https://doi.org/10.17221/443/2025-PSE

Assessment of mineral nutrients and risk elements in plants growing on soils polluted by magnesite emissions

Margita Kuklová[1], Ján Kukla[1], Jana Luptáková[2], František Hnilička[3], Tomáš Rýgl[3]*

[1]*Institute of Forest Ecology of the Slovak Academy of Sciences, Zvolen, Slovak Republic*
[2]*National Forest Centre – Central Forestry Laboratory, Zvolen, Slovak Republic*
[3]*Department of Botany and Plant Physiology, Czech University of Life Sciences Prague, Prague, Czech Republic*

**Corresponding author: kuklova@ife.sk*

Citation: Kuklová M., Kukla J., Luptáková J., Hnilička F., Rýgl T. (2026): Assessment of mineral nutrients and risk elements in plants growing on soils polluted by magnesite emissions. Plant Soil Environ., 72: 77–86.

Abstract: Changes in the content of mineral nutrients (Ca, Mg, K, Na) and risk elements (Mn, Cd) in the assimilatory organs of selected plant species were studied along the altitudinal gradient of A–D zones polluted by alkaline emissions from the magnesite factory Lubeník (Slovak Republic). Multivariate statistical analysis and comparison with background values in other studies demonstrate persistent intoxication of some plants by Mg (all study plants), K (*Lactuca saligna*, *Dryopteris filix-mas*), Mn (*Quercus polycarpa*, *Carpinus betulus*, *Betula pendula*, *Lactuca saligna*) and Cd (*Quercus polycarpa*, *Carpinus betulus*, *Betula pendula*, *Lactuca saligna*). Overall, *Lactuca saligna* accumulated the highest amounts of Mg, Cd, Na and K near the magnesite plant, suggesting its potential as an effective bioindicator of elemental pollution. Unbalanced Ca/Mg ratios, lower than 1, were recorded predominantly in all plant species sampled near the magnesite plant; unbalanced K/(Mg + Ca) ratios were predominantly in woody species.

Keywords: ecotoxicology; trees; herbs; macronutrients; toxic elements

Industrial activities are the biggest culprit of air pollution. Although mineral raw materials are extremely important for socio-economic development, the extraction of minerals and their use in various industrial processes play a leading role in increasing environmental pollution, and especially air pollution (Alaqouri et al. 2020a). The accumulation of toxic elements in the plant is closely related to environmental conditions (Atanasov et al. 2023). Changes in environmental quality can, to some extent, be monitored through bioindicators that reflect various disturbances caused by pollutants (Kateivas et al. 2022). Deciduous plants are often used to monitor pollution from risk elements, with the leaves often considered the most sensitive parts to emissions (Pedroso and Alves 2015). In the case of plants, the physiological mechanisms that allow crops to grow in soils containing high concentrations of mineral elements are based on their exclusion from the plant and/or tolerance of these elements through their sequestration as non-toxic compounds in cellular compartments (Kumari et al. 2022). Plants suffer from mineral nutrient deficiency stress when the availability of nutrients in the soil and the amount of nutrients received are below the level required to maintain metabolic processes at a specific growth stage. On the other hand, accumulation of risk elements is known to cause significant physiological and biochemical responses in vascular plants. Preeti and Tripathi (2011) state that there is a direct relationship between soil chemical characteristics and plant morphological and biochemical responses. For

Supported by the Grant Agency VEGA, Slovakia, Project No. 2/0001/25.

https://doi.org/10.17221/443/2025-PSE

example, in the case of Mn, soil-plant and plant-microbe are important interactions that control Mn availability in soil (Rengel 2000). The primary importance of nutrients that plants need from the soil does not lie in their total content but rather in the content of soluble and easily available nutrients, called available nutrients (El-Ramady et al. 2014). Ca and Mg are plant-essential nutrients, and the ionic form of each held on the soil exchange sites is the form taken up by plants. Schulte and Kelling (2025) state that the Ca:Mg ratio rarely limits plant growth if soil pH is maintained in the good growing range. The competition between Mg^{2+} and K^{+} is also very important and has been extensively studied. The presence of an excessive amount of K^{+} in the soil reduces the bioavailability of Mg (Van der Heijden et al. 2013).

The main consequences of the mining and high-temperature processing of magnesite at the plant in Lubeník (Slovakia), founded in 1934, are persistent soil alkalisation and damage to vegetation from Mg emissions. Emissions of solids reached approximately 800 t/year in the 1950s, and following the introduction of large-capacity rotary kilns, they increased to around 4 800 t/year between 1970 and 1980 (Hančuľák 2000). However, after the installation of dust removal equipment, emissions decreased to 500 t/year in 1990 and 85 t/year in 2000 (Bobro and Hančuľák 2001). In 2005, the magnesite plant released the following pollutants (t/year): 2 569.863 of particulate matter, 187.652 of sulphur dioxide, 276.250 of oxides of nitrogen, and 2 569.863 of carbon monoxide. In 2023, they were (t/year): 6.280 particulate matters, 5.795 sulphur dioxide, 87.403 oxides of nitrogen, and 106.905 of carbon monoxide (AIR 2024). The main pollutants in the Jelšava-Lubeník contaminated area are Mg, Mn, As, Cd, Hg, dust, fly ash, NO_x, and SO_2 (Michaeli and Boltižiar 2010).

