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Magnesium in Soils of Agricultural Landscapes of Western Siberia

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ABSTRACT

Background: Western Siberia has great potential for crop and livestock production; it is limited by degradation of soil fertility due to depletion of biophilic elements, including Mg. Intensification of agricultural production requires monitoring and optimization of magnesium nutrition of field crops. This study aimed at investigating changes in content of magnesium forms Gleyic Chernozems and Luvic Greyzemic Phaeozem in the Western Siberia during their long-term agricultural use.

Methods: Soil samples were taken from the fields of long-term experiments in 1978, 1988 and 2019. Three cores were taken from a soil layer 0-20, 20-40 cm thick and combined into composite samples. Composite samples were kept in the archives of the institute. Chemical analysis of composite soil samples was carried out in 2020. Chemical analyzes of soil and plants were carried out by conventional methods. Magnesium forms were extracted: easily exchangeable with 0.0025 M $CaCl_2$ solution, exchangeable with 1 M CH_3COONH_4, non-exchangeable with 1 M HNO_3 and determined on an atomic absorption spectrometer.

Result: Systematic use of the ammonia form of nitrogen fertilizers (60-120 kg a.m./ha per year) led to a decrease in mobile forms of magnesium in the most root-inhabited soil layer. The removal of magnesium by potatoes was small (8-10 kg/ha, 80 % falls on the tops). Consequently, a significant decrease in the reserves of magnesium available to plants in soils is associated not so much with the alienation of the element with yield, but with leaching processes due to the displacement of magnesium from the soil-absorbing complex by ammonium ions introduced with fertilizers and also, probably, potassium.

Key words: Biogenic elements, Farmland, Forms of magnesium, Gleyic chernozems, Luvic greyzemic phaeozem.

INTRODUCTION

The biogeochemical problem of deficiency of Ca, Mg, K, Co, Cu, Mo, Zn for agricultural crops leads to decrease in yield and deterioration in the quality of plant products and then to a deficiency of these elements in the food chain and the resulting diseases of animals and humans (Rosanoff, 2013; Jayalaxmi *et al*., 2015; Cazzola *et al*., 2020; Yakimenko *et al*., 2020). Magnesium's main physiological role is to participate in the process of photosynthesis and nitrogen metabolism (Voevodina and Voevodin, 2015; Nechaeva *et al*., 2019; Abbas *et al*., 2024).

The essential role of magnesium in the formation of the physical and physicochemical properties of the soil is also well known. Its gross content in the soils of the agricultural zone of the temperate zone is on average 0.5-1.5%, depending on the mineralogical and granulometric composition, as well as the type of soil formation (Maguire and Cowan, 2002; Sheudzhen, 2003; Shoba and Chudnenko, 2019). Magnesium is important for plant nutrition, which is in the soil absorbing complex (mobile, available, exchangeable) and in the soil solution (water-soluble, easily exchangeable). The richest in mobile magnesium are chernozems, chestnuts soils and others. Magnesium ions are highly hydrated and therefore very poorly absorbed by the soil (Jakovljeviã *et al*., 2003; Sheudzhen *et al*., 2015).

For a long time, the scientific press reported on the growing depletion of the magnesium fund in agricultural soils of not only light but also heavier granulometric composition (Afanas'ev, 2005; Bogdevich and Lomonos, 2009; Shil'nikov *et al*., 2008; Chaudhry *et al*., 2021). This is due to the leaching of magnesium from the upper soil layers, the increased migration ability of this cation and to the uncompensated removal of the element by crops and other anthropogenic influences (Godunova *et al*., 2013; Gransee and Führs, 2013; Litvinovich *et al*., 2020; Marschner, 2012; Nechaeva *et al*., 2019). Intensification of agricultural production requires monitoring and optimization of magnesium nutrition in field crops, especially for plants consuming large quantities of it (Frau *et al*., 2020; Guo *et al*., 2015).

Nutrient imbalance is one of the main factors limiting the yield and quality of crops (Wacal *et al*., 2019). World experience shows that mineral fertilizers contribute to the sustainable cultivation of crops, influence the abundance, activity and diversity of soil microflora by increasing the productivity of the system, the return of plant residues and

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the content of organic matter in the soil (Hamidi *et al*., 2023; Shuliko *et al*., 2024). Magnesium in mineral fertilizers led to significant changes in the population of rhizobia and free-living nitrogen-fixing bacteria in the soil, increased seed germination, increased plant height and crop yield (Rani Shobha Pujari and Latha, 2017; Prasanthli Golive *et al*., 2018; Singh *et al*., 2020; Soniya and Bhindhu, 2023).

