*Original Paper* *Plant, Soil and Environment, 66, 2020 (1): 14–21*

https://doi.org/10.17221/644/2019-PSE

# Influence of the depth of nitrogen-phosphorus fertiliser placement in soil on maize yielding

*Piotr Szulc[1]*, Wioletta Wilczewska[1], Katarzyna Ambroży-Deręgowska[2], Iwona Mejza[2], Daria Szymanowska[3], Joanna Kobus-Cisowska[4]*

*[1]Department of Agronomy, Poznan University of Life Sciences, Poznan, Poland*
*[2]Department of Mathematical and Statistical Methods, Poznan University of Life Sciences, Poznan, Poland*
*[3]Department of Biotechnology and Food Microbiology, Poznan University of Life Sciences, Poznan, Poland*
*[4]Department of Gastronomy Sciences and Functional Foods, Poznan University of Life Sciences, Poznan, Poland*
**Corresponding author: piotr.szulc@up.poznan.pl*

**Citation:** Szulc P., Wilczewska W., Ambroży-Deręgowska K., Mejza I., Szymanowska D., Kobus-Cisowska J. (2020): Influence of the depth of nitrogen-phosphorus fertiliser placement in soil on maize yielding. Plant Soil Environ., 66: 14–21.

**Abstract:** The study presents the results of 4-year field trials; their purpose was to assess maize yield in relation to the depth of a mineral two-component (NP) fertiliser application in the soil layer, the type of nitrogen fertiliser (ammonium nitrate and urea) and the date of its application. The yield grain was significantly dependent on changing weather conditions in the growing seasons. Initial fertilisation with two-component NP fertiliser, regardless of the years, significantly affected the grain yield. Row fertilisation with two-component NP fertiliser increases the availability of phosphorus in the acid soil environment, elevating maize grain yield. The efficiency of row NP fertiliser application is determined by the natural soil richness in phosphorus. Maize grain yield depended more on the date of application than the form of nitrogen, and its application before sowing was more effective. The application of ammonium nitrate in the BBCH 15/16 stage significantly reduced the number of production ears per unit area compared to the pre-sowing application of this fertiliser. Deep fertiliser placement under the soil surface can be another tool to alleviate the negative consequences of the increasingly high temperatures and droughts.

**Keywords:** *Zea mays* L.; drought stress; climatic condition; macronutrient; thermal requirement

Fertilisation is one of the basic factors of the agricultural practice of cereal plants growing that determines the amount of grain yield with appropriate quality (Fageria 2001, Ladha et al. 2005, Ciampitti and Vyn 2013). The effectiveness of applied fertilisation depends, among others, on soil and climatic conditions during the growing season and the fertilisers, which should be applied so that their uptake by plants occurs in accordance with their developmental rhythm (Scharf et al. 2002, Ziadi et al. 2007). Currently, increasing plant production is focused on the more effective use of components from a mineral fertiliser dose (Setiyono et al. 2010, Ciampitti et al. 2013). 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 utilization of these elements from mineral fertilisers (Andraski et al. 2000, Setiyono et al. 2010, Bélanger et al. 2011). Pre-sowing and top-dressing nitrogen fertilisation used in agricultural practice often leads to overdosing of this component and creates a threat to the natural environment (Szulc and Bocianowski 2013, Szulc et al. 2015, 2018). Phosphorus is an element that stimulates the development of the root system and increases the resistance of maize plants to periodic soil moisture deficits (Bocianowski et al. 2016). Low spring temperatures limit phosphorus uptake. Currently, inhibition of plant development is observed at maize plantations due to stymied phosphorus and nitrogen uptake as a result of periodic temperature decreases in spring and soil drought (Ziadi et al. 2007). This particularly applies to new maize cultivars with different environmental and especially thermal requirements. These adverse phenomena can be counteracted by increasing the amount of nutrients missing in the soil solution using broadcast or row fertilisation (Jagła et al. 2019). To optimize the availability of nitrogen and phosphorus, especially at the initial growth stages, these nutrients can be applied in the seed-sowing zone, or at a distance from the seeds (Grant et al. 2001). This applies to higher doses of mineral fertiliser. Such fertiliser application in the cultivation of agricultural plants is possible thanks to the continuous increase of the manufacture of better, more precise agricultural machines. Localized fertilisation is also used in weed control. Placing fertiliser in the soil improves plant nutrition, which results in higher competitiveness against weeds (Lègére et al. 2013). The row application of the component has a positive effect on the development and yielding of maize, it reduces fertilisation costs, decreases the risks arising from the relocation of elements to ground and surface waters, and is beneficial in dry years (Szulc et al. 2016). 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 maize yielding.