Plant species and different plant parts exhibit varying degrees of tendency to accumulate risk elements (Angelova et al. 2017, Tomczyk et al. 2020, Štofejová et al. 2022, and others). We assume that if contamination by Mg emissions persists, the content of the studied elements in the biomass of plant species will gradually increase, decreasing with increasing distance from the magnesite factory, and the content of elements in the assimilation organs of woody plants will be lower compared to the content in herbaceous species. The aim of this study was therefore to quantify the extent of changes in the content of macronutrients and risk elements accumulated in the assimilatory organs of selected woody and herbaceous plants along the altitudinal gradient polluted by emissions from the magnesite plant.

MATERIAL AND METHODS

Sampling and element analyses. The research was carried out along a vertical transect established in pollution zones A to D (48°39'N, 20°10'E) of the magnesite plant Lubeník in 2021. The research plots were selected in segments of changed geobiocoenoses of the *Fagetum pauper* inferiora group of forest types in the 3rd (oak-beech) vegetation grade. The phytocoenological research plots measuring 20 × 20 m were established at distances (m) A (400, Hyperspolic, Hypereutric Technosol); B (600, Eutric Cambisol); C (1 000, Eutric Cambisol), and D (1 500, Eutric Cambisol) from the pollution source.

Soil probes were dug at randomly selected places within each phytocoenological plot (400 m^2) with regard to the nature of the microrelief. Soil samples were taken from the mineral layers at 0–5, 10–20, and 20–30 cm in three replicates. The carbon (C) content in organic matter was determined by the Tyurin method (Kononova 1966). Active reaction of the soil was determined using a digital pH meter Inolab pH 720 (Weilheim, Germany) at a ratio of fine-earth to water of 1:2.5. Due to the magnesite dust fallout, the soil layers were strongly to slightly alkaline in zone A, slightly alkaline in zone B, neutral in zone C, and slightly acidic in the outermost zone D (Table 1). The contents of oxidable carbon (C_{ox}) in the 0–5 cm and 20–30 cm layers of soil differed significantly from each other, except for the contents in C and D zones. In the 10–20 cm layer, the lowest C_{ox} content in zone A was significantly different from that in zones B to D. C_{ox} contents in soils of all pollution zones were decreasing significantly from topsoil towards the lower mineral horizons (Kuklová et al. 2025).

Quantitative characteristics of plant species were assessed using the Braun-Blanquet phytocenological scale, refined by Zlatník (1978). Given that only segments of altered ecosystems (magnesite heap, pasture, and altered forests) are near the magnesite plant, we included 3 tree species at each research site, 2 forest undergrowth species, and 2 herb species on the magnesite heap and pasture. The age of the trees varied for the above reasons, ranging from 20 years (magnesite heap) to 40–60 years (pastures, forests). In zone A, in addition to sporadically occurring individuals of dwarf hornbeam, oak, and birch,

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Table 1. Variability of pH_{H_2O} and oxidable carbon (C_{ox}) (%) values in soil layers along pollution zones A–D

	Soil layer (cm)	Pollution zone			
		A (400)	B (600)	C (1 000)	D (1 500)
pH_{H_2O}	0–5	8.92 ± 0.04^{a}	7.93 ± 0.20^{ac}	7.17 ± 0.62^{bc}	6.04 ± 0.58^{b}
	10–20	8.43 ± 0.29^{a}	7.34 ± 0.21^{b}	6.76 ± 0.06^{c}	6.18 ± 0.17^{d}
	20–30	8.18 ± 0.10^{a}	7.3 ± 0.25^{b}	6.76 ± 0.07^{c}	6.18 ± 0.17^{d}
C_{ox}	0–5	1.03 ± 0.06^{c}	3.35 ± 0.23^{b}	7.15 ± 0.45^{a}	6.61 ± 0.41^{a}
	10–20	0.20 ± 0.01^{a}	0.32 ± 0.02^{b}	0.44 ± 0.03^{c}	0.38 ± 0.02^{d}
	20–30	0.12 ± 0.01^{c}	0.19 ± 0.01^{b}	0.33 ± 0.02^{a}	0.32 ± 0.02^{a}

Significantly different values (Tukey's *HSD* test, $P < 0.05$) are indicated by different letters (a, b, c, d)

there are also several small enclaves of herbaceous vegetation usually consisting only of two species (*Puccinellia distans* and *Lactuca saligna*; total herb cover +÷1$^{±4}$, i.e., on average 0.5% to 3%, and in a ¼ area of 20 × 20 m, up to 56% to 69%). Zone B, covered with grassy vegetation, has total cover +5, i.e., 87–100%, on average 94%, with sporadic occurrences of hornbeam, oak, and beech. In zone C, there is mainly hornbeam forest with variable tree density and canopy with density 0.5–0.7 and total herb cover 1÷-2^{+2}, i.e., on average 3% to 10%, and in a ¼ of an area of 20 × 20 m, up to 20%, and in zone D, there is beech forest with an admixture of hornbeam, oak, and beech (stand density 0.6–0.8) with a total cover of herb layer 1÷-2, i.e., on average 3% to 10%. The effect of magnesite emissions on the habitus and physiological state of trees was visible only in zone A, where all trees had dwarfed growth and twisted branches. Similar phenomena were not observed in the other polluted zones.