An analysis of literature data showed that the study of the magnesium state of soils was often carried out in vegetation or short-term field experiments. Studies of changes in the content of its forms in soils of agrocenoses are few. Studying changes in the content of various forms of magnesium in the soils of agrocenoses, taking into account the regional specifics of soil and climatic conditions, seems relevant.

The purpose of our research is to study the change in the content of magnesium forms in the soils of the forest-steppe of Western Siberia during long-term agricultural use in long-term stationary field experiments. The objects of research are soils of the forest-steppe zone of Western Siberia: Gleyic Chernozems in the southern forest-steppe and Luvic Greyzemic Phaeozem in the northern forest-steppe, according to the World Reference Base for Soil Resources (IUSS Working Group, 2015).

MATERIALS AND METHODS

A field experiment on Gleyic Chernozems heavy loamy (46% physical clay) soil was conducted in 1978-2019 at Omsk Agrarian Scientific Center (Omsk Region, Omsk District). On one plot of soil in the crop rotation, mainly perennial and annual grasses (hereinafter - Perennial and annual grasses) were grown, in parallel on the other - grain crops and grass mixtures (Cereals and fodder crops). In the experiments, methods were developed for increasing the productivity of crops under irrigation (Shuliko *et al*., 2022) and NP; due to the very high potassium content in the studied soil (exchangeable - 60 mg/100 g), potassium fertilizers were not used. A by-product of grain and leguminous crops- straw, was scattered over the field during harvesting and embedded in the topsoil.

Another field experiment on Luvic Greyzemic Phaeozem medium loamy (31% physical clay) soil was laid in 1988-2019 at Institute of Soil Science and Agrochemistry, Russian Academy of Science (Novosibirsk region, Iskitimsky district). Vegetable crops were grown in a crop rotation until 2000 and then potatoes were grown in monoculture. In experiments, the influence of the intensity of the potassium balance on the ecological and agrochemical state of agrocenoses was studied (Yakimenko, 2003). In this report, the most contrasting variants of this experiment are considered: without fertilizers, NP and NPK. In the experiments, both the main and by-products of the crops grown were taken into account and alienated from the plots.

Fertilizers were applied in the form of ammonium nitrate, double superphosphate and potassium chloride annually, taking into account the planned yield of a particular cultivated crop. The laying and carrying out of experiments were carried out according to the standard package of practices.

Soil samples were taken from the fields of long-term experiments in 1978, 1988 and 2019. Three cores were taken from a soil layer 0-20, 20-40 cm thick and combined into composite samples. Composite samples were kept in the archives of the institute. Chemical analysis of composite soil samples was carried out in 2020 by standard methods (Mineev *et al*., 2001; Spirina and Solov'yova, 2014). Soil forms of magnesium were extracted: easy-exchange - with a 0.0025 M $CaCl_2$ solution, exchange - 1 M CH_3COONH_4, non-exchange - 1 M HNO_3 and determined on an atomic absorption spectrometer "Kvant-2A" (LLC "Kortek", Russia). The same extracts are usually used in the determination of the corresponding forms of potassium. Taking into account the fundamental similarity of the behavior of potassium and magnesium cations in the soil absorbing complex and the similarity of their relationship with the mineral base of soils (Yakimenko, 2003), the same approaches can probably be applied to the study of the magnesium soil fund.

RESULTS AND DISCUSSION

On Gleyic Chernozems soil, initially rather highly fertile, the average crop yield during the experiments in the control variants (without fertilizers) of fodder and grain-grass crop rotations was 3.39-3.86 ton of fodder units per hectare (t f.u. ha^{-1}), whereas when making the calculated doses of NP fertilizers -5.20-5.24 t f.u. ha^{-1} (Table 1).

The application of only NP fertilizers on Luvic Greyzemic Phaeozem soil for vegetables and potatoes was ineffective (the average annual yield in control and NP, respectively, 6,5 and 7,6 t f.u. ha^{-1}), apparently due to the limited potassium nutrition of plants. The balanced application of mineral fertilizers in the NPK variant contributed to a significant increase in the yield of vegetable crops and potatoes (average annual - 11,4 t f.u. ha^{-1}).

