.87 \text{ mg dm}^{-3}$. The content of Mn in urban soils is diversified: Singapore $313\text{--}631 \text{ mg kg}^{-1}$; Baltimore (USA) $21\text{--}388 \text{ mg kg}^{-1}$; Chicago (USA) $641\text{--}797 \text{ mg kg}^{-1}$; Kielce (Poland) $1000\text{--}4900 \text{ mg kg}^{-1}$; Riga (Latvia) $1472\text{--}2960 \text{ mg kg}^{-1}$ [64–67].

Excessive calcium content in soils is an unfavorable characteristic. In our study, the average content amounted to $4837.72 \text{ mg dm}^{-3}$ Ca (small-leaved lime trees), $3609.73 \text{ mg dm}^{-3}$ Ca (horse chestnut trees), $4469.64 \text{ mg dm}^{-3}$ (maple trees), and $4741.01 \text{ mg dm}^{-3}$ (oak trees). It had a negative effect due to the extension of the quantitative ratio between Ca and Mg (optimally 6–8:1). Our research proves that in all tested sites, this ratio is much higher than the optimal: 24.8:1 (small-leaved lime trees sites), 23.5:1 (maple trees sites), 20.5:1 (oak-trees sites), and 17.9:1 (horse chestnut trees). The Singapore study showed that the average Ca:Mg ratio was 2.9:1, and it did not negatively affect plants' health status [66].

In general, the soils under study were characterized by a low salinity, i.e., $0.14\text{--}0.19 \text{ mS cm}^{-1}$. This may be due to the roads de-icing during winter with substances containing NaCl [57]. Our findings correspond with the results of earlier studies [68]. There was a similar salinity level in Maribor (Slovenia) [69]. However, the Na content measured was low. In the soils we studied, the average content of Na ranged from 16.90 mg dm^{-3} (small-leaved lime trees stands) to 26.73 mg dm^{-3} (horse chestnut trees stands). The excess of Na in soils deteriorates their structure and causes alkalization. Apart from that, it may disorder plants' uptake of other cations, affecting the condition of trees [70].

According to reference papers, there are different, species-dependent phosphorus contents in soil, e.g., 12.5 mg kg^{-1} for maize, and 620 mg kg^{-1} for beech trees [71,72]. The research carried out by us showed that the P content in soils in different sites was similar and ranged between 30.73 mg dm^{-3} (for maple trees) and 33.84 mg dm^{-3} (for small-leaved lime trees). According to other authors, the P content in Poznań soils is diversified. Golcz et al. [56] found that phosphorus was deficient in the researched sites. According to Breś [70], the P content depended on the research site ($9\text{--}163 \text{ mg dm}^{-3}$). The same researcher found K deficiencies and strong P reversion, which were confirmed by Kleiber [68].

The average K content measured in our study (density of soils 1.5 kg dm^{-3}) amounted to $107.75 \text{ mg dm}^{-3}$ (maple trees), $108.11 \text{ mg dm}^{-3}$ (horse chestnut trees), $114.46 \text{ mg dm}^{-3}$ (small-leaved lime trees), and $122.65 \text{ mg dm}^{-3}$ (oak trees). The K content measured in Singapore soils was $27\text{--}130 \text{ mg kg}^{-1}$ [66]. There were similar K amounts measured in Baltimore (USA) ($12\text{--}280 \text{ mg kg}^{-1}$) and Chicago (USA) ($140\text{--}199 \text{ mg kg}^{-1}$) [67,73]. When the K content is lower than 200 mg kg^{-1} , it may deteriorate trees' health [64]. However, our

study did not confirm this observation. Our research clearly showed that the trees health status was positively correlated with the K content.

Our study revealed differences in the soil micronutrients content. In our research, the soil Fe content at the small-leaved lime, oak, maple, and horse chestnut trees sites amounted to 68.46 mg dm^{-3} , 75.64 mg dm^{-3} , 69.90 mg dm^{-3} , and 83.20 mg dm^{-3} , respectively. Łukasiewicz [74] found optimal Fe content, i.e., about 54 mg kg^{-1} . The average Fe content in Upper Silesia soils (Poland) was $4484.5 \text{ mg kg}^{-1}$. Fe was accumulated in the topsoil layers with a high organic substance content [75]. The research carried out in Belgrade (Serbia) showed that Fe soil contamination in small-leaved lime and horse chestnut trees' sites amounted to $321.56 \text{ mg dm}^{-3}$ and $434.60 \text{ mg dm}^{-3}$, respectively [76], and exceeded the values found in our study.

