Scientific Papers. Series A. Agronomy, Vol. LXV, No. 1, 2022
ISSN 2285-5785; ISSN CD-ROM 2285-5793; ISSN Online 2285-5807; ISSN-L 2285-5785

EVOLUTION OF SOIL PHOSPHORUS CONTENT IN LONG-TERM EXPERIMENTS

Nicoleta MĂRIN, Mihail DUMITRU, Carmen SÎRBU

National Research and Development Institute for Soil Science, Agro-Chemistry and Environment - ICPA Bucharest, 61 Marasti Blvd, District 1, Bucharest, Romania

Corresponding author email: marinnicoleta37@yahoo.com

Abstract

Researches carried out in the long-term experimental fields of the agricultural research stations from Valu lui Traian, Turda and Lovrin (experiments started in 1967) and Teleorman and Secuieni (started in 1976 and 1975) highlighted that phosphorus fertilization in doses of 40, 80, 120, and 160 kg/ha led to statistically assured increases for wheat and maize production and to an increase in the level of soil supply with available phosphorus. Currently, in Romania 65.41% of the country's agricultural area are characterised by small, very small and extremely low values of soil available phosphorus content. The trend is worsening due to the low level of using phosphorus fertilizers (on average, between 2012-2019, 13 kg P/ha were applied, the deficit being 26.46 kg/ha). Therefore, it is required a minimum dose of phosphorus of 80 kg/ha, while over 120 kg P/ha are needed to ensure a better level of soil phosphorus content. Higher doses ensure not only higher yields but also better use of nitrogen-based fertilizers or nitrogen and potassium-based fertilizers. In all long-term experiments (39-51 years) high doses of phosphorus (over 120 kg P/ha) led to an increase in soil phosphorus stock at a very high level of supply in all experimental stations. Every 100 kg P/ha increases annually the soil phosphorus content with 0.59-1.90 mg/kg. Long-term (39- 51 years) fertilization with phosphorus, regardless of dose (up to 200 kg P/ha) did not lead to statistically assured increases of heavy metals (Cd, Cu, Pb, Zn, Mn) content in soil.

***Key words**: long-term experiences, phosphorus, wheat, maize.*

INTRODUCTION

The continuous growth of the world's population has led to the continuous improvement of agricultural technologies. The fertilization system ensured a production increase of about 40%. In the fertilization system, phosphorus has an important role because: it is found in all plant organs, takes part in building the molecular architecture of various nucleic acids contributing to the formation of genetic code, increases plant resistance to drought, counterbalances the excess of nitrogen, stimulates fruiting and increases fruit resistance to storage conditions, participates in enzymatic processes with a synthetic role, has an essential role in photosynthesis, increases yield quantity and quality (Marin, 2020; Borlan et al., 1994; Dodocioiu et al., 2009; Ștefanic et al., 2006; Lăcătușu, 2006).

FAO (1999) has estimated that fertilizers contribute with 55-57% to the increase in average production per hectare and 30-31% to the total increase of crop production. Lupu (2007) showed that worldwide fertilization contributes with 40% from the total increase in crop production.

Research regarding mineral fertilizers has shown that in short-term experiments, due to soil resilience, the results often do not show statistically significant changes in the physical, chemical or biological characteristics of the soil, excepting the excessive doses of fertilizers and sandy soils. Results had begun to appear highligthing that in the long run mineral fertilizers lead to negative changes in the physical, chemical or biological properties of the soil, with negative effects on crop production. For this reason, Academician Cristian Hera has decided to organize in a unitary network, in different pedoclimatic conditions, long-term experiments with the same doses of fertilizers applied. Between 1967-1975, 16 experimental fields were organized, some of them being still maintained today, but most of them disappeared after 1990 or have undergone changes due to the disorder in the economy and the drastic reduction of funds in agricultural research.

Long-term experiments will still remain, probably for a long time, the best tool for characterizing the soil as an environmental factor and for setting the critical thresholds of different soil properties, as well as for extrapolating experimental data to larger areas, despite the fact that they are not perfect (Dumitru et al., 2008).

The interaction between N and P can be considered the most important interaction between nutrients, having practical significance (Aulach et al., 2007). Research studies had calculated the N/P ratio of cereals (n = 759) and indicated that over 40% of crops reach maximum yield when this ratio is relatively close, ranging from 4 to 6 (Sadras, 2006).

