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CURRENT STATE AND DEVELOPMENT OF MACRO- AND MICRONUTRIENTS CONTENT IN ARABLE SOILS OF SLOVAKIA

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Abstract

The current state and development of macronutrients (P, K, Mg) and basic micronutrients (Cu, Zn, Mn) in arable soils of Slovakia were evaluated. The obtained results are based on the Soil Monitoring System of Slovakia (318 sites, sampled repeatedly in five-years cycle since 1993) including the arable land and grassland in Slovakia from the year 1993. In this contribution only arable soils were evaluated. The macronutrients have been analysed using Mehlich III method and for micronutrients the extraction with DTPA method has been used. The content of available phosphorus in arable soils of Slovakia is fluctuating within a wide range (from 15.60 to 177 mg.kg^{-1}) what is classified as low to very high content. Development of available phosphorus is slightly decreasing with time. The content of available potassium is also varying in wide range (115.70–295.60 mg.kg^{-1}), what represents low to good supply. At most sampled sites the available potassium is slightly decreasing with time. The content of magnesium is sufficient to high (mostly in the range from 50.61 to 889.50 mg.kg^{-1}). The development of magnesium during monitored period is without significant change. The content of microelements (Cu, Zn, Mn) is mostly medium to high . The content of Cu is distributed in the wide range of 0.31–5.07 mg.kg^{-1} (low to high content), content of Zn is distributed in the range of 1.26–3.60 mg.kg^{-1} (medium to high content) and Mn is in the wide range (3.05–80 mg.kg^{-1}) what represents low to medium content. The micronutrient contents are slightly decreasing during the monitored period.

Keywords: soil monitoring, macronutrients, phosphorus, potassium, magnesium, micronutrients, copper, zinc, manganese, arable soils, Slovakia

INTRODUCTION

The socio-economic changes after 1990 year strongly affected also soil fertility, especially the content of available macro- and micronutrients. In comparison with period before 1990 year the average doses of NPK were running between 220–230 kg ha^{-1}, later the average doses strongly decreased to 40–60 kg ha^{-1} only, and nowadays they are about 100 kg ha^{-1} whereas a significant portion of it is nitrogen (76.31 kg. ha^{-1}) while much smaller portions are prepresented by phosphorus (14.45 kg. ha^{-1}) and potassium (11 kg.ha^{-1}). It means that the application of P and K fertilizers is significantly lower, what refers to low supply of phosphorus in soils of Slovakia (total content of phosphorus is often between 0.02 and 0.15 kg. ha^{-1}).

The mineral components of phosphorus in soil have a different solubility and also different availability for plants. The most stabile component of phosphorus is apatite. Phosphorus creates strong bonds with calcium in calcareous soils and with iron and aluminium in acid soils. These forms are insoluble and therefore hardly available for plants. Phosphorus strongly affects biochemical processes in plants, it is a source of energy for enzymatic processes that has a significant role in synthesis of organic components and strongly affects all soil life (Michalík 2001).

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The potassium content in soils of Slovakia is significantly higher then the phosphorus content because the potassium rich rocks are abundant in Slovakia. This element is fixed especially in K-feldspars (microcline and orthoclase) and in micas (especially in biotite, which is easier weatherable then muscovite).

The total content of magnesium in soil is running in the range of 0.05–0.5% (Hrtánek & Kobza 1980). Magnesium occurs in numerous primary rocks (olivine, serpentine, biotite) and also in secondary rocks (chlorite, vermiculite, montmorillonite). In calcareous soils magnesium occurs in magnesite and dolomite. Low occurrence of Mg (about 5%) is sorbed on clay minerals and humic matters, very low concentration of Mg can be indicated in forms of soluble salts in soil solution (Kundler *et al.* 1970, Saalbach *et al.* 1970). High to toxic concentrations of Mg were determined in the surroundings of magnesite factories – Jelšava and Lubeník, Hačava (Kobza *et al.* 2010). These factories were based on local supply of magnesire raw material and were active for many decades. The polutant emissions and their atmospheric fallout contaminated their surroundings.

The name "microelements" reflects the fact of their small need for the plants as well as their slight concentration in soil. Their shortage as well as their surplus in soluble form can be harmful. The content of microelements depends on mineralogical composition. The higher content of microelements is characteristic for the amount of easily weatherable fraction that consists especially of biotite, augite and olivine. The high content of microelements is also characteristic in the neighbourhood of ore deposits and metallic redness (Kobza *et al.* 2024). Our goal is to provide evaluation of the content and development of available macronutrients (P, K, Mg) and most basic micronutrients (Cu, Zn, Mn) in topsoil of arable land in Slovakia.

MATERIALS AND METHODS

Soil Monitoring System of Slovakia has been running permanently since 1993. Soil monitoring network is based on ecological principles and it attempts to cover the whole geographical variability of Slovak soilscape. It includes all main soil types and subtypes data, soil substrates, climatic regions, emission regions, polluted and non-polluted regions as well as various land use (Figure 1). There are 318 monitoring sites situated on agricultural soil, including the pastureland at the upper boundary of forest in Slovak mountains. The positions of all soil monitoring sites are expressed in WGS 84 coordinates. The monitoring site has a circular shape, with a radius of 10 m and an area of 314 m^2. Two standard depths

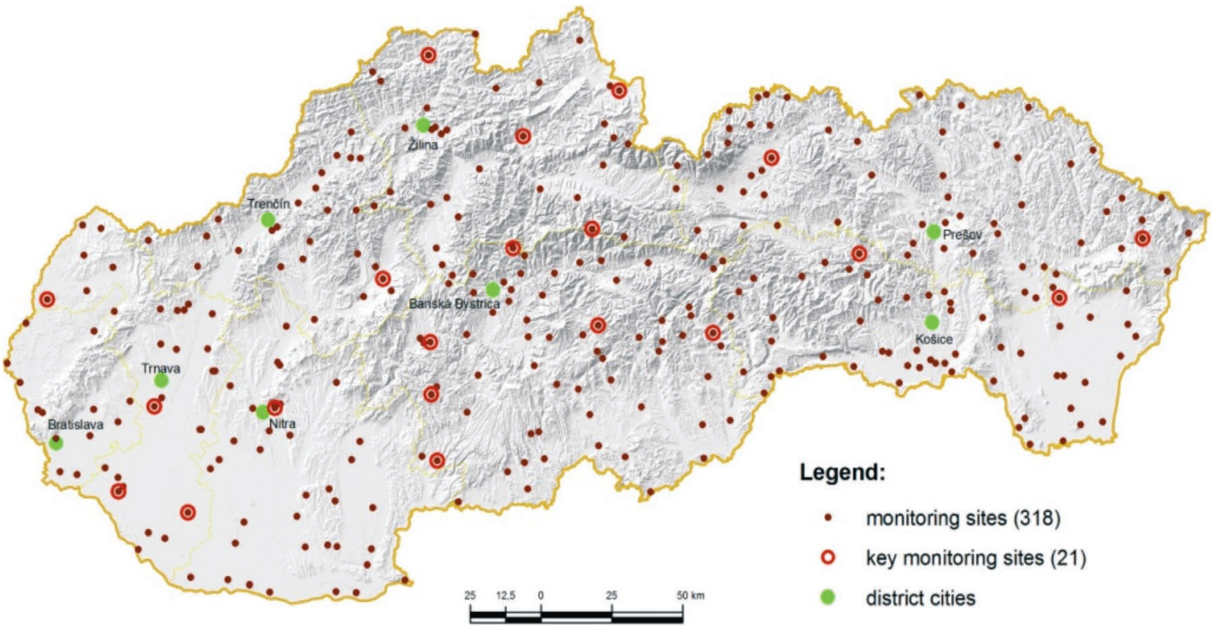

Figure 1 Soil monitoring network in Slovakia

(0–0.10 m and 0.35–0.45 m) on arable land have been sampled, but they were adjusted to represent the main soil horizons. The sampling follows 5-years cycle. he Soil Monitoring System in Slovakia involves the most important soil indicators concerning the soil threats according to the recommendation of the European Commission (EC) for united soil monitoring system of Europe (van Camp *et al.* 2004). In this contribution we evaluate the content and temporal dynamics of available macronutrients (P, K, Mg) and micronutrients (Cu, Zn, Mn) in top layer of arable soils in Slovakia.