In our study, the soil Mn content was diversified. It ranged from 5.0 to 60.7 mg dm^{-3} (small-leaved lime trees stands) and from 5.84 to 60.92 mg dm^{-3} (horse chestnut trees stands). The manganese content up to 25 mg dm^{-3} could be regarded as standard. Manganese deficit in the soil may result in the excessive growth of lateral roots, inhibit elongation growth and reduce frost resistance [33]. Earlier studies conducted in Poznań showed normal or reduced Mn amounts, which were on average $2 \text{ mg } 100 \text{ g}^{-1}$ (0–30 cm layer) [74]. There was high site-dependent variation in the Mn content in our study and in the research conducted by others [74,77].

The heavy metals accumulation in soil indicates the atmospheric pollution [58]. In general, there are much higher contents of heavy metals in areas along busy roads. This thesis was confirmed by Wong et al. [78], who said that car fumes were the primary source of lead. The analysis of Warsaw soils showed the highest heavy metals accumulation in the topsoil [79]. However, Horváth et al. [52] found the heavy metals concentration tended to increase with depth.

The Cd content was low; i.e., 0.13 – 0.62 mg dm^{-3} . The Pb content was low. Only at sites IV and VI the content of this metal was elevated; i.e., 28.38 and 33.46 mg dm^{-3} , respectively. Kleiber [68] found low heavy metals content in Luboń soils. The study conducted in Poznań also showed the average Cd content was low (0.55 – 0.75 mg dm^{-3}), and the Pb content was higher (10.3 – 14.9 mg dm^{-3}) [80]. The studies conducted in Wrocław and Paris led to similar conclusions—the soils located near roads were more heavy metals polluted [62,81]. Research by Aničić et al. [76] in the small-leaved lime and horse chestnut sites showed the Pb contamination was 6.23 mg dm^{-3} and 8.81 mg dm^{-3} , respectively. In our study, Cd content at the small-leaved lime trees sites amounted to 0.41 – 0.53 mg dm^{-3} , the Pb content ranged from 2.85 to 14.95 mg dm^{-3} . The results of our study are in line with other authors' findings [64,66,67].

4.2. Air Analysis

Air pollution is the result of natural processes and intense urban development. The pollution causes environmental threats such as acid rain, aggravated greenhouse effect, or ozone depletion [82]. Moreover, air pollution is harmful to the human respiratory system, eyes, and skin [83].

Our research shows that air pollution by SO_2 in Poznań amounted to an average of 3.95 – $4.40 \text{ } \mu\text{g m}^{-3}$ annually and did not exceed the standards set by national, EU, and WHO authorities— $20 \text{ } \mu\text{g m}^{-3}$ per year [47–49]. The level of air pollution by SO_2 in the Silesian Voivodeship (Poland) is about two times higher than in the Moravia–Silesian region (Czech Republic). Yearly mean values are 17.7 vs. $9.1 \text{ } \mu\text{g m}^{-3}$, and they are higher than the values recorded in our research [84]. Research carried out in five Polish cities (Wrocław, Poznań, Łódź, Warsaw, and Lublin) showed that the annual average SO_2 air pollution ranged from 2.83 – $14.7 \text{ } \mu\text{g m}^{-3}$ [85]. Higher values of annual SO_2 air pollution were found in Guangzhou (China)— $34.61 \text{ } \mu\text{g m}^{-3}$ [86]. Comprehensive research carried out in 2002–2012 in 49 Spanish cities showed that the average concentration of the analyzed compound in the air was $6.25 \text{ } \mu\text{g m}^{-3}$ per year [87], thus slightly exceeding the values found during our research.

