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The influence of long-term fertilisation on phosphorus dynamics in the soil

Jonas ARBAČAUSKAS, Aistė MASEVIČIENĖ, Gediminas STAUGAITIS, Lina ŽIČKIENĖ, Donatas ŠUMSKIS, Zigmas VAIŠVILA

Lithuanian Research Centre for Agriculture and Forestry
Savanorių 287, Kaunas, Lithuania
E-mail: jonas.arbacauskas@lammc.lt

Abstract

A long-term experiment on agricultural plant fertilisation was carried out on a sandy loam *Epicalcari-Endocalcari-Endohypogleyic Luvisol* in Central Lithuania from 1971 to 2019. The aim of the study was to determine the influence of long-term use of mineral phosphorus (P) fertilisers and their interaction with nitrogen (N) and potassium (K) fertilisers on P fertiliser uptake, mobile phosphorus (P_2O_5) concentration and P balance in the soil, and to evaluate its relationship with P leaching from sandy loam soils.

According to the data of the study, after 49 years different combinations of NPK fertilisers in the fertilised fields resulted in the variations of mobile P_2O_5 in the 0–20 cm soil layer: 62–71 mg kg^{-1} without P_0, 280–351 mg kg^{-1} with annual P_{95} fertilisation and 503–614 mg kg^{-1} with P_{190}, or 10 times higher compared to zero P application. Due to fertilisation with P, the total phosphorus (P_{tot}) concentration in the soil increased. The P balance showed that after 49 years of annual applications of P_{95} to agricultural crops, 45.4–68.7 kg ha^{-1} was incorporated, and when P_{190} was applied, 131.0–160.3 kg ha^{-1} was incorporated in excess of the need for this element by plants. The most inefficient uptake 5.4–11.4% P was observed after annual application of P_{190} without the use of N and K fertilisers. The uptake increased to 27.3–32.6% when $N_{216}K_{190}$ fertiliser was applied together with P_{95}. With increasing rates of P fertilisers, P_2O_5 leaching from the soil 0–40 cm layer increased. Without P application, its annual leaching was as follows: in 1976–1998 – 0.43–0.77 kg ha^{-1}, in 1976–2019 – 0.82–0.90 kg ha^{-1}.

This study was able to establish significant relationships between P fertiliser uptake and NPK fertiliser rates, between mobile P_2O_5 concentration in the soil and P balance, and between P_{tot} concentration in the soil and P balance.

Key words: NPK fertilisation, balance, mobile phosphorus, leaching.

Introduction

Phosphorus (P) is one of the key elements influencing ecosystem sustainability and crop productivity (Johnston et al., 2014). More than 170 P-containing soil mineral types have been identified. However, P is very stable or insoluble in the soil, and only a very small amount of it is present in the soil solution. Phosphorus fertilisers are an important means of increasing crop yields in soils with low levels of plant available P (Vaišvila, 1996; Cordell et al., 2009; Johnston et al., 2014). Meanwhile, in the countries, where crop production is intensive, crops are often over-fertilised with P resulting in the accumulation of large amounts of this element in the soil leading to its increased leaching (Barberis et al., 1995; Tóth et al., 2014). Inefficient use of P fertilisers is becoming an increasing problem in Europe as well as a number of mobile P_2O_5 compounds enter water bodies, deteriorating their quality and causing eutrophication (Scholz et al., 2013; Withers et al., 2015). Phosphorus losses from soils also depend on the type of soil, its texture as well as climatic conditions (Glaesner et al., 2013; Bergström et al., 2015). The efficient use of P fertilisers is also important for the fact that the raw materials for the production of these fertilisers are scarce around the world, and they are not renewable, which makes P fertilisers more expensive (Jordan-Meille et al., 2012; Schoumans et al., 2015).

To reduce leaching losses of P from the soil and to optimize uptake of this nutrient by plants, it is important to know the cycle of the turnover of P in the soil and the best fertilisation practices (Veneklaas et al., 2012; Tóth et al., 2014; Bergström et al., 2015). A strategy for the efficient use of P fertilisers must ensure good yields of agricultural crops with minimal negative impact on the environment. In addition, the most important factor for the sustainable use of P fertilisers is the analysis of mobile P_2O_5 concentration in the soil

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(Benton, 2012; Johnston et al., 2014; Tóth et al., 2014; Braun et al., 2019). Phosphorus uptake by agricultural plants and fertiliser efficiency depend not only on the mobile P_2O_5 concentration in the soil, but also on its buffer capacity, acidity (pH), solubility of P compounds, moisture, physical properties of soil (Benton, 2012) and on securing plant nutrition by other nutrients (Ågren et al., 2012). The evaluation of the above properties facilitates a more efficient use of P reserves in the soil and developing limitations on the use of P fertilisers (Johnston et al., 2014; Medinski et al., 2018).