Referring to the soil nomenclature and classification, it uses the national Morphogenetic Soil Classification System of Slovakia (Societas pedologica slovaca 2014) which individual soil types were corelated to the WRB (IUSS Working group WRB 2022).

Since the beginning of the Soil Monitoring System in Slovakia (1993) various analytical procedures have been used. Originally, available phosphorus was analysed using Egner´s method, available potassium using the Schachtschabel´s method and magnesium was analysed according to Mehlich II. method. Nowadays, for all macronutrients (P, K and Mg) the Mehlich III. method is used. These methods are possible to compare based on following linear regression equations (Kobza & Gáborík 2008) – Figures 2–4.

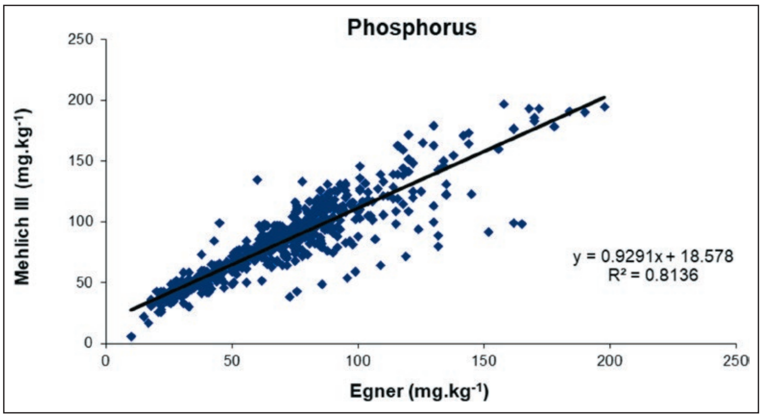

Figure 2 Regression relationship for phosphorus (mg.kg^{-1}) determined with Engler´s and Mehlich III method

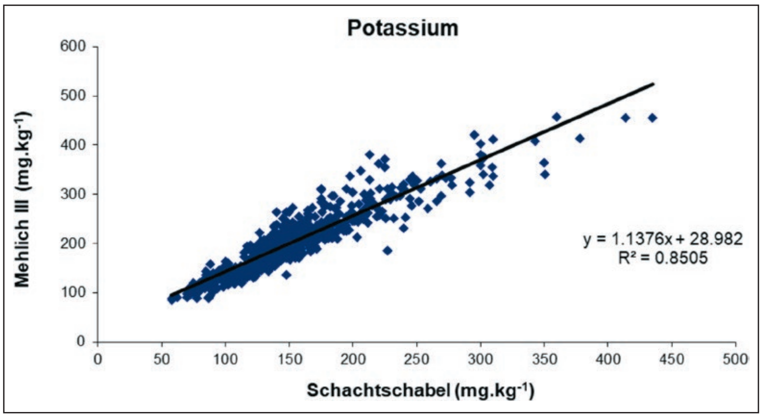

Figure 3 Regression relationship for potassium (mg.kg^{-1}) determined Schachtschabel´s and Mehlich III method

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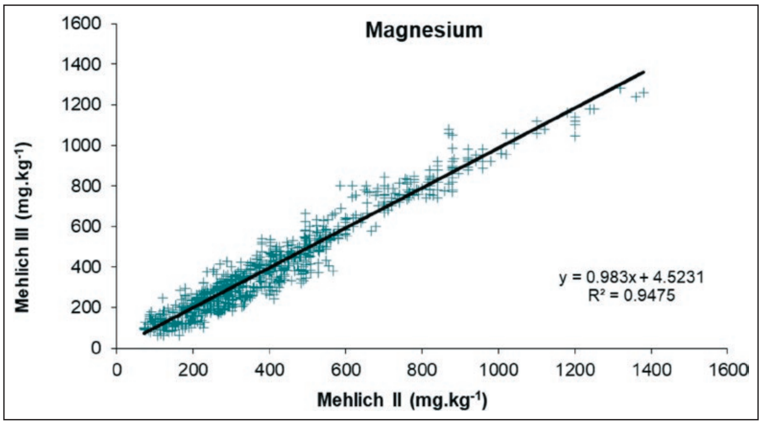

Figure 4 Regression relationship for magnesium (mg.kg^{-1}) determined with Mehlich II and Mehlich III method

The criteria for evaluation of macroelements according to Mehlich III for arable land are given in the Table 1.

Table 1
Criteria for evaluation of macroelements (P, K, and Mg) according to Mehlich III in arable soils (Kobza & Gáborík 2008)

Content	**Soil**		
	S	**L**	**C**
Phosphorus (mg.kg^{-1})			
low	< 60	< 50	< 40
sufficient	61-95	51-85	41-70
good	96 -145	86-125	71-100
high	146-200	126-165	101-135
very high	> 200	> 165	> 135
Potassium (mg.kg^{-1})			
low	< 90	< 130	< 170
sufficient	91-150	131-200	171-260
good	151-230	201-300	261-370
high	231-350	301-400	371-500
very high	> 350	> 400	> 500
Magnesium (mg.kg^{-1})			
low	< 80	< 110	< 145
sufficient	81-135	111-175	146-220
good	136-200	176-255	221-340
high	201-300	256-340	341-470
very high	> 300	> 340	> 470

Three basic microelements (Cu, Zn and Mn) are periodicaly monitored in the Soil Monitoring System of Slovakia but only since the 2nd monitored cycle (1997). These microelements are analysed using the extraction with DTPA (diethylene triamine pentaacetic acid). This is an extraction agent belonging to the category of weak extractans for the purpose to obtain conncentration of elements which can be easily transported in specific conditions (pH, temperature, moisture, sorption capacity, *etc.*) through root system into the vegetative and generative parts of plants and to influence the quality of agricultural crops.

The criteria for evaluation of microelements content are presented in the following Table 2.

Table 2

Criteria for evaluation of microelements content (Jurání *et al.* 1985)

Microelements	Texture	Content		
		small	medium	high
B (Berger – Truog)	sandy	< 0.40	0.41–0.70	> 0.70
	loamy	< 0.60	0.61–1.00	> 1.00
	clayey	< 0.80	0.81–1,50	> 1.50
Cu (Lindsay – Norvell)	small, medium, clayey	< 0,80	0,81–2.70	> 2.70
Zn (Lindsay – Norvell)	small, medium, clayey	< 1.00	1.01–2.50	> 2.50
Mn (Lindsay – Norvell)	small, medium, clayey	< 10.0	10.1–100.0	> 100.0
Fe (Lindsay – Norvell)	small, medium, clayey	< 8.0	8.1–75.0	> 75.0

All chemical and physical procedures have been prepared according to Unified standard operation procedures developed for soil analyses used in Soil Monitoring of Slovakia (Kobza *et al.* 2011). The graphical outputs of basic data and their mathematic/statistical evaluation were processed in GIS.

RESULTS AND DISCUSSIONS

Macroelements

Phosphorus

The content of available nutrients including phosphorus in soils is a result of natural supply and level of fertilization. The natural supply of phosphorus in soils is low, its content is in the range of 0.02–0.04%, i.e. 200–400 mg P.kg^{-1} (Mengel, 1965). In conditions of Slovakia natural supply of phosphorus is also low. The content of phosphorus is an important indicator for plant nourishment. Its important role determined by its participation in energetic processes, such as photosynthesis, respiration, carbohydrate metabolism and proteins (Balík *et al.* 2017, Ivanič *et al.* 1984, Michalík 2001, Vaněk *et. al.* 2012). The lack of phosphorus can be caused by various factors e.g. by soil texture, pH, temperature and water regime (Prášková *et al.* 2017, Smatanová *et al.* 2017).

