

Received 15.03.2013
Reviewed 16.04.2013
Accepted 07.05.2013

A – study design
B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Calcium and magnesium uptake with the yield of meadow vegetation in relation to their content in atmospheric precipitation, ground water and soil solution

Barbara SAPEK^{ABCDEF}

Institute of Technology and Life Science, al. Hrabka 3, 05-090 Raszyn, Poland; tel. +48 22 735-75-66, e-mail: B.Sapek@itp.edu.pl

For citation: Sapek B. 2013. Calcium and magnesium uptake with the yield of meadow vegetation in relation to their content in atmospheric precipitation, ground water and soil solution. Journal of Water and Land Development. No. 18 p. 73–83

Abstract

The question was how and under which conditions the concentration and load of calcium and magnesium in atmospheric precipitation, ground water and soil solution may affect their uptake by vegetation in a managed meadow. The answer was based on results of Ca and Mg determinations in atmospheric fallout near Falenty, and in soil waters from two long-term meadow experiments on mineral soils situated in Masovian Province. Obtained results showed a complex effect of Ca and Mg deposition and associated effects of these components in ground water and soil solution on their uptake by plants due to fertilisation effect, harvesting and other factors of human impact. No distinctly positive effect was found of the increased deposition of Ca with atmospheric fallout on its uptake by plants on a long term basis. Such an effect was demonstrated for Mg load but only in very acidic soil. Under favourable physical and water conditions and at weakly acidic soil pH this effect was negative. The enrichment of ground water in Ca was accompanied by the increase of its uptake by plants and, at the same time, by the decrease of Mg uptake from very acidic soil. Under such soil pH, decreased Ca uptake was associated with its higher concentration in soil solution. Neutralization of soil acidity facilitated the increased Mg concentration in soil solution and its decreased uptake by plants. Obtained results inspire to undertake similar studies in natural grassland ecosystems and in the so-called lands of ecological use.

Key words: *atmospheric precipitation, calcium, ground water, magnesium, soil solution, uptake with meadow plant yield*

INTRODUCTION

Plants ability to take up nutrients through their above-ground parts used in foliar fertilisation is a way of feeding plants more and more often used in grasslands [JANKOWSKA-HUFLEJT 2009; SKURZYŃSKI 2009]. Therefore, nutrient load deposited directly on plants and soil by atmospheric precipitation may, under specific conditions, significantly affect their content in and uptake with the yield. At a lack or deficit of nutrients in soil, atmospheric precipitation may be

a source sustaining the development or regeneration of natural ecosystems as shown e.g. by SCHLESINGER *et al.* [1982], ARIANOUTSOU [1989], and CHADWICK *et al.* [1999]. The content of calcium and magnesium in precipitation, mainly neutralising the excess of acid-forming ions, may largely affect the fertility of natural ecosystems and nutrient uptake by plants. Acid rains may in turn accelerate nutrient washout from above-ground plant parts, mainly leaves, which are a source of regeneration of ecosystem fertility [POTTER *et al.* 1991]. An assessment of the role of atmos-

pheric nutrient deposition in maintaining fertility found in the literature pertains mainly to forest ecosystems [JONARD *et al.* 2009; POTTER *et al.* 1991] including natural evergreen shrubs SCHLESINGER *et al.* [1982], ARIANOUTSOU [1989]. Due to permanent soil cover by sward, permanent grasslands are equally efficient absorbers of atmospheric nutrient deposits which secures the maintenance and development of natural grassland ecosystems. KACORZYK *et al.* [2012] showed that nutrient load including that of calcium and magnesium ($35.5 \text{ kg Ca} \cdot \text{ha}^{-1}$ and $3.4 \text{ kg Mg} \cdot \text{ha}^{-1}$ on average) delivered with atmospheric fallout to mountain grasslands provides hay production of $1.5\text{--}2.0 \text{ t} \cdot \text{ha}^{-1}$.

Atmospheric fallout is one of the supplies of soil water phase composed of ground water and soil solution and being a source of plant feeding. Fertility of this phase will depend, among others, on chemical composition of precipitation. Soil waters are the source of soluble nutrients including calcium and magnesium [PRUSINKIEWICZ 2011; SZPERLIŃSKI 2002]. Availability of these components to and their uptake by plants depends on their content in soil solution [PRUSINKIEWICZ 2011; WARCHAŁOWA 1976]. In the earlier paper SAPEK [2011] estimated the dynamics of calcium and magnesium uptake by plants in long-term meadow experiments and compared it with the washout of Ca and Mg from soil, pH and the form of nitrogen fertiliser considering the effect of soil neutralisation with calcium fertilisers. This paper is an advancement of presented problems.

The aim of this study was to answer the question if, how and under which conditions the load of calcium and magnesium in atmospheric fallout, ground water and soil solution may affect their uptake by grassland vegetation.

MATERIAL AND METHODS

The study was based on two long-term meadow experiments situated in Masovian Province in Janki (J) and Laszczki (L) established in 1981 and 1982, respectively. An after-effect of liming and application of ammonium and calcium saltpetre on soil and vegetation and on nutrient release and ground water quality was evaluated.

Experiment was set up on very acid (pH_{KCl} : J – 4.5, L – 4.3) mineral soils differing in the organic matter content (C_{org} : J – 19.0 , L – $38.0 \text{ g} \cdot \text{kg}^{-1}$), calcium (Ca_{tot} : J – 1.44 , L – $2.58 \text{ g} \cdot \text{kg}^{-1}$), magnesium (Mg_{tot} : J – 0.47 , L – $0.89 \text{ g} \cdot \text{kg}^{-1}$) and the content of particles $<0.02 \text{ mm}$ (J – 18.4 , L – 22.4%), and moisture (J – 22.1% vol., L – 26.6% vol.).

Experiment was designed with the random block method in four repetitions with 6 distinguished fertilisation variants fertilised with a constant dose of phosphorus ($34.9 \text{ kg P} \cdot \text{ha}^{-1}$) and potassium ($125 \text{ kg K} \cdot \text{ha}^{-1}$). Variants were not limed (Ca_0) or limed once in the

beginning of experiment (1981/1982) with a single or double dose of calcium carbonate calculated according to the criterion of hydrolytic acidity 1Hh and 2Hh (Ca_1 , Ca_2). Study objects were fertilised with nitrogen at a dose of 120 and $240 \text{ kg N} \cdot \text{ha}^{-1}$ (N_1 , N_2) in three parts under each cut in a form of ammonium saltpetre (AN) and since 1992, in parallel, on a half of 50 m^2 plots – with calcium saltpetre (CN).