Hera (2010) has shown that the level of soil available phosphorus is strongly affected by the use of mineral fertilizers and organic matter. After 26 years, 126 ppm of available phosphorus was accumulated in the plots fertilized with 160 kg P_2O_5/ha/year, comparing to 3.6 ppm in the control plots. Under the influence of organic fertilization, the available phosphorus content increased from 10.4 ppm in control plots to 25.1 ppm in plots fertilized every 4 years with 60 t manure/ha. The results showed that the annual application of 81 kg P2O5/ha is required for the typical cambic chernozem soil from Fundulea, of which 44 kg P_2O_5/ha re needed to maintain the normal soil content and 37 kg P_2O_5/ha are needed to increase the available phosphorus content with 1 mg/kg.

The researches carried out on the chernozem from Caracal, the luvosol from Oradea, the luvosol from Podul Iloaiei, the eutricambosol from Targu Mures, the cambic chernozem from Perieni, the albic luvosols from Albota and from Livada, and the reddish-molic preluvosol from Simnic, have showed increases in the amounts of soil available with increasing doses of phosphorus based fertilizers, when they were 80-160 kg P_2O_5/ha, both in the case of exclusively mineral fertilization, and especially organic + minera fertilization, while the lack of fertilizers with phosphorus leads to a very sharp decrease in the availability of phosphorus for plants and the achievement of minimum levels that are difficult to change over time, slowing down the plant growth and low yields (Nedelciuc et al., 1989; Mărcuș, 1989; Mocanu et al., 2007; Ciobanu et al., 2003; Vintilă et al., 1989; Rizea et al., 2008; Borza et al., 2001).

MATERIALS AND METHODS

Previous researches concluded that the best crop yields are obtained by fertilizing with nitrogen and phosphorus. Under these conditions, the treatments were established only with these elements, applied in doses of 0, 40, 80, 120, and 160 kg/ha.

In order to highlight the effect of fertilization on the trend of soil phosphorus content, soil samples were collected from experimental fields organized in the agricultural research stations of Valu lui Traian, Turda and Lovrin (experiments starting in 1967), and Teleorman and Secuieni (starting in 1976 and 1975).

Soil samples were collected from the topsoil, at a depth of 0-20 cm, and soil analyzes were performed by the following methods:

- total nitrogen (N%): Kjeldahl method, disintegration with H_2SO_4 at 350°C, potassium sulphate and copper sulphate as catalyst - SR ISO 11261: 2000;
- available phosphorus (mobile): according to the Egner-Riehm-Domingo method and dosed colorimetric with molybdenum blue, according to the Murphy-Riley method (reduction with ascorbic acid);
- total phosphorus, colorimetric method. ICPA Methodology 1986, chap. 8, point 2, PT 2.

RESULTS AND DISCUSSIONS

In Romania, research carried out within the Soil Quality Monitoring System in the grid of 16 x 16 km showed that, on 0-50 cm depth, the soil supply with available phosphorus (P) is extremely low (< 4 mg/kg) on 11.36% from the area (107 sites), very low (4-8 mg/kg) on 21.02% from the area (198 sites), low (9-18 mg/kg) on 33.01% from the area (311 sites), medium (19-36 mg/kg) on 20.70% from cases (195 sites), high (37-72 mg/kg) on 9.45% from cases (89 sites) and very high (> 72 mg/kg) on 4.48% from total area (42 sites). Low, very low, and extremely low values represent 65.41% from the total agricultural area of the country (Dumitru et al., 2000).

The insufficient doses applied in agriculture led to a decrease of soil phosphorus content. Thus, in 2000 compared with 1990, the areas with low, very low and extremely low P stocks increased with 29%, from 4,473,000 ha to 6,330,000 ha (Dumitru, 2003).

Even in such conditions, organic and mineral phosphorus-based fertilizers are not adequately applied. Data presented in Table 1 showed a continuous increase of soil phosphorus deficit. On average, for 2012-2019 period, 13 kg P/ha were applied, the deficit being of 26.46 kg/ha. Therefore, it was expected to increase the agricultural area affected by phosphorus deficit and to obtain low crop yields. Furthermore, the increase of water deficit leads to a reduced phosphorus uptake in plants. At such high deficit, the recommendations of European Union for reducing with 20% the mineral fertilizers doses could be difficult to apply.