During the 1st General Pedological Survey of Agricultural Soils (KPP) in Slovakia (1961–1970) the content of available phosphorus (using Egner´s method) was rather low (7.6–38.7 mg.kg^{-1}), reaching a mean value of 22.3 mg.kg^{-1} (Kobza & Styk 1997). Later, due tothe influence of long-term systematic fertilization using often high doses of fertilizers (especially during the 70ties and 80ties of the last century) the significant increase of available nutrients in plough horizon of agricultural soils was detected (phosphorus about 200% and potassium about 100%). Later, after political and economical changes at the beginning of 90th of the last century the fertilizer doses decreased significantly (from 220–230 kg NPK ha^{-1} to 40–60 kg NPK ha^{-1}). Nowadays, the average fertilizer dose is 100.71 kg NPK.ha^{-1} of which phosphorus portion is only 16.86 kg. ha^{-1} (ÚKSUP 2023), i.e. only 16.86% from average dose of NPK fertizer. Therefore, the one of the main topics of soil monitoring in Slovakia is the regular observation of available nutrients. The current average content of available phosphorus (according to Mehlich III) in plough horizon of main soil types in Slovakia is presented in the Table 3.

Table 3
Content of available phosphorus (Mehlich III) in plough horizon (0–10 cm) of main soil types in Slovakia (correlated with WRB 2022, IUSS Working Group WRB 2022)

Soils	P (mg.kg^{-1})		
	X_{min}	X_{max}	X
Chernozems on loess	16.60	360.00	93.57 (g)
Luvisols on loess	20.40	401.00	81.56 (s)
Planosols and Retisols on loess-like loam	5.69	262.00	69.22(s)
Cambisols on crystalline rocks	10.70	135.00	58.50 (s)
Cambisols on volcanic rocks	5.69	81.60	44.97 (l)
Cambisols on flysch	10.60	122.00	50.60 (l)
Rendzic Leptosols	32.40	192.00	106.10 (g)
Fluvisols on calcareous fluvial sediments	9.31	85.90	46.91 (l)
Fluvisols on non-calcareous fluvial sediments	14.10	230.00	63.42 (s)
Phaeozems on calcareous fluvial sediments	9.40	216.00	65.00 (s)
Phaeozems on non-calcareous fluvial sediments	50.50	446.60	139.70 (h)
Regosols on quartzite eolian sands	105.00	244.00	177.00 (vh)

Explanations: X_{min} – minimum value, X_{max} – maximum value, X – arithmetic mean, l – low content, s – sufficient content, g – good content, h – high content, vh – very high content

The content of available phosphorus in arable land of main soil types of Slovakia is presented in the Table 3. The mean content of available phosphorus is rather variable, ranging from 44. 97 to 177 mg.kg^{-1}, i.e. from low to very high content (Kobza & Gáborík 2008). The lowest value of available phosphorus was determined in Cambisols on flysch and volcanic rocks, high to very high content of available phosphorus was determined in Phaeozems on non-calcareous fluvial sediments and Regosols on quarzite eolian sands. Content of phosphorus in soils depends on specific genesis and level of P-fertilization (Kobza 2016). In addition, the lowest supply of available phosphorus was determined on grassland (15–40 mg.kg^{-1}) (Kobza *et al.* 2024) where the level of P-fertilization was low also in the past. Phosphorus ferti-

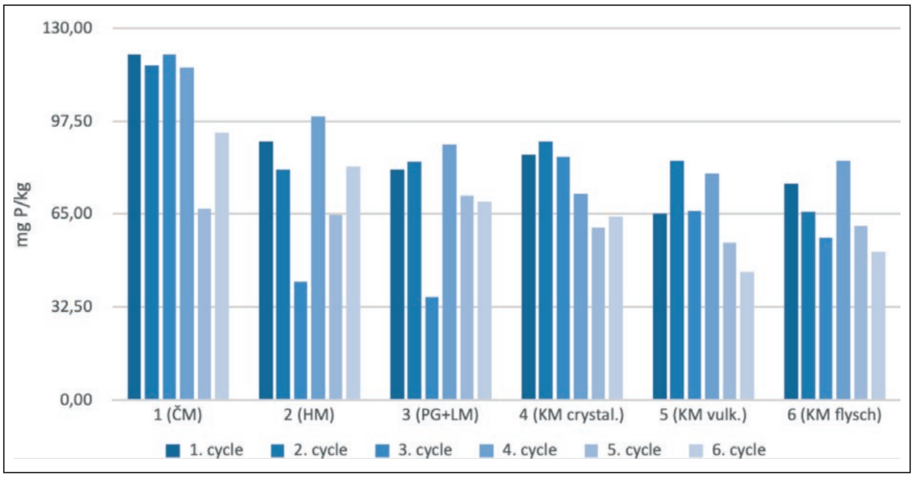

Figure 5a Current development of available phosphorus content in main soil types (arable soils) of Slovakia
Explanations: ČM – Chernozems, HM – Luvisols, PG + LM – Planosols + Retisols, KM crystal. – Cambisols on crystalline rocks, KM volc. – Cambisols on volcanic rocks, KM flysch – Cambisols on flysch

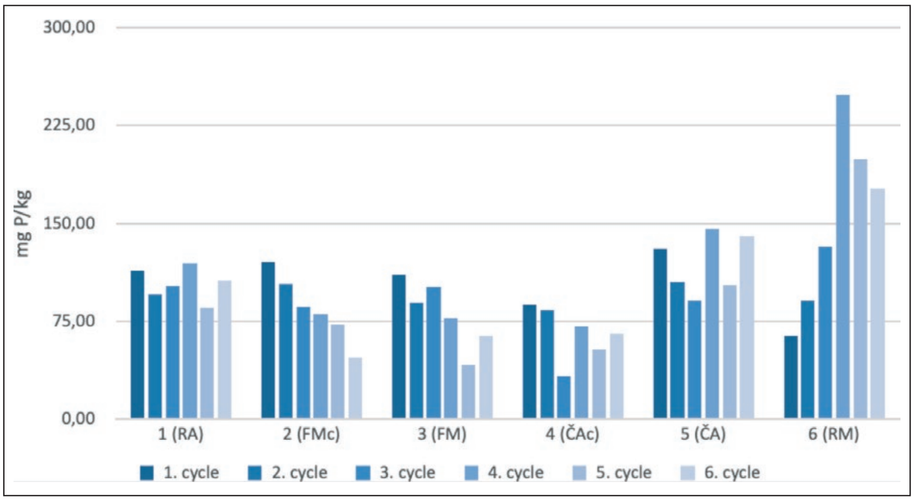

Figure 5b Current development of available phosphorus content in main soil types (arable soils) of Slovakia
Explanations: RA – Rendzic Leptosols, FM^c – Fluvisols on calcareous fluvial sediments, FM – Fluvisols on non-calcareous fluvial sediments, $ČA^c$ – Phaeozems on calcareous fluvial sediments, ČA – Phaeozems on non-calcareous fluvial sediments, RM – Regosols

lization was subsequently reduced with decrease of phosphorus supply also on arable land. The value of Riehm index decreased to 37.9 (Ložek *et al.* 2019). It means the unfavourable soil phosphorus supply that corresponds to the 70th years of the last century. This negative trend of decreasing of available phosphorus soil content has been continuing also in this period. It was confirmed by results of the 13th cycle of agrochemical soil testing realized during the years of 2012–2017 (ÚKSUP 2017).

The current development of available phosphorus in arable soils is presented in the following figures 5a–b.

In general, the content of available phosphorus has a slightly decreasing trend that is caused by decreasing level of fertilization after 1990 and was confirmed also by Gáborík *et al.* (2014). The statistical differences of available phosphorus between the 1st and the 6th monitoringcycle are mostly significant (Tables 4a, b, c). High content of available phosphorus in some soils can be caused by P-fertilization and also as a result of old phosphorus supply in some soils (Chernozems, Phaeozems, Fluvisols) (Kobza *et al.* 2019, 2024).