In order to ensure a more efficient use of P fertilisers, recommendations for the fertilisation of agricultural crops for farmers are prepared to achieve the planned yields by minimising the leaching of P compounds from the soil (Tóth et al., 2014; Braun et al., 2019). Recommendations for the use of P fertilisers in Europe are usually based on a two-step approach. The first step involves the determination of plant available P concentration in soil; the second step is the determination of the relationship between plant available P concentration in the soil and agricultural crop yield calculations based on the data from fertilisation field trials. The mobile P concentrations in the soil are usually divided into three groups: low, medium and high (and sometimes very high). Using the above data, the recommended rates of P fertiliser for agricultural crops is calculated. In some European countries (France, Italy, Switzerland and the Netherlands), recommendations for the use of P fertilisers also take into account other soil properties such as soil texture, clay and organic matter content, soil acidity, carbonate content and soil type (Jordan-Meille et al., 2012).

Recommendations for P fertilisation of agricultural plants in Lithuania are prepared according to similar principles. The key element for such calculations is the concentration of plant available P in the soil, determined by the Egnér-Riehm-Domingo (A-L) method. Soil type, texture and acidity are also taken into account. Phosphorus fertiliser rates for agricultural crops are adjusted considering the relationship between crop yields and plant available P concentrations obtained from short-term crop fertilisation trials on soils with different properties (Vaišvila, 1996; Management of agroecosystem…, 2010).

On 20 May 2020, as an integral part of The European Green Deal (Communication…, 2019), the European Commission unveiled the From Farm to Fork (2020) and Biodiversity Strategies (Communication…, 2020) to stand for a fair, healthy and environmentally-friendly food system, while protecting nature and reversing the degradation of ecosystems. From Farm to Fork and Biodiversity Strategies put forward ambitious targets to reduce nutrient losses by at least 50%, while ensuring no deterioration in soil fertility. This is expected to result in 20% reduction of fertiliser use. These targets will require substantial changes in agricultural practices, while using fertilisers.

However, the influence of P fertilisers and their interaction with other plant nutrients on crop yield, soil P content and soil P leaching trends are best demonstrated by long-term crop fertilisation trials conducted under site-specific soil and climatic conditions (Blake et al., 2000; Buczko et al., 2018; Johnston, Poulton, 2018). The losses from leaching of biogenic elements are impacted not only by the fertilisation practices but also by climate conditions, especially by precipitation levels. Soil coverage by plants, humidity of soil and air temperature have an important impact as well (Arheimer el al., 2012; Thodsen at al., 2017; Kim et al., 2018).

A long-term experiment on agricultural plant fertilisation was carried out since 1971 on a sandy loam *Luvisol* in the Middle Lithuanian Lowland. The aim of the study was to determine the influence of long-term use of mineral phosphorus (P) fertilisers and their interaction with nitrogen (N) and potassium (K) fertilisers on P fertiliser uptake, mobile phosphorus (P_2O_5) concentration and P balance in the soil, and to evaluate its relationship with P leaching from sandy loam soil.

Materials and methods

23°74′97.6″ E), Radviliškis distr., Lithuania, on a sandy loam *Epicalcari-Endocalcari-Endohypogleyic Luvisol* (WRB, 2015). Before the start of the experiment (1971), in the soil arable (0–20 cm) layer, pH_{KCl} was 6.9 ± 0.22, humus content – 2.2 ± 0.32%, total nitrogen (N_{tot}) – 0.17 ± 0.03%, total phosphorus (P_{tot}) – 0.301 ± 0.043%, mobile phosphorus (P_2O_5) – 64 ± 11.4 mg kg^{-1} and mobile potassium (K_2O) – 96 ± 12.0 mg kg^{-1}. Perennial grasses, winter wheat, spring rapeseed, annual grasses, spring barley and sugar beets were grown according to the crop rotation in the experimental area. The article presents data on the calculation of P in the soil, its uptake and balance for 1971–1986, 1971–1998 and 1971–2019 experimental periods, i.e., for 16, 28 and 49 years. Concentrations of P_{tot} and mobile P_2O_5 were determined in the topsoil 0–20cm. Phosphorus leaching was determined in the 0–40cm layer starting from 1976.

Experimental design. The experiment was carried out according to the research design based on several factors compiled by Перегудов и др. (1976). The experimental design includes 27 treatments (Table 2). The scheme indicates the average annual fertilisation (kg ha^{-1}) by N, P_2O_5 and K_2O, respectively: N_0, N_{108}, N_{216}; P_0, P_{95}, P_{190}; K_0, K_{95}, K_{190}. The experimental plot size was 6 × 9 m, each treatment was repeated twice. To fertilise agricultural plants throughout the experimental years, ammonium nitrate (34.4% N), granulated superphosphate (19% P_2O_5) and crystal potassium chloride (KCl) (60.0% K_2O) were used. Before sowing, fertiliser was spread manually and incorporated into the soil using a cultivator.

Experimental methods. The P_2O_5 concentration in the soil was determined by the Egnér-Riehm-Domingo (A-L) method. Other soil analyses were performed by using the following methods: soil pH_{KCl} – in 1 M KCl (extraction ratio 1:5) by the potentiometric method; humus – by the dry combustion method using a carbon analyser "liquiTOC II" (Elementar Analysensysteme GmbH, Germany); N_{tot} – by the Kjeldahl method; mobile K_2O – by the (A-L) method; P_{tot} – by mineralising the soil using a royal acid solution (HNO_3 and HCl mixture at 1:3 ratio) followed by the colorimetric method.

