Effect of Deicing Salts on Urban Soils and Health Status of Roadside Trees in the Opole Region

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ABSTRACT: This article reports on a study whose aim was to evaluate the impact of snow removal salts on urban soil properties and the health of roadside trees. The evaluation was done by chemical analyses of soil samples and plant matter combined with toxicity testing, performed with a Protoxkit F™, a protozoan microbiotest. Samples were collected at 45 locations on three main roads in the town of Opole (Poland). The roads differed in the snow removal technology and amount of chemical substances (mostly NaCl) used on them during the winter. The study showed that when soil was exposed to a high level of NaCl, it tended to be more alkaline and also exhibited increased content of Na^+ and Cl^-. The toxic effects of the soil extract on protozoa appeared at 26.0 mg Na^+/100 g soil dry mass (s.d.m.) and 12.0 mg Cl^-/100 g s.d.m., whereas salt injury symptoms (chlorosis and necrosis of the edge of leaf blades) appeared at 13.2 mg Na^+/100 g s.d.m. and 3.9 mg Cl^-/100 g s.d.m., becoming more severe at 26.0 mg Na^+/100 g s.d.m. and 12.0 mg Cl^-/100 g s.d.m. because of extensive necrosis and defoliation. The lysimetric experiment, which was used to test soil samples collected from the city park area, indicated that salt plays a significant role in the pollution of soil in urban areas, with the least toxic salt being $CaCl_2$. Environ Toxicol 19: 296–301, 2004.

Keywords: urban soil; roadside tree; deicing salt; microbiotest; salinity; toxicity; experiment

INTRODUCTION

The influence of different anthropogenic factors has a disturbing effect on the state of urban soil by changing its natural features and internal processes. Geomechanical transformations are often accompanied by chemical changes. The accumulation of different pollutants and their subsequent synergetic and antagonistic reactions lead to an increasing level of toxicity in urban soil (Mannings et al., 1996; Linde et al., 2001). One of the observed changes is the salinification of urban soils, a side effect of salting the roads in winter. Part of the salt mixture (4%–13% of the total amount of spread chemicals), the main components of which are NaCl and $CaCl_2$, permeates from roads to adjacent lawns and green areas and causes plant damage (Supłat, 1996). Many authors (Fluckinger and Braun, 1981; Munns and Termaat, 1986; Chmielewski, 1996) have shown a direct correlation between the content of Na^+ and Cl^- ions in the soil and the degree of plant damage. The higher the concentration of Na^+ and Cl^- is in the soil, the higher is their accumulation in plants and, in consequence, the greater the damage to plants. The most significant symptoms of salts on roadside trees are reduction in biomass, chlorosis and necrosis, and, in extreme cases, the entire destruction of

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a plant. Of course, many factors can induce plant chlorosis. The influence of exhaust and combustion gases on the health of trees growing in urban area should not be omitted. However, in many cases an initial diagnosis of the causes of plant injury is possible by analyzing color intensity as well as the position of any alterations that have occurred on the leaf blade. According to Hartmann et al. (1988), the first symptoms of tree damage from salts used for snow removal purposes appear in early spring as light chlorosis of the leaf blade edge, which subsequently spreads to the middle. These symptoms are often unilaterally intensified on the tree-crown side facing the road. Naturally, the intensity of these symptoms cannot be linked solely to salinification; other factors must also be taken into account, the most important of which is the complexity of the urban environment. This includes the microclimate and the location and conditions of plant growth, as well as the characteristics of the trees, that is, species type, age, and health.