Table 4a

Statistical testing (F-test) of macroelements content between the 1st and 6th monitorig cycle (Mg between the 2nd and the 6th cycle)

Soils test	**Chernozems**			**Luvisols**			**Planosols + Retisols**			**Cambisols on crystalline rocks**		
	P	K	Mg	P	K	Mg	P	K	Mg	P	K	Mg
Calculated	1.23^-	1.84^-	2.18^-	2.84^+	1.24^-	1.06^-	2.22^+	$1{,}16^-$	1.09^-	3.25^+	1.14^-	1.72^-
$P_{0.05}$	2.1	2.1	2.7	2.1	2.1	2.5	1.8	1,8	2.5	3.2	3.2	6.4
$P_{0.01}$	2.9	2.9	4.2	2.9	2.9	3.7	2.4	2,4	3.7	5.4	5.4	16.0
- non-significant difference, +significant difference, ++ strongly significant difference												

Table 4b

Statistical testing (F-test) of macroelements content between the 1st and 6th monitored cycle (Mg between the 2nd and the 6th cycle)

Soils test	Cambisols on volcanic rocks			Cambisols on flysch			Rendzic Leptosols			Fluvisols on calcareous fluvial sediments		
	P	K	Mg*	P	K	Mg	P	K	Mg	P	K	Mg
Calcuated	1.49^{-}	1.47^{-}	–	1.32^{-}	2.75^{-}	1.05^{-}	3.74^{-}	1.48^{-}	1.68^{-}	5.00^{++}	1.31^{-}	1.02^{-}
$P_{0.05}$	9.3	9.3	–	2.5	2.7	3.4	5.1	5.1	18.5	2.1	2.1	2.7
$P_{0.01}$	29.5	29.5	–	3.7	4.2	6.0	11.0	11.0	98.5	2.8	2.8	4.2
Mg* - low frequency of file												

Table 4c

Statistical testing (F-test) of macroelements content between the 1st and 6th monitored cycle (Mg between the 2nd and the 6th cycle)

Soils test	Fluvisols on non-calcareous fluvial sediments			Phaeozems on calcareous fluvial sediments			Phaeozems on non-calcareous fluvial sediments			Regosols* on quarzite eolian sands		
	P	K	Mg	P	K	Mg*	P	K	Mg	P	K	Mg*
Calculated	2.47^{+}	6.19^{-}	1.98^{-}	4.8^{++}	1.54^{-}	2.46^{-}	2.78^{+}	1.28^{-}	1.84^{-}	–	–	–
$P_{0.05}$	2.1	2.1	3.2	2.7	2.7	2.7	2.5	2.5	4.3	–	–	–
$P_{0.01}$	2.9	2.9	5.4	4.2	4.2	4.2	3.7	3.7	8.5	–	–	–
Regosols* - low frequency of file												

Potassium

Potassium is a very important nutrient for the crops. It has a big influence on regulation of water regime in plants and creation of favourable turgor in the cells. Potassium directly activates enzymatic reactions, and it is helpful for synthesis of albumen, sacharides, fat, starch and celulosis. Significance of potassium consists of increasing the plant resistance against stress factors, e.g. the high concentration of cell sap by the influence of frost when their point is moved to the lower one. In addition, potassium is helpful against fungal and bacterial diseases by the creation of more stabile cell walls.

The primary sources of potassium in soil are mineral. It is released mainly from the feldspars and mica minerals. The secondary silicates are created by weathering. Most important are the clay minerals that can fix the significant part of free potassium released from primary minerals (Torma 1999). The potassium content in soil is controled not only by soil minerals but also by fertilizers and organic manures, atmospheric rainfall and deposits, irrigation water, as well as by seeds for sowing and seedlings crops and all these sources contribute to total potassium content in the soil (Bujnovský *et al.* 1994). Behaviour of potassium depends on various factors, e.g. the soil depth, skeleton content and pH. The acid soil reaction increases the potassium mobility in soil profile (Baier 1980, Barber 1984, Johnson 1986).

The potassium supply in comparison with phosphorus is better as a result of better mineral sources available in most Slovak soils. Content of available potassium during the period of General Survey of Agricultural Soils (KPP) accomplished in 1960–1970 was in the range of 64.4–129.1 $mg.kg^{-1}$ with a mean value of 108 mg K kg^{-1} (Kobza & Styk 1997). Later, during the 70th and 80th of the last century the content of available potassium was increasing due to intensive K-fertilization. At the beginning of Soil Monitoring of Slovakia (1993 year) the content of available potassium in plough horizon of arable soils was in the range of 150–300 $mg.kg^{-1}$ that presents the medium supply of this nutrient in arable soils (Kobza & Gáborík 2008). Later, by the influence of decreasing fertilization the available potassium content in arable soils was declining (on average by ca 15–20%). The current mean dose of potassium applied into the soil using K-fertilizers is 11.85 kg per ha (ÚKSUP 2023). Current development of available potasium content (from 1993 year) is illustrated on the Figures 6a–b.

Table 5

Content of available potassium (Mehlich III) in plough horizon (0–10 cm) of main soil types in Slovakia

Soils	K (mg.kg^{-1})		
	X_{min}	X_{max}	X
Chernozems on loess	123.00	705.00	295.60 (g)
Luvisols on loess	91.50	662.00	267.12 (g)
Planosols and Retisols on loess-like loam	58.80	241.00	115.70 (l)
Cambisols on crystalline rocks	116.00	562.00	223.30 (g)
Cambisols on volcanic rocks	89.10	507.00	223.00 (g)
Cambisols on flysch	61.10	292.00	156.90 (s)
Rendzic Leptosols	172.00	413.00	267.00 (g)
Fluvisols on calcareous fluvial sediments	51.70	393.00	203.48 (g)
Fluvisols on non-calcareous fluvial sediments	136.00	373.00	209.90 (g)
Phaeozems on calcareous fluvial sediments	80.00	411.00	222.40 (g)
Phaeozems on non-calcareous fluvial sediments	161.00	698.00	342.80 (h)
Regosols on quartzite eolian sands	43.20	287.00	138.62(s)

Explanations: X_{min} – minimum value, X_{max} – maximum value, X – arithmetic mean, l – low content, s – sufficient content, g – good content, h – high content, vh – very high content

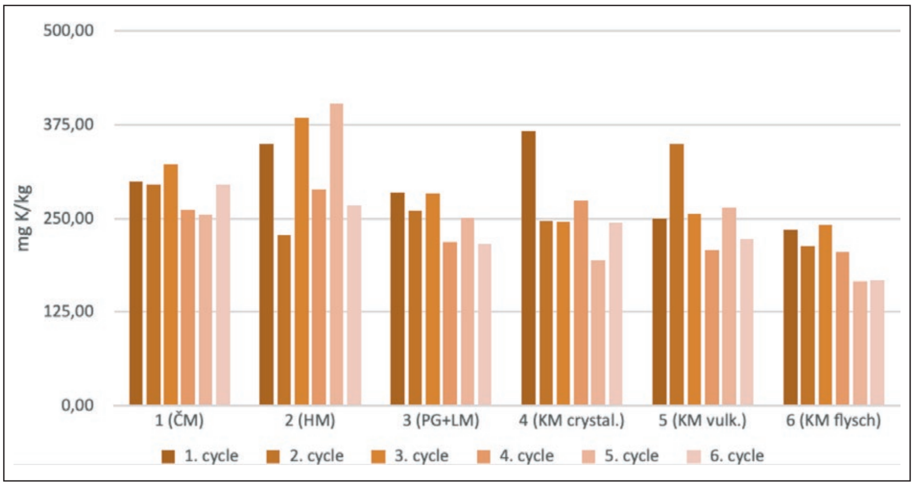

Figure 6a Current development of available potassium content in main soil types (arable soils) of Slovakia
Explanations: ČM – Chernozems, HM – Luvisols, PG + LM – Planosols + Retisols, KM crystal. – Cambisols on crystalline rocks, KM volc. – Cambisols on volcanic rocks, KM flysch – Cambisols on flysch

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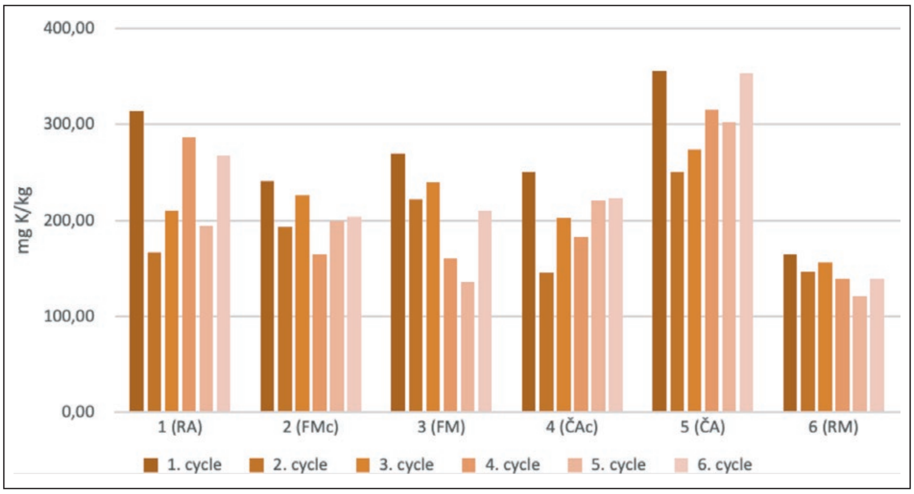