Long-term agricultural use of the soil, both intensive and extensive, inevitably affects, to one degree or another, the physicochemical properties of the soil, which can affect the transformation processes of the fund of macro- and microelements contained in it, including magnesium (Zav'yalova, 2015; Mohamad *et al*., 2016; Dornbush and Von Haden, 2017; Dubovik and Dubovik, 2019; Yang *et al*., 2019). The different intensity of the use of mineral fertilizers in the variants of the experiments carried out, the specificity of individual crops and the technologies of their cultivation led to changes in the effective fertility of the studied soils (Table 2).

The humus content (determined by Tyurin's method) in the Gleyic Chernozems soil changed insignificantly as a result of long-term cultivation. This is associated with a significant proportion of perennial grasses in crop rotations and, accordingly, a large amount of root and crop residues entering the soil (Weißhuhn *et al*., 2017; Boiko, 2019; Levin *et al*., 2021). The pH value of the soil under study increased slightly during the experiment - by 0.2-0.3 units. To the greatest extent, changes in soil properties affected the fund of ash elements - phosphorus and potassium: the content of mobile phosphorus (according to Chirikov) in variants with its introduction increased 2 times in comparison with the original soil and the content of exchangeable potassium (according to Maslova) with a permanent deficit of its balance similarly decreased (Table 2).

In the variants of the experiment on Luvic Greyzemic Phaeozem soil, the humus content sharply decreased in comparison with virgin soil (Table 2), which is probably due to the permanent mineralization of soil organic matter with a small input of plant material. In the NPK variant, the humus content was higher than in the control and NP. This associated with a much higher yield with optimized crop nutrition and a corresponding input of plant residues into the soil (Voronkova *et al*, 2019; Matvienko *et al*., 2023) .

The reaction of the soil environment of the control variant during the experiment changed little, relative to virgin lands and in the variants, with the introduction of nitrogen fertilizers, it significantly decreased. The additional use of potash fertilizers did not affect the acidity of the soil in comparison with the NP option. The level of mobile phosphorus in the soil of the control variant decreased significantly in comparison with virgin soil and as a result of systematic long-term use of phosphorus fertilizers, it increased significantly; a similar situation was observed with the potassium state of the soil with or without potassium (Table 2). It should be noted that all changes in the indicated soil agrochemical properties in all variants of the experiments occurred mainly in the 0-20 cm soils layer. The absorption capacity of the studied soils in the upper layer of various variants of long-term experiments slightly differed from the virgin (initial) values.

The level of easily exchangeable magnesium gives an idea of the degree of depletion of the soil, its ability to desorb the ions of the element into the soil solution. These cations make up the most mobile fraction of exchangeable magnesium, which is dislocated on the outer (planar) faces of crystallites and in the organic matter (Xie *et al*., 2020;

Table 1: The total yield of crops and the intake of macronutrients in long-term field experiments in the forest-steppe of Western Siberia.

Options	Total yield, ton of feed units ha^{-1}	Introduced with fertilizers, kg of active ingredient $hectare^{-1}$		
		Nitrogen	Phosphorus	Potassium
Gleyic chernozems (1978-2019)				
Perennial and annual grasses				
No fertilizers	158.3	-	-	-
NP	214.7	2739	3288	-
Cereals and fodder crops				
No fertilizers	138.9	-	-	-
NP	213.2	3138	2796	-
Luvic greyzemic phaeozem (1988-2019)				
Vegetable crops and potatoes				
No fertilizers	199.0	-	-	-
NP	232.0	3820	2180	-
NPK	347.0	3820	2180	6060

Table 2: Changes in soil properties in experiments (soil layer 0-20 cm).

Options	Humus content, %	Water pH	P_2O_5	K_2O	Absorption capacity, milligram-equivalent 100 g of $soil^{-1}$
			mg 100 g of $soil^{-1}$		
Gleyic chernozems					
Original content (1978)	6.5	6.8	13	60	36.3
No fertilizers (2019)	6.2	7.1	12	33	35.6
NP (2019)	6.6	7.0	25	32	36.2
F test of significance at 5% level	0.3	0.2	4	5	
Luvic greyzemic phaeozem					
Original content (1988)	4.9	7.3	18	12	21.5
No fertilizers (2019)	3.0	7.1	10	7	21.2
NP (2019)	3.1	6.7	55	7	21.4
NPK (2019)	3.4	6.8	48	25	21.7
F test of significance at 5% level	0.3	0.3	5	3	1.2