Since 2000 phosphorus fertilisation was abandoned in both experiments to assess a possibility of limitation of P release to the environment. Experiments carried out according to this scheme were ended in 2007. Due to a change in the experimental project in Laszczki, harvesting was abandoned there since 2004. Detailed description of the experiments and fertilisation variants are given in SAPEK [2006] and SAPEK and SAPEK [2011]. Results of analyses from four variants: $\text{Ca}_0\text{N}_2\text{AN}$, $\text{Ca}_0\text{N}_2\text{CN}$, $\text{Ca}_2\text{N}_2\text{AN}$, $\text{Ca}_2\text{N}_2\text{CN}$ were used in this study. Soils from these experimental variants differed in pH_{KCl} (Tab. 1).

Table 1. Mean pH_{KCl} of the 0–10 cm soil layer from four fertilisation variants of meadow experiments in the years 1995–2007

Experiment	Value	Soil pH_{KCl}			
		$\text{Ca}_0\text{N}_2\text{AN}$	$\text{Ca}_2\text{N}_2\text{AN}$	$\text{Ca}_0\text{N}_2\text{CN}$	$\text{Ca}_2\text{N}_2\text{CN}$
Janki	mean	3.6	4.3	5.0	6.6
	CV%	5.1	11.67	12.0	3.6
Laszczki	mean	3.6	5.8	5.5	6.9
	CV%	9.1	9.6	9.3	5.7

Explanations: $\text{Ca}_0\text{N}_2\text{AN}$, $\text{Ca}_2\text{N}_2\text{AN}$, $\text{Ca}_0\text{N}_2\text{CN}$, $\text{Ca}_2\text{N}_2\text{CN}$: Ca_0 – not limed variants, Ca_2 – limed variants, N_2 – fertilisation with $240 \text{ kg N} \cdot \text{ha}^{-1}$ in a form of ammonium saltpetre – AN and calcium saltpetre – CN; $\text{Ca}_0\text{N}_2\text{CN}$, $\text{Ca}_2\text{N}_2\text{CN}$ – mean for the years 2000–2007 CV% – coefficient of variability.

Atmospheric fallout was sampled in Falenty and represented wet precipitation, both rain and snow [SAPEK 2011]. Sampling methods, analyses and other data on atmospheric precipitation collected from meteorological station situated near experimental fields in Falenty are given in SAPEK *et al.* [2003] and in SAPEK and NAWALANY [2006]. Mean precipitation for presented study periods (Tab. 2) are given in this paper. Samples of ground water were taken from wells installed in buffer zones of experiments. The description of sampling sites, sampling protocol and frequency is given in SAPEK *et al.* [2003] and SAPEK [2006].

Table 2. Annual mean atmospheric precipitation near Falenty in selected periods of meadow experiments

Precipitation mm	Years					
	1988–2007	1992–2007	2000–2007	1988–2003	1992–2003	2000–2003
Mean	518.5	531.0	523.0	505.3	517.6	475.0
SD	79.4	84.3	94.8	77.0	85.9	96.5
CV%	15.3	15.9	18.1	15.2	16.6	20.3

Explanations: SD – standard deviation, CV% – as in Table 1. Source: SAPEK and NAWALANY [2006].

Soil solutions were taken from the experiment in Jan-ki where suction apparatuses were installed in the four mentioned above fertilisation objects. The method of sampling soil solutions with suction apparatuses equipped with pore cups and the way of calculating the washout of soil components can be found in SAPEK and PIETRZAK [1996] and PIETRZAK *et al.* [2006]. Calcium and magnesium was determined with the atomic absorption spectrophotometric method [SAPEK 1979].

The amount of calcium and magnesium taken up by dry plant yield in selected study periods was estimated and expressed as percent of atmospheric load of these elements. Mean uptake of the elements from variants AN and CN was taken for comparisons. Calcium input with superphosphate and calcium saltpetre was accounted for in calculations (Tabs 3–6). Due to abundant but non-homogenous results, the relationships between calcium and magnesium uptake and their content in atmospheric precipitation, ground wa-

Table 3. Calcium input with precipitation and superphosphate and its uptake by plants (mean from fertilisation variants) fertilised with ammonium saltpetre (AN) and calcium saltpetre (CN) at a rate of 240 kg N·ha⁻¹ in the Janki experiment

Specification	Years	Amount	
		kg·ha ⁻¹ ·y ⁻¹	%
AN fertilisation			
Ca (I) from precipitation	1988–2007	17.4	
Ca (II) from precipitation	2000–2007	17.4	
Ca (I) uptake by plants	1988–2007	30.1	
Ca (II) uptake by plants after the abandonment of P fertilisation in 2000	2000–2007	24.7	
Contribution of atmospheric Ca I to Ca I uptake by plants	1988–2007		57.7
Contribution of atmospheric Ca II to Ca II uptake by plants	2000–2007		70.6
Ca input with superphosphate	1988–2007	46.1	
Atmospheric Ca I compared with Ca from superphosphate	1988–2007		37.7
CN fertilisation			
Ca (I) from precipitation	1992–2007	18.2	
Ca (II) from precipitation	2000–2007	17.4	
Ca (I) uptake by plants	1992–2007	33.9	
Ca (II) uptake by plants after the abandonment of P fertilisation in 2000	2000–2007	37.5	
Contribution of atmospheric Ca I to Ca I uptake by plants	1992–2007		53.6
Contribution of atmospheric Ca II to Ca II uptake by plants	2000–2007		46.3
Ca input with superphosphate	1992–2007	46.1	
Atmospheric Ca I compared with Ca from superphosphate			39.5
Ca input with CN (kg/ha)	1992–2007	343.0	
Atmospheric Ca I compared with Ca from CN			5.3

Table 4. Calcium input with precipitation and superphosphate and its uptake by plants (mean from fertilisation variants) fertilised with ammonium saltpetre (AN) and calcium saltpetre (CN) at a rate of 240 kg N·ha⁻¹ in the Laszczki experiment