Figure 6b Current development of available potassium content in main soil types (arable soils) of Slovakia
Explanations: RA – Rendzic Leptosols, FM^c – Fluvisols on calcareous fluvial sediments, FM – Fluvisols on non-calcareous fluvial sediments, ČA^c – Phaeozems on calcareous fluvial sediments, ČA – Phaeozems on non-calcareous fluvial sediments, RM – Regosols

The development of available potassium content in evaluated soils is more or less variable and heterogenous. In comparison with values detected at the beginning of soil monitoring we can observe the slight decrease of available potassium content in arable land that was already confirmed in previous work (Kobza *et al.* 2024). The heterogeneity of evaluated nutrient can be caused by different K-fertilization, consumption of this nutrient by various plants as well as different mineral composition (Kobza 2016a). The highest content of available potassium was observed in Chernozems, Phaeozems and Luvisols (IUSS Working Group WRB 2022). These soils are among the most important cultivated soils in Slovakia. The lowest content of available potassium was determined in Planosols, Retisols and Regosols on quarzite eolian sands situated mostly in Záhorská Lowland.

Magnesium

Magnesium is the fifth main nutrient in plant nourishment (Hrtánek & Kobza, 1980). Average content of magnesium in litosphere is 2.5% and its content in soils is in the range of 0.05–0.5% (Čurlík *et al.*, 2003). Magnesium is distributed in several primary relatively easily weatherable minerals (olivine, serpentine, biotite), and also in secondary minerals (smektites, chlorite, vermikulite). In calcareous soils magnesium is a component of magnesite ($MgCO_3$), respectively dolomite ($MgCO_3.CaCO_3$) which are abundant in great (Kobza & Gáborík 2009). Magnesium has a significant influence on quality of agricultural crops, as well as on the content of carbohydrates and it has also a significant influence on formation of proteins. Consumption of agricultural products with sufficient content of magnesium is important against „civilizing deseases“ such as the deseases of blood circulation system and cancer (Kobza 2013).

The content of available magnesium differs in different soil types and it is in correlation with soil texture, pH value and potassium content (Fecenko & Ložek 2000). Most arable soils in Slovakia has a good supply of magnesium (Kobza *et al.* 2019, 2024). It depends on natural supply of this element in soil parent material. In comparison with the 10th cycle of Agrochemical testing of agricultural soils (ASP) the area with high supply of magnesium decreased by ca 18.19% (Kobza & Gáborík 2008). On the other side the areas with low and medium supply of magnesium extended. It is caused probably by the lack of liming by dolomite where magnesium is the main component. The content of available magnesium in main soil types (arable soils) of Slovakia is presented in the Table 6.

Table 6
Content of available magnesium (Mehlich III.) in plough horizon (0–10 cm) of main soil types in Slovakia

Soils	Mg (mg.kg^{-1})		
	X_{min}	X_{max}	X
Chernozems on loess	291.00	529.00	388.60 (vh)
Luvisols on loess	128.00	595.00	370.06 (vh)
Planosols and Retisols on loess-like loam	63.80	525.00	221.50 (g)
Cambisols on crystalline rocks	150.00	509.00	290,60 (h)
Cambisols on volcanic rocks	185.00	409.00	253.00 (g)
Cambisols on flysch	95.00	422.00	240.20 (g)
Rendzic Leptosols	344.00	924.00	667.00 (vh)
Fluvisols on calcareous fluvial sediments	126.00	850.00	394.28 (vh)
Fluvisols on non-calcareous fluvial sediments	186.00	838.00	438.30 (vh)
Phaeozems on calcareous fluvial sediments	176.00	1174.00	609.40 (vh)
Phaeozems on non-calcareous fluvial sediments	163.00	549.00	333.00 (h)
Regosols on quartzite eolian sands	23.30	101.00	52.22 (l)

Explanations: X_{min} – minimum value, X_{max} – maximum value, X – arithmetic mean, l – low content, s – sufficient content, g – good content, h – high content, vh – very high content

The content of available magnesium in plough horizon is fluctuating in a wide range of 52.22–667 mg.kg^{-1} (low to very high content). The lowest content of available magnesium is in Regosols on quarzite eolian sands distributed mostly in Záhorská Lowland). However, in most arable soils the values of available magnesium are good to very high (221.50–667 mg.kg^{-1}), what was confirmed also in previous works (Kobza *et al.* 2019, 2024, Gáborík & Prístavka 2015). It means that arable soils in Slovakia have a good supply of magnesium despite no Mg-fertilizers (except liming by dolomite fertilizers) were applied to soil neither in the past nor nowadays. Most soils of Slovakia has sufficient natural sources of magnesium.

The current development of available magnesium content since the 2nd monitoring cycle i.e. since 1997 (in the 1st cycle Mg was not monitored) is shown on the Figure 7a, b.

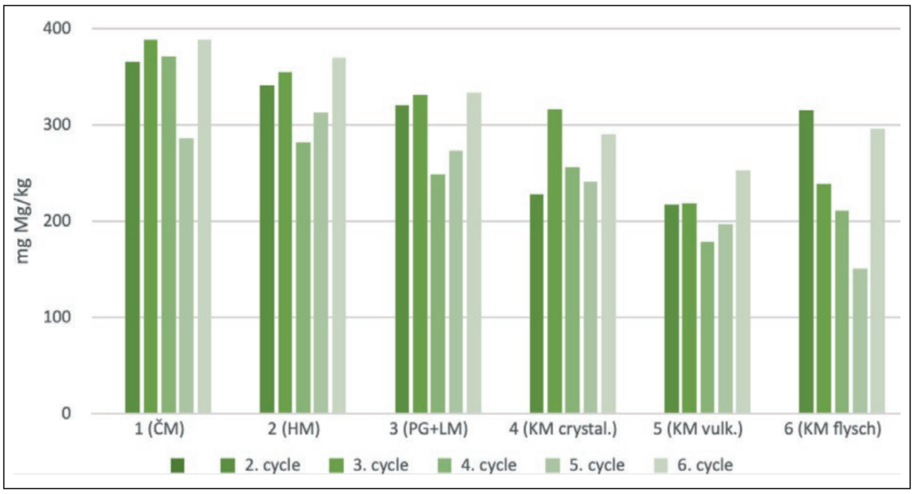

Figure 7a Current development of available magnesium content in main soil types (arable soils) of Slovakia
Explanations: ČM – Chernozems, HM – Luvisols, PG + LM – Planosols + Retisols, KM crystal. – Cambisols on crystalline rocks, KM volc. – Cambisols on volcanic rocks, KM flysch – Cambisols on flysch

Original paper

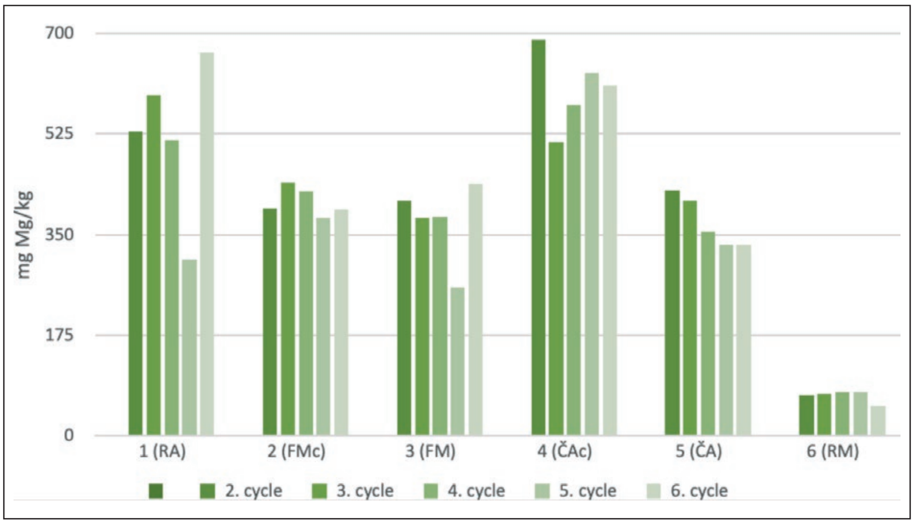

Figure 7b Current development of available magnesium content in main soil types (arable soils) of Slovakia
Explanations: RA – Rendzic Leptosols, FM^c – Fluvisols on calcareous fluvial sediments, FM – Fluvisols on non-calcareous fluvial sediments, ČA^c – Phaeozems on calcareous fluvial sediments, ČA – Phaeozems on non-calcareous fluvial sediments, RM – Regosols