Buernor *et al*., 2024). The content of easily exchangeable magnesium in the upper root layer of Gleyic Chernozems soil during its long-term extensive (without fertilization) agricultural use practically did not change (Table 3). This was facilitated by the predominant cultivation of grasses, a stable level of organic matter in the soil, which is the soiled carrier of this fraction of magnesium, as well as an increased, in general, the magnesium fund of the studied soil (de Mello Prado, 2021; Chebotarev and Brovarova, 2023). On the contrary, in the control variant of the experiment on Luvic Greyzemic Phaeozem soil, the content of easily exchangeable magnesium significantly decreased in comparison with virgin soil. The level of humus in this soil during its agricultural use has significantly decreased (Table 2) and the cultivation of row crops contributed to a certain activation of the leaching processes; it is known that magnesium ions have an increased migratory ability (Senbayram *et al*., 2015; Chernousenko *et al*., 2023) In addition, the removal of the element with the alienated main and secondary plant products could also have a certain effect (Yakimenko and Naumova, 2021).

Long-term application of mineral fertilizers in the variants of experiments on the studied soils caused a significant decrease in the content of easily exchangeable magnesium in the arable and subsoil layers (0-40 cm), both relative to the control and virgin lands (Table 3). With comparable crop yields in fertilized and non-fertilized experiments (for example, control and NP on Luvic Greyzemic Phaeozem soil, Table 1), it can be assumed that the removal of magnesium by plants was not decisive in the depletion of its soil reserves; the main influence was probably provided by the leaching processes (Gransee and Führs, 2013; Lu *et al*., 2024). It is known that monovalent cations (NH_4, K, H) - are strong antagonists of Mg, suppressing the processes of its fixation in the soil and absorption by plants (Xie *et al*., 2020). In our experiments, the long-term application of ammonium nitrate caused the loss of the most mobile part of the magnesium fund of the upper soil layer (0-40 cm). Additional application of potassium chloride (Luvic Greyzemic Phaeozem soil) and a concomitant significant increase in the yield of cultivated crops did not fundamentally affect this process, nevertheless, the tendency for a further decrease was obvious. Earlier, the scientific press reported on the intensification of the processes of magnesium leaching from the soil with the intensive use of mineral fertilizers (Shil'nikov *et al*., 2008; Bogdevich and Lomonos, 2009; Tikhomirova, 2011; Marschner, 2012; Senbayram *et al*., 2015).

Table 3: Changes in the content of magnesium forms in the soil of long-term field experiments.

Options	Soil layer,	Content of forms of magnesium, mg 100 g of soil^{-1}		
	cm	Easily exchangeable	Exchangeable	Non-exchangeable
		Gleyic chernozems		
Original content (1978)	0-20	6.0	58	370
	20-40	4.5	52	360
		Perennial and annual grasses (2019)		
No fertilizers	0-20	5.8	58	370
	20-40	3.9	52	355
NP	0-20	3.3	53	340
	20-40	2.6	50	335
		Cereals and fodder crops (2019)		
No fertilizers	0-20	5.3	58	365
	20-40	4.2	51	340
NP	0-20	3.9	50	330
	20-40	3.5	52	340
F test of significance at 5% level	1.4	5.0	41	
		Luvic greyzemic phaeozem		
Original content (1988)	0-20	1.24	15	335
	20-40	1.35	19	360
		Vegetable crops and potatoes (2019)		
No fertilizers	0-20	0.91	12	330
	20-40	1.12	16	350
NP	0-20	0.72	11	320
	20-40	0.69	10	340
NPK	0-20	0.63	8	315
	20-40	0.64	8	340
F test of significance at 5% level		0.18	3.5	23

Long-term extensive agricultural use of Gleyic Chernozems soil did not affect the soil level of exchangeable Mg (Table 3). Probably, the predominant cultivation of grasses weakened the processes of infiltration and leaching and the mineralization in the upper soil layers of a large number of plant residues (Boiko, 2019) contributed to the compensation of the removal of the element with the harvest. However, judging by the slight decrease in the content of the easily exchangeable fraction of magnesium, it is obvious that, despite the external invariability of the pool of intracellularly absorbed cations, the soil's ability to desorb magnesium ions into the soil solution to a certain extent decreased. Some equilibrium between its forms, which existed in virgin soil, turned out to be disturbed.

In the control variant of the experiment on Luvic Greyzemic Phaeozem soil, the level of exchangeable magnesium slightly decreased in comparison with virgin soil (Table 3). This could be due to the long-term cultivation of vegetables crops and potatoes with a small supply of post-harvest plant residues to the soil, as well as infiltration processes.