Specification	Amount		
	Years	kg·ha ⁻¹ ·y ⁻¹	%
AN fertilisation			
Ca (I) from precipitation	1988–2003	17.9	
Ca (II) from precipitation	2000–2003	19.4	
Ca (I) uptake by plants	1988–2003	46.8	
Ca (II) uptake by plants after the abandonment of P fertilisation in 2000	2000–2003	54.2	
Contribution of atmospheric Ca I to Ca I uptake by plants	1988–2003		38.2
Contribution of atmospheric Ca II to Ca II uptake by plants	2000–2003		35.9
Ca input with superphosphate	1988–2003	46.1	
Atmospheric Ca I compared with Ca from superphosphate			38.8
CN fertilisation			
Ca I from precipitation	1992–2003	19.1	
Ca (II) from precipitation	2000–2003	19.5	
Ca (I) uptake by plants	1992–2003	46.5	
Ca (II) uptake by plants after the abandonment of P fertilisation in 2000	2000–2003	67.2	
Contribution of atmospheric Ca I to Ca I uptake by plants	1992–2003		41.1
Contribution of atmospheric Ca II to Ca II uptake by plants	2000–2003		29.0
Ca input with superphosphate	1992–2003	46.1	
Atmospheric Ca I compared with Ca from superphosphate			41.4
Ca input from CN	1992–2003	343.0	
Atmospheric Ca I compared with Ca from CN			5.6

Table 5. Magnesium input with precipitation and its uptake by plants (mean from fertilisation variants) fertilised with ammonium saltpetre (AN) and calcium saltpetre at a rate of 240 kg N·ha⁻¹ in the Janki experiment

Specification	Amount		
	Years	kg·ha ⁻¹ ·y ⁻¹	%
AN fertilisation			
Mg I from precipitation	1988–2007	2.4	
Mg II from precipitation	2000–2007	2.4	
Mg I uptake by plants	1988–2007	7.8	
Mg II uptake by plants after the abandonment of P fertilisation since 2000	2000–2007	6.9	
Contribution of atmospheric Mg I to Mg I uptake by plants	1988–2007		30.8
Contribution of atmospheric Mg II to Mg II uptake by plants	2000–2007		34.8
CN fertilisation			
Mg I from precipitation	1992–2007	3.0	
Mg II from precipitation	2000–2007	2.4	
Mg I uptake by plants	1992–2007	5.8	
Mg II uptake by plants after the abandonment of P fertilisation since 2000	2000–2007	5.2	
Contribution of atmospheric Mg I to Mg I uptake by plants	1992–2007		51.7
Contribution of atmospheric Mg II to Mg II uptake by plants	2000–2007		46.1

Table 6. Magnesium input with precipitation and its uptake by plants (mean from fertilisation variants) fertilised with ammonium saltpetre (AN) and calcium saltpetre (CN) at a rate of 240 kg N·ha⁻¹ in the Laszczki experiment

Specification	Amount		
	Years	kg·ha ⁻¹ ·y ⁻¹	%
AN fertilisation			
Mg I from precipitation	1988–2003	2.4	
Mg II from precipitation	2000–2003	2.4	
Mg I uptake by plants	1988–2003	16.0	
Mg II uptake by plants after the abandonment of P fertilisation since 2000	2000–2003	15.3	
Contribution of atmospheric Mg I to Mg I uptake by plants	1988–2003		15.0
Contribution of atmospheric Mg II to Mg II uptake by plants	2000–2003		15.7
CN fertilisation			
Mg I from precipitation	1992–2003	2.4	
Mg II from precipitation	2000–2003	2.4	
Mg I uptake by plants	1992–2003	15.6	
Mg (II) uptake by plants after the abandonment of P fertilisation since 2000	2000–2003	15.5	
Contribution of atmospheric Mg I to Mg I uptake by plants	1992–2003		15.4
Contribution of atmospheric Mg II to Mg II uptake by plants	2000–2003		15.5

ter and soil solution were tested with non-parametric Spearman rank correlation test and expressed as Spearman correlation coefficient (r_s).

RESULTS AND DISCUSSION

CALCIUM AND MAGNESIUM IN WET PRECIPITATION AND THEIR UPTAKE BY PLANTS

Comparison of calcium and magnesium loads deposited on the surface of mown meadows with the amount of these components taken up by plants was not aimed to assess their real uptake from rainfall. This would need specific radioisotope methods. The comparison provides, however, information on a possible effect and importance of natural sources of the two elements. The need of balancing nutrient loads delivered to natural ecosystems was expressed e.g. by ARIANOUTSOU [1989] who assessed productivity and nutrient cycling in natural scrublands in northeastern Greece (maquis) and by SCHLESINGER *et al.* [1982]

who studied nutrient losses in the surface runoff from chaparral (southern California) after fire. Also JONARD *et al.* [2009], based on forest monitoring in France, Walloon and Luxemburg, underlined the need of the assessment of nutrients deposited by precipitation to establish feeding status of forest tree stands.

Calcium. The proportion of calcium load from precipitation to its amount taken up by meadow vegetation differed in relation to soil properties, type and dose of nitrogen fertiliser and to the presence or absence of P fertilisation (Tab. 3, 4). In the case of less fertile and drier soil in Janki, atmospheric Ca load constituted 57.7% of Ca taken up annually by plants fertilised with ammonium saltpetre. After the abandonment of fertilisation with superphosphate (which enriched the soil in Ca itself) the percent increased to 70.6%. Atmospheric Ca load equalled 37.7% of the amount annually delivered to the soil with superphosphate (Tab. 3). When the soil was fertilised with calcium saltpetre (the years 1992–2007) the share of atmospheric Ca in plant uptake slightly decreased to

53.6%. However, annual input of $342.8 \text{ kg Ca} \cdot \text{ha}^{-1}$ with calcium saltpetre and parallel abandonment of phosphorus fertilisation decreased the contribution of atmospheric Ca to plant uptake to 46.3%. In the case of CN fertilisation, atmospheric Ca load (5.6%) was of negligible importance (Tab. 3).

More favourable soil-water conditions in the experiment in Laszczki, particularly higher content of soil Ca (resulting in bigger yielding) markedly decreased the impact of atmospheric Ca on plant uptake (Tab. 4). The proportion of atmospheric calcium to the amount taken up by plants in this experiment was similar at both forms of nitrogen fertilisation (AN – 38.2% and CN – 41.1%). The abandonment of P fertilisation, especially with the application of AN, did not exert a significant effect on the above proportions (38.2% and 35.9%). Study period in this experiment was by 4 years shorter which might possibly affect the obtained results.

Magnesium. Atmospheric load of magnesium in the Janki experiment at AN and P fertilisation constituted 30.8% of its amount taken up by plant yield (Tab. 5). After the abandonment of P fertilisation the respective share was 34.8%. As in the case of calcium, application of CN and no P fertilisation increased the share of atmospheric Mg in the amount of the element taken up by plants to ca 50% (Tab. 3, 5). In more fertile and richer in magnesium soil in the Laszczki experiment, the share of atmospheric Mg load in plant uptake was ca 15% (Tab. 6). Moreover, in contrast with weaker and poorer in Mg soil in the Janki experiment, both the applied form of nitrogen fertiliser (AN and CN) and the abandonment of P fertilisation had no significant effect on the contribution of atmospheric Mg load (Tab. 6).