The P content in lysimeter leachates was determined by the colorimetric method after acidification and colouring the water with ammonium molybdate. The P content in plants was determined by combusting plant material in a muffle furnace at 550°C temperature, dissolving ash in HNO_3 and HCl acids and diluting with water by the colorimetric method. The P balance (B) in the soil was calculated using the difference between the amount of P added with the fertiliser (T) and the amount of P accumulated in the crop (D): B (kg ha^{-1}) = T − D. Phosphorus uptake from fertilisers was calculated by the difference method most commonly used in field experiments (Syers et al., 2008). This is the ratio of the amounts of P stored in the yield increase (P_p) to that added as fertiliser (P_t), expressed as a percentage: P (%) = P_p / P_t × 100. The higher the value (%) obtained, the higher the uptake of P fertilisers and the lower the probability that unabsorbed P from plants will be fixed in the soil in forms inaccessible to plants or leach into water bodies.

The measurements of P leaching from the soil were performed using Шилова (1955) lysimeters. They were buried to a depth of 40 cm in the soil in nine application plots – $N_0P_0K_0$, $N_0P_{95}K_{95}$, $N_0P_{190}K_{190}$, $N_{108}P_{95}K_0$, $N_{108}P_0K_{95}$, $N_{108}P_{95}K_{95}$, $N_{216}P_0K_{190}$, $N_{216}P_{190}K_0$ and $N_{216}P_{190}K_{190}$. The lysimeter screen size was 40 × 57 cm, a receiver capacity – 3 litres. Lysimeter water samples were taken in spring before fertilisation (April–May) and in autumn after harvesting (October–November). Soil samples were collected once in four years, at the end of crop rotation. Crop yield samples were collected each year from two replications of all treatments of the experiment.

The amount of phosphate (kg ha^{-1}) leached from the soil was calculated by multiplying the average annual phosphate (PO_4^{3-}) concentration in lysimeter leachates by the annual precipitation (m^3 ha^{-1}) and the leaching rate, which is 0.34 in light loam soils of the Middle Lithuanian Lowland (Baigys, Gaigalis, 2012). The obtained PO_4^{3-} amount in kg ha^{-1} was converted to P_2O_5.

Meterological conditions. The average air temperature and precipitation by individual experimental periods are presented in Table 1. These data show global warming since the average air temperature 1971–1990, 1991–2005 and 2006–2020 was 0.5; 1.0 and even 1.8°C higher than the multi-year rate. During the 2006–2020 experimental period, the average annual precipitation exceeded the multi-annual precipitation rate (566 mm). During the 1971–1990 and 1991–2005 experimental periods, its levels were close to the multi-annual norm (585 and 529 mm, respectively).

Table 1. Meterological conditions (Skėmiai, Radviliškis distr., 1971–2020)

Month	Temperature °C				Precipitation mm			
	1971–1990	1991–2005	2006–2019	Multi-annual average	1971–1990	1991–2005	2006–2020	Multi-annual average
January	−4.9	−2.8	−4.1	−5.4	39	31	46	34
February	−3.3	−2.6	−3.1	−4.5	26	33	29	25
March	0.1	0.5	1.1	−2.6	31	31	29	32
April	5.9	7.0	7.6	5.6	38	30	34	40
May	12.4	12.3	12.9	12.3	48	44	49	36
June	15.5	15.5	16.7	15.8	64	58	47	62
July	16.9	17.9	18.8	17.0	81	68	92	70
August	16.0	17.3	18.0	16.4	64	59	77	67
September	11.9	12.7	13.4	11.8	49	45	51	54
October	6.7	6.9	7.4	6.9	48	49	51	47
November	1.8	1.6	4.0	1.7	48	40	50	55
December	−1.5	−1.8	0.6	−2.5	48	41	48	44
	Average annual air temperature °C				Average annual amount of precipitation mm			
	6.5	7.0	7.8	6.0	585	529	602	566

Statistical analysis. Statistical significance of the experimental data was assessed using Duncan's multiple range test; significant differences were established between the data lettered a, b, c, d, e, f, etc. at 5% probability level ($P \leq 0.05$) (Raudonius, 2017). Mean and their ratios as well as standard deviations (SD) were calculated using software *Excel* (Microsoft, USA). To determine the strength and nature of the relationship between the variables, correlation and regression data analysis was performed using software *Statistica*, version 7 (Hill, Levicki, 2005).

Results and discussion

Uptake of phosphorus (P) fertilisers. According to the performed experiment, the uptake of P fertilisers depended mainly on the rates of these fertilisers as well as on the fertilisation with N and K fertilisers (Table 2).