We carried out sampling of plant assimilation organs in the second half of July 2021. Samples of 4 herb species, *Dryopteris filix-mas* (L.) Schott (male fern), *Lactuca saligna* L. (willowleaf lettuce), *Rubus idaeus* L. (raspberry), and *Puccinellia distans* (Jacq.) Parl. (weeping alkaligrass), and 3 tree species, *Carpinus betulus* L. (hornbeam), *Quercus polycarpa* Schur (multi-fruited oak), and *Betula pendula* Roth (silver birch), were collected using stratified random sampling. Approximately 30 tree leaves and 30 herb shoots were collected from each plant species in 4 replicates (leaves came from the lower third of the tree crowns on a southwest exposure). Plant samples were dried at 80 °C for 48 h and homogenised using a Fritsch planetary micro-mill (< 0.001 mm). Total amounts of Ca in plants and Mg, K, Na, and Mn in soil and plants were determined after mineralisation of the samples with concentrated HNO_3, mixed with 2 mL of deionised water at 190 °C for 15 min in a fast-wave microwave pressure digestion system MWS-2 (Berghoff, Germany) by the FAAS technique using an air-acetylene flame and SensAA apparatus (Braeside, Australia). The total amounts of Ca in soils and Cd in soils and plants were determined after mineralisation of the samples in *aqua regia* solution and analysed by ICP-AES (inductively coupled plasma atomic emission spectrometry) using the VARIAN 725-ES spectrometer (Austin, Texas) according to ISO 11885.

Data analyses. Data were analysed using Statistica, Version 9.0 (StatSoft, Tulsa, USA). PCA was carried out in the PAST program (version 4.03,Hammer et al. 2001). For normally distributed data, the variability of Ca, Mg, K, Na, Mn, and Cd across plant species was assessed using a one-way ANOVA followed by a Tukey's post hoc test. Hierarchical cluster analysis (HCA) was used to decompose the nutrient and risk element content in plants into several relatively homogeneous subsets. To calculate the distances, we used Ward's amalgamation rule with Euclidean distance. Principal component analysis (PCA) was used to evaluate relationships between elements in plant species and classify differences between control and contaminated zones along an altitudinal gradient polluted by magnesite emissions. Eigenvalues below 1 were not considered significant. Pearson's correlation coefficients were used to check the relationships between element concentrations in the soils and plants.

RESULTS AND DISCUSSION

Variability of total content of elements in plant species along the pollution gradient of zones A–D. Based on hierarchical cluster analysis, the first group of plants with the lowest Ca content (724–1 019 mg/kg) was represented by *P. distans* in

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zones A and B and *D. filix-mas* in zone C. The fourth group with the highest Ca content in assimilatory organs comprised the species *Q. polycarpa*, *C. betulus*, and *B. pendula* in zone D, as well as *R. idaeus* sampled in zones C and D (6 530–9 647 mg/kg). A significant increase in Ca content between zones A and D was detected in the leaves of *C. betulus*, *Q. polycarpa*, and *B. pendula* (Figure 1A). According to Kirkby (2012), the average concentration of Ca in the dry matter of plant shoots sufficient for adequate growth is 5 000 mg/kg. Alaqouri et al. (2020a) state that the content of Ca in 1-year-old (1 299–2 452 ppm) and 2-year-old (2 985–4 751 ppm) needles of Scots pines sampled near the magnesite plant in Russia linearly increased from the source of emissions up to a distance of 25 km. The first group with the lowest Mg content in plants was represented by the species *P. distans* in zones A and B and the species *C. betulus* in zones B, C, and D, as well as the *Q. polycarpa* species in zone D (3 259–5 843 mg/kg). The fourth group with the highest content of Mg in assimilatory organs belonged to the species *L. saligna* sampled in zones A and B (15 742–16 304 mg/kg). The Mg content of plants generally decreased with increasing distance from the pollution source. The exception was species *Q. polycarpa*, whose Mg con-