Table 1. The evolution of soil phosphorus consumption, the amount of applied fertilizers and the soil phosphorus deficit

	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**AVERAGE 2012-2019**
Total annual phosphorus consumption by crop (tons)	200121	338045	367566	322356	371221	472728	529144	492980	325148
Total annual phosphorus deficit (tons)	87121	-224045	-248566	-189356	-245221	-327728	-341144	-291980	-244395
Total annual phosphorus deficit /ha (kg/ha)	-9,27	-23,85	-26,46	-20,15	-26,1	-34,88	-36,31	-31,08	-26,01
Quantity of P based fertilizers applied annually (thousands t) / (kg/ha)	113/12	114/12	119/13	133/ 14	126/13	145/15	188/20	201/21	142/15
Organic fertilizers, total (thousands t) / (kg/ha for arable lands)	13293/ 1410	13580/ 1450	16262/ 1730	15212/ 1620	14927/ 1590	12625/ 1340	14717/ 1570	15323/ 1630	14492/ 1543
Organic fertilized area (thousands ha)	443	453	542	507	498	421	490	511	483
Irrigated area (thousands ha)	165.4	180.9	145.4	173.2	152.6	211.6	266.1	-	-

Table 2 shows the effect of long-term phosphorus (superphosphate) fertilization on the level of soil available phosphorus content (mg/kg) in the studied experimental fields.

In all soils, P fractions are adsorbed on the surface of clay particles, especially iron and aluminium hydroxides and complexes of organic matter. At pH values lower than 5.8, the concentration of P in the soil solution is controlled by iron and aluminium phosphates, while below this value, by Ca and Mg phosphates. However, Al, Fe, Ca, and Mg phosphates can coexist in a wide range of soil pH (McDowell et al., 2001). This explains why the highest values of soil available phosphorus content are found in the Phaeozem from Teleorman, with pH values between 5.33 and 5.96, and a high content of clay and humus ranging between 3.72-4.56%.

The very different evolution of the level of available soil phosphorus under the effect of the same doses of superphosphate is due not only to the different soil characteristics analysed and different climatic conditions but also to the disorder that settled in research in the early postrevolutionary years. Experimental treatments in 1990-2000 no longer strictly reflected the experimental plan for different periods of time.

Table 2. Evolution of the level of available soil P under the long-term fertilization with phosphorus (superphosphate)

Dose of P_{AL} (kg/ha)	Valu lui Traian* Calcaric Chernozem	Turda Typical Chernozem	Lovrin Typical Chernozem	Teleorman Cambic Phaeozem	Secuieni Typical Chernozem
0	31	30	45	60	8
40	53^{XXX}	80^{xxx}	41	90^{xxx}	33^{xxx}
80	70^{XXX}	133^{xxx}	59^{xx}	145^{xxx}	75^{xxx}
120	101^{XXX}	145^{xxx}	93^{xxx}	194^{xxx}	97^{xxx}
160	141^{XXX}	156^{xxx}	95^{xxx}	204^{xxx}	114^{xxx}
DL 5%	10	6	10	4	9
DL 1%	14	8	14	6	12
DL 0,1%	21	11	21	10	16

*In the experimental field from Valu lui Traian the applied phosphorus doses were 0, 50, 100, 150, and 200 kg P/ha associated with the same N, and K doses.

The **typical Chernozem from Valu lui Traian** is medium supplied with phosphorus (31 mg P_{AL}/kg). On this soil, the application of 50 kg P/ha doses did not lead to significant increases in wheat yield (the control plot ensured a wheat yield of 4717 kg/ha, while the fertilized variant with 50 kg P/ha ensured a yield of 4907 kg/ha). The highest yield (6388 kg/ha) was obtained with a dose of 100 kg P/ha, and a very significant yield increases of 35%. Doses of 150 and 200 kg P/ha led to productions levels of 5649 and, respectively, 5767 kg/ha of wheat, ensuring distinctly significant yield increases (20 and 22%) compared to the control variant (Lupașcu et al., 2017).

Under irrigation conditions, the highest maize yield was obtained after fertilization with 100 kg P/ha and 150-200 kg N/ha.