In recent years studies concerning both the assessment of pollution levels on land and in aquatic ecosystems and the adverse anthropogenic impact of this pollution on the natural environment have been supported by a new method—microbiotests (Blaise et al., 2000). The advantages of using biotests with organisms representing different trophic and functional elements of ecosystems (bacteria, protozoa, rotifers, crustaceans and algae) have been shown in many studies (Knoke et al., 1999; Persoone et al., 2000; Nicolau et al., 2001). Recently, the use of ciliates in toxicological tests and their potential in standard bioassays have been demonstrated in many ways (Persoone et al., 2000). Ciliate protozoa are widely distributed and hold ecological significance in all ecosystems. Furthermore, as test organisms, ciliates fulfill all the requirements for assessing environmental risk and impact, as they are eukaryotic, their biology and general responses are widely understood, their generation time is short, and laboratory handling is relatively easy.

The aim of this study was to assess the impact of deicing salts on urban soils and plants. The objectives were (1) to determine, through a combination of traditional chemical analyses and microbiotests, to what extent road-side soils in Opole are contaminated by gritting salts, (2) to establish the relationship between the level of soil salinity and the health conditions of road-side trees, and (3) to estimate, by means of lysimetric experiments, the toxicity level of urban soils subjected to various deicing salts.

MATERIALS AND METHODS

Fieldwork

The fieldwork was conducted within the area of Opole, the capital of Opole region, in southern Poland. Samples were collected in the central part of the town, along three main roads. The roads examined by the study are characterized by similar traffic intensity; however, the amount of chemicals used in winter (mostly NaCl and sporadically $CaCl_2$) varied as follows: Road 1 (RD1), salts not used; RD2, 160 g/m^2/season, RD3, 230 g/m^2/season. The fieldwork included (1) an inventory of trees along the selected roads, taking into account the varieties of species, (2) macroscopic observations of leaves and the health status of tree canopies, and (3) site selection and sample collection. Soil and plant (leaves) samples were collected in September 2001. To collect soil samples, 45 sites were designated, taking into account characteristic features such as the type of buildings, the area of open space below the trees, soil compactness, and the type of road surface. These test areas differed with respect to tree health conditions. Roadside soil samples were taken from below the trees, from a depth of 0–20 cm, using a stainless-steel trowel. The mass of each sample was 1.0 kg. At the same time, the soil in a city park was sampled from three 100-m^2 areas. Twenty samples were taken from each area and then mixed to give three separate samples. The plant material was collected from the small-leafed lime *Tilia cordata* L., the best represented species in plantings, considering the damage stage of leaves and tree canopy. Leaves were collected from one species of tree to avoid the possibility of species-dependent differences in nutrient accumulation and salt tolerance. From each tree 100 leaves with the same degree of leaf blade damage were collected. The assessment of health conditions of trees was done according to a 4-point scale called a European classification (Kronenbilder, 1986).

Laboratory Studies

The laboratory studies consisted of physical and chemical analyses of the soil samples and plant material and toxicological analyses of soil samples. Initially, the soil samples were dried at room temperature, then sieved with a sieve of 1-mm-sized mesh and homogenized. The physical and chemical properties of the soil samples were assessed using the following standard methods: (1) grain-size content by Casagrande's areometric method, (2) pH (H_2O) by a glass electrode with a sample:water ratio of 1:2.5 and pH (KCl) measured on a sample of soil and KCl (1N) in a ratio of 1:2.5, (3) the organic carbon content by Tiurin's method, (4) the content of exchangeable cations in the ammonium acetate (pH 7) by atomic absorption spectrometry, and (5) the content of cations and anions in the water extract by flame photometry. A water extract from soil samples was prepared as follows: a sample (soil and distilled water in a ratio of 1:5) was continuously shaken for 1 h at room temperature, then filtered using the dense pore filter paper to slow filtering of fine deposits.

The plant samples were first washed with bidistilled water and then dried at 30°C, before being subjected to dry mineralization by burning them in a furnace at 450°C–

500°C. They were then extracted with a solution of nitric acid (1:4) and ammonia (1:4). In the extract, the concentration of cations (Na, K, Mg, and Ca) was determined by atomic absorption spectrometry and the chlorides by the argentometry method. The total amount of the 45 soil samples and 45 plant samples was analyzed in three replicates.