During the experimental period, P was best absorbed from mineral fertilisers by agricultural plants (up to 32.6%) after fertilising with P_{95} on average annually together with N_{108} and N_{216} and K_{95} and K_{190} fertilisers. Assessing the results from an ecological point of view and in order to ensure soil sustainability, the most optimal fertiliser combination for P uptake from fertiliser was $N_{108}P_{95}K_{95}$. The uptake of P fertilisers decreased significantly with agricultural crops being fertilised at significantly higher rates (P_{190}) than those required to ensure optimal plant nutrition. In addition, the uptake of P fertilisers decreased significantly throughout the experimental period without fertilisation with K and especially N fertilisers for a prolonged period. During the 1971–1986, 1971–1998 and 1971–2019 experimental periods, having had the average annual fertilisation rate of only P_{190} kg ha^{-1}, agricultural plants assimilated 11.4, 9.5 and 7.6 % of P fertilisers, respectively. As the experimental period lengthened, fertilisation, especially that with higher (N_{216} and P_{190}) fertiliser rates, resulted in high P concentration

Table 2. Uptake of phosphorus (P_2O_5) fertilisers depending on the fertilisation intensity

N	P_2O_5	Average annual fertiliser rate kg ha^{-1}		
		K_2O		
		0	95	190
		Experimental periods: 1971–1986, 1971–1998 and 1971–2019		
		Uptake of P fertilisers %		
0	0	–	–	–
	95	14.2 / 12.3 / 11.6	12.1 / 10.2 / 13.0	18.9 / 13.6 / 14.0
	190	11.4 / 9.5 / 7.6	8.9 / 7.0 / 7.4	7.5 / 6.7 / 7.5
108	0	–	–	–
	95	20.9 / 21.4 / 15.6	28.0 / 30.6 / 25.2	21.4 / 24.3 / 22.9
	190	11.6 / 12.1 / 9.7	18.5 / 19.4 / 15.0	13.4 / 16.2 / 15.6
216	0	–	–	–
	95	14.6 / 14.7 / 7.0	22.5 / 26.1 / 17.3	30.8 / 32.6 / 19.6
	190	11.5 / 11.9 / 7.4	15.2 / 16.8 / 12.4	19.5 / 20.1 / 14.6

in the soil, which reduced the influence of P fertiliser rates on the uptake of these fertilisers.

To reduce P loss from soil and optimise the uptake of this plant nutrient, it is important to know about P metabolism in soil and best practices for P fertilisation (Veneklaas et al., 2012; Tóth et al., 2014; Bergström et al., 2015). Plants are reported to absorb 20–30% of P from fertilisers with the remainder chemically sorbed, biologically immobilised and leached (López-Arredondo et al., 2014). In addition, P uptake from fertilisers and soil also depends on plant nutrition with other essential nutrients and other conditions (Johnston et al., 2014).

During individual experimental periods, a very strong and significant dependence (r = 0.95–0.96, P < 0.01) of the P fertiliser uptake (y, %) on the rates of NPK fertilisers and their interaction (x, kgha^{-1}) was observed (Table 3). However, the analysis of individual parameters of the regression equation showed that such significant dependence of the P fertiliser uptake was only observed on the P rates (a_2), and to a lesser extent but also significantly – on those of N fertilisers (a_1). As the rates of P fertilisers increased, the uptake of P fertilisers decreased steadily (a_5). The interactions between N and P (a_7), N and K (a_8) as well as those between P and K (a_9) fertilisers had a positive effect on the uptake of P fertilisers.

According to long-term crop fertilisation experiments in the UK, Germany and Poland, the effects of P fertilisers on crop yield and P balance are greater when other essential nutrients are sufficient in their nutrition (Blake et al., 2000).

Table 3. Dependence of phosphorus (P_2O_5) fertiliser uptake on mineral NPK fertiliser rates

$y = a_0 + a_1N + a_2P + a_3K + a_4N^2 + a_5P^2 + a_6K^2 + a_7NP + a_8NK + a_9PK$ coefficient values										R^2
a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	
1971–1986										
−0.85	0.031	0.34	0.0075	−0.00019	−0.0015	−0.00009	0.00015	0.00019	0.000054	0.91**
1971–1998										
−1.72	0.06	0.33	0.015	−0.00032	−0.0015	−0.00015	0.00021	0.00022	0.000088	0.90**
1971–2019										
−1.16	0.057	0.26	0.026	−0.00033	−0.0012	−0.00017	0.000097	0.00014	0.00012	0.92**

R^2 – coefficient of determination; * and ** – significant at the P < 0.05 and P < 0.01 probability levels; a_0 – free member, a_1 – a_9 NPK fertilisers and their interaction coefficients

Mobile phosphorus (P_2O_5) concentration and balance in the soil. According to the performed experiment, the average annual P balance in the fields fertilised with P fertilisers was positive (Table 4). Having fertilised agricultural crops with P_{95} kg ha^{-1} annually for 49 years, 45.4–68.7 kg ha^{-1} of this plant nutrient was applied with fertilisers, and with P_{190} – actually, 131.0–160.3 kg ha^{-1} was applied in excess compared to the amount accumulated in the crop yield. In the plots not fertilised with P fertilisers, the P balance was negative and agricultural plants absorbed an average of 15.6–31.3 kg ha^{-1} P from the soil annually. Similar trends in P

Table 4. Influence of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) fertiliser rates on the average annual P balance and mobile P_2O_5 concentration in the soil during different experimental periods