In general, no significant difference of magnesium content in soils was recorded between the 2nd and 6th monitoring cycle (Tables 4a, b, c). The variability of available magnesium content in presented cycles can be caused by mineralogical composition of soils and its heterogeneity in soil environment (Kobza *et al.* 2009, 2014, 2019) because Mg fertilization was not done in Slovakia. Finally, it may be said that arable soils in Slovakia have a good supply of available magnesium except Regosols on quarzite eolian sands mostly distributed in Záhorská Lowland what was already confirmed in the previous works (Gáborík *et al.* 2015, Kobza *et al.* 2019, 2024).

Microelements

Copper

Copper belongs to the most important microelements. Its shortage restricts root growth of some plants (especially vineyards) and can cause chlorosis of leaves. It can cause also a limited creation of flowers. Wilting of plants is another common symptom. Crops sensitive to copper sortage are salad and spinach and also red beet, onion and legumes (Demo *et al.* 2002).

The current content of copper in main soil types (arable soils) in Slovakia is presented in the Table 7.

The mean copper content in agricultural soils of Slovakia is ranging from 0.73 to 5.07 mg.kg^{-1} (small to high content). The lowest content of copper was indicated in Regosols on quarzite eolian sands (distributed mostly in Záhorská Lowland). The highest content of copper was determined in Fluvisols on calcareous and non-calcareous alluvial sediments. Increased content of copper is also in Cambisols on crystalline rocks where the geochemical anomalies, especially in mountain and submountain regions, increase the mineral variability. In addition, the increased values of copper content were observed also in soils under the vineyards as an influence of Cu-chemicals used for grape cultivation.

The current development of copper content is shown on the Figure 8a, b.

Original paper

Table 7
Content of copper (DTPA) in plough horizon (0-10 cm) of main soil types in Slovakia

Soils	Cu (mg.kg^{-1})		
	X_{min}	X_{max}	X
Chernozems on loess	0.87	3.28	2.36 (m)
Luvisols on loess	1.19	13.71	2.16 (m)
Planosols and Retisols on loess-like loam	0.89	4.19	1.60 (m)
Cambisols on crystalline rocks	1.00	9.80	3.30 (h)
Cambisols on volcanic rocks	0.74	2.85	1.73 (m)
Cambisols on flysch	0.90	4.00	1.80 (m)
Rendzic Leptosols	0.05	15.13	2.13 (m)
Fluvisols on calcareous fluvial sediments	1.60	25.70	5.07 (h)
Fluvisols on non-calcareous fluvial sediments..	0.69	25.00	4.04 (h)
Phaeozems on calcareous fluvial sediments	1.95	5.00	3.40 (h)
Phaeozems on non-calcareous fluvial sediments	1.62	5.88	3.36 (h)
Regosols on quartzite eolian sands	0.43	0.99	0.73 (l)

Explanations: X_{min} – minimum value, X_{max} – maximum value, X – arithmetic mean, l – low content, m – medium content, h – high content

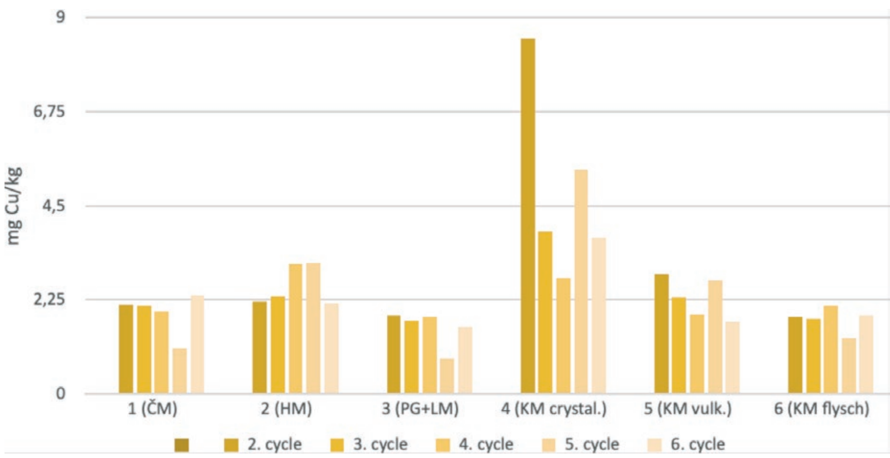

Figure 8a Current development of copper content in main soil types of Slovakia (arable soils)
Explanations: ČM – Chernozems, HM – Luvisols, PG + LM – Planosols + Retisols, KM crystal. – Cambisols on crystalline rocks, KM volc. – Cambisols on volcanic rocks, KM flysch – Cambisols on flysch

Original paper

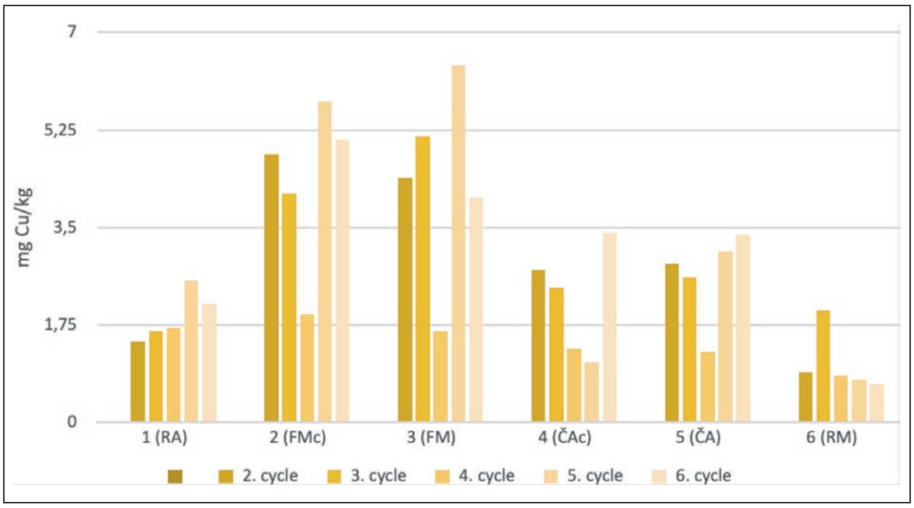

Figure 8b Current development of copper content in main soil types (arable soils) of Slovakia
Explanations: RA – Rendzic Leptosols, FM[c] – Fluvisols on calcareous fluvial sediments, FM – Fluvisols on non-calcareous fluvial sediments, ČA[c] – Phaeozems on calcareous fluvial sediments, ČA – Phaeozems on non-calcareous fluvial sediments, RM – Regosols

Table 8a
Statistical testing (F-test) of microelements content in arable soils between the 2[nd] and the 6[th] monitored cycle

Soils test	Chernozems			Luvisols			Planosols + Retisols			Cambisols on crystalline rocks		
	Cu	Zn	Mn	Cu	Zn	Mn	Cu	Zn	Mn	Cu	Zn	Mn
Calculated	1.27-	1.89-	1.21-	1.94-	1.49-	2.34+	1.26	1.05	2.33	5.26++	5.90++	2.58-
$P_{0.05}$	2.5	2.5	2.5	2.1	2.1	2.1	1.8	1.8	1.8	2.7	2.7	2.7
$P_{0.01}$	3.7	3.7	3.7	2.9	2.9	2.9	2.4	2.4	2.4	4.2	4.2	4.2
- non-significant difference, +significant difference, ++ strongly significant difference												

Table 8b
Statistical testing (F-test) of microelements content in arable soils between between the 2[nd] and the 6[th] monitored cycle