The toxicological analyses comprised the analysis of the soil samples collected along roads RD1–RD3 and a lysimetric experiment. The toxicological analyses of the soil samples were conducted with a filtered water extract of the soil using the microbiotest with protozoa, according to the standard operational procedure (Protoxkit F™). This microbiotest with the ciliate *Tetrahymena thermophila* evaluates the growth inhibition of unicellulars submitted for 24 h to a toxicant. After the processing of the data, the LC_{50} values (calculated in percentage dilution of water extract of soils) were transformed into toxic units (TU) according to the formula: $TU = 100/LC_{50}$. The arbitrary (log) toxicity scale of Persoone et al. (1993) was used to express the degree of toxicity. The water extracts from the soils were classified as nontoxic if TU = 0, slightly toxic if TU ≤ 1, toxic if TU = 1–10, very toxic if TU = 11–100, and extremely toxic if TU ≥ 100. The water extract for the toxicological study was obtained using mixed soil sample and bidistilled water (1:5). During the roadside soil sample preparation, the samples collected from all five sites were mixed and homogenized. Thus, three mixed soil samples were obtained for each of the investigated roads. The control soil was the sample collected in the park. We used the same procedure of water extract preparation as described for the chemical analysis. Analysis was done of three replicates of all 10 soil samples.

The lysimetric experiment was carried out with the soil samples collected in the city park from the test areas not directly exposed to the chemicals used to grit roads in winter. Means values of the chemical properties of the park soil were: H_2O pH 7.35, KCl pH 7.05, electrical conductivity 462 μS/cm, and organic carbon content 3.6%. The soil samples of a preserved structure were collected in plastic lysimeters 15 cm in diameter and 20 cm tall. In a laboratory, three series of lysimeters fitted with filters were prepared. To the top of the soil were applied 3.2 g of NaCl, $CaCl_2$, and a 65:35 mixture of NaCl and $CaCl_2$, that is, amounts corresponding to the salt doses used in winter recalculated per 1 m^2 of road surface. The soil samples in the lysimeters used as the control were not subjected to salts. The soil surface in each lysimeter was sprinkled with water of a chemical composition approximating rain and snow precipitation. Lysimeters were sprinkled three times, using 400 cm^3 of water each time, which was equal to the mean level of atmospheric precipitation for spring, summer, and autumn in 1999–2000. The supernatants for the toxicological analysis were collected after each sprinkle stage. The experiment was performed in three replicates.

TABLE I. Particle size distribution of soil material <1 mm

	Sand		
Roadside	1–0.1	0.1–0.02	<0.02
RD-1	68	23	9
RD-2	73	21	6
RD-2	69	22	9
Park	64	23	13

The material collected, both from the roadside sites and from the park, was represented by limestone soils with similar physical and chemical properties.

RESULTS AND DISCUSSION

Soil Properties

The grain-size content of the analyzed roadside soils is presented in Table I. The soil structure (<1 mm) was formed mainly of light loamy sands with minor amounts of loose and poor loamy sands. Between 68% and 73% of sandy formations were characterized by high permeability, and thus the soil extract easily penetrated deeper layers of the profile together with soluble forms of pollutants. With a low percentage (6%–9%) of clay, soil has both inadequate nutrients and an inadequate holding capacity for normal plant growth (Mullins, 1991).

