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Effect of phosphorus application technique on effectiveness indices of its use in maize cultivation

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Abstract: The study presents results of 4-year field trials; their purpose was to assess the effectiveness indices of phosphorus recovery in maize cultivation depending on the depth of two-component fertiliser (NP) placement in the soil layer, type of nitrogen fertiliser (ammonium nitrate and urea) and time point of the application. The hypothesis of the experiment assumed that different depth of NP fertiliser placement improved the indices of phosphorus application in maize cultivation. Row fertilisation with two-component NP fertiliser, regardless of the year, clearly affected phosphorus accumulation (uptake) with grain yield. The recovery metabolism index, i.e., the phosphorus recovery of a mineral fertiliser component was at a low level (on average < 12%). Row application, regardless of the depth of fertiliser placement, was more effective in relation to broadcast sowing. The index of agricultural efficiency of phosphorus confirms the significant impact of the depth of NP fertiliser placement at 5 cm in the soil as optimal for agricultural practice. The use of nitrogen in maize cultivation before sowing, compared to the application of this component at the BBCH 15/16 stage, significantly increases agricultural effectiveness of phosphorus applied as mineral fertiliser. The placement of NP fertiliser deep in the soil profile was more effective compared to traditional broadcast fertilisation. The method of fertiliser application in maize cultivation can thus be a tool increasing cultivation profitability in both economic and environmental terms.

Keywords: *Zea mays* L.; macronutrient; deficiency; field experiment; soil moisture; precipitation

Phosphorus (P) is a nutrient that plays a fundamental role in the initial maize developmental stages as well as grain formation and its maturation (Nash and Halliwell 1999, Plénet et al. 2000, Aghaie et al. 2013, Szulc et al. 2020). It stimulates the development of the root system and indirectly increases plants' resistance to periodic soil moisture deficiencies (Mollier and Pellerin 1999). Numerous literature reports indicated a large impact of soil temperature on phosphorus uptake by maize. The plants then have clear symptoms of its deficiency in the form of red discoloration along the edges of the leaf blades and their subsequent withering, especially in the case of water shortage, and a marked inhibition of growth and development. These symptoms occur, especially in years with cold springs, even with sufficient phosphorus content in soil (Boring et al. 2018). Subsequently, an underdeveloped root

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system prevents phosphorus absorption in quantities sufficient for the plant (Nkebiwe et al. 2016). Current efforts to increase global cereal production, including maize, must be directed towards more effective component utilisation from a dose of mineral fertiliser. The increase in grain yield per unit of phosphorus and nitrogen used is particularly important due to concerns regarding the negative impact of the excess of these nutrients on the natural environment (Szulc et al. 2016a). The key role in this aspect may be the greater ability of plants to uptake them (Peng et al. 2010) and to utilise a component (Niu et al. 2007) from a dose of mineral fertiliser. Hence, the constant direction of research on the role of nitrogen and phosphorus in shaping plant production is to determine biologically and economically justified optimal doses thereof, taking into account factors influencing the uptake and utilisation of these elements from mineral fertilisers (Nkebiwe et al. 2016). The hypothesis of the experiment assumed that the depth of the NP fertiliser application affected phosphorus utilisation efficiency indicators in maize cultivation. The adopted assumptions were verified on the basis of a 4-year field experiment using 4 depths of NP fertiliser application, two nitrogen carriers, and two nitrogen application time points. The purpose of the field experiments was to determine the effect of the depth of two-component mineral fertiliser (NP) placement in the soil layer on phosphorus effectiveness indices in maize grain cultivation.