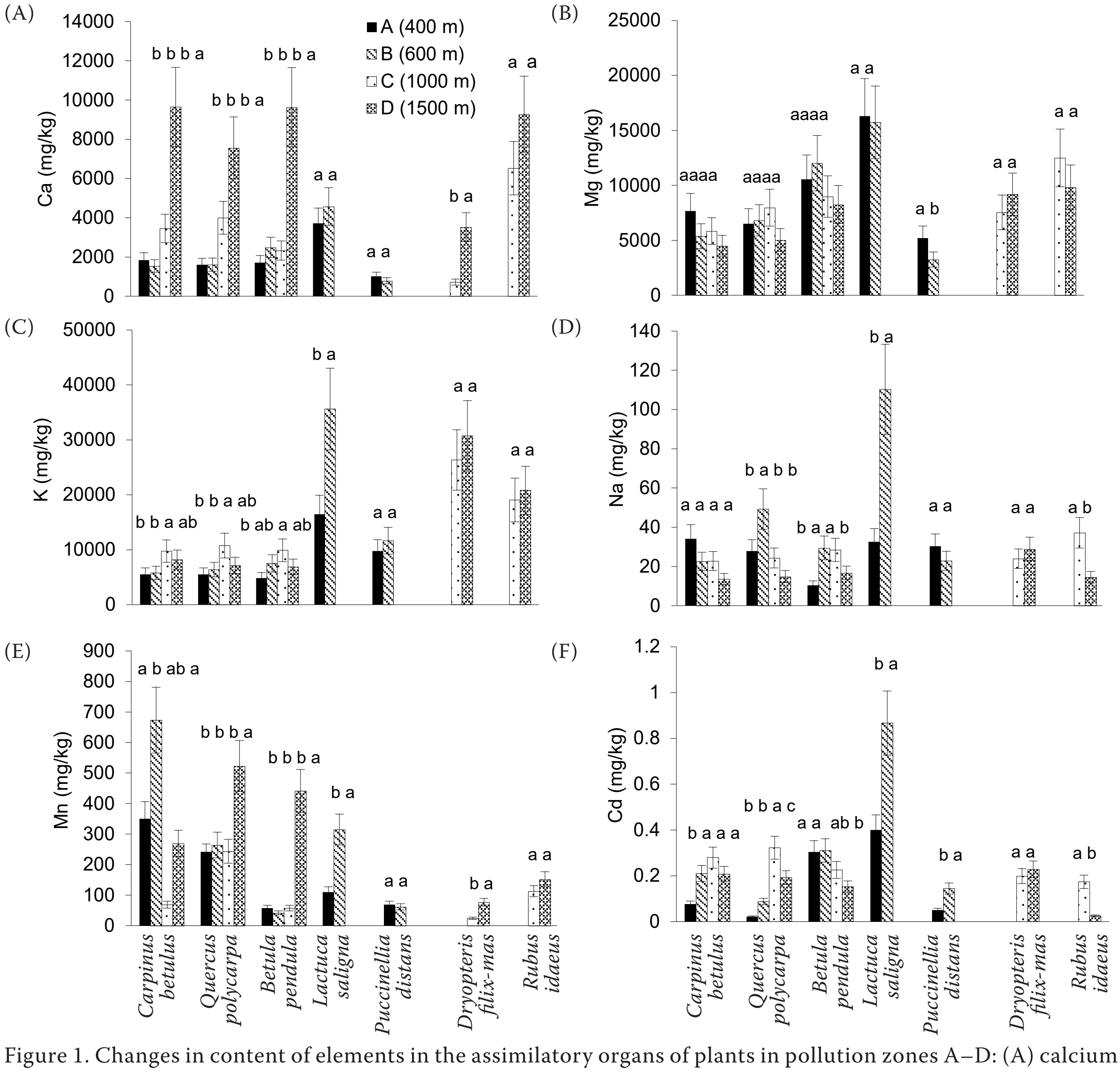

Figure 1. Changes in content of elements in the assimilatory organs of plants in pollution zones A–D: (A) calcium (Ca); (B) magnesium (Mg); potassium (K); (D) potassioum (Na); (E) manganese (Mn), and (F) cadmium (Cd). Significantly different values (Tukey's *HSD* test, $P < 0.05$) are indicated by different letters (a, b, c)

