J. Elem. s. 165–176

DOI: 10.5601/jelem.2014.19.1.604

DETERMINATION OF SPATIAL VARIABILITY OF SOME MAGNESIUM FORMS IN PHAEOZEM USING GEOSTATISTICAL METHODS*

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Abstract

The spatial variability analysis of soil properties facilitates the prediction of their contents across various sites, useful for design of site-specific farming practices. Intrapopulation and spatial variation of soil available (Mg-A), exchangeable (Mg-E) and water-soluble (Mg-H_2O) magnesium forms was evaluated in a field on Phaeozem soil, located in the village Orlinek near Mrocza, in the Province of Kujawy and Pomorze (*województwo kujawsko-pomorskie*), north-western Poland. Soil samples were collected from an area of 0.5 ha situated within an 80-hectare arable field. In April 2007, 50 soil samples were collected in a 10 x 10 m grid square pattern from the field cropped with winter wheat. The content of Mg forms was analyzed with descriptive statistics and the geostatistic modeling of semivariograms to plot variability maps. The Mg-A content ranged from 4.9 to 12.2 mmol kg^{-1}, while the Mg-E form varied from 5.6 to 16.4 mmol kg^{-1}. The average content of Mg-H_2O was 1.27 mmol kg^{-1}. All the properties revealed a normal content distribution, which coincided with similar values of means, medians and significantly lower values of standard deviations (SD) than the means. Moderate variability of all the Mg forms content was confirmed by the coefficient of variation (CV%), falling within 19.4-23.6%. The spatial dependence of the Mg forms content was evaluated by the use of semivariograms and kriged maps. The parameters of variogram models, except for the Mg-A content, revealed a share of random variance (a nugget) in total variability (sill). The content of Mg-E demonstrated high spatial dependence (the nugget effect <25%), while the content of Mg-H_2O and the percentage share of Mg-E in the sum of base cations (S) fell within the moderate class of spatial variability (the nugget effect between 25% and 75%). The spatial correlation of the properties studied was assessed by 11.1 to 21.3 m range. The spatial variation maps showed that the Mg-A and Mg-E contents had a similar distribution in the research area, while the Mg-H_2O content and the percentage of the Mg-E in (S) presented a different pattern of variability. The maps revealed that almost 80% of the field showed a very high Mg-A content (Class I abundance), which suggested that Mg fertilizer is unnecessary.

Key words: available Mg, exchangeable Mg, water-soluble Mg, spatial variability, geostatistics, Phaeozem.

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* The study was financed by the MNiSW under research project No 1588/PO1/2007/32.