Hera and Borlan (1984) showed that in most cases the combined application of nitrogen and phosphorus fertilizers leads to higher yields compared to the separate application of these elements.

After 44 years of application of phosphorus fertilizers, the soil phosphorus level (Chernozem from Valu lui Traian) increased very significantly with the applied dose of superphosphate, the P doses of 150 and 200 kg/ha leading to very high levels of available soil phosphorus content (101 and 141 mg/kg).

Blake et al. (2000) compared the phosphorus content from three long-term experiments (30 years) and showed that soil type significantly affected soil phosphorus dynamics, due to different organic matter contents. The application of phosphorus in both inorganic and organic (manure) fertilizers have an important effect on the soil phosphorus availability, uptake, leaching or fixing, but the rate of soil phosphorus recovering through crop from mineral fertilizers does not exceed 35%, with the lowest recovery (18%) in the soils with the highest clay content in Rothamsted. The most efficient use of phosphorus (on average 47% in Bad Lauchestaedt and 37% in Rothamsted) was in manure-treated soils. The highest amount of leached or fixed phosphorus (8 and 25 kg/ha/year) occurs in superphosphate-treated soils.

When the phosphorus inputs from the fertilizer exceed the P outputs through crop, the accumulation of soil P gradually increases over time (Kuo et al., 2005).

In the long term (44 years) experiments from Valu lui Traian, cadmium values varied between 0.40 and 0.47 mg/kg, not statistically significantly altered by the treatments applied. Copper values varied between 21 and 24 mg/kg, the values not being correlated with the treatments applied. Lead content values have not statistically significantly changed under the applied treatments, ranging from 20 to 21 mg/kg. The treatments applied did not significantly affect the total zinc content in soil, the values maintaining at 83-84 mg/kg.

On the **Phaeozem** from **SCDA Teleorman**, phosphorus fertilization led to a very significant increase of wheat production with the increase of dose, crop yield increases ranging between 15 and 23%. For each kilogram of phosphorus, the wheat production increased with 13.4 kg P/kg in the case of fertilization with 40 kg P/ha, with 9.3 kg/kg at a dose of 80 kg P/ha, with 5.6 kg/kg at a dose of 120 kg P/ha and with 5.0 kg/kg at a dose of 160 kg P/ha.

Davidescu et al. (1974) showed that phosphorus has a slightly higher effect in case of wheat sown after wheat, compared to wheat cultivated in rotation with maize, as is the case of this experiment.

The Phaeozem from SCDA Teleorman has a high content (60 mg/kg) of available phosphorus (P_{AL}). The data presented in table 2 show that after 39 years of superphosphate fertilization the available phosphorus content in soil increased very significantly in all variants (doses of 40, 80, 120 and 160 kg P/ha), the soil becoming very well supplied with phosphorus. In the variant fertilized with the maximum dose of phosphorus (160 kg/ha) the available phosphorus reached 204 mg/kg in soil.

In the same experiment, the total phosphorus content of the soil increased significantly when 40 kg P/ha were applied and very significantly when doses of 80, 120 and 160 kg P/ha were applied. The values of total phosphorus increased from 0.094% in the control variant to 0.146% in case of application the dose of 160 kg P/ha.

The total phosphorus content in the ploughed soil layer is the difference between phosphorus inputs (from fertilizers, root supply from the underlying horizons) and exports (crop export, losses by erosion). The main source for plant nutrition is the non-occluded mineral phosphates existing on soil particles surface. Plant nutrition is determined by the processes of desorption and diffusion of phosphate ions through the soil solution (Borlan et al., 1990).

When higher doses of phosphorus than the crop consumption are applied, the soil available phosphorus content increases significantly.

Tang et al. (2008) showed that for every 100 kg P/ha, the excess of phosphorus increases with 2-6 mg/kg in soil. In our experiments the excess increased with 0.59-2.84 mg/kg. In Teleorman, the accumulation of phosphorus had values of 0.59 mg/kg by applying 40 kg P/ha, 1.10 mg/kg at the dose of 80 kg P/ha, 1.32 mg/kg at a dose of 120 kg P/ha, and 1.56 mg/kg at a dose of 160 kg P/ha.