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tent increased between zones A and C, and species *D. filix-mas,* with a higher value in the control zone D (Figure 1B). Differences in Mg content found in plants were generally not significant except for the species *P. distans*. In many plants, the optimum Mg concentration is 0.15–0.50% (1 500–5 000 mg/kg) of leaf dry weight (Grzebisz 2011). On the other hand, the content of Mg in needles of Scots pines sampled by Alaqouri et al. (2020a) near the magnesite plant in Russia decreased from the source of emissions up to a distance of 25 km. The first group with the lowest K content in plants was represented by *C. betulus*, *Q. polycarpa*, and *B. pendula* in zone A, and by *C. betulus* and *Q. polycarpa* in zone B (4 836–6 385 mg/kg). The fifth group with the highest content of K included the species *D. filix-mas* in zones C and D and *L. saligna* in zone B (26 338–35 615 mg/kg). The K content in the leaves of *C. betulus*, *Q. polycarpa*, and *B. pendula* increased from zone A to zone C, where it was significantly higher (Figure 1C). At the same time, in the *L. saligna* species, it was significantly higher in zone B. K contents in samples of *P. distans*, *D. filix-mas*, and *R. idaeus* from different zones were not significantly different. Kirkby (2012) found out that the average concentration of K in the dry matter of plant shoots sufficient for adequate growth is 10 000 mg/kg. K content in Scots pine needles was also lowest at a distance of 1 km (4 592–2 770 ppm) and highest at a distance of 3 km (5 723–4 194 ppm) from the magnesite plant (Alaqouri et al. 2020b). The first group with the lowest Na content in plants was represented by the species *C. betulus*, *Q. polycarpa*, *B. pendula*, and *R. idaeus* collected in zone D, as well as *B. pendula* in zone A (10–17 mg/kg). The fifth group with the highest Na content consisted of the species *Q. polycarpa* in zone B (49 mg/kg), and the sixth group consisted of the species *L. saligna* in zone B (110 mg/kg). The Na contents in *C. betulus* leaves decreased from zone A to zone D and did not differ significantly (Figure 1D). In *Q. polycarpa* leaves, they were significantly higher in zone B, and in *B. pendula* leaves in zones B and C. Significantly different were also the Na contents found in *R. idaeus* species. Markert (1995) reports a Na content of 150 mg/kg for the reference plant. On the other hand, Alaqouri et al. (2020b) found that the Na content in needles of Scots pines (135–206 ppm) increased up to a distance of 25 km from the magnesite plant. The first group with the lowest Mn content in plants was represented by the species *B. pendula* and *P. distans* collected in zones A and B, *C. betulus*, *B. pendula*, and *D. filix-mas* in zone C, as well as *D. filix-mas* in zone D (24–77 mg/kg). The fourth group with the highest Mn content consisted of the species *C. betulus* growing in zone B and *Q. polycarpa* with *B. pendula* in zone D (441–673 mg/kg). The highest content of Mn in *C. betulus* leaves in zone B differed significantly from other zones. Significantly higher Mn contents were also found in the leaves of *Q. polycarpa*, *B. pendula*, and *D. filix-mas* in zone D and in *L. saligna* in zone B (Figure 1E). Kabata-Pendias (2011) found that sufficient or normal Mn content in plants is 30–300 mg/kg, and excessive or toxic Mn content is 400–1 000 mg/kg. The highest Mn contents (mg/kg) were, as a rule, in control zone D (*Q. polycarpa*, *B. pendula*, and *R. idaeus*). In the Jelšava-Lubeník area, Fazekaš et al. (2018) found a high Mn concentration in *Elytrigia repens* (400 mg/kg). According to Alaqouri et al. (2020a), the Mn content in Scots pine needles was lowest in a 10 km distance (28 and 95 ppm) and highest in a 25 km distance (48 and 169 ppm) from the source of magnesite emissions. The first group with the lowest Cd content in plants consisted of the species *C. betulus*, *Q. polycarpa*, and *P. distans* collected in zone A, *Q. polycarpa* in zone B, and *R. idaeus* in zone D (0.02–0.09 mg/kg). The fifth group, with the highest Cd content, included *L. saligna* sampled in zone B (0.867 mg/kg). The content of Cd in *C. betulus* and *Q. polycarpa* leaves increased from zone A to zone C. On the other hand, the Cd content in *B. pendula* leaves decreased from zone B to zone D. The highest content of Cd in *L. saligna* species was found in zone B and differed significantly from the Cd content found in zone A (Figure 1F). The average Cd contents in plants decreased from zone B (0.324 mg/kg) to zone D (0.162 mg/kg) and were 6.5 and 3.2 times higher compared to the limit value of 0.05 mg Cd/kg in the reference plant given by Markert (1995). Alaqouri et al. (2020b), on the other hand state that the Cd contents in samples of 1-year-old (0.149–0.328 ppm) and 2-year-old (0.168–0.355 ppm) needles of Scots pine sampled near the magnesite plant in Russia increased up to a distance of 25 km from the source of emissions.

Molar ratios of main mineral nutrients in plant species along the pollution gradient of zones A–D. In the assimilatory organs of plants, the values of the Ca:Mg and K:Mg ratios generally increased from pollution zone A to zone D, while the values of the Mg:K ratio, on the contrary, decreased (Table 2).

The values of the K:(Mg + Ca) ratio increased only towards zone C, and the values of the Ca:K ratio generally increased up towards zone D, but

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Table 2. Molar ratios of main mineral nutrients in plant species