THE RELATIONSHIP BETWEEN CALCIUM AND MAGNESIUM UPTAKE BY PLANTS AND THEIR CONCENTRATIONS AND LOADS IN WET PRECIPITATION

Due to abandoned harvesting in the Laszczki experiment after 2003, calcium and magnesium uptake by plants from the two experiments and the concentrations and loads of these elements in atmospheric precipitation were taken from the years 1988–2003 when objects fertilised with ammonium saltpetre were compared. Comparisons between the objects fertilised with calcium and ammonium saltpetre refer to data from the years 1995–2003. Changes in Ca and Mg uptake by plants and in concentrations of both elements in precipitation were presented based on data from objects of most extreme pH values and fertilised with AN in the Laszczki experiment (Fig. 1a–d). Most statistically significant relationships were found just under such conditions. Other results pertaining to AN fertilised objects in Janki and to those fertilised with CN in both experiments are discussed only in the text.

Significant decrease of Ca uptake with time was found only for very acid ($\text{Ca}_0\text{N}_2\text{AN} - r_{s2} = -0.59^*$) and acid ($\text{Ca}_2\text{N}_2\text{AN} - r_{s2} = -0.61^{**}$) soil fertilised with AN in Janki. In the Laszczki experiment a significant decrease of Mg uptake with time was noted in fertilisation variant $\text{Ca}_2\text{N}_2\text{AN}$ ($r_{s2} = -0.52^*$) in the soil of pH optimum for grasslands ($\text{pH}_{\text{KCl}} = 5.9$) (Tab. 1, Fig. 1d). Fertilisation with CN and decreasing soil acidity facilitated the decreased Mg uptake by plants in the Janki experiment ($\text{Ca}_0\text{N}_2\text{CN} - r_{s2} = -0.63^*$ and $\text{Ca}_2\text{N}_2\text{CN} - r_{s2} = -0.66^*$) but resulted in the increased Ca uptake in the Laszczki experiment ($\text{Ca}_0\text{N}_2\text{CN} - r_{s2} = 0.76^{**}$) with time. In other variants no significant temporal changes in the uptake of analysed elements were noted.

In the study period 1988–2003 the concentration and load of Ca in atmospheric precipitation near Falenty were fairly stable while those of Mg significantly increased with time ($r_1 = 0.62^*$, $r_{1\text{bis}} = 0.56^*$). The course and direction of changes in the concentrations and loads of both elements are presented in Fig. 1a–d.

To answer the question put at the end of introduction, a search was undertaken for statistically significant correlations between the concentration or load of Ca and Mg in precipitation near Falenty and the uptake of these elements by meadow vegetation at different soil pH in four fertilisation variants fertilised with two forms of saltpetre. Expected result was found only in four cases in the Laszczki experiment. In acid soil of the variant $\text{Ca}_0\text{N}_2\text{AN}$ ($\text{pH}_{\text{KCl}} = 3.6$) an increased load of Mg in precipitation was accompanied by a greater Mg uptake by plants ($r_{3\text{bis}} = 0.48^*$) (Fig. 1b). In the variant $\text{Ca}_2\text{N}_2\text{AN}$ ($\text{pH}_{\text{KCl}} = 5.8$), significant negative correlation was found, however, between both Mg concentration and load in atmospheric precipitation and the uptake of this element by plants ($r_3 = -0.55^*$, $r_{3\text{bis}} = -0.52^*$, respectively) (Tab. 1, Fig. 1d). In the soil fertilised with calcium saltpetre ($\text{Ca}_2\text{N}_2\text{CN}$) an increased load of Ca in precipitation significantly increased Ca uptake by plants ($r_{3\text{bis}} = 0.65^*$). One may expect that the negative correlation between Mg load and uptake is associated with a complex interaction of calcium compounds differing in solubility which, apart from Mg, are the components of atmospheric precipitation. Calcium compounds may weaken Mg absorption by plants which was demonstrated by HAWLICZKA *et al.* [2003]. The authors underlined a complex effect of the form and solubility of calcium and magnesium compounds present in atmospheric fallout on the environmental behaviour of these elements. Despite higher content of Ca in precipitation, its soluble forms exert smaller effect on rain pH than magnesium [HAWLICZKA *et al.* 2003]. Therefore, the rainfall becomes more acid with increasing Mg content, which in turn facilitates washing out of Mg from soil and meadow sward and consequently decreases its uptake by plant yield.