Doses of phosphorus did not bring significant changes in soil reaction. Superphosphates (simple and concentrated) can cause sporadic temporary effects of soil acidification by the incongruent solubilization of the contained monosubstituted phosphate, which over time results in disubstituted calcium phosphate and phosphoric acid. Thus, the generated acidity is neutralized over time in reactions with the soil hydrated sesquioxide, so that simple (17-20% P_2O_5) and concentrated (34-44% P_2O_5) superphosphates do not change sustainably the soil reaction. Bases (Ca, Mg) and the effect of slightly increase of the soil T value adsorption of phosphoric acid ions on soil particles also contribute to this situation (Borlan, 1998; Vintilă et al., 1984).

The application of phosphorus together with nitrogen in long-term experiments has led to significant increases in soil humus, according to the applied doses.

The content of heavy metals (cadmium, copper, lead, nickel, manganese and zinc) did not change statistically significant under the long-term fertilization with nitrogen and phosphorus of the cambic phaeozem from SCDA Teleorman.

Cadmium values ranged from 0.9 to 1.2 mg/kg and no correlation was found between the applied phosphorus doses over 39 years and the level of cadmium in the soil. The average cadmium level in the variants fertilized only with nitrogen was 0.99 mg/kg, in those fertilized with nitrogen and 40 kg/ha phosphorus the cadmium values were 1.07 mg/kg, in the variants fertilized with nitrogen and 80 kg/ha phosphorus the cadmium values were 1.05 mg/kg, in that's fertilized with nitrogen and 120 kg/ha phosphorus the average cadmium level was 1.00 mg/kg, and in the plots fertilized with nitrogen on a background of 160 kg/ha phosphorus cadmium level was 1.02 mg/kg. The average value of cadmium in plots fertilized only with different doses of phosphorus was 1.03 mg/kg. No cadmium accumulation was observed under the annual application of doses of 40-160 kg/ha P_2O_5 for 39 years. As in all experiments, also at **SCDA Turda**, the highest crop yield increases were ensured by nitrogen fertilization, but phosphorus fertilization ensured very significant additions to the crop yields, the best results were obtained under 80 kg P/ha application. Each kg of phosphorus from supephosphate applied on the chernozem at Turda ensured a crop yield increase of 9.1 kg of maize seeds/kg of P in case of fertilizing with P_{40}, 3.7 kg/kg at P_{80} applied dose, 1.6 kg/kg at

P_{120} applied dose and 1.7 kg/kg at P_{160} applied dose. All the doses of NP ensured very significant additions to the crop yield. The highest crop yield (9632 kg/ha) was obtained in the variants fertilized with $N_{120}P_{120}$. In order to reach the potential of the new varieties, it is required to increase the fertilizers consumption. Within irrigation systems, a proper fertilization is mandatory in order to at least double the crop yield per unit of used water, to prevent the drastic decrease of the soil nutrients level and to avoid nutrients unbalance occurrence. Irrigation without organic and mineral fertilizers lead to an economic inefficiency and decrease of soil fertility on long term. The nitrogen consumption has to increase up to 2040 level up to 1500-20000 thousand tons of N, phosphorus consumption up to 650-980 thousand tons of P_2O_5 and potassium consumption up to 500-700 thousand tons K_2O.The higher doses of phosphorus (120 and 160 kg/ha) improved significantly the soil phosphorus content (of the chernozem from SCDA Turda), 145 and 156 mg/kg P comparing with 30 mg/kg in control. Phosphorus doses up to 80 kg P/ha are maintaining doses which ensure the crop requirements and starting point for accumulation in soil. For higher crop yields and for P accumulating in soil, the applied doses have to be at least 120 kg P/ha.

Phosphorus fertilization ensured significant increases of the maize yield. The dose of P_{40} gave an increase of 5.6%, dose of P_{80} an increase of 8.7%, dose of P_{120} an increase of 9.4%, and the dose of P_{160} an increase of 7.4%.

The level of phosphorus in the Chernozem from Turda increased distinctly significantly after fertilization with P_{80}, and very significantly in the variants fertilized with P_{120} and P_{160}, when the values reached the range of very good phosphorus supply (93 and 95 mg/kg P).

The target for available phosphorus supply in Belgium is between 120 and 180 mg P/kg. This level should be reached in our country as well.

The application of phosphorus fertilizers, natural or industrial products, always positively affects the soil available phosphorus content.