MATERIAL AND METHODS

Experimental field. A field trial was carried out at the Department of Agronomy of Poznań University of Life Sciences, on the fields of the Gorzyń Experimental and Educational Unit, in the years 2015–2018. It was conducted for four years in the same random block design (split-split-plot) with 3 factors and 4 field replicates. The following variables were tested: A – 1st order factor – NP fertiliser application depth [A1 – 0 cm (broadcast); A2 – 5 cm (in rows); A3 – 10 cm (in rows); A4 – 15 cm (in rows)]; B – 2nd order factor – type of supplementary nitrogen fertiliser [B1 – ammonium nitrate; B2 – urea]; C – 3rd order factor-date of supplementary nitrogen fertilisation [C1 – before sowing; C2 – top dressing in the BBCH 15/16 stage]. The same level of mineral fertilisation (100 kg N/ha, 30.8 kg P/ha, and 107.9 kg K/ha) was applied in all experimental objects. Fertilisation was balanced against phosphorus, which was applied at the whole required dose in the form of ammonium phosphate (18% N, 46% P_2O_5), according to the experimental design under the 1st order factor. K fertilisation was performed before maize sowing potassium salt (60%). The control object (0 kg N/ha and 0 kg P/ha) was also the purpose for calculating the indices of the effectiveness of phosphorus utilisation in maize cultivation in the experiment. Dry grain yield in the control object was as follows: 2015 – 5.2 t/ha; 2016 – 7.4 t/ha; 2017 – 6.9 t/ha, 2018 – 4.3 t/ha. The fertiliser coulters (on objects with initial fertilisation)

Table 1. Time points (dates) of agrotechnical treatments in 2015–2018

Treatment type	2015	2016	2017	2018
1. Deep ploughing (30 cm)*	5. XI*	9. XI*	26. X*	20. XI*
2. Harrow smoothing	9. III	1. IV	31. III	1. IV
3. Fertiliser application according to the experimental design	16. IV	5. IV	20. IV	20. IV
4. Sowing maize	24. IV cultivar P7631	28. IV cultivar P7905	25. IV cultivar P7905	24. IV cultivar P7905
5. Herbicide application: [1]Lumax 537.5 SE (3.5 L/ha[1]); [2]Maister Power (1.5 L/ha); [3]Lumax 537.5 SE (3.5 L/ha); [4]Lumax 537.5 SE (3.5 L/ha).	29. IV[1]	28. V[2]	28. IV[3]	25. IV[4]
6. Supplementary nitrogen fertilisation	25. V	23. V	1. VI	14. V
7. Harvest with a plot harvester	6. X	28. IX	17. X	3. IX

*treatment performed in the autumn of the previous year

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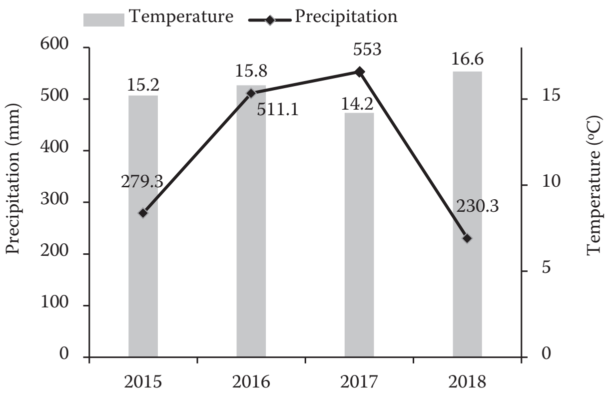

Figure 1. The sum of atmospheric precipitation and the average daily air temperature in maize growing seasons

were set 5 cm aside from the seeds. The application depth of NP fertiliser was according to the 1st order factor levels. Maize sowing was performed with a precision seeder, with a built-in granular fertiliser applicator. The plot size was 24.5 m^2 (length – 8.75 m, width – 2.8 m). The net plot area for harvesting was 12.25 m^2. Nutrient contents (N, P, K, Mg) in the soil before the establishment of the experiment were at a medium level, while the pH ranged from 4.5 (2015) to 5.6 (2017). Organic carbon content in the study was from 0.99% C (2018) to 1.07% C (2016).

Meteorological conditions. Characteristics of meteorological conditions that prevailed during the period of field research were based on data from the meteorological station belonging to the Experimental and Educational Department in Gorzyń. Thermal conditions during maize vegetation in the years of research were similar to each other and averaged 15.2 °C in 2015, 15.6 °C in 2016, 14.2 °C in 2017, and 16.6 °C in 2018. Definitely greater differences between years occurred in the amount of total rainfall. The highest sum was recorded in 2017 (553.0 mm), while the lowest sum of precipitation was recorded in the first and last year of the study: 279.3 mm and 230.3 mm, respectively (Figure 1).