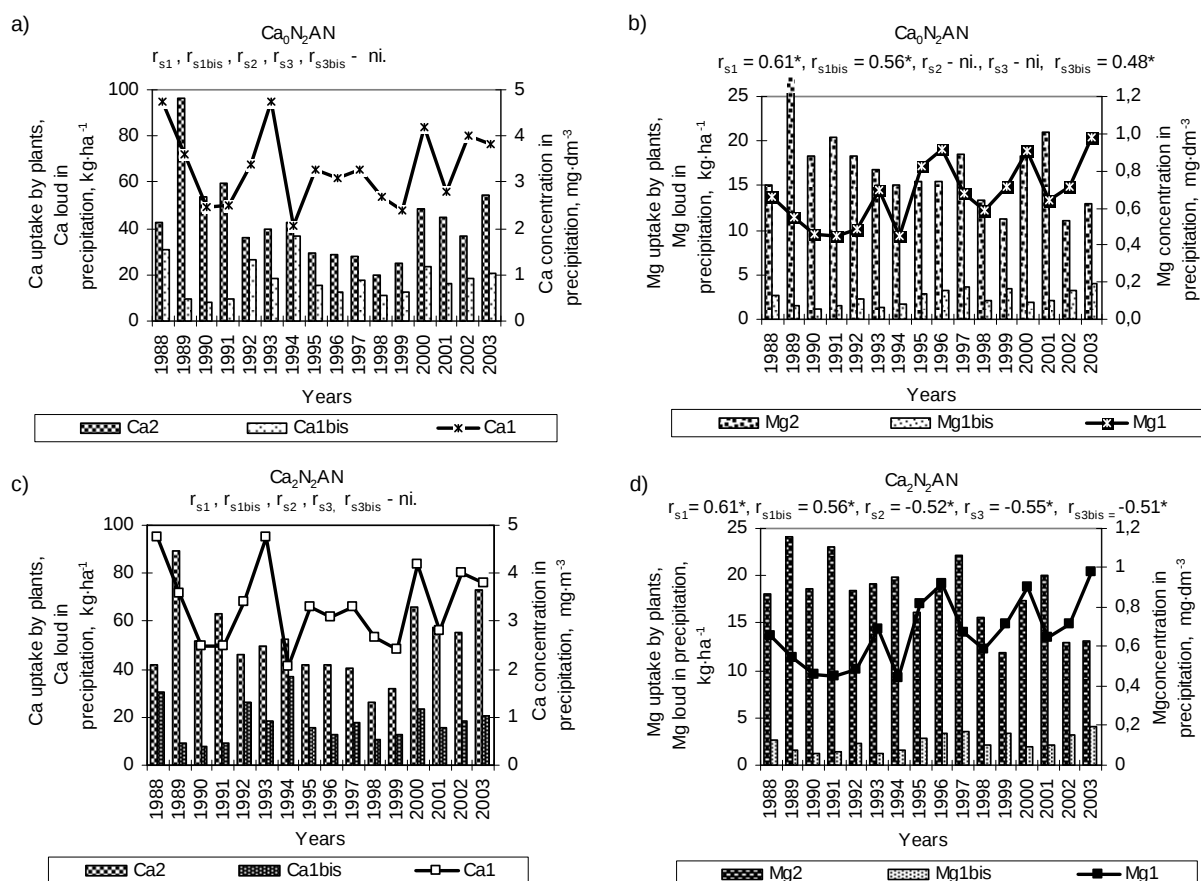


Fig. 1. Concentrations (Ca₁, Mg₁) and loads (Ca_{1bis}, Mg_{1bis}) of calcium and magnesium in atmospheric precipitation and their uptake by plants (Ca₂, Mg₂) in fertilisation variants Ca₀N₂AN (a, b) and Ca₂N₂AN (c, d) of the experiment in Laszczki; Spearman correlation coefficients: r_{s1} – concentration in precipitation x years, r_{s1bis} – load in precipitation x years, r_{s2} – uptake by plants x years, r_{s3} – uptake by plants x concentration in precipitation, r_{s3bis} – uptake by plants x load in precipitation

RELATIONSHIPS BETWEEN CALCIUM AND MAGNESIUM UPTAKE BY PLANTS AND THEIR CONCENTRATION IN GROUND WATER

Comparison of calcium and magnesium concentrations in ground water from under studied meadows shows a higher concentrations of these elements in the

Laszczki than in the Janki experiment (Tab. 7). The differences pertain mainly to magnesium concentrations. Temporal changes in the concentration of both elements in ground water in the years 1995–2003 were insignificant. However, some enrichment in calcium with time was observed in Laszczki (Fig. 2c).

Table 7. Mean pH and concentrations of calcium and magnesium in ground water and soil solution in meadow experiments

Sample	Experiment	Fertilisation variant ¹⁾	Years	pH ¹⁾		Ca		Mg	
				mean	CV%	mean mg-dm ⁻³	CV%	mean mg dm ⁻³	CV%
Ground water	Janki		1995–2003	7.5	4.6	64.2	16.8	6.15	26.6
Ground water	Laszczki			7.6	3.7	93.1	22.4	14.0	10.7
Soil solution	Janki	Ca ₀ N ₂ AN	1996–2007	8.01	2.9	74.8	20.7	17.5	53.1
Soil solution	Janki	Ca ₂ N ₂ AN		8.01	3.3	94.9	16.0	25.8	43.0
Soil solution	Janki	Ca ₀ N ₂ CN		7.96	6.2	87.8	37.1	17.7	52.0
Soil solution	Janki	Ca ₂ N ₂ CN		8.13	3.0	71.8	38.7	31.8	53.5

Explanations: Ca₀N₂AN, Ca₂N₂AN, Ca₀N₂CN, Ca₂N₂CN – variants in soil fertilised with 240 kg N in a form of ammonium saltpetre (AN) and calcium saltpetre (CN), not limed (Ca₀) and limed (Ca₂) acc. to the hydrolytic acidity criterion 2 Hh; CV% – coefficient of variability.

¹⁾ pH of soil solutions – mean value from the years 1997–2002.

An assessment of the relationship between calcium and magnesium uptake by plants and the study years in soils of extreme pH_{KCl} (3.6 and 6.6–6.9)

showed significant decrease of Mg uptake by plants in the Janki experiment in soil formerly limed and fertilised with calcium saltpetre (Ca₂N₂CN, $r_{s2bis} = -0.83^{**}$)