The long-term application (51 years) of phosphorus and nitrogen fertilizers did not lead to a statistically significant increase of the soil heavy metals content (Cd, Cu, Mn, Pb, Zn), the values of these elements being in the normal content class: less than 1 mg/kg Cd, 17 mg/kg Cu, 15 mg/kg Pb, 48 mg/kg Zn and 303 mg/kg Mn.

At SCDA Secuieni, long-term fertilization (42 years) with nitrogen and phosphorus showed a continuous, statistically significant increase in corn grain yield. In the case of phosphorus fertilization, statistically assured increases occurred starting with the dose of 80 kg P/ha, which ensured a significantly distinct increase compared to the unfertilized control of 9%. Doses of 120 and 160 kg P/ha provided very significant crop yield increases (17-18%). At the same doses (0, 40, 80, 120 and 160 kg/ha), nitrogen fertilizers provided double production increases compared to phosphorus fertilizers. The highest production (9805 kg/ha) was obtained in the variants fertilized with $N_{160}P_{160}$. The lowest production (5569 kg/ha) was obtained in non-fertilized variants (Marin et al., 2021).

The data from the Code of Good Agricultural Practice estimate that for one tonne of main production and the corresponding amount of secondary harvest, 27.5 kg N/ha, 12.5 kg P/ha, and 16.6 kg K/ha are up taken from the soil. At the maximum production of 9805 kg/ha, 269.6 kg N/ha, 122.6 kg P/ha and 161.8 kg K/ha were up taken from the soil. We should return at least these amounts of nutrients to the soil. Long-term fertilization (42 years) with doses of 40-160 kg P/ha led to very significant increases in the level of total phosphorus and available phosphorus in soil (chernozem).

The level of available phosphorus in the soil increased from very low (4-8 mg/kg) in the control variants, to medium (19-36 mg/kg) in the fertilized variants with 40 kg P/ha, and to very high (over 72 mg/kg) in variants that received over 80 kg P/ha, but the long-term recommended dose for fertilization with N_{120}-N_{160} is 120 kg P/ha. On the **chernozem from Lovrin** the available phosphorus content did not change statistically significantly in the variants in which the phosphorus doses were of 40 kg P/ha. On a background of 80 kg P/ha, the application of low doses of nitrogen (0, 50, 100 kg/ha) leads to statistically assured increases of the soil available phosphorus, but by increasing the doses of nitrogen to 150 and 200 kg/ha, once as production increases, phosphorus no longer accumulates in soil. The very significant increase of soil available phosphorus content was identified by applying doses of 120-160 kg P/ha. After 51 years, the available phosphorus in soil increased very significantly in the fertilized variants with 120 and 160 kg P/ha, reaching 93 and 95 mg/kg compared to 45 mg/kg in the unfertilized control. On agricultural land in Lovrin, the dose of phosphorus should be increased to 120 kg/ha.

In Belgium, values below 120 mg P/ha are considered low and for this, doses of 115 kg P/ha are recommended for this range of low values of available phosphorus in soil. The targeted level of available phosphorus content in Belgium is between 120 and 180 mg P/ha. We must also go towards this goal.

Long term application of chemical fertilizers with nitrogen and phosphorus did not lead to a statistically increase the heavy metals content (cadmium, copper, manganese, lead and zinc) in soil, the values of these elements being in the normal range: less than 1mg/kg Cd, 17 mg/kg Cu, 15 mg/kg Pb, 48 mg/kg Zn, 303 mg/kg Mn.

CONCLUSIONS

The small, very small and extremely low values of soil available phosphorus contents affect 65.41% of the country's agricultural area, and the trend is worsening.

On average, in the period 2012-2019, 13 kg P/ha were applied and the deficit was 26.46 kg/ha.

Phosphorus (superphosphate) fertilization has led to very significant increases in wheat and maize yields, but their values are also depending on the climate regime.

The dose of 80 kg P/ha can be appreciated as a maintaining dose that always ensures yield increases and a better use of nitrogen fertilizers.

In all long-term experiments (39-51 years) high doses of superphosphate phosphorus (over 120 kg P/ha) led to increased phosphorus stocks in soil at a very high level of supply in all experimental stations.

For every 100 kg P/ha the excess of phosphorus in soil increases annually with 0.59-1.90 mg/kg.