Measurements and chemical analysis. Samples of maize grain were as taken randomly from each plot for chemical analysis at harvest (BBCH 99). The plant samples were dried at 55 °C, ground and next mineralised at 600 °C. The obtained ash was then dissolved in 33% HNO_3. Phosphorus concentration was measured by the vanadium-molybdenum method using a Specord 40 (Analytik Jena, Jena, Germany) at a wavelength of 436 nm. The total uptake of P (kg/ha) was computed as a sum of P uptake by grain (grain yield of dry matter × P content).

Assay methods. The use of phosphorus per dose of the mineral fertiliser was calculated with the formula:

$$PR = (P_f - P_c) \times 100/D$$

where: PR – phosphorus recovery (%); P_f – phosphorus uptake by fertilised plants (kg/ha); P_c – phosphorus uptake by plants in the control (unfertilised) plot (kg/ha); D – phosphorus rate (30.8 kg P/ha).

Agricultural effectiveness was calculated with the following formula:

$$AE = (GY_p - GY_0)/100$$

where: AE – agricultural effectiveness (kg dry matter/kg P in fertilisers); GY_P – grain yield in the field with a dose of phosphorus (t/ha); GY_P – grain yield in the field without applying phosphorus (t/ha).

Statistical analysis. The statistical analyses such as analysis of variance (ANOVA), Tukey's *HSD* (honestly significant difference) test for comparisons of pairs of means were performed in the study years separately and over the years according to the model of data obtained from the experiment designed as a split-split-plot (Szulc et al. 2016b). All calculations were carried out using the Statistica 13 software package (2017). Statistical significance was defined at P-value < 0.01 or P-value < 0.05 depending on the source of variation.

RESULTS

The data presented in Table 2 indicate that variable climatic conditions in the years of the study significantly influenced the P-uptake, the P-recovery, and the maize cultivar used. Significantly the highest phosphorus uptake was recorded in 2016 and significantly the lowest in 2017–2018. Only the agricultural effectiveness of phosphorus use was not found to be significantly influenced by the year of research. It was observed that in each successive year from the beginning of the study, there was a decrease in the plant's percentage P-recovery, with an insignificant difference between the means in 2015 and 2016 (12.22% and 11.47%), and a similarly negligible difference between the means in 2017 and 2018 (7.70% and 7.81%). The results given in Table 2 indicate the significant impact of NP fertiliser application depth (A) on the plant's P-uptake and P-recovery. The use of a depth of at least 5 cm resulted in a significant increase in both P-uptake and P-recovery. For a depth of 10 cm, the highest means for both traits were obtained, but they did not differ significantly from the means for the other fertiliser application

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Table 2. Mean values of the traits for the years (Y) and other factors

Factor	The levels of the factors	P uptake (kg/ha)	P recovery (%)	AE of P use (kg DM/kg P in fertilisers)
Y	2015	23.02^{b}	12.22^{a}	31.64^{a}
	2016	28.88^{a}	11.47^{a}	25.87^{a}
	2017	18.62^{bc}	7.70^{b}	28.41^{a}
	2018	17.89^{c}	7.81^{b}	19.20^{a}
A	A1	19.97^{b}	6.76^{b}	19.01^{b}
	A2	22.63^{a}	10.56^{a}	30.71^{a}
	A3	23.31^{a}	11.52^{a}	29.24^{ab}
	A4	22.49^{a}	10.36^{a}	26.16^{ab}
B	B1	22.10^{a}	9.80^{a}	25.57^{a}
	B2	22.10^{a}	9.80^{a}	26.99^{a}
C	C1	22.04^{a}	9.71^{a}	27.48^{a}
	C2	22.16^{a}	9.89^{a}	25.08^{b}