The pH values of the analyzed soils indicated their alkaline reaction (Table II). A reaction ranging from neutral to alkaline or the complete saturation of a sorptive complex is typical for limestone soils. These are soils formed on the substratum of calcareous rocks, such as limestone and marls that dominate the region of Opole. However, progressive alkalization of soils in urban areas has been observed in many countries (Strzyszcz, 1981; Sauve et al., 1996), as well as in tropical climates where in natural conditions acidic soils prevail (Jim, 1998). The alkalization of these soils is associated with the presence of a mixture of calcareous debris in urban buildings and a deposition of alkaline dust. Moreover, pH values close to 7.5–8.0 usually occur in saline soils that are overloaded with dissolved salts (Bouzille et al., 2001). In the Opole area, there has been an increase in soil pH levels accompanied by increased salt content. Among the basic cations occurring in the sorptive complex, the majority of cations in the analyzed soils were Ca^{2+} ions, whereas Na^{+} ions were of secondary importance. The amount of Ca^{2+} ions increased in the soil sorptive complex and simultaneously decreased in the water extract. Changes in Ca concentrations indicate cation exchange capacity differentiation among particular roadside soils, which are highly affected by organic carbon content. The higher the cation exchange capacity of soils, the more

TABLE II. Selected chemical properties of the urban soils studied in Opole, Poland

	RD-1	RD-2	RD-3
pH KCl	7.4–7.9 (7.6)	7.2–7.5 (7.4)	7.7–8.2 (7.9)
pH H_2O	7.7–8.0 (7.8)	7.3–7.7 (7.5)	7.9–8.3 (8.0)
C org. (%)	1.1–1.9 (1.5)	1.7–2.4 (2.1)	2.4–2.9 (2.7)
Concentrations of base cations and anions in water extract of soils (mg/100 g s.d.m.)			
Na	3.4–3.7 (3.5)	13.2–15.8 (15.0)	26.0–33.0 (31.0)
K	3.1–4.0 (3.6)	1.9–2.6 (2.3)	6.0–6.9 (6.5)
Ca	7.5–9.9 (9.1)	3.7–4.6 (4.2)	4.2–4.5 (4.4)
Mg	0.2–0.5 (0.3)	0.1–0.3 (0.2)	0.1–0.4 (0.2)
Cl^-	0.8–1.6 (1.0)	3.9–4.8 (4.4)	12.0–17.0 (15.0)
SO_4^{2-}	1.23–2.21 (1.85)	6.98–7.32 (7.20)	8.79–9.96 (9.26)
HCO_3^-	25.87–36.29 (30.86)	41.93–44.10 (42.94)	46.79–53.20 (49.65)
Electrical conductivity [μS cm^{-1}]	109.0–212.0 (147.0)	149.0–265.0 (194.0)	562.0–790.0 (640.0)
Concentrations of exchangeable base cations in soils (me/100 g s.d.m.)			
Na^+	1.7–2.0 (1.90)	3.00–3.56 (3.40)	5.10–5.87 (5.32)
K^+	0.32–0.48 (0.40)	0.65–0.91 (0.80)	0.69–0.91 (0.83)
Ca^{2+}	19.56–20.86 (20.02)	27.90–29.00 (28.30)	31.09–35.35 (32.34)
Mg^{2+}	0.33–0.42 (0.38)	0.57–0.65 (0.63)	0.38–0.48 (0.41)
Salt content [%]	0.04–0.06 (0.05)	0.073–0.082 (0.078)	0.098–0.213 (0.116)

limited is the Ca^{2+} mobility (Strzyszcz, 1981). The Na^+ ions content in the soil sorptive complex changed gradually between the samples collected along the roads where snow was removed without (RD1) and with (RD3) the use of salts, with mean values of 1.9 and 5.32 me/100 g s.d.m., respectively. This suggests that Na^+ ions in deicing salt displace other ions in the exchange sites in the soil. Norrström and Jacks (1998) emphasized the importance of this process, in which Na^+ ions from deicing salts displace other base cations, for soil chemistry. In general, K^+ and Mg^{2+} ions are considered to be bound to the soil exchange sites less than Ca^{2+} and thus are more easily displaced. Despite the Na^+ ions being easily washed out of the sorptive complex, their increasing absorption by the surface of soil colloids has unfavorably affected the physical properties of soils.