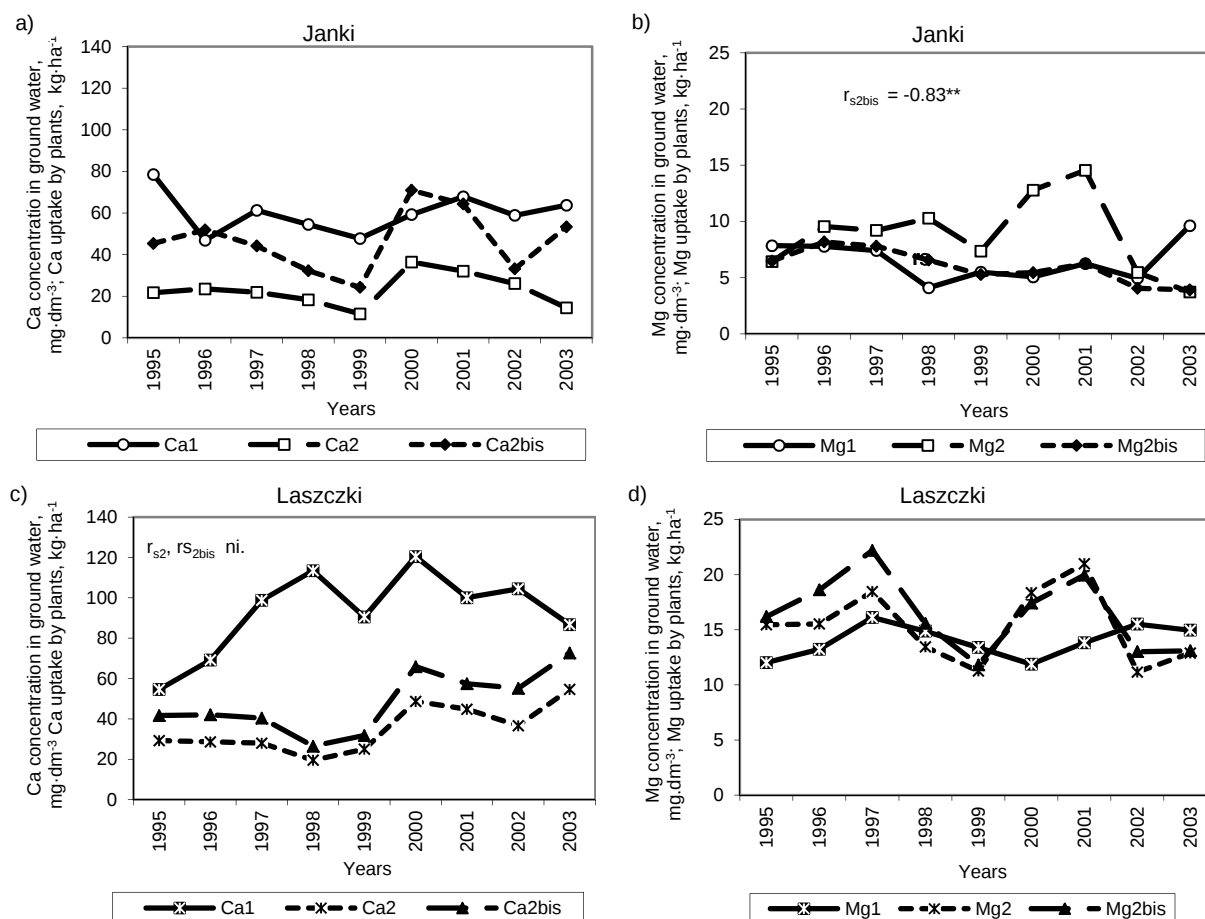


Fig. 2. Concentrations of calcium and magnesium in ground water (Ca_1 , Mg_1) and their uptake by plants in fertilisation variants Ca_0N_2AN (Ca_2 , Mg_2) and Ca_2N_2CN (Ca_{2bis} , Mg_{2bis}) of the experiment in Janki (a, b) and in Laszczki (c, d) in the years 1995–2003; Spearman correlation coefficients: r_{s2} – years x uptake by plants from the variant Ca_0N_2AN , r_{s2bis} – years x uptake by plants from the variant Ca_2N_2CN

(Fig. 2b). Similar relationship was also demonstrated in the soil fertilised with ammonium saltpetre (Ca_2N_2AN , $r_{s2} = -0.52^*$) of the Laszczki experiment for the period 1988–2003 (Fig. 1d). A tendency for increasing Ca uptake with time was observed in objects of extreme soil pH in the Laszczki experiment but calculated Spearman correlation coefficients were insignificant ($r_{s2} = 0.62$, $r_{s2bis} = 0.63$) though close to the critical value ($r_s = 0.64$) (Fig. 2c).

The relationships between calcium and magnesium uptake and their concentrations in ground water in both experiments were statistically insignificant. Lines of changes of studied relationships in compared fertilisation variants in soils of extreme pH values for both experiments showed mostly opposite direction for both calcium and magnesium (Fig. 2a, b, c, d). It would thus appear that with increasing Ca concentration in ground water one should expect its greater uptake by plants. However, increasing concentration of calcium in ground water could result from its washout from soil and from the enrichment by precipitation that contained substantial load of this element (Fig. 1a, c, Tab. 3, 4). Decreased Mg uptake by plants with increasing abundance of this element in ground water

(particularly in the Janki experiment) would indicate its stronger than Ca washout from soil [GLIŃSKI 1999] (Fig. 2b, d). Much smaller Mg load in atmospheric precipitation could additionally deepen its deficit in the soil (Tab. 5, 6).

RELATIONSHIPS BETWEEN CALCIUM AND MAGNESIUM UPTAKE BY PLANTS AND THEIR CONCENTRATION IN SOIL SOLUTION AND THE LOAD WASHED OUT FROM SOIL TO SOLUTION

Results of analysis of soil solutions are from the Janki experiment. Changes of the mean Ca concentrations in solutions from AN and CN fertilised variants in the years 1996–2007 showed an increasing trend of this concentration with time (Fig. 3a, b). However, changes in the mean amounts of Ca taken up by meadow vegetation from these objects showed an opposite direction. It means that the lower Ca concentration in soil solution was accompanied by the greater Ca uptake by plants. Such a relationship was statistically verified only in CN fertilised variant ($r_{s1} = -0.65^*$) (Fig. 3b). In contrast with calcium, magnesium concentration in soil solution at the AN fertilisa-