However, the main factor influencing the change in the conditions of exchangeable magnesium in the soils of the experiments was the use of mineral fertilizers.In Gleyic Chernozems and Luvic Greyzemic Phaeozem the level of exchangeable magnesium in NP variants decreased in comparison with virgin lands and control variants not only in the arable layer but also in the subsoil layer (Table 3).

Probably, the long-term use of ammonium nitrate, as noted above, contributed to the displacement from the soil complex not only of extramicellar easily exchanged magnesium cations but also of its more strongly intramicellar absorbed ions. With the additional application of potash fertilizers and an increase in crop yields, there was a tendency for a further decrease in the content of exchangeable magnesium in the arable and sub-arable soil horizons.

The scale of losses of soil magnesium in intensive agrocenoses, as well as the nearest resources for replenishing the level of its exchangeable form, can be estimated by the content of non-exchangeable magnesium in the soil. It is believed that non-exchangeable cations are genetically related to three-layer clay minerals (Maguire and Cowan, 2002; Härdter *et al*., 2005; Gransee and Führs, 2013). The quantity and quality of these minerals in a particular soil determine both the absolute content of the exchangeable and non-exchangeable forms of soil magnesium and the ratio between them. The content of non-exchangeable magnesium in the soils of the variants of our experiments, possibly due to the relatively high absolute values, did not vary as clearly as in the case of the more mobile forms of this cation (Table 3). Nevertheless, it can be assumed that with long-term extensive agricultural use of soils, the content of non-exchangeable magnesium in them changes little. At the same time, with the long-term use of mineral fertilizers and increased crop yields, there is an obvious tendency to a decrease in the non-exchangeable form of magnesium in the soil. This reflects a weakening of the potential capacity of the soil due to a decrease in the level of mobile forms of this element.

CONCLUSION

Studies carried out in long-term stationary field experiments have shown that the systematic introduction of the ammonium form of nitrogen fertilization into soils was accompanied by a significant decrease in the content of mobile forms of magnesium in the most root-inhabited layer of all studied soils, under all crops grown, regardless of their yield. With the additional application of potash fertilizers, a tendency for a further decrease in the level of mobile magnesium in the soil was observed. A significant decrease in the reserves of the most mobile magnesium fractions in soils of intensive agrocenoses with little change in the content of non-exchangeable magnesium indicates a decrease in the ability of these soils to maintain the optimal level of this cation in the soil solution and the soil absorbing complex.

To conclude, studying nutrients interaction, the content of various forms of magnesium in the soil when growing crops requires taking into account regional specifics - soil type, climate, *etc*. Research of regional aspects of the influence of long-term intensive agricultural use of soil on crop yields and soil fertility indicators, including magnesium content are still significant and are likely to remain because of changes in climate and associated crop phenology.

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Authors contribution

Vasily Boiko, Vladimyr Yakimenko, Artem Timokhin: Conceptualization, methodology, writing review and editing; Vasily Boiko: validation; Vasily Boiko, Vladimyr Yakimenko, Artem Timokhin: investigation (experiment, sampling), Vladimyr Yakimenko: agrochemical analysis, data curation; Vasily Boiko, Vladimyr Yakimenko: writing-original draft. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors are declaring that there is no conflict of interest in the publication of the paper.

REFERENCES

Abbas, Z., Hassan, M.A., Huang, W., Yu, H., Xu, M., Chang, X., Fang, X. and Liu, L. (2024) Influence of magnesium oxide (MgO) Nanoparticles on Maize (*Zea mays* L.). Agronomy. 14: 617. doi: 10.3390/agronomy14030617.

Afanas'ev, R.A. (2005) Magnesium in the system soil - plant - animal. Plodorodie. 5: 19-21.

Bogdevich, I.M. and Lomonos, O.L. (2009). Magnesium fertilizers on sod-podzolic soils: An analytical review. Minsk: Institute of Soil Science and Agrochemistry. 40.

Boiko, V.S. (2019). Field fodder production on irrigated chernozems in the forest-steppe of Western Siberia. Omsk: Publishing House of Maksheeva. 312.

Buernor, A., Kabiru, M., Chaouni, B., Akley, E., Anas, R., Silatsa, F., Asante, M., Dahhani, S., Hafidi, M., Jibrin, J. and Jemo, M. (2024). Soybean yield variability in Northern Ghana: Effects of rhizobia inoculation, P application and soil exchangeable Mg content. Plant and Soil. doi: 10.1007/s11104-024-06503-2.