Values in columns marked with the same letter do not differ significantly ($\alpha = 0.01$ or $\alpha = 0.05$). A – application depth; B – types of nitrogen fertiliser; C – dates of nitrogen application AE – agricultural effectiveness; DM – dry matter

depths. No significant interaction was found between NP fertiliser application depth and the year of research. Irrespective of the year, the other factors – the type of supplementary nitrogen fertiliser (B) and date of application of supplementary nitrogen fertiliser (C) – did not significantly affect the plant's P-uptake or P-recovery. However, from Table 3, we conclude that both of these factors interacted significantly with the year of research (Y) and with each other. Significantly the highest mean P-uptake for the Y × B combination (28.38 and 29.37 kg/ha) was obtained in 2016. Other years produced significantly lower averages of this trait (the difference being significant for 2017–2018 compared with 2015 and 2016). Within the years of research, no significant differences were found between the means of the P-uptake. This means that the two types of N fertiliser (ammonium nitrate and urea) influenced the P-uptake equally within each year, but led to significant differences between years, except for 2017 and 2018, when the mean values of the P-uptake were the lowest.

The results for the second trait can be interpreted similarly. It is observed that P-recovery decreases in successive years (from 2015); yet, within each year separately, the two types of fertilisation did not produce significant differences in the means. A significant interaction was obtained between the date of nitrogen

Table 3. Mean values for the combinations years × types of nitrogen fertiliser and years × dates of nitrogen application

Year	Types of nitrogen fertiliser (B)	P uptake (kg/ha)	P recovery (%)	AE of P use (kg dm/kg P in fertilisers)
2015	B1	23.70^{b}	13.19^{a}	33.06^{a}
	B2	22.34^{b}	11.25^{ab}	30.22^{ab}
2016	B1	28.38^{a}	10.76^{bc}	23.87^{bc}
	B2	29.37^{a}	12.18^{ab}	27.88^{abc}
2017	B1	18.87^{c}	8.06^{d}	28.73^{ab}
	B2	18.36^{c}	7.34^{d}	28.08^{abc}
2018	B1	17.45^{c}	7.18^{d}	16.60^{d}
	B2	18.32^{c}	8.43^{cd}	21.79^{cd}
	Dates of nitrogen application (C)	P uptake (kg/ha)	P recovery (%)	AE of P use (kg DM/kg P in fertilisers)
2015	C1	23.78^{b}	13.31^{a}	34.91^{a}
	C2	22.25^{c}	11.13^{b}	28.37^{b}
2016	C1	28.35^{a}	10.72^{b}	26.14^{b}
	C2	29.40^{a}	12.22^{ab}	25.61^{b}
2017	C1	17.98^{e}	6.79^{d}	28.48^{b}
	C2	19.26^{d}	8.62^{c}	28.34^{b}
2018	C1	18.03^{e}	8.02^{cd}	20.41^{c}
	C2	17.74^{e}	7.60^{cd}	17.98^{c}

Values in columns marked with the same letter do not differ significantly ($\alpha = 0.01$ or $\alpha = 0.05$). AE – agricultural effectiveness; DM – dry matter

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application and year (Table 3). It was found that significantly the highest P-uptake by the plant occurred in 2016, with the date of application (before sowing or top dressing at the BBCH 15/16 stage) not significant. A noticeably lower mean P-uptake was recorded in 2015. By contrast, the years 2017–2018 produced significantly the lowest average P-uptake compared with 2015 and 2016. Similarly, for the second trait, the highest mean P-recovery was obtained in 2015 (13.31%), and the mean values fell in subsequent years. Clearly, the lowest P-recovery was recorded in 2017–2018.

It should be noted that the date of nitrogen application did not cause significant differences in the means of either trait within each year, except for 2017, when the mean P-utilisation was significantly higher with NP application by top dressing at the BBCH 15/16 stage than with application before sowing. The study showed (Table 3) that the agricultural effectiveness of phosphorus use depends on NP fertiliser application depth, the date of supplementary NP fertilisation, and certain interactions of the factors with years and with each other.