The results of the water extract analysis drew attention to significant increases in the levels of sodium and chlorides in the RD1 and RD3 samples. Their mean values were 8.8 and 15 times higher, respectively. The possible causes of the increasing level of urban soil salinity are the salts, mainly NaCl, used in winter. As the sampling was conducted in autumn, it was concluded that the high Na^+ and Cl^- content was a result of salting during the previous winter. Studies conducted in many Polish towns point to the soluble salt content, in particular of Na^+ and Cl^-, as an important indicator of soil salinity (Czerwiński, 1978; Dużyński and Kusza, 1999). The introduction of NaCl into soils radically changes the concentrations of ions within the soil extract, affecting its osmotic value. Alongside the increase in the osmotic force, the amount of water accessible to plants decreases. According to Mekdaschi et al. (1988), with 0.5% salinity, water becomes completely inaccessible. In the analyzed samples the content of soluble salts did not exceed 0.3%, but when Na^+ and Cl^- ions are present, even in small amounts, serious plant injuries may occur.

Analysis of the Plant Material

The analysis of the mineral content of the tissues revealed that, on the one hand, the soil salinity induced an increase in Na^+ and Cl^- content in tree leaves, but, on the other hand, it reduced the accumulation of K^+, Ca^{2+}, and Mg^{2+} ions (Table III). The effect of salinity on the nutrient composition of plant tissues has been extensively investigated, and several researchers have confirmed that the effects of salinity stress on plant health may occur through an ionic im-

TABLE III. Mean values of base cation and Cl^- ion contents in leaves of *Tilia cordata* L. growing by roads RD1–RD3 (mg/100 g dry mass)

	RD1	RD2	RD3
Na^+	175	790	1010
K^+	2740	2040	1780
Ca^{2+}	2053.6	1925.2	1873.9
Mg^{2+}	345.9	224.2	179.3
Cl^-	620	1610	2110
K^+/Na^+	15.65	2.58	1.76

balance, particularly of Ca^{2+} and K^+ (Cerda et al., 1995; Essa, 2002). The K^+ content in plant tissues represents the main cation in plant cells and is an important component of the osmotic potential of the cell (Reggiani et al., 1995). In our study the mean content of K^+ in leaves was 1.3 times lower on RD2 and 1.5 times lower on RD3 in comparison to RD1. Therefore, we can conclude that leaf K^+ concentrations were lower when the soil salinity levels were higher. The reduced amount of K^+ ions could probably be offset by enhanced accumulation of Na^+ ions. With the higher level of soil salinity, the content of Na^+ in leaves increased by 4.5 and 5.8 times, respectively, in comparison to soil samples with the lowest level of salinity. The intensity of these changes is expressed as the K^+/Na^+ ratio. In general, higher values of this ratio were noted in the samples of leaves collected along RD1 (mean 15.65), followed by RD2 (mean 2.58) and RD3 (mean 1.76). Increasing Na^+ content and decreasing K^+ content and K^+/Na^+ ratios in plant leaves may be attributed to the effect of competition between Na^+ and K^+ ions on the absorptive sites of the plant roots (Ioneva, 1988).

The level of soil salinity also has a remarkable effect on the increase of the Cl^- content in leaves. The content of chlorides in the dry mass of leaves reflects the process of Cl^- ion intake from the soil. The symptoms of Cl^- accumulation are characteristic pathological changes in leaves (Chartzoulakis et al., 2002). Macroscopic observations of the health conditions of roadside trees have confirmed different degrees of leaf blade damage. The occurrence of toxic symptoms in the form of chlorosis and necrosis on the edge of leaf blades (weak damage) was discovered on RD2, where the content of Na^+ and Cl^- in the dry mass of leaves was 630–846 and 1198–2511 mg/100 kg d.m., respectively. A further increase in the concentration of ions caused more extensive damage, including dieback and falling leaves. Necrotic changes in the leaves, which extended over 60% of the blade area (strong damage) occurred only along RD3, the one that experienced an intensive application of salt during snow removal.