In industrialized areas, the primary sources of NO₂ emissions are heavy traffic and fossil fuel combustion [88,89]. The level of NO₂ air pollution is higher in the Silesian Voivodeship (yearly mean value is 26.2 µg m⁻³). In the Moravia–Silesian region, it is 23.5 µg m⁻³ per year. Heavy traffic, thermal, and power plants are considered primary emission sources [84]. Research by Beelen et al. [90] showed that the annual average NO₂ content in the air of European cities ranged from 15.3 µg m⁻³ (Heraklion, Greece) to 57.7 µg m⁻³ (Barcelona, Spain). Meanwhile, the data collected by us indicate that the average annual level of NO₂ air pollution in Poznań ranged from 23.28 µg m⁻³ (at small-leaved lime trees sites) to 29.51 µg m⁻³ (at horse chestnut trees sites), and was lower than provided for by Polish, European, and global standards—40 µg m⁻³ per year [47–49]. A much higher level of air pollution by NO₂ was found in Guangzhou (China)—66.44 µg m⁻³ yearly [86] and in Thessaloniki (Greece)—78 µg m⁻³ per year [91].

Polish air pollution standards provide for a yearly maximum permissible NO_x pollution of 30 µg m⁻³ [47]. Meanwhile, during the research period, the annual average concentration of this compound in the air in Poznań ranged from 36.82 µg m⁻³ (at small-leaved lime trees sites) to 46.34 µg m⁻³ (at horse chestnut trees sites) and exceeded the permissible values. For comparison, studies conducted in Europe proved the NO_x content in the air ranged from 21.5 µg m⁻³ yearly (Heraklion, Greece) to 101.2 µg m⁻³ per year (Turin, Italy) and 101.3 µg m⁻³ per year (Barcelona, Spain) [90].

The data collected by us showed that average annual air pollution with CO in Poznań ranged from 365.78 µg m⁻³ to 467.32 µg m⁻³. Despite such high pollution values, it did not exceed the annual limit values in Poland—10,000 µg m⁻³ [47]. However, it is worth noting that it was much higher than the average concentration of the analyzed compound in the air of 49 Spanish cities in 2002–2012—350 µg m⁻³ per year [87]. On the other hand, it was lower than in Thessaloniki (Greece)—625 µg m⁻³ per year [91].

The particulates with a diameter equal or less than 2.5 µm can cause coughing and breathing difficulties [92]. In the case of the Poznań agglomeration, the PM sources are the production processes. Poznań is an important center of many industries [82]. The most significant PM amounts are produced by sectors such as energy, chemical, mining, metal production, and construction, as confirmed by Wang et al. [93]. The data suggest a decrease in the emissions of PM₁₀ and PM_{2.5} to the atmosphere. It may be the result of the actions of the local authorities who promoted the idea of public transport and introduced some improvements (bus lanes) that made it a more attractive mean of transportation [94]. The data collected by us showed that the annual average PM₁₀ air pollution was 40.21 µg m⁻³. The values found in our research only slightly exceeded the annually permissible Polish and European levels—40 µg m⁻³ [47,48]—while they exceeded the annually permissible values established by the WHO—20 µg m⁻³ [49]. For comparison, the yearly PM₁₀ concentration in the air of Kuopio (Finland) was 10.3 µg m⁻³ [95], in Thessaloniki (Greece)—39.25 µg m⁻³ [91], in Tabriz (Iran)—75.7 µg m⁻³ [96], and in Guangzhou (China)—as much as 88.64 µg m⁻³ [86].

Our analyses showed that the average PM_{2.5} air pollution in Poznań amounts to 32.25 µg m⁻³ per year. It is worth noting that this value exceeds the permissible annual levels: Polish—20 µg m⁻³ [47], European—25 µg m⁻³ [48], and WHO—20 µg m⁻³ [49]. Similar pollutant values were found in Tabriz (Iran)—31.1 µg m⁻³ yearly [96]. However, in other European cities, the lowest level of PM_{2.5} air pollution was in Kuopio (Finland)—6.2 µg m⁻³ per year [95]. The average concentration of the analyzed compound in the air in 49 Spanish cities in 2002–2012 was 13 µg m⁻³ annually [87], and in Thessaloniki (Greece)—23 µg m⁻³ per year [91]. Therefore, these values were much lower than in Poznań.

Polish C₆H₆ air pollution standards amount to 5 µg m⁻³ per year [47]. The data collected during our research showed that the average annual C₆H₆ air pollution was 1.61 µg m⁻³, and it was much lower than the acceptable standards. For comparison, the highest mean concentration of C₆H₆ in Polish cities was found in Łódź—3.45 µg m⁻³ per

year [85]—and it was over two times higher than in Poznań. On the other hand, during research in Spain, the average annual C_6H_6 air pollution was found to be $0.05 \mu g m^{-3}$ [97].