Cazzola, R., Della Porta, M., Manoni, M., Iotti, S., Pinotti, L. and Maier, J.A. (2020) Going to the roots of reduced magnesium dietary intake: A tradeoff between climate changes and sources. Heliyon. 6(11): e05390. doi: 10.1016/j.heliyon.2020.e05390.

Chaudhry, A.H., Nayab, S., Hussain, S.B., Ali, M. and Pan, Z. (2021). Current understandings on magnesium deficiency and future outlooks for sustainable agriculture. International Journal of Molecular Sciences. 22(4): 1819. doi: 10.3390/ijms22041819.

Chernousenko, G.I., Khitrov, N.B. and Pankova, E.I. (2023). Magnesium in saline gypsum-bearing soils of Russia. Eurasian Soil Science. 56: 854-867. doi: 10.1134/S1064229323600537.

Dornbush, M.E. and Von Haden, A.C. (2017). Intensified Agroecosystems and Their Effects on Soil Biodiversity and Soil Functions. Soil Health and Intensification of Agroecosytems. Academic Press. 173-193. doi: 10.1016/B978-0-12-805317-1.000 08-7.

Dubovik, E.V. and Dubovik, D.V. (2019) Relationships between the organic carbon content and structural state of typical chernozem. Eurasian Soil Science. 2: 171-183. doi: 10.1134/S1064229319020042.

IUSS Working Group, (2015). WRB, World Reference Base for Soil Resources 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps; FAO: Rome, Italy. 203.

Frau, L., Libohova, Z., Joost, S., Levasseur, C., Jeangros, B., Bragazza, L. and Sinaj, S. (2020). Regional investigation of spatial-temporal variability of soil magnesium-a case study from Switzerland. Geoderma Regional. 21: 1-11. doi: 10.1016/j.geodrs.2020.e00278.

Godunova, E.I., Chizhikova, N.P. and Shkabarda, S.N. (2013). Natural enough magnesium in soil stavropol height at different levels in agricultural landscapes agrogen impact. Dostizheniya nauki i tekhniki APK. 4: 9-11.

Gransee, A. and Führs, H. (2013). Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. Plant Soil. 368: 5-21. doi: 10.1007/s11104-012-1567-y.

Guo, W., Chen, S., Hussain, N., Cong, Y., Liang, Z. and Chen, K. (2015). Magnesium stress signaling in plant: Just a beginning. Plant Signaling and Behavior. 10(3). doi: 10.4161/15592324.2014.992287.

Hamidi, N.H., Ahmed, O.H., Omar, L., Ch'ng, H.Y., Johan, P.D., Paramisparam, P., Musah, A.A. and Jalloh, M.B. (2023). Co-application of inorganic fertilizers with charcoal and sago bark ash to improve soil nitrogen availability, uptake, use efficiency and dry matter production of sorghum cultivated on acid soils. Sustainability. 15: 827. doi: 10.3390/su15010827.

Härdter, R., Rex, M. and Orlovius, K. (2005). Effects of different Mg fertilizer sources on the magnesium availability in soils. Nutrient Cycling in Agroecosystems. 70: 249-259. doi: 10.1007/s10705-005-0408-2.

Jakovljeviã, M.D., Kostiã, N.M. and Antiã-Mladenoviã, S.B. (2003). The availability of base elements (Ca, Mg, Na, K) in some important soil types in Serbia. Proceedings for Natural Sciences, Matica Srpska Novi Sad. 104: 11-21. doi: 10.2298/ZMSPN0304011J.

Jayalaxmi, B., Vijayalakshmi, D., Ravindra, U., Revanna, M.L., Ramanjini, P.H.G. and Chandru, R. (2015). Effect of different processing methods on proximate, mineral and antinutrient content of lima bean (*Phaseolus lunatus*) seeds. Legume Research. 39(4): 543-549. doi: 10.18805/lr.v0iOF.7108.

Levin, K., Auerswald, K., Reents, H. and Hülsbergen, K.J. (2021). Effects of organic energy crop rotations and fertilisation with the liquid digestate phase on organic carbon in the topsoil. Agronomy. 11: 1393. doi: 10.3390/agronomy11071393.