ANALIZA ZMIENNOŚCI PRZESTRZERNNEJ WYBRANYCH FORM MAGNEZU W CZARNEJ ZIEMI Z WYKORZYSTANIEM METOD GEOSTATYSTYCZNYCH

Abstrakt

Analiza zmienności przestrzennej parametrów glebowych umożliwia oszacowanie ich zawartości między miejscami pobrania próbek glebowych, co jest podstawą stosowanego coraz częściej systemu rolnictwa precyzyjnego. Badano zmienność zarówno wewnątrzpopulacyjną, jak i przestrzenną dotyczącą zawartości Mg przyswajalnego (Mg-A), wymiennego (Mg-E) oraz wodnorozpuszczalnego (Mg-H_2O) w czarnej ziemi w okolicach wsi Orlinek k. Mroczy (województwo kujawsko-pomorskie). Próbki glebowe pobierano z obszaru 0,5 ha znajdującego się w obrębie 80-hektarowego pola produkcyjnego, na którym uprawiano pszenicę ozimą. W kwietniu 2007 r. pobrano 50 prób glebowych rozmieszczonych w siatce kwadratów o boku 10 m x 10 m. Zawartości badanych form magnezu analizowano z wykorzystaniem podstawowych statystyk opisowych oraz metod geostatystycznych, które posłużyły do wykreślenia map ich zmienności. Zawartość Mg-A wynosiła 4,9-12,2 mmol kg^{-1}, zawartość Mg-E od 5,6 do 16,4 mmol kg^{-1}, średnia zawartość Mg-H_2O 1,27 mmol kg^{-1}. Wszystkie badane parametry wykazywały normalny rozkład zawartości, co potwierdzone zostało przez zbliżone wartości średnich, median oraz istotnie niższe wartości odchylenia standardowego (SD), w porównaniu ze średnimi. Umiarkowaną zmienność zawartości badanych form magnezu potwierdzono za pomocą współczynnika zmienności (CV%), którego wartości mieściły się w granicach 19,4-23,6%. Zależność przestrzenną zawartości badanych form magnezu oszacowano za pomocą semivariogramów oraz wykreślonych na ich podstawie map rastrowych. Parametry modeli variogramów, z wyjątkiem zawartości Mg-A, wskazywały na udział zmienności losowej (samorodek) w kształtowaniu całkowitej zmienności tego parametru. Zawartość Mg-E wykazywała wysoką zależność przestrzenną (efekt samorodka <25%), natomiast zawartość Mg-H_2O oraz udział procentowy Mg-E w sumie zasadowych kationów (S) mieściły się w umiarkowanej klasie zmienności (efekt samorodka między 25% a 75%). Korelację przestrzenną badanych parametrów oznaczono z wykorzystaniem zakresu od 11,1 do 12,3 m. Mapy zmienności przestrzennej wykazały, że zawartości Mg-A i Mg-E charakteryzowały się podobnym do siebie rozmieszczeniem na powierzchni badanego obszaru, natomiast zawartość Mg-H_2O oraz udział procentowy Mg-E w (S) wykazywały odmienne rozmieszczenie w porównaniu z pozostałymi parametrami. Mapy rastrowe wykazały bardzo wysoką zawartość Mg-A (I klasa zasobności) na prawie 80% powierzchni badanego pola, co wskazywało, że nawożenie magnezem nie jest konieczne.

Słowa kluczowe: Mg przyswajalny, Mg wymienny, Mg wodnorozpuszczalny, zmienność przestrzenna, geostatystyka, czarna ziemia.

INTRODUCTION

Several primary and secondary minerals are original sources of the soluble and available forms of Mg in soil. Magnesium is taken up by plants in the form of cations (Mg^{2+}), which play a crucial role in photosynthesis as an essential element of chlorophyll molecules. Magnesium is also vital for animal and human metabolism (GRZEBISZ 2011), for example it is a constituent or activator of over 300 enzymes (EBEL, GUNTER 1980, COWAN 2002). Magnesium also determines important metabolic reactions, such as the synthesis of proteins, nucleic acids. In addition, it participates in the transfer of energy within the plant. Available magnesium, together with calcium (Ca^{2+}), potassium (K^+), and sodium (Na^+), is a major cation related to the sum of base cations (S). Regarding plant nutrition, the most important forms of magnesium are exchangeable and water-soluble ones (IDRICEANU et al. 1999). Both represent so-called available Mg form, which is used in agronomy to define the classes of magnesium abundance (PN-R-04020:1994/Az1).

Soil nutrients often vary significantly across a field, so that uniform fertilization may result in an over-application in some parts of the field and under-fertilization in others. Nutrient runoff and leaching from over-fertilized areas may contaminate groundwater, while in under-fertilized areas crop yield may be limited (CAHN et al. 1994). Magnesium deficiency in Polish soils as well as marked enrichment of groundwater with Mg have been recorded (ŁABĘTOWICZ et al. 2004, SAPEK 2007, 2008). Magnesium levels in soil decline over time due to crop removal, soil erosion and leaching (KOBIERSKI et al. 2011, KONDRATOWICZ-MACIEJEWSKA, KOBIERSKI 2011). Low soil pH, and/or high levels of potassium (K^+) and calcium (Ca^{2+}), low temperatures and arid soil conditions can all contribute to Mg deficiency (MARSCHNER 1995).