Average annual fertiliser rate kg ha^{-1}			Average annual P balance kg ha^{-1}			Mobile P_2O_5 concentration in 0–20 cm soil layer[1] mg kg^{-1}		
N	P_2O_5	K_2O	1971–1986	1971–1998	1971–2019	1986	1998	2019
0	0	0	−23.8	−18.5	−15.6	69 abc	55 a	64 a
0	0	95	−29.9	−23.6	−20.4	92 bc	50 a	62 a
0	0	190	−30.0	−23.5	−20.5	78 abc	63 a	67 a
0	95	0	65.4	65.7	68.7	265 i	324 e	351 e
0	95	95	61.5	62.6	67.3	186 def	283 cde	335 de
0	95	190	54.3	58.8	66.4	224 gh	297 de	352 e
0	190	0	160.6	155.2	159.9	437 p	627 j	591 ghi
0	190	95	159.5	155.0	160.3	224 gh	536 gh	579 fg
0	190	190	162.3	155.5	160.1	341 kl	629 j	614 i
108	0	0	−29.7	−25.8	−22.4	71 abc	57 a	71 a
108	0	95	−31.0	−26.4	−22.7	62 ab	56 a	64 a
108	0	190	−36.1	−34.4	−27.4	79 abc	53 a	63 a
108	95	0	52.6	49.6	58.1	182 def	282 cde	321 cde
108	95	95	44.0	40.6	48.9	244 hi	264 cd	327 cde
108	95	190	45.7	41.3	51.1	190 efg	243 bc	295 bc
108	190	0	154.3	142.9	149.1	360 lm	575 h	578 fg
108	190	95	138.5	128.0	139.0	410 nop	533 gh	581 fghi
108	190	190	144.0	129.5	138.0	303 j	520 fg	579 fg
216	0	0	−35.1	−32.2	−31.3	99 c	53 a	62 a
216	0	95	−37.3	−33.3	−30.9	63 ab	59 a	64 a
216	0	190	−33.7	−28.6	−25.9	58 a	58 a	63 a
216	95	0	53.6	49.7	57.3	164 de	210 b	302 bcd
216	95	95	43.3	37.7	47.6	151 d	215 b	322 cde
216	95	190	38.3	36.2	45.4	201 fg	214 b	280 b
216	190	0	148.9	137.0	144.6	307 jk	478 f	503 j
216	190	95	139.1	126.5	135.2	308 jk	420 f	551 f
216	190	190	133.8	124.8	131.0	387 mn	484 f	554 f

Note. [1] – in 1971, before the start of the experiment, the average mobile P_2O_5 content in the 0–20 cm soil layer was 64 ± 11 mg kg^{-1}; different letters (a, b, c, etc.) indicate significant differences between the compared experimental applications at $P \leq 0.05$.

balance were found in both 1971–1986 and 1971–1998 experimental periods.

Both the P balance and variations in the mobile P_2O_5 concentration in the soil depended on P fertiliser rates. The average annual application of $N_{108}P_{95}K_{95}$ fertiliser for agricultural crops in 1986, 1998 and 2019 resulted in 244, 264 and 327 mg kg^{-1} mobile P_2O_5 found in the 0–20 cm soil layer, respectively. Meanwhile, having fertilised the plants with twice the rates of the $N_{216}P_{190}K_{190}$ fertilisers annually, the mobile P_2O_5 concentrations in the 0–20 cm soil layer were 387, 484 and 554 mg kg^{-1}, respectively. Fertilisation with P fertilisers for the first 15 years had the greatest impact on the concentration of mobile P_2O_5 in the soil. In the following years, when higher levels of mobile P_2O_5 had accumulated in the soil, the influence of fertilisation on its variations in the soil was smaller. This means that in the presence of excess P balance, the P unabsorbed by plants accumulated in the soil and, when the concentration limit of about 300 mg kg^{-1} was reached, its accumulation in the soil slowed down due to leaching and chemical sorption.

In order to determine a long-term strategy for the use of P fertilisers, it is important to evaluate the changes in mobile P_2O_5 concentration in the soil and the accumulation of this element in agricultural crops (Johnston et al., 2014). According to Ekholm et al. (2005), the key tool for evaluation of P content changes and its leaching is the calculation of the P balance in the soil. Based on long-term experiments of fertilisation of agricultural plants in the UK, Germany and Poland, it was concluded that the impact of P fertilisers on overall P balance depends not only on P fertilisation practices but also on the concentration of other macro-nutrients in the soil (Blake et al., 2000; Johnston et al., 2014).

According to the data of the statistical analysis, the variation of mobile P_2O_5 concentration (y; mg kg^{-1}) depending on its balance (x; kg ha^{-1}) in the soil was described by a second-degree polynomial equation (Table 5). The quadratic dependence between the above indicators was very strong and significant during all years of the experiment: in 1971–1986 – r = 0.91, and in 1971–1998 and 1971–2019 – r = 0.99 at the $P < 0.01$ probability level.