Soils test	Cambisols on volcanic rocks			Cambisols on flysch			Rendzic Leptosols			Fluvisols on calcareous fluvial sediments		
	Cu	Zn	Mn	Cu	Zn	Mn	Cu	Zn	Mn	Cu	Zn	Mn
Calculated	6.53	2.48	19.79	1.88-	1.92-	2.47-	2.42-	1.52-	1.56-	1.27	1.27	1.60
$P_{0.05}$	19.0	19.0	19.0	2.7	2.7	2.7	9.3	9.3	9.3	2.1	2.1	2.1
$P_{0.01}$	99.0	99.0	99.0	4.2	4.2	4.2	29.5	29.5	29.5	2.9	2.9	2.9
- non-significant difference, +significant difference, ++ strongly significant difference												

Table 8c
Statistical testing (F-test) of microelements content in arable soils between between the 2[nd] and the 6[th] monitored cycle

Soils test	**Fluvisols on non-calcareous fluvial sediments**			**Phaeozems on calcareous fluvial sediments**			**Phaeozems on non-calcareous fluvial sediments**			**Regosols on quarzite eolian sands**		
	Cu	**Zn**	**Mn**	**Cu**	**Zn**	**Mn**	**Cu**	**Zn**	**Mn**	**Cu**	**Zn**	**Mn**
Calculated	2.26	2.23	3.18	1.09-	2.85+	1.34-	2.26	2.23	3.18	–	–	–
$P_{0.05}$	2.1	2.1	2.1	2.7	2.7	2.7	2.1	2.1	2.1	–	–	–
$P_{0.01}$	2.9	2.9	2.9	4.2	4.2	4.2	2.9	2.9	2.9	–	–	–
- non-significant difference, +significant difference, ++ strongly significant difference, Regosols – low frequency of file												

Statistical testing (F-test) of microelements content in arable soils between the 2nd and the 6th monitored cycle is in Tabs. 8 a, b, c.

The results obtained from several monitoring cycles showed that the copper content is rather variable. The highest content was found in Fluvisols and Cambisols with a varied geological and mineralogical composition containing rocks with a wide choice of heavy metals including copper. The higher content of copper was determined not only in extraction with aqua regia but also in DTPA (diethylene triamine pentaacetic acid). In this case copper is evaluated as a micronutrient. The copper content in evaluated soils is mostly medium to high (Table 7). Similar results were obtained also in Czech Republic (Poláková *et al.* 2017).

Zinc

Zinc is an activator and stabilizer of enzymes responsible for metabolism of plants – consumption of sacharides, oxidation processes and transformation of amino acids. The synthesis of RNA, proteins and amyloids is decreasing under the zinc shortage and the formation of chlorophyle can be disturbed (Fecenko & Ložek 2000). The optimal content of zinc in soils is in the range of 1.01–2.5 $mg.kg^{-1}$ and this amount is classified as medium content (Kobza & Gáborík 2008).

The content of zinc in arable soils in Slovakia is presented in the Table 9.

Table 9

Content of zinc (DTPA) in plough horizon (0-10 cm) of main soil types in Slovakia

Soils	**Zn ($mg.kg^{-1}$)**		
	X_{min}	X_{max}	X
Chernozems on loess	0.40	3.64	1.26 (m)
Luvisols on loess	0.15	4.62	1.28 (m)
Planosols and Retisols on loess-like loam	1.30	5.18	2.31 (m)
Cambisols on crystalline rocks	0.60	3.70	1.50 (m)
Cambisols on volcanic rocks	2.21	3.38	2.62 (h)
Cambisols on flysch	0.60	3.90	1.60 (m)
Rendzic Leptosols	2.15	4.77	3.40 (h)
Fluvisols on calcareous fluvial sediments	0.87	21.60	2.91 (h)
Fluvisols on non-calcareous fluvial sediments	1.20	17.40	3.45 (h)
Phaeozems on calcareous fluvial sediments	0.68	6.32	2.01 (m)
Phaeozems on non-calcareous fluvial sediments	0.56	5.31	3.23 (h)
Regosols on quartzite eolian sands	1.38	2.80	2.21 (m)
Explanations: X_{min} – minimum value, X_{max} – maximum value, X – arithmetic mean, l – low content, m – medium content, h – high content			

The content of zinc in arable soils is mostly in the range of 1.26–3.45 $mg.kg^{-1}$ (medium to high content). The highest values of zinc were measured in Fluvisols and Phaeozems on non-calcareous fluvial sediments and in Rendzic Leptosols. Other soils have mostly a medium supply of zinc (Table 9). Nowadays, it can be said that medium to high content of zinc is predominant in arable soils of Slovakia.

The current development of zinc content in arable soils is illustrated on the Figures 9a, b.

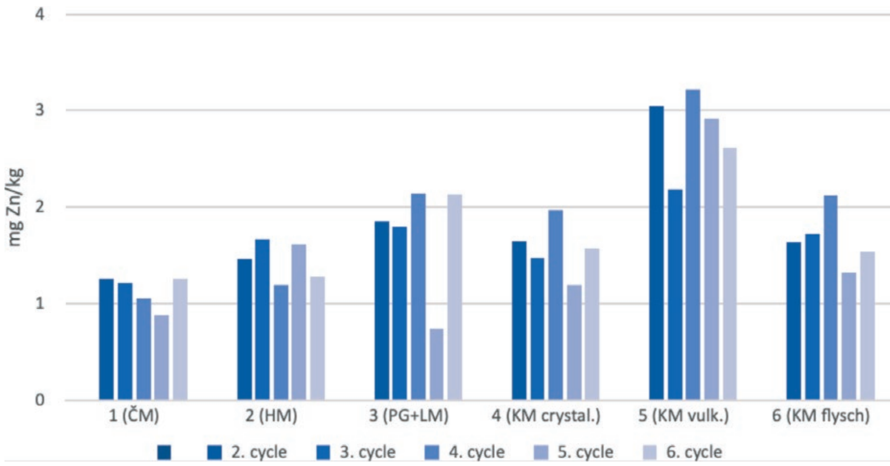

Figure 9a Current development of zinc content in main soil types (arable soils) of Slovakia
Explanations: ČM – Chernozems, HM – Luvisols, PG + LM – Planosols + Retisols, KM crystal. – Cambisols on crystalline rocks, KM volc. – Cambisols on volcanic rocks, KM flysch – Cambisols on flysch

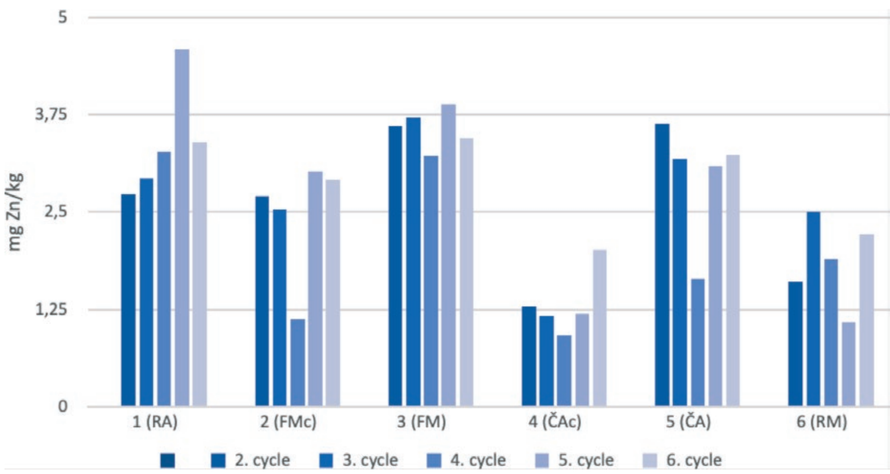

Figure 9b Current development of zinc content in main soil types (arable soils) of Slovakia
Explanations: RA – Rendzic Leptosols, FM^c – Fluvisols on calcareous fluvial sediments, FM – Fluvisols on non-calcareous fluvial sediments, $ČA^c$ – Phaeozems on calcareous fluvial sediments, ČA – Phaeozems on non-calcareous fluvial sediments, RM – Regosols

The development of zinc content in arable soils of Slovakia is more or less variable and depends on mineralogical composition and its heterogeneity. Similarly, like for copper also for zinc the significant deficiency was not indicated in evaluated soils, what we already mentioned in some previous works (Kobza 2016b, Kobza *at al.* 2019). The difference of mean values of zinc for concrete soil types between the 2nd and the 6th monitored cycle is mostly statistically not significant. It is caused by natural variability of this element in evaluated soils.