Litvinovich, A.V., Pavlova, O.Yu., Lavrishchev, A.V. and Bure, V.M. (2020). Losses of Ca, Mg, K, Na, Fe and F from irrigated meadow-gray soil as a result of migration. Empirical models of the eluviation process (according to laboratory experience). Agrohimiâ. 1: 58-69. doi: 10.31857/S0002188120010056.

Lu, Z., Degryse, F., Wu, J., Huang, C., Yu, Y., Mclaughlin, M. and Zhang, F. (2024). Slow-and fast-release magnesium-fortified macronutrient fertilizers improve plant growth with lower Mg leaching loss. Journal of Soils and Sediments. doi: 10.1007/s11368-024-03752-7.

Maguire, M.E. and Cowan, J.A. (2002). Magnesium chemistry and biochemistry. Bio Metals. 15: 203-210. doi: 10.1023/a:1016058229972.

Marschner, H. (2012) Marschner's Mineral Nutrition of Higher Plants. London: Publishing house Academic Press. 651. doi: 10.1016/C2009-0-63043-9.

Matvienko, A.I., Gromova, M.S. and Menyailo, O.V. (2023). Effect of mineral nitrogen and glucose application on temperature sensitivity (Q10) of soil organic matter mineralization. Eurasian Soil Science. 56: 584-590. doi: 10.1134/S1064229323600124.

de Mello Prado, R. (2021). Magnesium. In: Mineral Nutrition of Tropical Plants. Springer, Cham. 165-174. doi: 10.1007/978-3-030-71262-4_9.

Mohamad, R.S., Verrastro, V., Al Bitar, L., Al Chami, Z., Roma, R. and Moretti, M. (2016). Effect of different agricultural practices on carbon emission and carbon stock in organic and conventional olive systems. Soil Research. 54:173-181. doi: 10.1071/SR14343.

Nechaeva, T.V., Gopp, N.V., Savenkov, O.A. and Smirnova, N.V. (2019). Magnesium in soils and plants of a sloping agrolandscape in the South-East of West Siberia. The Journal of Soils and Environment. 4: 1-20. doi: 10.31251/pos.v2i4.91.

Mineev, V.G., Sychev, V.G. and Amelyanchik, O.A. (2001). Workshop on Agrochemistry. Moscow: Publishing house Moscow State University. 689.

Prasanthi, G., Kumar, N.G., Raghu, S., Srinivasa, N. and Gurumurthy, H. (2018). Study on the effect of different levels of organic and inorganic fertilizers on microbial enzymes and soil mesofauna in soybean ecosystem. Legume Research. 42(2): 233-237. doi: 10.18805/LR-3850.

Rani, S.P. and Latha, A. (2017). Effect of calcium, magnesium and boron on nutrient uptake andyield of rice in Kole lands of Kerala. Indian Journal of Agricultural Research. 51(4): 388-391. doi: 10.18805/ijare.v51i04.8429.

Rosanoff, A. (2013) Changing crop magnesium concentrations: Impact on human health. Plant Soil. 368: 139-153. doi: 10.1007/s11104-012-1471-5.

Senbayram, M., Gransee, A., Wahle, V. and Thiel, H. (2015). Role of magnesium fertilizers in agriculture: Plant-soil continuum. Crop and Pasture Science. 66: 1219-1229. doi: 10.1071/CP15104.

Sheudzhen, A.K.H. (2003). Biogeochemistry. Maykop: State Unitary Republican Publishing and Printing Enterprise of Adygea. 1028.

Sheudzhen, A.K.H., Bondareva, T.N., Onishchenko, L.M., Bochko, T.F., Lebedovskiy, I.A., Osipov, M.A. and Esipenko, S.V. (2015). Content and forms of magnesium compounds in leached chernozem of the Western Ciscaucasia under conditions of agrogenesis. Polythematic Online Scientific Journal of Kuban State Agrarian University. 112: 1717-1727.

Shil'nikov, I.A., Sychev,V.G., Zelenov, N.A., Akanova, N.I. and Fedotova, L.S. (2008). Liming as a factor in productivity and soil fertility. Moscow: All-Russian Research Institute of Agrochemistry. 340.

Shoba, V.N. and Chudnenko, K.V. (2019). The equilibrium of clay minerals with aqueous solutions in soils. Russian Geology and Geophysics. 60(5): 532-541. doi: 10.15372/RGG2019035.

Shuliko, N.N., Khamova, O.F., Timokhin, A.Yu., Boiko, V.S., Tukmacheva, E.V. and Krempa, A. (2022). Influence of long-term intensive use of irrigated meadow-chernozem soil on the biological activity and productivity of the arable layer. Scientific Reports. 12: 14672. doi: 10.1038/s41598-022-18639-1.