In order to control side-effects of inadequate fertilization and other mismanaged faming practice, spatial variability of soil nutrient concentrations needs to be identified for development of site-specific farming practice that will match agricultural input with the actual crop requirements. The spatial variability of soil properties is evaluated with the use of geostatistical analysis for detection, estimation and mapping spatial patterns of soil variables (SEBAI et al. 2007). Geostatistics, originally applied in the mining industry (MATHERON 1963), has been proven useful in soil science for defining and mapping the spatial variation of soil properties. The main techniques used in geostatistics are variography and krigging. Variography involves drawing semivariograms to define and model the spatial variability, whereas krigging uses the modeled variation to estimate values between sampling points (BURGESS, WEBSTER 1980). Finally, krigged values are used to develop maps for site-specific farming practices (MULLA 1989).

The objective of the study was to evaluate and compare the intrapopulation and spatial variability of different forms of magnesium using traditional statistics and geostatistical techniques.

MATERIAL AND METHODS

The spatial heterogeneity of soil magnesium forms was investigated on an 80-hectare arable field, located in the village Orlinek near Mrocza, (the province of Kujawy and Pomorze, *województwo kujawsko-pomorskie*; 53° 15’ 31” N, 17° 32’ 43” E). An area of 0.5 ha was selected for the research purposes. The soil was classified as Gleyic Phaeozem (IUSS Working Group WRB 2006). Winter wheat after winter oilseed rape was cultivated on the field. In total, 50 soil samples were collected in April 2007 from the topsoil (0-20 cm) using the point sampling method with a 10 x 10 m regular grid square pattern. The soil samples were air-dried and passed through a 2 mm mesh sieve.

The soil fractions <2 mm were analyzed to determine available Mg (Mg-A), after extraction in 0.0125 mol dm^{-3} $CaCl_{2,}$ according to the Schachtschabel method; exchangeable Mg (Mg-E) was determined in 0.1 M $BaCl_2$ (ISO 11260:1994), and water-soluble Mg (Mg-H_2O) was assayed after extraction in distilled water (soil /water – 1/5). The content of Mg^{2+} and Ca^{2+}, K^+ and Na^+ in extracts was determined by atomic absorption spectroscopy (AAS) on a Philips PU 9100X spectrometer. Basic physicochemical properties of soil were determined: particle-size by the Cassagrande method, modified by Prószyński; soil fraction >2 mm content applying the sieving method; pH in 1 M KCl – potentiometrically (PN-ISO 10390:1997); the organic carbon content – in a dry combustion CN analyzer (Vario Max CN). The assays were verified with the TILL-3 certificate. Based on the exchangeable cation content (Ca^{2+}, Mg^{2+}, K^+, Na^+), the sum of base cations (S) was calculated.

The data were evaluated with the use of traditional statistical methods (Statistica v. 10.0 Software). In order to characterize the differentiation in a whole population of data sets, arithmetic and geometric means, standard deviation, the coefficient of variation and skewness and kurtosis were calculated. For estimation and visualization of the spatial variability of Mg forms in the surface horizon of the field, geostatistical methods were used. Empirical and the best fitted model variograms were plotted as well as the sill, nugget, nugget effect and the range of the influence were calculated. The mean squared deviation ratio (MSDR) was used to verify the agreement of model variogram with the empirical variogram. The data were estimated with the punctual krigging method. To express the level of spatial dependence, the relative nugget effect $[Co/(Co+\mathrm{C})]\cdot 100$ was used, as described in CAMBARDELLA and KARLEN (1999). Raster maps showing the spatial variability of the magnesium forms were plotted based on the semivariograms. All geostatistical analyses were processed using the software Isatis of Geovariance.