Zone	Ca:Mg				Ca:K				Mg:K				K:Mg				K:(Mg + Ca)			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Carpinus betulus	0.15	0.17	0.36	**1.30**	0.32	0.26	0.35	**1.15**	**2.22**	**1.50**	0.96	0.88	0.45	0.67	**1.04**	**1.13**	0.39	0.57	0.77	0.49
Quercus polycarpa	0.15	0.14	0.30	0.91	0.28	0.25	0.36	**1.03**	**1.90**	**1.72**	**1.19**	**1.13**	0.53	0.58	0.84	0.89	0.46	0.51	0.65	0.46
Betula pendula	0.10	0.13	0.16	0.71	0.35	0.20	0.23	**1.37**	**3.50**	**1.60**	**1.46**	**1.93**	0.29	0.63	0.68	0.52	0.26	0.56	0.59	0.30
Lactuca saligna	0.14	0.18			0.22	0.08			**1.59**	0.44			0.63	**2.26**			0.55	**1.92**		
Puccinellia distans	0.12	0.15			0.10	0.04			0.86	0.28			**1.17**	**3.57**			**1.04**	**3.12**		
Dryopteris filix-mas			0.06	0.23			0.03	0.11			0.46	0.48			2.17	2.08			**2.05**	**1.68**
Rubus idaeus			0.32	0.57			0.33	0.43			1.06	0.76			0.95	1.32			0.72	0.84
Average	0.13	0.15	0.24	0.74	0.25	0.17	0.26	0.82	2.02	1.11	1.03	1.04	0.61	1.54	1.14	1.19	0.54	1.33	0.95	0.76

their minimum was in zone B. Values of the Ca:Mg ratio higher than 1 were only in leaves of *C. betulus* and of the Ca:K ratio in leaves of all woody species in zone D. Higher than 1 were values of the Mg:K ratio in leaves of *C. betulus* in zones A and B and in the *Q. polycarpa* and *B. pendula* leaves in zones A–D. Values of the K:Mg and K:(Mg + Ca) ratios above 1 were in *P. distans* species in zones A and B, in *Dryopteris-filix-mas* species in zones C and D, and in shoots of *L. saligna* in zone B. Results by Ostrowska and Porębska (2017) also indicate that in basic cereal products, except for maize grain, the Ca:Mg ratios were less than 1. Most nutrition specialists recommend a Ca:Mg ratio of 2:1 for various crop types (Durlach 1989). Döring (1974) states that a K:Mg ratio of 3:1, or a little wider, is a favourable ratio for plants. The highest K:Mg values were in herb species. According to Grzegorczyk et al. (2013), the nutritional value of K:(Mg + Ca) ratios in plants ought to remain within the 1.8–2.2 range. In the Lubeník, the highest ratios were for shoots of *P. distans* and *D. filix-mas*.

Relationship of element contents to plant species along the pollution gradient of zones A–D. The correlation coefficients of Ca, Mg, K, Na, Mn, and Cd content with the first two principal component axes are greater than 0.75, indicating a significant accumulation of the studied elements in woody and herbaceous species affected by magnesite emissions (Figure 2). High amounts of Ca in *C. betulus*, *Q. polycarpa*, *B. pendula*, and *R. idaeus* in control zone D revealed that these contents are very different from those in the other zones. These plants, on the other hand, had low Na and Mg content. The Mn content in *C. betulus* leaves sampled in zones B and D and in *Q. polycarpa*, *B. pendula*, and *R. idaeus* samples taken in zone D also do not overlap with the Mn contents in other species and zones. Increased fallout of alkaline dust in zones A to B caused higher concentrations of Mg in the species *L. saligna*. The contents of K, Na, and Cd accumulated by the stems of *L. saligna* in zone B were inversely correlated with the contents of Ca and Mn. Overall, *L. saligna* accumulated the highest amounts of Mg, Cd, Na, and K. On the other hand, the content of Cd in *C. betulus*, *Q. polycarpa*, and *P. distans* in zones A to B was significantly lower compared to the other zones.

Relationship between the total content of elements in the soil and the content in the assimilation organs of plants. The total content of studied elements (except K and Na) was substantially higher in the topsoil layer (Table 3). In the