Shuliko, N.N., Timokhin, A.Yu., Khamova, O.F., Boiko, V.S., Tukmacheva, E.V., Korchagina, I.A. and Veinbender, A.A. (2024). Biological and agrochemical properties of the meadow-chernozem soil of Omsk Irtysh region and fodder crop productivity as influenced by mineral fertilizers. Sel's kokhozyaistvennaya Biologiya [Agricultural Biology]. 59(1): 156-173. doi: 10.15389/agrobiology.2024.1.156eng.

Singh, V., Sharma, M., Upadhyay, H. and Siddique, A. (2020). Ameliorative effect of seed priming on germination, vigour index and tolerance index against short term moisture stress in maize (*Zea mays* L.). Indian Journal of Agricultural Research. 54(3): 378-382. doi: 10.18805/IJARe.A-5351.

Soniya, V.P. and Bhindhu, P.S. (2023). Yield and rhizosphere-microflora of cowpea in response to magnesium fertilization in lateritic soils of Kerala. Legume Research. 46(7): 951-955. doi: 10.18805/LR-4554.

Spirina, V.Z. and Solov'yova, T.P. (2014). Agrochemical Methods for Studying Soils, Plants and Fertilizers. Tomsk: Publishing House of Tomsk State University. 336.

Tikhomirova, V.Y.A. (2011). Effect of soil environment, mineral fertilizers, potassium, weather conditions on the magnesium supply of agricultural crops. Agrohimiâ. 5: 84-89.

Voevodina, L.A. and Voevodin, O.V. (2015). Magnesium for soil and plants. Scientific Journal of Russian Scientific Research Institute of Land Improvement Problems. 2: 70-81.

Voronkova, N.A., Balabanova, N.F. and Tyumentseva, E.Y.U. (2019). The state of soil fertility during long-term use of fertilizers in agrocenosis. IOP Conference Series: Earth and Environmental Science. 315(5): 052064. doi: 10.1088/1755-1315/315/5/052064.

Wacal, C., Ogata, N., Basalirwa, D., Sasagawa, D., Masunaga, T., Yamamoto, S. and Nishihara, E. (2019). Growth and K nutrition of sesame (*Sesamum indicum* L.) seedlings as affected by balancing soil exchangeable cations Ca, Mg and K of continuously monocropped soil from upland fields converted paddy. Agronomy. 9(12): 819. doi: 10.3390/agronomy9120819.

Weißhuhn, P., Reckling, M., Stachow, U. and Wiggering, H. (2017). Supporting agricultural ecosystem services through the integration of perennial polycultures into crop rotations. Sustainability. 9: 2267. doi: 10.3390/su9122267.

Xie, K., Cakmak, I., Wang, S., Zhang, F. and Guo, S. (2020). Synergistic and antagonistic interactions between potassium and magnesium in higher plants. The Crop Journal. 9. doi: 10.1016/j.cj.2020.10.005.

Yakimenko, V.N., Konarbaeva, G.A., Boiko, V.S. and Timokhin, A.Y.U. (2020). Ecological evaluation of the content of heavy metals in soils of agrocenosis of Western Siberia. Ecology and Industry of Russia. 24: 52-57. doi: 10.18412/1816-0395-2020-12-52-57.

Yakimenko, V. and Naumova, N. (2021). Tuning potassium and magnesium fertilization of potato in the South of West Siberia. Agronomy. 11: 1877. doi: 10.3390/agronomy11091877.

Yakimenko, V.N. (2003). Potassium in Agrocenoses of Western Siberia. Novosibirsk: Publishing house of the Siberian Branch of the Russian Academy of Sciences. 231.

Yang, F., Tian, J., Fang, H., Gao, Y., Xu, M., Lou, Y., Zhou, B. and Kuzyakov, Y. (2019). Functional soil organic matter fractions, microbial community and enzyme activities in a mollisol under 35 years manure and mineral fertilization. Journal of Soil Science and Plant Nutrition. 19: 430-439. doi: 10.1007/s42729-019-00047-6.

Zav'yalova, N.E. (2015). The impact of mineral fertilizers and lime on the transformation of humic acids in a soddy-podzolic heavy loamy soil of the Cis-Ural region. Eurasian Soil Science. 6: 627-633. doi: 10.1134/S1064229315060149.