Toxicological Studies

The analysis of water extracts from the roadside soil samples revealed a lack of toxicity in RD1 and RD2. Only along RD3 was the toxic effect apparent, and the values of LC_{50} ranged from 31.3% to 74.9%. Considering that some of the pollution associated with the sorptive complex of soils was inaccessible with the test used because of a lack of direct contact with cells of the tested protozoa, these values should be treated as estimates. They only give a general view of the varied level of pollution and of the threat to the soil environment within the town. Analyses of the real level of soil toxicity would be too risky with the use of only one microbiotest. Several authors (Wangberg et al., 1995; Rojickova-Padrova et al., 1998) have outlined the characteristics of an ideal bioassay Their findings corroborated the general belief that a suite of tests is needed in order to evaluate correctly environmental pollution, as a single test reflects the sensitivity of that test only. In the analyzed case, there is a high probability that the noted changes are the effects of the substances used to prevent road slipperiness. A relatively low value of soil conductivity (109.0–790 μS/cm) is indicative of a comparatively low content of freely soluble salts. However, even a small amount of NaCl inserted into the soil may induce chemical reactions, resulting in new compounds of higher toxic activity.

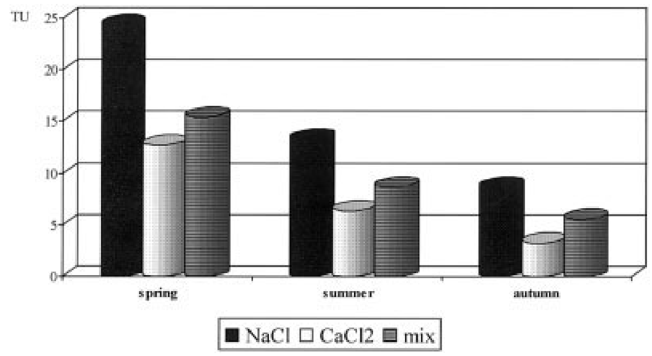

Fig. 1. Mean TU values of water extracts of urban soils exposed to different deicing salts in a simulated experiment.

The elimination of the influence of other environmental factors on soil properties during the lysimetric experiment enabled the changes caused by the salts to be observed. The mean toxicity values of the water extracts, analyzed after the application of the subsequent salts and after precipitation in doses corresponding to spring, summer, and autumn are presented in Figure 1. The highest TU values were obtained in water extracts that contained NaCl, and the lowest were in extracts containing $CaCl_2$. All the analyzed water extracts of soils should be considered toxic (class 2) only after the "spring precipitation." As would be expected, the easily soluble salts were washed out by subsequent precipitation from a 20-cm-deep layer of soil, leading to a gradual decrease in the toxicity of subsequent water extracts of the soils. In comparison to the "spring season," the toxicity of solutions decreased in the "summer season" by 40.0%–53.8%. With the exception of soil samples treated with NaCl, the other water extracts from the soil samples could be classified as slightly toxic (class 1) because their TU values fell below the limit of 1. Further washing between the summer and autumn seasons, caused a decrease in toxicity of 30.8% for NaCl, 33.3% for the mixture of salts, and 50% for $CaCl_2$.

CONCLUSIONS

1. In this study a correlation between the level of salinity of urban soils and the health condition of roadside trees has

been shown. The highest dose of salt (mostly NaCl) used on RD3 caused a remarkable increase in the salinity of the soil extract, which had a toxic effect on the tested organisms. The consequence of this evident increase in soil salinity is damage to the leaves and tree canopies.

2. The results from the park samples, which were treated with salts and analyzed using the protozoan *Tetrahymena thermophila*, displayed the following sequence of toxicity: NaCl > NaCl:$CaCl_2$ (65:35) > $CaCl_2$.

3. The comparison of results obtained from the lysimetric experiment and the analysis of the roadside soils indicated that salts play a significant role in the pollution of soil extracts in urban areas.

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