Long-term fertilization (39-51 years) with phosphorus, regardless of dose (up to 200 kg/ha P) did not lead to statistically assured increases in soil heavy metals content (Cd, Cu, Pb, Zn, Mn).

ACKNOWLEDGEMENTS

This work was supported by two grants of the Romanian Ministry of Research, Innovation and Digitization, project number PN 19 34 03 02 (Innovative system for discriminating between organic and conventional agriculture for food security) and project number 44 PFE /2021, Program 1 - Development of national research-development system, Subprogramme 1.2 - Institutional performance - RDI Excellence Financing Projects.

REFERENCES

Aulakh, M.S., Garg, A.K., B. S. Kabba, B.S. (2007). Phosphorus accumulation, leaching and residual effects on crop yields from long-term applications in the subtropics, Soil Use and Management, British Society of Soil Science. DOI: 10.1111/j.1475-2743.2007.00124.x;

Blake, L., Mercik, S., Koerschens, M., Moskal, S., Poulton, P. R., Goulding, K. W. T., Weigel, A., Powlson, D. S. (2000). Phosphorus content in soil, uptake by plants and balance in three European long-term field experiments. *Nutrient Cycling in Agroecosystems*, *56*. 263–275.

Borlan, Z., Hera, Cr., Bunescu, O. (1990). *Agrochimia fosforului. Aspecte actuale de interes practic și științific*. Editura CERES București.

Borlan, Z., Hera, Cr., Dornescu, D., Kurtinecz, P., Rusu, M., Buzdugan, I., Tănase, Gh. (1994). *Fertilitatea și fertilizarea solurilor*. Editura CERES București.

Borlan, Z. (1998). Prognoza evoluției caracteristicilor agrochimice și corelarea lor cu cerințele de amendare și fertilizare a solurilor agricole. În ”Monitoringul stării de calitate a solurilor din România„ vol.II, Publistar București

Borza, I., Țărău, D., Țîmbota, I. (2001). Fertility evolution of luvosol albic pseudogleyed in the Lugoj –Făget depresion, as a result of long term mineral fertilization. *CIEC Proceedings, Role of fertilizers in sustainable agriculture*. 21-22 August 2000, Suceava, Romanian Academy.

Ciobanu, Gh., Sarca, Gh., Ciobanu, C., Lazăr, Gh. (2003). Evoluția potențialului fosfatic în experiențe de lungă durată cu îngrășăminte și amendamente, în condițiile solului brun-luvic de la Oradea. Simpoziom CIEC, Caracal. Lucrări Științifice, Folosirea îngrășămintelor cu fosfor în România. Aspecte actuale și de perspectivă. Editura AGRIS - Redacția Revistelor Agricole, București.

Davidescu, D., Borlan, Z., Davidescu, V., Hera, C. (1974). *Fosforul în agricultură*. Editura Academiei RSR.