RESULTS AND DISCUSSION

The texture of topsoil was represented by 21 sandy loam samples; 28 fine sandy loam and a single medium sandy loam sample. While identifying the agronomic category, it was noticed that the vast majority of samples were in the average category of soils and only 7 represented light soil. The Ap horizon grain size composition showed 57% to 77% of sand fraction, 11% to 23% of silt fraction and 7% to 20% of clay fraction (Table 1). Most soil samples had neutral reaction, and only in some samples the reaction was

Table 1

Basic statistics of selected properties (n=50)

Parameters	Fraction percentage			pH	C_{org}	Ca^{2+}	K^+	Na^+	Hh	(S)	CEC
	sand	silt	clay	1M KCl	(g kg^{-1})	(mmol kg^{-1})					
Min.	57.0	11.0	7.0	6.48	13.1	137.8	2.5	0.6	3.0	150.1	156.1
Max.	77.0	23.0	20.0	7.19	25.1	350.1	7.4	1.7	10.5	368.2	371.9
Arithmetic mean	66.4	18.4	15.2	6.78	18.7	251.8	4.7	0.9	6.3	268.8	275.1
SD	4.77	2.91	2.92	0.18	2.83	53.57	1.17	0.26	2.20	55.0	54.7

SD – standard deviation, Hh – hydrolytic acidity, (S) – sum of base cations, CEC – cation exchange capacity

Table 2

Basic statistics of selected properties (n=50)

Parameters	Mg-A	Mg-E	Mg-H_2O	%Mg-E in (S)
	(mmol kg^{-1})			
Min.	4.88	5.60	0.82	2.80
Max.	12.2	16.40	1.96	7.00
Arithmetic mean	8.43	11.34	1.27	4.27
Median	8.44	11.70	1.25	4.35
SD	1.75	2.68	0.25	0.84
Kurtosis	-0.511	-0.300	0.326	0.808
Skewness	-0.135	-0.333	0.537	0.453
CV(%)	20.8	23.6	19.4	19.8

Mg-A – available magnesium; Mg-E – exchangeable magnesium;
Mg-H_2O – water soluble magnesium; SD – standard deviation
CV (%) – coefficient of variation; (S) – sum of base cations

slightly acid (pH <6.6). The organic carbon content ranged from 13.1 to 25.1 g kg^{-1}, with the average value of 18.7 g kg^{-1} (Table 1). The soil sorption complex was mostly saturated by alkaline cations.

The cation content varied in respective soil samples. The base cations were dominated by Ca^{2+} (137.8-350.1 mmol kg^{-1}), followed by Mg^{2+} (5.6-16.4 mmol kg^{-1}) and K^+ (2.5-7.4 mmol kg^{-1}) and Na^+ (0.6-1.7 mmol kg^{-1}). The share of magnesium cations in the cation exchange capacity (CEC) ranged from 2.67% to 6.66%. The hydrolytic acidity ranged from 3.0 to 10.5 mmol kg^{-1}. The data sets of selected magnesium forms, derived from soil analysis, were initially evaluated using basic statistical parameters. The means and medians were used as primary estimates of the central tendency, and the standard deviation and CV were used as estimates of the population variability. The results summarized in Table 2 show the available Mg average from 4.88 to 12.2 mmol kg^{-1}. The average values of exchangeable Mg ranged from 5.61 to 16.4 mmol kg^{-1} and water-soluble Mg from 0.82 to 1.96 mmol kg^{-1}. The properties showed similar values of means and medians but a significantly lower SD than the means, which is an important condition for normal frequency distribution (MULLA, MCBRATNEY 2000). Additionally, all the properties demonstrated a low degree of skewness: from –0.333 to 0.537 (Table 2), which suggests that the data distribution was approximately symmetric. Another measure of the data distribution shape is the kurtosis, which defines the height and sharpness of the peak relative to the rest of the data (BALANDA and MACGILLIVRAY 1988). Kurtosis values calculated for available and exchangeable Mg were –0.551 and –0.300, respectively, suggesting that those properties were slightly platykurtic, the peaks were just a bit shallower than the normal distribution peak. The water soluble Mg content and the percentage of Mg-E in the sum of cations (S) revealed the positive kurtosis below one, which indicated a slightly leptokurtic distribution. The exchangeable Mg content in the study of STUTTER et al. (2004) showed marked deviation from normality with consistent positive skewness (0.87-2.52) and kurtosis (0.30-9.18). According to these authors, the differences were related to the dynamics of organic material decomposition as a result of varying litter decomposition rate and vegetation types. The same Mg form achieved the values of skewness and kurtosis closer to zero in the study of BUSCAGLIA and VARCO (2003). One of the most frequent measures of spreading about the mean is the coefficient of variation – CV (MULLA, MCBRATNEY 2000). The data of magnesium forms showed moderate variability, which was confirmed by the coefficient of variation (CV) ranging from 19.4 to 23.6% (Table 2). Those moderate class values established for CVs (WILDING 1985) were consistent with the results by DAMPNEY et al. (1997), and ŠTÍPEK et al. (2004). A moderate and high variability range (CV = 18.2-43.7%) was reported for exchangeable Mg by BUSCAGLIA and VARCO (2003) and BREJDA et al. (2000). A lower CV (10%) value of the exchangeable Mg content was noted by YANAI et al. (2003) in an onion field for more than 20 years, and that of available Mg by CAVIGELLI et al. (2005) in a no-till corn field (15.2%). On the other hand, COBO et al. (2010) found that exchangeable Mg was the most variable chemical parameter, with the coefficients of variation ranging from 60 to 120%. According to MULLA and MCBRATNEY (2000), the properties such as soil pH, texture or porosity are the least variable, while those connected to water or solute transport are more variable.