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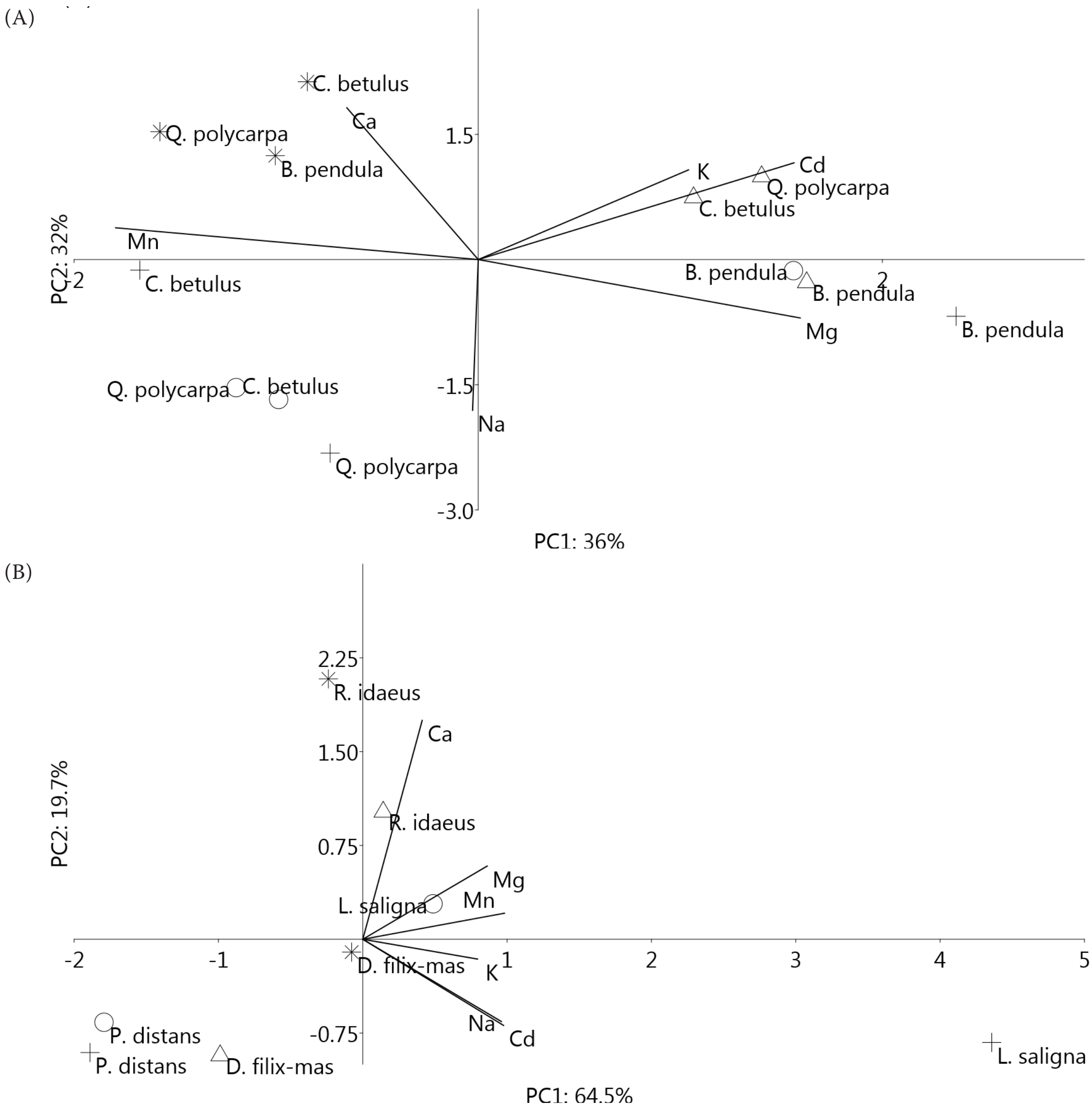

Figure 2. Principal component analysis (PCA) with profile elements in plants; (A) woody plants; (B) herbaceous plants; (dot-A zone (400 m); plus-B zone (600 m); triangle-C zone (1 000 m); star-control zone (1 500 m) from the pollution source

soil layer 0–5 cm, the content of Ca, Mg, and Na decreased from zone A toward zone D, while K and Mn, on the contrary, increased. In the 10–20 cm layer, the content of Ca, Mg, and Na also decreased from zone A towards zone D; however, the content of K and Mn reached a maximum in zone B and subsequently decreased towards zone D. The Cd content generally increased from zone A to zone C in both layers.

Table 4 summarises the results of the correlation analysis of average element content in the 0–5 cm soil layer and in plant assimilation organs.

The correlation between Ca content in soil and tree leaves is slightly negative. However, for herb species, there is a strong positive correlation with *P. distans*. The closest positive correlation between Mg contents in plants and soils was found in the case of *C. betulus* and *P. distans*. The higher soil K content also increased K content in the evaluated woody species. The values of the correlation coefficients indicate moderate positive correlations. For herb species, positive correlations were found for *P. distans*, *D. filix-mas*, and *R. idaeus*. For Na, a strong positive correlation was observed with the herb

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Table 3. Variability of element contents in soil layers (mg/kg dry weight ± standard deviation)

Pollution zone	Ca	Mg	K	Na	Mn	Cd
	0–5 cm					
A (400)	22 409 ± 6 118[a]	177 552 ± 48 472[a]	998 ± 272.5[a]	155 ± 35[a]	2 940 ± 670[a]	0.52 ± 0.08[a]
B (600)	17 745 ± 4 844[ab]	84 997 ± 23 204[b]	4 480 ± 1 223[b]	585 ± 133[b]	3 408 ± 777[a]	1.05 ± 0.17[b]
C (1 000)	10 221 ± 2 790[b]	50 539 ± 13 797[b]	3 993 ± 1 090[b]	183 ± 42[ab]	3 387 ± 772[a]	1.45 ± 0.23[b]
D (1 500)	6 026 ± 1 645[b]	15 092 ± 4 105[b]	4 694 ± 1 281[b]	394 ± 90[b]	3 431 ± 782[a]	1.05 ± 0.13[b]
	10–20 cm					
A (400)	919 ± 251[a]	8 833 ± 2 411[a]	3 500 ± 956[a]	476 ± 108[ab]	646 ± 147[a]	0.20 ± 0.03[b]
B (600)	815 ± 222[a]	6 352 ± 1 734[a]	6 302 ± 1 720[a]	726 ± 166[a]	1 140 ± 260[a]	0.18 ± 0.03[b]
C (1 000)	696 ± 190[a]	11 032 ± 3 011[a]	4 357 ± 1 189[a]	195 ± 44[b]	759 ± 173[a]	0.32 ± 0.05[a]
D (1 500)	447 ± 122[a]	6 116 ± 157[a]	5 525 ± 1 508[a]	576 ± 131[a]	738 ± 168[a]	0.13 ± 0.02[b]