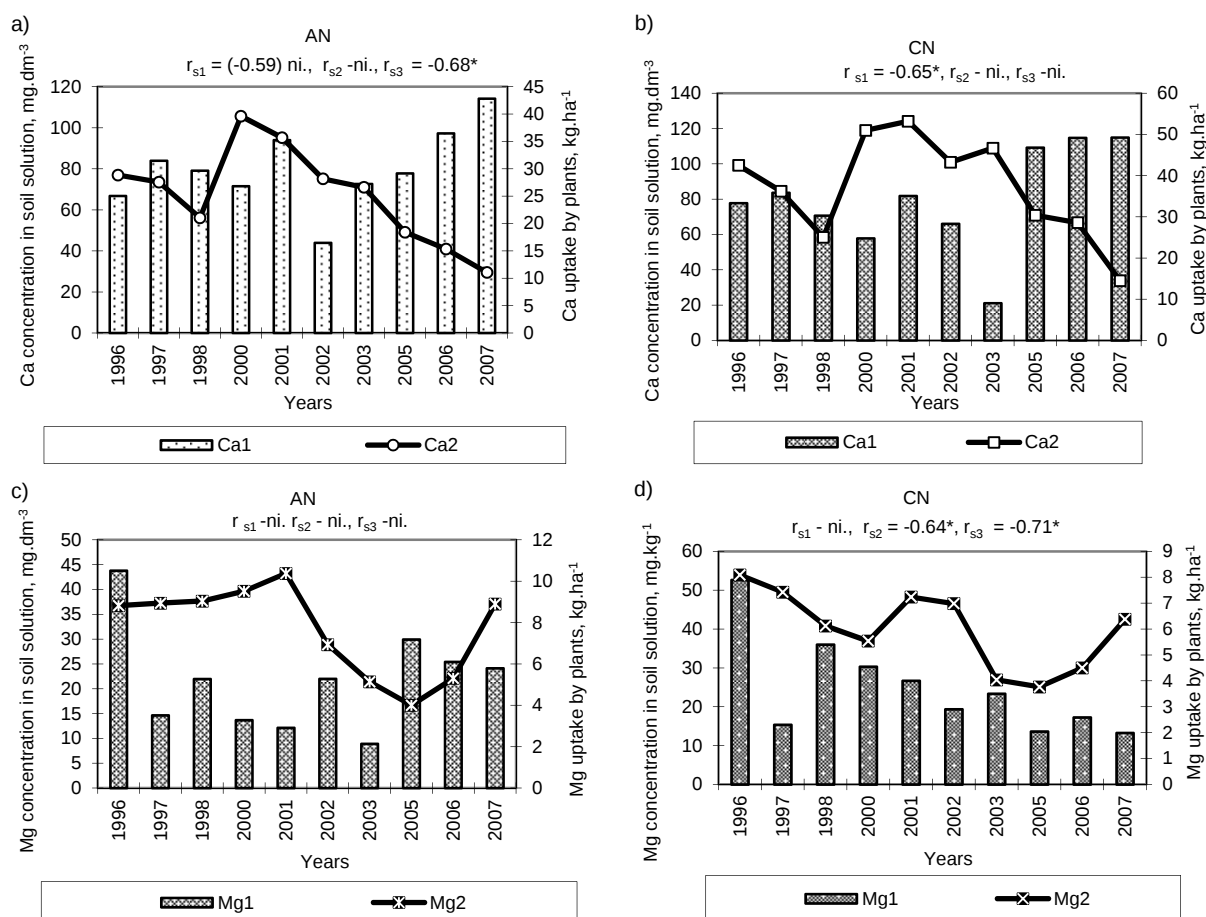


Fig. 3. Changes of the mean annual calcium (Ca_1) and magnesium (Mg_1) concentration in soil solution from objects fertilized with ammonium salt pter (AN) – a), c) and calcium salt pter (CN) – b), d) and their uptake by plants (Ca_2 , Mg_2) from the experiment in Janki in the years 1996–2007; Spearman correlation coefficients: r_{s1} – concentration in soil solution x uptake by plants, r_{s2} – concentration x years, r_{s3} – uptake x years

tion did not show clear trend of temporal changes. Fertilisation with CN facilitated a significant decrease of Mg in soil solution ($r_{s2} = -0.64^*$) and, consequently, a significant decrease of Mg uptake by plants ($r_{s3} = -0.71^*$). No significant relationship between Mg concentration in soil solution and Mg uptake by plants was, however, found at AN fertilisation (Fig. 3c, d).

Since calculated loads of calcium and magnesium washed out to soil solutions represent only four-year period (2000–2003), the changes and relationships between washout and uptake by plants were compared in soils of four objects differing in pH (Tab.1). Decreasing soil acidity (pH_{KCl} : $\text{Ca}_0\text{N}_2\text{AN} - 3.6 > \text{Ca}_0\text{N}_2\text{CN} - 4.3 > \text{Ca}_2\text{N}_2\text{AN} - 5.0 > \text{Ca}_2\text{N}_2\text{CN} - 6.6$) was accompanied by a greater Ca uptake by plants and a smaller uptake of magnesium (Fig. 4a, b). This relationship was already found in earlier studies [SAPEK 2011]. Mean load of calcium washed out to soil solution was similar among study years despite differences in soil pH. This could result in a similar and alkaline pH of soil solutions (Fig. 4a, Tab. 7). Under the same conditions a tendency of increasing Mg washout to soil solution was observed (Fig. 4b). No significant relationship was found between Ca and

Mg uptake by plants and their washout to soil solution ($r_{s1} - \text{ni.}$) but the counteractive course of changes in the concentration of both elements would indicate that one might expect smaller Mg uptake by plants with decreasing soil acidity and consequently a greater washout of this element from soil (Fig. 4b). Performed assessment of studied relationships could have been affected by a low number of study years, more so that they involved a period of abandoned P fertilisation. Observed counteractive behaviour of the two elements confirms their environmental antagonism [GORLACH, MAZUR 2002]. Regardless of soil pH, however, increasing washout of magnesium loads to soil solution was accompanied by increasing amounts of washed out calcium, which was confirmed by significant positive Spearman correlation coefficient ($r_{s2} = 0.55^*$) (Fig. 4c) for the years 2000–2003.

SUMMARY AND CONCLUSIONS

Obtained results did not unequivocally show a positive effect of calcium and magnesium from atmospheric precipitation, ground water or soil solution on the uptake of these elements by meadow vegeta-

tion. From the load of Ca and Mg delivered to experimental meadow and from the amounts removed in dry mass of yield one may assume that systematic atmospheric deposition supplements nutrient losses from soils, especially calcium losses from acid soil not limed and fertilised with ammonium saltpetre. This may be evidenced by long persistent soil $\text{pH}_{\text{KCl}} =$

3.6 and its low variability (5%). Such an effect demonstrated partly in this study operates in permanent, managed and fertilised meadows exemplified here by presented long-term meadow experiments. The effect is complex and much less visible due to fertilisation, harvesting, soil properties and other biological and anthropogenic factors.