Table 5. Dependence of mobile phosphorus (P_2O_5) concentration on the balance of this element in the soil (1971–2019)

y	*x*	Experimental period	Parameters of equation $y = a + bx + cx^2$			R^2
			a	b	c	
Mobile P_2O_5 concentration in soil mg kg^{-1}	Average annual P balance kg ha^{-1}	1971–1986	133.1	1.85	−0.0034	0.83**
		1971–1998	123.9	2.51	0.0032	0.98**
		1971–2019	145.4	3.25	−0.0025	0.99**

** – significant at the $P < 0.01$ probability level

In Germany, since 1902, the fertilisation of agricultural crops with mineral and organic fertilisers has increased the concentration of mobile P_2O_5 in the soil up to six times. However, when they applied only NK fertilisers and had a negative P balance in the soil, the concentration of this element in the soil decreased more compared to the zero variant (Medinski et al., 2018). Another long-term experiment found that in unfertilised fields P was released from sparingly soluble forms for at least 30 years after the experiment was set up (Gransee, Merbach, 2000). In Romania, starting with 1986, when the usage of P fertiliser decreased substantially, the area of low and very low P content soils increased significantly (Dodociou et al., 2012).

Total phosphorus (P_{tot}) concentration in the soil. According to the experimental data, due to long-term fertilisation both mobile P_2O_5 and P_{tot} concentrations in the soil increased, because part of P, which is supplied as fertiliser, is chemically bound in the soil. That was confirmed by the data from long-term research conducted by Azevedo et al. (2018). The data of our experiment revealed that P_{tot} concentration in the soil was changing at a slower rate compared to changes of mobile P_2O_5 concentration (Table 6).

During the experimental period 1971–2019, the P_{tot} concentration in the plots not fertilised with P fertilisers ranged from 0.284% to 0.293%. On average, having applied higher rates of N and K ($N_{216}K_{190}$) fertilisers

Table 6. Influence of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) fertiliser rates on total phosphorus (P_{tot}) concentration in the soil (2019)

N	P_2O_5	Average annual fertiliser rate kg ha^{-1}		
		K_2O		
		0	95	190
		P_{tot} concentration (%) in 0–20 cm soil layer		
		P_{tot} concentration in 1971 – 0.301%		
0	0	0.290 a	0.293 ab	0.284 a
	95	0.537 fg	0.492 ef	0.539 fg
	190	0.725 k	0.686 ijk	0.664 hijk
108	0	0.357 bc	0.327 ab	0.334 ab
	95	0.509 ef	0.462 de	0.419 cd
	190	0.695 jk	0.702 jk	0.594 gh
216	0	0.280 a	0.358 bc	0.315 ab
	95	0.519 ef	0.485 def	0.460 de
	190	0.690 jk	0.614 hi	0.677 ijk

Note. Different letters (a, b, c, etc.) indicate significant differences between the compared experimental applications at $P \leq 0.05$.

annually but without P fertilisation (P_0), a slightly higher level of P_{tot} was detected in the 0–20 cm soil layer – 0.315%, which was apparently influenced by higher amounts of plant residues left in the soil. Meanwhile, with the annual incorporation of P_{95} and P_{190}, the P_{tot} in the soil during the whole experimental period increased significantly by 0.460% and 0.677%, respectively. However, the highest P_{tot} content (0.725%) was found in the soil after the application of P_{190} fertiliser rate but without N and K (N_0K_0) fertilisation. Anyway, most importantly, the total P concentration in the soil of plots not fertilised with P fertilisers hardly changed during 49 years. Similar results were obtained in Germany, where a 110-year crop fertilisation experiment showed a positive P balance in the soil with the P_{tot} concentration increasing up to two-fold compared to unfertilised fields (Medinski et al., 2018).

Long-term fertilisation of agricultural plants with mineral P fertilisers resulted in a strong and significant dependence ($r = 0.89$, $P < 0.01$) of the P_{tot} concentration (y; %) on the average annual P balance (x; kg ha^{-1}) in the 0–20 cm soil layer (Table 7). Therefore, the P unabsorbed by the plants could be converted to exchangeable and non-exchangeable forms.

Table 7. Relationship between total phosphorus (P_{tot}) concentration in the soil and P balance (1971–2019)

y	x	Parameters of equation $y = a + bx + cx^2$			R^2
		a	b	c	
P_{tot} concentration in soil %	Average annual P balance kg ha^{-1}	0.266	0.0011	−0.0000033	0.81**

** – significant at the $P < 0.01$ probability level

Phosphorus leaching from the soil. Phosphorus not used in agricultural plant nutrition can contaminate surface waters and cause their eutrophication (Bergström et al., 2015). Although it is estimated that, due to low P mobility in the soil, it leaches only about 1 kg ha^{-1} per year (Glaesner et al., 2013). According to the experimental data, high concentration of mobile P_2O_5 in the soil significantly increase phosphorus leaching (Table 8).

The lowest average annual phosphate (PO_4^{3-}) concentration in lysimeter leachates was in the plots not fertilised with P fertilisers. In 1976–1998, only 0.29–0.53 mg L^{-1} was detected, which corresponds to only 0.43–0.77 kg ha^{-1} leaching of P_2O_5. During 1976–2019, such P_2O_5 leaching was close but slightly higher – 0.82–0.90 kg ha^{-1}. Meanwhile, the annual fertilisation of agricultural crops with P_{190} kg ha^{-1} and mobile P_2O_5 accumulation of 478–629 mg kg^{-1} in the soil resulted in P_2O_5 leaching of 4.15–5.51 kg ha^{-1} from the 0–40 cm layer of soil in 1976–1998 and 5.63–6.18 kg ha^{-1} in 1976–2019 annually. This is eight to ten times more than in the plots not fertilised with P.