The collected data showed that the average level of O_3 air pollution in Poznań was $50.57 \mu g m^{-3}$ (per 8 h) and was much lower than the acceptable Polish and European standards— $120 \mu g m^{-3}$ per 8 h [47,48]—and the WHO standards— $100 \mu g m^{-3}$ per 8 h [49]. The air O_3 concentration in Poznań was also lower than average 8-h level in Augsburg (Germany)— $117 \mu g m^{-3}$ [98], Thessaloniki (Greece)— $53.5 \mu g m^{-3}$ [91], and Tabriz (Iran)— $59.43 \mu g m^{-3}$ [96]. The highest average 8-h O_3 concentration level in large Polish cities was found in Łódź— $66.75 \mu g m^{-3}$ [85]. On the other hand, the results of studies conducted in Spain showed that the average 8-h concentration of this compound was $47.17 \mu g m^{-3}$ [87].

The data collected by us showed the annual level of Pb air pollution in Poznań was on average $2.08 \mu g m^{-3}$ and exceeded the Polish standards, which indicates the level of $0.5 \mu g m^{-3}$ as permissible per year [47]. The level of air pollution in Poznań was also much higher than in Kuopio (Finland)— $0.002 \mu g m^{-3}$ per year [95]. The primary anthropogenic sources of global Pb pollution are leaded gasoline, coal combustion, industry, and waste incineration [99]. Even though leaded gasoline is not used in most European countries anymore, lead is still widely present in the environment [100].

4.3. Trees Health Status

Our research shows that NO , NO_2 , and O_3 (in the air) and pH and Mn (in the soil) had the most significant negative impact on the studied species' health condition.

Many authors also describe the negative effect of O_3 on the deciduous trees' health, pointing to the damaging effects of this gas within the leaf blade [11,19,101,102]. The available sources also indicate a very negative impact of SO_2 on the health status of plants, but they describe very high levels of contamination—over $140 \mu g m^{-3}$ [103,104]. Our research, however, did not confirm such an impact—probably due to the too low level of SO_2 air pollution (on average $4.10 \mu g m^{-3}$). The available sources also point out the possible synergistic negative impact of $SO_2 + O_3$ [11,105], which we also did not confirm in our study. Data on the negative effect of particle matter (PM) concentrations on the health status of deciduous trees in urbanized areas can be found in the literature [106]. Our research also did not confirm such a negative effect in any of the species studied.

Our research has shown that the health of small-leaved limes and maples can be negatively affected by soil pH. In our study, the pH level for the stands of these trees was on average 8.38 and 8.00, respectively. Similarly, in their research, Bach et al. [25] found that the neutral and alkaline reaction of anthropogenic soils in urban environments is considered one of the main factors responsible for tree growth and health status. In contrast, Cekstere and Osvalde [64] prove that pH was a less significant factor influencing tree health. Our research also showed that the health of small-leaved lime, maple, and horse chestnut trees is adversely affected by the content of Mn in the soil. This was confirmed by Kleiber et al. [77], who found a positive correlation between the Mn content and the deterioration of the small-leaved lime trees health status.

5. Conclusions

1. The oak trees turned out to be the most resistant to the environmental factors tested, while the horse chestnut trees were the least useful species for the city. Small-leaved lime and maple trees turned out to be quite tolerant species, although selective factors may harm them.
2. The area where horse chestnut trees grew turned out to be the most Fe, Mn, Na, and Pb soil-polluted and air-polluted with most of the substances recorded.
3. Factors that can potentially adversely affect the trees' growth in the city are primarily tropospheric O_3 in the air and Mn content in the soil.
4. Most of the substances determined in urban air were characterized by a synergistic interaction with each other, enhancing air pollution.

5. Air pollution exceeding the acceptable standards was noted in the case of NO_x (39.81 µg m⁻³, permissible 30.00 µg m⁻³), PM₁₀ (40.21 µg m⁻³, permissible 40.00 µg m⁻³), PM_{2.5} (32.25 µg m⁻³, acceptable 20.00 µg m⁻³) and Pb (2.08 µg m⁻³, acceptable 0.5 µg m⁻³).

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