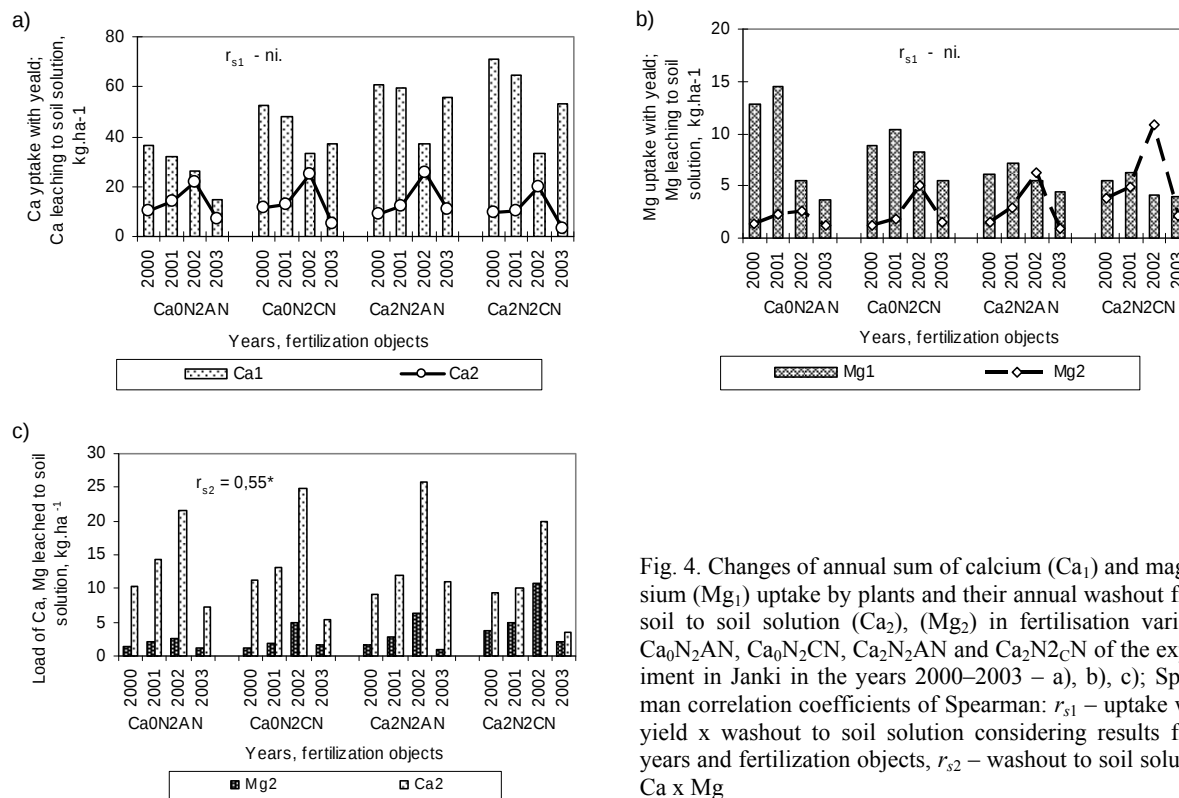


Fig. 4. Changes of annual sum of calcium (Ca_1) and magnesium (Mg_1) uptake by plants and their annual washout from soil to soil solution (Ca_2), (Mg_2) in fertilisation variants $\text{Ca}_0\text{N}_2\text{AN}$, $\text{Ca}_0\text{N}_2\text{CN}$, $\text{Ca}_2\text{N}_2\text{AN}$ and $\text{Ca}_2\text{N}_2\text{CN}$ of the experiment in Janki in the years 2000–2003 – a), b), c); Spearman correlation coefficients of Spearman: r_{s1} – uptake with yield x washout to soil solution considering results from years and fertilization objects, r_{s2} – washout to soil solution $\text{Ca} \times \text{Mg}$

Results of long-term studies in permanent mown meadow on mineral soil presented in this study allow for the following conclusions:

- Substantial calcium deposit from atmospheric precipitation in Falenty constituting nearly 50% of the amount taken up by plants did not exert an unequivocal effect on long-term uptake at fertilisation with both ammonium and calcium saltpetre.
- In fertile soil of favourable physical and water conditions and slightly acidic $\text{pH}_{\text{KCl}} = 5.8$ there was a significant, negative effect of the concentration and load of magnesium from atmospheric deposition on the uptake by plants and significant, positive effect of the load in strongly acid soil of $\text{pH}_{\text{KCl}} = 3.6$. This conclusion points to a complex process of mutual interactions between atmospheric Ca and Mg differing in solubility.
- Observed tendency of a positive effect of calcium concentration in ground water on its uptake by plants and of a negative effect on magnesium uptake in very acid soils of both experiments could be a result of ground water enrichment with atmospheric Ca and, consequently, of limited Mg availability from this source for plants.

- Diminished uptake of calcium by plants in the study decade in acid soil poor in humus caused substantial enrichment of soil solution in this element, particularly at fertilisation with calcium saltpetre, and significant decrease of magnesium concentration in this solution.
- Soil neutralization facilitates the decreased Mg uptake by plants, which increases its washout from soil to soil solution. Irrespective of soil pH, increasing calcium washout to soil solution is accompanied by magnesium washout with important contribution of atmospheric precipitation.
- Results obtained under conditions of experimental productive meadow inspire to undertake similar studies on the effect of atmospheric calcium and magnesium on their concentrations in soil waters and on the uptake by plants in natural meadow ecosystems and in lands of ecological use.

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Barbara SAPEK

**Pobranie wapnia i magnezu z plonem roślinności łąkowej
na tle ich zawartości w opadzie atmosferycznym, wodzie gruntowej i roztworze glebowym**

STRESZCZENIE

Słowa kluczowe: *magnez, opad atmosferyczny, pobranie z plonem roślin łąkowych, roztwór glebowy, wapń, woda gruntowa*

Postawiono pytanie, czy, w jakich warunkach i w jaki sposób stężenie oraz ładunek wapnia i magnezu w opadzie atmosferycznym oraz w wodzie gruntowej i roztworze glebowym mogą wpływać na pobranie tych składników z plonem roślinności w warunkach użytkowanej łąki. Odpowiedzi na to pytanie poszukiwano na podstawie wyników oznaczeń Ca i Mg w opadzie atmosferycznym z rejonu Falent oraz w wodzie glebowej z dwóch długoletnich doświadczeń łąkowych na glebie mineralnej, usytuowanych w województwie mazowieckim. Na podstawie uzyskanych wyników badań stwierdzono złożony i uwikłany wpływ depozytu Ca i Mg z opadu oraz związane z nim oddziaływania tych składników w wodzie gruntowej i w roztworze glebowym na ich pobieranie z plonem z uwagi na działanie nawożenia, zbioru plonu oraz pozostałych czynników antropogenicznych. Nie stwierdzono jednoznacznie dodatniego oddziaływania zwiększenia ładunku Ca z opadu atmosferycznego na jego pobranie przez rośliny w wieloleciu. Wpływ taki wykazano w odniesieniu do ładunku Mg, lecz tylko na bardzo kwaśnej glebie. W korzystnych warunkach fizyczno-wodnych i słabo kwaśnego odczynu gleby ten wpływ był ujemny. Wzbogaceniu wody gruntowej w Ca towarzyszyło zwiększenie jego pobrania z plonem roślin i jednocześnie zmniejszenie pobrania Mg z gleby bardzo kwaśnej. W takich warunkach odczynu gleby zmniejszeniu pobrania Ca towarzyszyło większe jego stężenie w roztworze glebowym. Zubożenie nadmiaru kwasowości gleby sprzyjało zwiększeniu stężenia Mg w roztworze glebowym i mniejszemu jego pobraniu przez rośliny. Uzyskane wyniki inspirowały do podjęcia podobnych badań w warunkach naturalnych ekosystemów łąkowych i tzw. użytków ekologicznych.