Table 2 shows that agricultural effectiveness increased significantly after the use of an NP fertiliser at application depth of at least 5 cm in rows. Other depths (10 cm and 15 cm) caused a negligible decrease in efficiency. The influence of factor A on the examined trait was independent of the year of the study (interaction with years is insignificant). Apart from the experimental factors, climatic conditions in the study years 2015–2018 did not significantly affect agricultural effectiveness. However, the interaction of certain factors or their combinations with the year of research was noted. The significant interaction between the type of supplementary nitrogen fertiliser and year (Y × B) indicates that the greatest agricultural effectiveness of phosphorus use occurred in 2015, and then a slight decrease in efficiency was noted in subsequent years. Indeed, the lowest agricultural effectiveness was recorded in 2018, compared with the previous years. However, the use of ammonium nitrate or urea did not cause differences in effectiveness within the years. In turn, the significant interaction between the date of supplementary NP fertilisation and year (Y × C) indicates that significantly the highest agricultural effectiveness of phosphorus use was obtained in 2015 with the application of NP fertiliser before sowing. Significantly the lowest agricultural efficiency was recorded in 2018, with the date of fertilisation (before sowing or top dressing) being not relevant (Table 3).

DISCUSSION

Soil moisture is one of the characteristics determining the supply of nutrients to the growing root system of the plant. According to Qin et al. (2005), the diffusion process, as a result of which phosphorus is carried towards the root, occurs faster in a moist rather than dry environment. As soil moisture decreases, the proportion of air-filled soil pores increases, making the conduction of water and diffused nutrients more difficult (Mackay and Barber 1984). The above literature data explain the higher effectiveness of row fertilisation in the years characterised by rainfall deficit in the present study, as compared to broadcast fertilisation. According to Pabin et al. (2004), a positive correlation between the fertiliser placement depth in the soil and crop yields was mainly determined by the weather, especially precipitation. In the case of its deficit, there is a clear positive impact of the deeper placement of NPK fertilisers in the soil profile. Singh et al. (2005) also claimed that fertilisers placed in a high-moisture soil could be more accessible to plants than those placed shallower or on the surface. Placing a two-component NP mineral fertiliser near maize seeds leads to higher phosphorus uptake by plants, greater P-recovery of this component from mineral fertiliser, and higher unit phosphorus production (Nkebiwe et al. 2016). Better efficiency of fertiliser application to the soil, compared to traditional fertilisation performed on the soil surface, is conditioned by a high concentration of the component in close proximity to the roots, stimulation of root system growth (Forde and Lorenzo 2001), change of rhizosphere biological properties (Ghorbani et al. 2008) and a reduction of nutrient loss to the environment (Dell et al. 2011, Szulc et al. 2016a). In turn, other works on the comparison of fertiliser application methods found that starting (row) fertilisation increased soil-fertiliser contact by placing phosphorus in a soil zone with a higher root concentration (Grant et al. 2001). This resulted in greater efficiency of such a method of nutrient application (Kruczek and Szulc 2006), which was demonstrated in the current study. Phosphorus in most regions of the world is the most important nutrient, after nitrogen, limiting agricultural production. Like any other nutrient, its deficiency, especially in the early stages of growth and development of annual plants, including maize (Kruczek and Szulc 2006), can lead to irreversible yield limitations, which cannot be compensated by its application at later growth stages (Colomb et al.

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2000). The presented results confirm the beneficial effect of localised phosphorus application in maize cultivation on fertilisation effectiveness indices. In the present study, row fertilisation, regardless of the depth of fertiliser application, was on average more effective during the 4 years of research compared to broadcast fertilisation. The utilisation of P from NP mineral fertiliser, as a result of this fertilisation method, was higher in our study compared to broadcast fertilisation (A1) and was at the following level: for a depth of 5 cm – an increase of 56.2%; for a depth of 10 cm – an increase of 70.4%; for a depth of 15 cm – an increase of 53.2%.

Unfavourable weather conditions (rainfall deficit) during the growing season hinder nutrient absorption by maize, mainly phosphorus, which leads to growth inhibition. The research results unambiguously show that this unfavourable phenomenon can be almost completely counteracted by localised fertilisation carried out simultaneously with seed sowing (Jagła et al. 2019, Szulc et al. 2020).

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