Table 8. Influence of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) fertiliser rates and mobile P_2O_5 concentration in the soil on P leaching from 0–40 cm soil layer

Average annual fertiliser rate kg ha^{-1}			Mobile P_2O_5 concentration in soil mg kg^{-1}		Average annual PO_4^{3-} concentration in lysimeter leachate mg L^{-1}		P_2O_5 leached from soil every year kg ha^{-1}	
N	P_2O_5	K_2O	1998	2019	1976–1998	1976–2019	1976–1998	1976–2019
0	0	0	55 ± 5.6	64 ± 3.5	0.53 a	0.62 a	0.77	0.90
0	95	95	283 ± 19.8	335 ± 12.1	1.83 b	2.38 e	2.66	3.46
108	0	95	56 ± 8.5	64 ± 8.5	0.30 a	0.58 a	0.44	0.84
108	95	0	282 ± 19.7	321 ± 12.7	2.70 c	2.00 b	3.93	2.90
108	95	95	264 ± 15.5	327 ± 11.3	1.96 b	1.86 b	2.85	2.70
0	190	190	629 ± 17.0	614 ± 15.6	3.01 d	4.20 d	4.38	6.10
216	0	190	58 ± 8.5	63 ± 9.9	0.29 a	0.56 a	0.43	0.82
216	190	0	478 ± 14.1	503 ± 11.3	2.86 cd	4.25 d	4.15	6.18
216	190	190	484 ± 11.3	554 ± 18.4	3.79 e	3.87 f	5.51	5.63

Note. Different letters (a, b, c, etc.) indicate significant differences between the compared experimental applications at $P \leq 0.05$.

The annual application of P_{95}, i.e., the maximum allowed rate (40 kg ha^{-1} P) according to HELCOM (2020) recommendations resulted in P_2O_5 leaching from 2.66 to 3.93 kg ha^{-1} annually. According to the experimental data, the average PO_4^{3-} concentration in the soil significantly depended on the P_2O_5 concentration in the 0–20 cm soil layer. The dependence of PO_4^{3-} concentration in the soil solution on soil P content in 1976–1998 and 1976–2019 was described by the following regression equations: $y = -0.31 + 0.012x - 0.00011x^2$ ($r = 0.96$, $p < 0.01$) and $y = 0.21 + 0.052x + 0.0000029x^2$ ($r = 0.98$, $p < 0.01$), respectively. The studies conducted in Western European countries show similar trends. In the UK, there was little P leaching from the soil observed when P concentration in the soil arable layer (according to Olsen) was less than 60 mg kg^{-1}. As the mobile P_2O_5 concentration in the soil increased, its leaching also increased (Hesketh, Brookes, 2000). The studies in Germany also found a positive and significant correlation between the mobile P_2O_5 concentration in the soil arable layer and the annual P concentration in lysimeter leachates (Rupp et al., 2018).

Long-term fertilisation trials are important in assessing the long-term effects of fertilisers on soil and the efficiency of their use. In the course of such long-term trials, not only the generations of researchers change but also the goals, evaluation criteria and understanding. Fifty years ago, the prevailing opinion was that only well-cultivated P-rich soils could produce a good crop yield, which is why the aim was abundant fertilisation with P. At that time, P fertilisers were also cheaper, and less attention was paid to ecology. As show the results of the study, in 49 years, very high rates of P_{190} fertilisers increased the mobile P_2O_5 concentration in the 0–20 cm soil layer almost 10 times – from 57 to 554 mg kg^{-1}.

However, from an ecological point of view, significantly higher P amounts from the 0–40 cm layer were leached out – the annual average of 5.97 mg kg^{-1}, while only 0.85 mg kg^{-1} were leached out from the plots not fertilised with P. Moreover, the P balance shows that at such a high rate of fertilisation about 131–160 kg ha^{-1} P_2O_5 remains unassimilated by plants every year. Meanwhile, the P_{95} fertilisation rate, which is close to the rate prescribed by HELCOM and used in some European Union countries as the maximum rate limiting P for organic fertilisers (40 kg ha^{-1} P = 92 kg ha^{-1} P_2O_5) was also rather high, because the annual balance of P obtained was higher – 45–68 kg ha^{-1} P_2O_5. Therefore, such an annual rate could only be applied in individual years and for more demanding plants, and for the majority of plants the P_{30}–P_{60} rates would suffice.

Importantly, this long-term study established the dependence of P fertiliser uptake on mineral NPK fertiliser rates, and a relationship between the total P_{tot} and mobile P_2O_5 concentrations in the soil and the P balance was found.