Dodocioiu, A.M., Susisnski, M., Mocanu, R. (2009). *Agrochimie*. Editura SITECH Craiova.
Dumitru, M. (2000). *Monitoringul Stării de Calitate a Solurilor din România*, Editura GNP București.
Dumitru, M. (2003). Producția vegetală și folosirea îngrășămintelor în România. Simpoziom CIEC, Caracal. Lucrări Științifice Folosirea îngrășămintelor cu fosfor în România. Aspecte actuale și de perspectivă. Editura AGRIS – Redacția Revistelor Agricole, București.
Dumitru, M., Popescu, I., Călinoiu, I., Tatomir, C. (2008). Fertilizarea haldelor de steril rezultate din exploatările miniere la zi în bazinul carbonifer Rovinari. Lucrări Științifice ale Simpozionului Internațional *Reconstrucția ecologică și necesarul de îngrășăminte în zona Gorjului*. Editura NEW AGRIS, Revistele Agricole, București.
Hera, C., Borlan, Z. (1984). *Optimizarea agrochimică a sistemului sol-plantă*. Editura Academiei, București.
Hera, C. (2010). CIEC – 77 Years dedicated to enhancing soil fertility for the benefit of sustainable and performing agriculture. 15th World Ferilizer Congress of The International Scientific Centre for fertilizers (CIEC). Meeting the fertilizer demand on a changing globe: biofuels, climate change and contaminants". Proceedings. Editura Academiei Române.
Kuo, S., Huang, B., Bembenek, R. (2005). Effects of long-term phosphorus fertilization and winter cover cropping on soil phosphorus transformations in less weathered soil. *Biol. Fertil. Soils*, *41*. 116–123.
Lăcătușu, R. (2006). *Agrochimie*. Editura Terra Nostra Iași.
Marin, N. (2020). *Managementul N,P,K în agricultură*. Editura Terra Nostra, Iași.
Lupașcu, N., Dumitru, M., Mărin, N., Tanc, M. (2017). Influence of long term fertilization with nitrogen and phosphorus on wheat production and on several chemical characteristics of the soil. *Scientific Papers, Series A, Agronomy, LX.*
Lupu, C. (2007). Influence of nitrogen and phosphorus fertilizers upon corn grain yield at SCDA Secuieni. In 45 year of scientific activity. Reverential volume, Ion Ionescu de la Brad Publishing House, Iași (In Romanian).
Marin, N., Lupu, C., Șerban, M., Preda, C. (2021). Long term nitrogen and phosphorus fertilization influence upon soil. *Romanian Agricultural Research, 38*.
Mărcuș, Ș. (1989). Influența fertilizării asupra producției de grâu în experiența de lungă durată pe solul brun de pădure de la Târgu Mureș. *Analele I.C.C.P.T., LVII.*
McDowell, R. W., Sarpley, A. N., Condrom, L. M., Haygarth, P. M., Brookes P. C. (2001). Processes controlling soil phosphorus release to runoff and implications for agricultural management. *Nutrient Cycling in Agroecosystems, 59*. 269–284.
Mocanu, R., Dodocioiu, A. M., Roșculete, C., Susinski, M. (2007). Efectul fertilizării de lungă durată asupra producției și calității grâului de toamnă pe cernoziomul de la Caracal. *Lucrările Științifice ale Simpozionului Internațional CIEC*. Editura AGRIS-Redacția Revistelor Agricole, București.
Nedelciuc, C., Pătrășcoiu, C., Nedelciuc, M.,, Ionescu, Șt., Toma, M. (1989). Evoluția regimului fosfatic al cernoziomului cambic irigat din Câmpia Caracalului sub influența fertilizării. *Analele I.C.C.P.T., LVII.*
Rizea, N., Lazăr, R., Kovacsovics, B., Lăcătușu, R., Lungu, M., Ștefănescu, D., Burlacu, Gh., Dumitrașcu, N., Ciobanu, V., Păunescu, G., Lupu, C., Ailincăi, C., Negrilă, M., Kurtinecz, P., Ștefănescu, M. (2008). Calitatea solului și a recoltei sub impactul fertilizării de lungă durată. *Lucrări Științifice ale Simpozionului Internațional Reconstrucția ecologică și necesarul de îngrășăminte în zone Gorjului*. Editura NEW AGRIS – Reviste Agricole București.
Rusu, M., Mărghitaș, M., Mihăiescu, T., Oroian, I., Dumitraș, A. (2005). *Tratat de Agrochimie*. Editura CERES, București.
Sadras, O.V. (2006). The N: P stoichiometry of cereal, grain legume and oilseed crops. *Field Crop Research 95*. 13–29.
Ștefanic, Gh., Săndoiu, D.I., Gheorghiță, N. (2006). *Biologia solurilor agricole*. Editura ELISAVAROS București.
Tang, Xu., Li, J., Ma, Y., Hao, X., Li, X. (2008). Phosphorus efficiency in long-term (15 ani) wheat-maize cropping systems with various soi land climate conditions. *Field Crop Research 108*. 231–237.
Vintila, I., Borlan, Z., Răuţă, C., Daniliuc, D., Ţigănaş, L. (1984). *Situația agrochimică a solurilor din România. Prezent și viitor*. Editura CERES București.
Vintilă, I., Dornescu, D., Nițescu, S., Alexandrescu A., Tătărușanu, E. (1989). Evoluția stării agrochimice a unui sol brun luvic sub influența îngrășămintelor minerale cu N, P, K, în cadrul unei experiențe de lungă durată. *Analele I.C.P.A., XLIX.*
XXX FAO. (1999). Ferilizer Strategies. International Fertilizer Industery Association.