The variability in statistical parameters of Mg forms across different literature reports, including the present one, was probably the result of the influence of climate, plants, soil type and depth, landscape features as well as the management history (e.g. crop rotation, fertilization, tillage) (BUSCAGLIA, VARCO 2003, STUTTER et al. 2004).

Since the normality of the data was the general observation, we did not transform values before geostatistical analyses. Geostatistical parameters are presented in Table 3 and Figures 1-4. Experimental semivariograms of available and exchangeable Mg content and the share of Mg-E in (S) were well-described by the Gaussian model while the semivariograms of water-soluble Mg data could only be described by a spherical model. All the semivariograms, except for the available Mg, revealed the percentage of

Table 3

Parameters of variogram models (n=50)

Parameters	Model	Sill (Co+C)	Nugget (Co)	Nugget effect Co/(Co+C)	Range	MSDR	Spatial depen-dence
		(mmol kg^{-1})^2		(%)	(m)		
Mg-A	G	3.16	-	-	21.3	1.0005	-
Mg-E	G, NE	5.97	0.37	6.2	21.3	0.9997	S
Mg-H_2O	Sf, NE, L	0.054	0.02	37.0	11.1	1.0002	M
%Mg-E in (S)	G, NE	0.75	0.19	25.3	18.0	1.0004	M

Mg-A – available magnesium; Mg-E – exchangeable magnesium;
Mg-H_2O – water soluble magnesium; (S) – sum of base cations
G – Gaussa, Sf – spherical, L – linear, NE – nugget effect
MSDR – mean squared deviation ratio, S – strong, M – moderate