Conclusions

1. The concentration of mobile phosphorus (P_2O_5) in the 0–20 cm layer of a sandy loam *Epicalcari-Endocalcari-Endohypogleyic Luvisol* before the experiment was 64 ± 11.4 mg kg^{-1}, and after 49 years it was found different against the background of nitrogen (N) and potassium (K) fertilisers in different P-fertilised plots: 62–71 mg kg^{-1} without P, 280–351 mg kg^{-1} with annual P_{95} fertilisation and 503–614 mg kg^{-1}, or 10 times higher, with P_{190}. Under the influence of P fertilisers, the mobile P_2O_5 concentration in the soil increased significantly during the first two decades compared to the later years.

2. Due to fertilisation with P, the total phosphorus (P_{tot}) concentration in the soil increased. If before the start of the trial it was 0.301 ± 0.043%, then after 49 years it was 0.280–0.357% in P-unfertilised plots, 0.509–0.537% in the plots fertilised with P_{95} annually and 0.690–0.725% in the plots fertilised with P_{190}.

3. The P balance showed that after 49 years of annual applications of P_{95} to agricultural crops, 45.4–68.7 kg ha^{-1} was incorporated and, when P_{190} was applied, 131.0–160.3 kg ha^{-1} was incorporated in excess of the need for this element by plants. The most inefficient uptake – 5.4–11.4% P – was observed after annual applications of P_{190} without the use of N and K fertilisers. The uptake increased to 27.3–32.6% when $N_{216}K_{190}$ fertiliser was applied together with P_{95}.

4. With increasing rates of P fertilisers, mobile P_2O_5 leaching from the 0–40 cm soil layer increased. Without P application, its annual leaching was as follows: in 1976–1998 it was 0.43–0.77 kg ha^{-1}, and in 1976–2019 – 0.82–0.90 kg ha^{-1}. Annual fertilisation with P_{95} resulted in the leaching of 2.66–3.93 and 2.70–3.46 kg ha^{-1}, and with P_{190} the leaching amounted to 4.15–5.51 and 5.63–6.18kg ha^{-1}, respectively.

5. The long-term study established a significant relationship (r = 0.96**) between P fertiliser uptake and NPK fertiliser rates, between mobile P_2O_5 concentration in the soil and P balance (r = 0.99**) and between P_{tot} concentration in the soil and P balance (r = 0.90**).

6. Long-term analysis revealed that P_{95} fertilisation rate, which is close to HELCOM (40 kg ha^{-1} P = 92 kg ha^{-1} P_2O_5) rate, was too high, as it exceeded the need for this element for plants. Therefore, it is recommended to apply such annual rate only to highly demanding plants and for the majority of the plants P_{30}–P_{60} rates would be sufficient.

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Ilgalaikio tręšimo įtaka fosforo dinamikai dirvožemyje

J. Arbačauskas, A. Masevičienė, G. Staugaitis, L. Žičkienė, D. Šumskis, Z. Vaišvila

Lietuvos agrarinių ir miškų mokslų centras

Santrauka

Ilgalaikis žemės ūkio augalų tręšimo eksperimentas vykdytas 1971–2019 m. Vidurio Lietuvoje, smėlingo lengvo priemolio sekliai karbonatingame giliau glėjiškame išplautžemyje. Tyrimo tikslas – nustatyti ilgalaikio mineralinių fosforo (P) trąšų naudojimo ir jų sąveikos su azoto (N) bei kalio (K) trąšomis įtaką fosforo trąšų pasisavinimui, judriojo P_2O_5 koncentracijai bei balansui dirvožemyje ir įvertinti jo ryšį su P išplovimu iš smėlingo priemolio. Tyrimo duomenimis, po 49 metų skirtingais NPK trąšų deriniais tręštuose laukeliuose judriojo P_2O_5 dirvožemio 0–20 cm sluoksnyje nustatyta nevienodai: netręšus fosforu (P_0) – 62–71 mg kg^{-1}, kasmet patręšus P_{95} – 280–351 mg kg^{-1}, patręšus P_{190} – 503–614 mg kg^{-1}, arba 10 kartų daugiau nei netręšus fosforo trąšomis. Dėl fosforo trąšų įtakos taip pat didėjo suminio fosforo koncentracija dirvožemyje. Fosforo balansas parodė, kad žemės ūkio augalus 49 metus kasmet tręšiant P_{95}, P buvo įterpta 45,4–68,7 kg ha^{-1}, o P_{190} – 131,0–160,3 kg ha^{-1} daugiau nei yra šio elemento poreikis augalams. Augalai neefektyviausiai (5,4–11,4 %) P pasisavino kasmet tręšiant P_{190} ir nenaudojant azoto bei kalio trąšų. Pasisavinimas padidėjo iki 27,3–32,6 %, kai su P_{95} buvo įterpiama $N_{216}K_{190}$ trąšų. Didinant fosforo trąšų normas, P_2O_5 išplovimas iš dirvožemio 0–40 cm sluoksnio didėjo.
Tyrimo metu nustatytas esminis priklausomumas tarp fosforo trąšų pasisavinamumo ir NPK trąšų normų, judriojo P_2O_5 koncentracijos dirvožemyje ir P balanso, suminio fosforo koncentracijos dirvožemyje ir P balanso.

Reikšminiai žodžiai: NPK tręšimas, balansas, judrusis fosforas, išplovimas.