Manganese

The role of manganese in plant physiology concerns several important processes such as the activation of enzymes, participation in phosphate reactions and oxidation and decarbonation reactions of organic acids of three-carbonation cycle. Furthermore, manganese increases the intensity of respiration and metabolism what stimulates the development of vegetative organs of crops. In addition, manganese positively influences the formation of L-ascorbic acid (C vitamin) as well as RNA and DNA synthesis. Its shortage hinders the chloroplasts formation and this resuts in decreasing activiy of photosynthesis processes and lowers the synthesis of sacharides and amyloids (Fecenko & Ložek 2000).

The content of manganese in arable soils of Slovakia is presented in the Table 10.

Table 10

Content of manganese (DTPA) in plough horizon (0–10 cm) of main soil types in Slovakia

Soils	**Mn (mg.kg^{-1})**		
	X_{min}	X_{max}	X
Chernozems on loess	19.50	136.00	45.78 (m)
Luvisols on loess	3.35	109.00	22.64 (m)
Planosols and Retisols on loess-like loam	6.35	56.40	25.90 (m)
Cambisols on crystalline rocks	20.00	94.40	48.50 (m)
Cambisols on volcanic rocks	21.20	30.20	24.76 (m)
Cambisols on flysch	18.20	98.70	54.90 (m)
Rendzic Leptosols	15.00	38.70	26.20 (m)
Fluvisols on calcareous fluvial sediments	9.30	36.60	18.29 (m)
Fluvisols on non-calcareous fluvial sediments	13.10	59.70	33.23 (m)
Phaeozems on calcareous fluvial sediments	6.90	22.20	15.45 (m)
Phaeozems on non-calcareous fluvial sediments	7.59	82.90	45.68 (m)
Regosols on quartzite eolian sands	14.10	24.00	19.72 (m)

Explanations: X_{min} – minimum value, X_{max} – maximum value, X – arithmetic mean, l – low content, m – medium content, h – high content

The mean manganese content in arable soils of Slovakia is in the range of 15.45–54.90 mg.kg^{-1}, that refers to its medium content. Nowadays, it may be said that soils in Slovakia have a good supply of this micronutrient. The prospective lack of manganese in some soils can be caused more by local conditions than its absence in soil (Demo *et al.* 2002).

The current development of manganese content is illustrated on the following Figures 10a–b.

The development of manganese content is rather variable since the beginning of soil monitoring of Slovakia in 1993 (Figures 10a-b). This variability was reported already in some previous works (Kobza & Gáborík 2008, Kobza *et al.* 2014, 2019). The general trend is mostly in direction of its slight decrease in comparison with the 2nd monitored cycle (start of regular monitoring of microelements). Its variability is caused mostly by way of cultivation as well as by pedogenetic processes, e.g., by soil erosion because

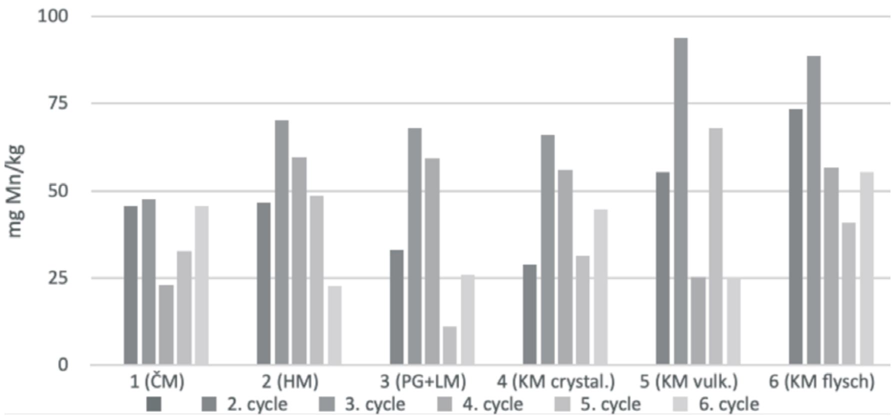

Figure 10a Current development of manganese content in main soil types (arable soils) of Slovakia
Explanations: ČM – Chernozems, HM – Luvisols, PG + LM – Planosols + Retisols, KM crystal. – Cambisols on crystalline rocks, KM volc. – Cambisols on volcanic rocks, KM flysch – Cambisols on flysch

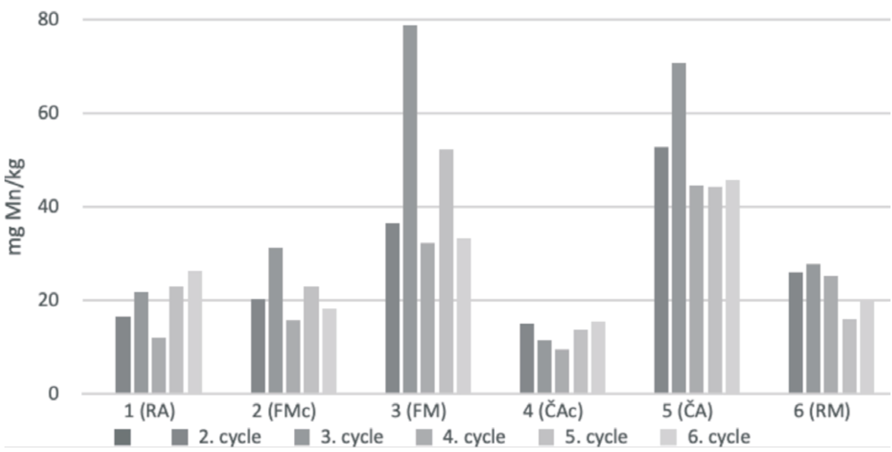

Figure 10b Current development of manganese content in main soil types (arable soils) of Slovakia
Explanations: RA – Rendzic Leptosols, FM^c – Fluvisols on calcareous fluvial sediments, FM – Fluvisols on non-calcareous fluvial sediments, ČA^c – Phaeozems on calcareous fluvial sediments, ČA – Phaeozems on non-calcareous fluvial sediments, RM – Regosols

this micronutrient was not aplicated as fertiliser neither nowadays nor in the past (Kobza 2016b, Kobza *et al.* 2019).

The measured values of manganese content in previous monitoring cycles were running mostly in the range of 10–100 mg.kg^{-1} what represents medium content of manganese in soils (Kobza & Gáborík 2008).

CONCLUSION

It was determined that the content of available phosphorus (using Mehlich III method) in arable soils of Slovakia is fluctuating in the wide range (from 44.97 to 177 mg.kg^{-1}) and represents low to very high content. The development of available phosphorus resources reflected the lowering of fertilisation doses resuling in slight decrease of the available phosporus content.

Similarly, the content of available potassium (Mehlich III method) is also fluctuating in the wide range (115.7–342.8 mg.kg^{-1}). The lowest values of available potassium content was measured in Planosols and Retisols (IUSS Working Group WRB 2022) and Regosols on quartzite eolian sands (mostly in Záhorská nížina – lowland), the highest values of available potassium content are in Phaeozems on non-calcareous fluvial sediments and in Chernozems. The development of available potassium content is rather variable and depends on various level of K-fertilization.

The content of magnesium (Mehlich III method) is sufficient to high in agricultural soils of Slovakia (mostly in the range from 52.22 to 667 mg.kg^{-1}). The lowest content of magnesium was determined in Regosols on quartzite eolian sands and the highest content of magnesium was determined in Rendzic Leptosols. In general, based on obtained results it may be said that in arable soils of Slovakia the magnesium supply is good to high.

In addition, the content of microelements (Cu, Zn, Mn – extracted with DTPA) is mostly medium to high in arable soils of Slovakia. The development of microelements content shows slight decrease since the starting of monitoring in 1993. The local increased values of microelements content were indicated in the regions with the influence of geochemical anomalies and in areas with cultivation of some special crops (e.g. vineyards with influence of Cu-chemical preparates).

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