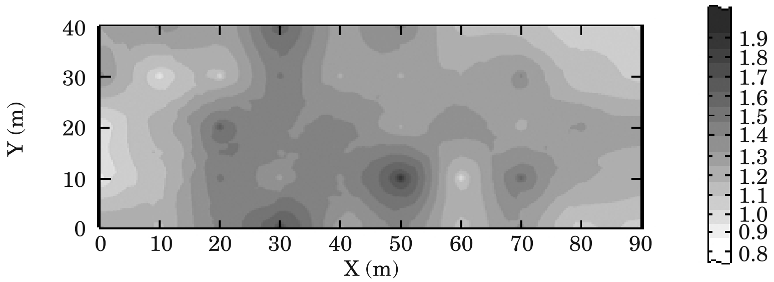

Fig. 1. Spatial variability of water-soluble Mg content (Mg-H_2O), mmol kg^{-1}

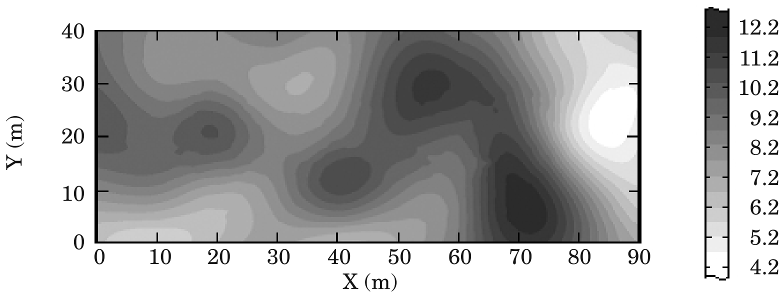

Fig. 2. Spatial variability of available Mg content (Mg-A), mmol kg^{-1}

random variability (nugget, Co) in total variability (sill, $Co+C$), which can be explained by sampling error, or random and inherent variability (SUN et al., 2003). To determine the grade of spatial dependence of each Mg form, the nugget-to-sill ratios from all semivariograms were calculated. As reported by CAMBARDELLA et al. (1994), HUANG et al. (2006), ROSSI et al. (2009), WANG et al. (2009), if the ratio is lower than 25%, the spatial variability is considered strong; if the ratio falls within 25 and 75%, the dependence is moderate; and if the ratio is higher than 75%, the variability is considered weak. A similar

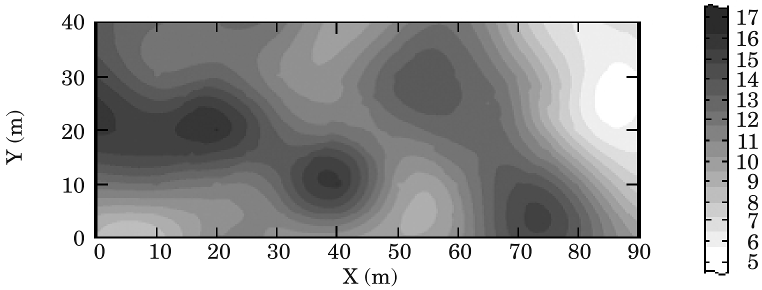

Fig. 3. Spatial variability of exchangeable Mg content (Mg-E), mmol kg^{-1}

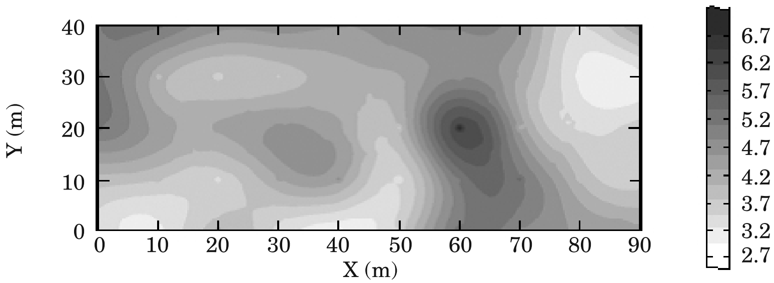

Fig. 4. Spatial variability of Mg-E share in sum of base cations (S), %

approach was used in this study. The exchangeable Mg content in the soil samples revealed strong variability (the nugget effect – 6.2%), while the water-soluble Mg content and the percentage share of Mg-E in (S) values were moderately variable (the nugget effect – 37.0% and 25.3%) – Table 3. The relative nugget effect in the total variance of available Mg (4-23%) reported by Štípek et al. (2004), or moderate (32-70%) – by Tabi and Ogunkunle (2007) did not emerge in our study, which revealed no share of random variability. The lack or a low share of the nugget effect in total variability of Mg forms suggest that the variables were spatially dependent and they were mainly influenced by internal factors, e.g. the soil type, texture, topography, while the external factors (e.g. fertilization, tillage) were less essential.