Different letters indicate significant differences ($P < 0.05$) among pollution zones

species *L. saligna*. The soil Mn content showed the strongest positive relationship with that of *P. distans*. Significant positive correlations were found between the Cd content in soil and in leaves of *Q. polycarpa* and *C. betulus*. A high positive correlation was also observed for the herb species *R. idaeus*.

Table 5 summarises the results of the correlation analysis of average element content in the 10–20 cm soil layer and in plant assimilation organs. The correlations between Ca content in soils and assimilatory organs of plants were positive only in *L. saligna* and *P. distans* species. The closest positive correlation between Mg content in soils and plants was found in the case of *Q. polycarpa*, *L. saligna*, *P. distans*, and *R. idaeus*. In the case of K, high positive correlations were found for the species *L. saligna*, *P. distans*, *D. filix-mas* and *R. idaeus*; in the case of Na, for *L. saligna*, *D. filix-mas* and *R. idaeus*; and in the case of Cd, for *R. idaeus*. The soil Mn content showed the closest positive relationship with that of *L. saligna* and *C. betulus*.

Overall, the content of K and Na did not change significantly with soil depth (0–5 and 10–20 cm); therefore, the values of their correlation coefficients for plants did not differ substantially either. The correlation coefficients found for Ca and Mg contents in two soil layers and plants were also not markedly different, except for the *L. saligna* species. The higher Cd content in the 0–5 cm soil layer was reflected in higher correlation coefficients for the species *C. betulus*, *Q. polycarpa*, and *R. idaeus*.

Although pollutant concentrations in the study area decreased over time, based on multivariate statistical analysis and comparison with background values in other studies, persistent intoxication of plants with Mg (all study plants), K (*L. saligna*, *D. filix-mas*), Mn (*Q. polycarpa*, *C. betulus*, *B. pendula*, *L. saligna*) and Cd (*Q. polycarpa*, *C. betulus*, *B. pendula*, *L. saligna*) was demonstrated. The higher amounts of Ca and Mg were accumulated in leaves of woody species compared to herbs accumulating more K. Unbalanced Ca/Mg ratios, lower than 1, were

Table 4. Pearson's correlation coefficients (r) of element contents in 0–5 cm soil layers and assimilatory organs of plants within A–D pollution zones (n = 12 for trees; n = 8 for herbs)

Element (in soil and plant)	Plant species						
	Betula pendula	*Carpinus betulus*	*Quercus polycarpa*	*Lactuca saligna*	*Puccinellia distans*	*Dryopteris filix-mas*	*Rubus idaeus*
Ca	–0.588	–0.653	–0.699	0.023	0.953	–0.337	–0.010
Mg	0.585	0.869	0.348	0.099	0.838	–0.093	0.552
K	0.745	0.627	0.562	0.498	0.985	0.994	0.991
Na	0.540	–0.276	0.635	0.973	0.049	0.682	0.454
Mn	0.228	0.187	0.476	0.086	0.821	0.076	0.475
Cd	–0.215	0.993	0.904	0.325	–0.397	0.022	0.815

https://doi.org/10.17221/443/2025-PSE

Table 5. Pearson's correlation coefficients (*r*) of element contents in 10–20 cm soil layers and assimilatory organs of plants within A–D pollution zones (*n* = 12 for trees; *n* = 8 for herbs)

Element (in soil and plant)	Plant species						
	Betula pendula	*Carpinus betulus*	*Quercus polycarpa*	*Lactuca saligna*	*Puccinellia distans*	*Dryopteris filix-mas*	*Rubus idaeus*
Ca	–0.535	–0.558	–0.545	0.684	0.926	–0.510	–0.017
Mg	0.326	0.688	0.854	0.857	0.956	–0.067	0.855
K	0.553	0.373	0.320	0.975	0.903	0.997	0.971
Na	0.114	0.058	0.582	0.912	0.032	0.757	–0.752
Mn	0.153	0.715	0.024	0.947	0.181	0.167	0.604
Cd	0.288	0.506	0.606	–0.041	–0.115	–0.181	0.994

recorded in all plant species sampled in the vicinity of the magnesite factory; unbalanced K/(Mg + Ca) ratios were predominantly in woody species. Higher positive correlation coefficients for element content in soil and plants were observed in herbs than in woody species. Since there are currently no relevant and up-to-date studies in this area, we will continue to conduct further research on soil-plant interactions and plant nutrient uptake.

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Received: October 6, 2025
Accepted: January 21, 2026
Published online: February 5, 2026