The range of influence is considered as the distance beyond which the observations are not spatially dependent (Sun et al. 2003) and it is a very important parameter for planning the sampling scheme. In our study, the distance ranged from 11.1 to 21.3 m (Table 2). These values were higher than the sampling distance (10 m), which proved that the sampling scheme was proper and all the variables were spatially correlated. Additionally, the sampling distance for Mg-A and Mg-E contents could be even longer if researched further. The range values for the same property assume different values in different studies, mainly due to the size of an area studied and sampling intervals. The range of available Mg was between 40 and 50 m when soil was sampled every 10 m (Tabi, Ogunkunle 2007), exchangeable Mg ranged 459-522 m when soil samples were collected in the 750 x 750 m grid (Cobo et al. 2010) and 322-660 m when the grid was established with regular intervals of 50 m with 129 sampling points (De Leão et al. 2011).

The water-soluble Mg content (Figure 1) was irregularly distributed in the soil surface horizon and did not show any similarities with the map representing Mg-A and Mg-E distribution, which suggested that additional factors may control the distribution of this form of magnesium. A comparison of the krigged maps of spatial distribution of Mg forms revealed that Mg-A and Mg-E showed comparable spatial variation (Figures 2, 3). Indeed, both maps showed four nests of higher results distributed irregularly, yet in the same way, among a lower data set. The long-term intensive use of Phaeozem must have resulted in the variation of respective parameters, especially the organic carbon content, which was significantly positively correlated with respective magnesium forms (Table 4). The content of clay fraction

Table 4

Correlation coefficients significant at $p<0.05$ ($n=50$)

Parameters	Mg-A	Mg-E	Mg-H_2O
C_{org}	0.494	0.458	0.301
Clay fraction	0.554	0.680	
(S)	0.410	0.643	
Mg-E	0.845		

Mg-A – available magnesium; Mg-E – exchangeable magnesium;
Mg-H_2O – water soluble magnesium; (S) – sum of base cations

demonstrated a significant positive effect on the content of exchangeable and available magnesium forms (r = 0.680, and r = 0.554, $p<0.05$). The above relationship was additionally confirmed by a high coefficient of correlation (r = 0.845; $p<0.05$) between Mg-A and Mg-E contents (Table 4). The content of these magnesium forms was significantly positively correlated with the sum of base cations (S). The map showed that almost 80% of the area revealed a very high Mg-A abundance class, while 14% of the field – a high amount of this Mg form and only 6% fell within the moderate Mg-A abundance class (Figure 2). The water-soluble Mg data (Figure 1) was irregularly distributed in the soil surface horizon and did not show any similarities with the map representing Mg-A and Mg-E distribution, which suggests that additional factors may control the distribution of that form. The highest share of Mg-E in (S) was detected at 60-70 m of length and all across the width of the area (Figure 4). Relatively high values of this ratio were also recorded along the northern perimeter of the field (0-70 m of length) and along the western edge of the field (15-40 m of the width).

CONCLUSIONS

1. The results of soil magnesium forms in the experimental area showed moderate intrapopulation and spatial variability, which was confirmed by the values of the coefficients of variation and semivariogram parameters.

2. The spatial range values indicated that with the sampling interval established in the study (10 m) the sampling design was proper and all the Mg forms were spatially correlated. The sampling distance for Mg-A and Mg-E contents could be even longer and fewer samples would need to be collected.

3. The nugget-to-sill ratios calculated to determine the level of spatial dependence of each Mg form showed a strong and moderate share of random variance (nugget, *Co*) in total variability (sill, *Co+C*) of Mg-E and Mg-H_2O, while Mg-A was defined by the structural variance only. This suggests that structured variance was dominant over the nugget effect/random component. The results of nugget-to-sill ratios can facilitate the evaluation of the contribution of geologic and pedologic soil forming factors in the total variability, which can camouflage the influence of external factors, such as tillage or other management practices.

4. The spatial variability map of Mg-A displayed most of the analyzed area (almost 80%) having a very high available magnesium level, despite the fact that although no Mg fertilizer had been applied there over the last several years. This indicates high native soil Mg content, which means that application of mineral Mg fertilization is not recommended.

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