## MATERIAL AND METHODS

**Experimental field.** The field trial was carried out at the Department of Agronomy of Poznan University of Life Sciences, in 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 sowing 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 (AN); B2 – urea (U)]; C – 3rd order factor-date of supplementary nitrogen fertilisation [C1 – before sowing; C2 – top dressing in the BBCH 15/16]. 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, 20.2% P), according to the experimental design under the 1st order factor. N and K fertilisation

Table 1. Average monthly air temperature and monthly total precipitation for the growing season

| | IV | V | VI | VII | VIII | IX | X | Mean/sum |
|---|---|---|---|---|---|---|---|---|
| **Temperature** (°C) | | | | | | | | |
| 2015 | 9.3 | 13.9 | 16.9 | 20.1 | 23.4 | 15.2 | 8.2 | 15.2 |
| 2016 | 9.6 | 16.3 | 19.9 | 20.3 | 19 | 17.3 | 8.4 | 15.8 |
| 2017 | 7.3 | 13.7 | 17.4 | 18.0 | 18.9 | 13.3 | 10.6 | 14.2 |
| 2018 | 12.9 | 16.9 | 18.5 | 20.2 | 21.3 | 15.8 | 10.9 | 16.6 |
| **Precipitation** (mm) | | | | | | | | |
| 2015 | 17.6 | 27.2 | 66.6 | 85.4 | 35.4 | 28.1 | 19 | 279.3 |
| 2016 | 47.3 | 47.3 | 123.8 | 132.8 | 50.3 | 4.6 | 105 | 511.1 |
| 2017 | 40.6 | 56.8 | 68.2 | 168.0 | 82.0 | 45.6 | 91.8 | 553.0 |
| 2018 | 36.2 | 17.4 | 25.6 | 70.5 | 11.6 | 44.2 | 24.8 | 230.3 |
| **Values of coefficient in vegetation periods of maize** | | | | | | | | |
| 2015 | 0.63 | 0.63 | 1.31 | 1.37 | 0.48 | 0.61 | 0.74 | 0.82 |
| 2016 | 1.64 | 0.93 | 2.07 | 2.11 | 0.85 | 0.08 | 4.03 | 1.67 |
| 2017 | 1.85 | 1.33 | 1.30 | 3.01 | 1.39 | 1.14 | 2.79 | 1.82 |
| 2018 | 0.93 | 0.33 | 0.46 | 1.12 | 0.17 | 0.93 | 0.73 | 0.67 |

Table 2. Nutrient content and soil pH before establishing the experiment in maize growing seasons

| Specification | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|
| P | 4.0 | 10.4 | 8.3 | 4.9 |
| K (mg kg DM soil) | 11.1 | 9.7 | 10.8 | 11.6 |
| Mg | 2.9 | 4.4 | 5.3 | 5.3 |
| pH (1 mol KCl/L) | 4.5 | 4.6 | 5.6 | 5.1 |

DM – dry matter

were performed before maize sowing using U (46% N) and potassium salt (60%). The fertiliser coulters (on objects with initial fertilisation) were set 5 cm aside from the seeds. The application depth of NP fertiliser was according to the 1st order factor levels. Gross plot size: 24.5 $m^2$ (length – 8.75 m, width – 2.8 m). The net plot area for harvesting was 12.25 $m^2$. Soil abundance in nutrients and soil pH before establishing the experiment in maize growing seasons are presented in Table 1. The magnesium content in the soil was determined by the Schachtschabel method, potassium by the Egner-Riehm method, and phosphorus by the Olsen method.

**Meteorological conditions**. 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 (Table 2). 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 (Table 2). Calculated hydrothermal coefficients of water preservation according to Sielianinow (Table 2), taking comprehensively into account both air temperature and atmospheric precipitation, allowed to state that weather conditions for maize growth and development in two years of research were favourable (2016, 2017), while in 2015 and 2018 unfavourable due to periodic soil moisture deficits.

**Statistical analysis.** The statistical analyses such as analysis of variance (ANOVA), Tukey's *HSD* (honestly significant difference) test for comparisons of

Table 3. Results of the four-stratum: year (Y); depths of fertilisation (A); types of nitrogen fertiliser (B); dates of nitrogen application (C) ANOVA

| Source of variation | Degrees of freedom | Mean squares | | | |
|---|---|---|---|---|---|
| | | grain yield | TKW | number of productive ears | number of kernels per ear |
| Blocks | 3 | 1.48 | 322.97 | 3.75 | 3 579.93 |
| Y | 3 | 231.36** | 10108.59* | 84.40** | 37 870.20** |
| Error 1 | 9 | 4.95 | 1974.40 | 3.30 | 2 840.00 |
| A | 3 | 11.76** | 580.22 | 0.78 | 5 583.04* |
| Y × A | 9 | 1.93 | 635.48 | 1.69 | 688.13 |
| Error 2 | 36 | 2.21 | 392.61 | 1.04 | 1 745.77 |
| B | 1 | 0.88 | 1216.70** | 0.03 | 1 078.07 |
| Y × B | 3 | 1.57* | 103.60 | 0.15 | 435.62 |
| A × B | 3 | 1.32 | 67.83 | 1.15 | 1 967.28 |
| Y × A × B | 9 | 1.09* | 242.32 | 0.70 | 2 813.16 |
| Error 3 | 48 | 0.48 | 139.64 | 0.84 | 1 444.49 |
| C | 1 | 2.52** | 333.75 | 0.49 | 3 349.34 |
| Y × C | 3 | 0.93** | 124.68 | 0.30 | 4 041.49* |
| A × C | 3 | 0.24 | 268.32 | 0.21 | 424.60 |
| B × C | 1 | 0.70 | 141.76 | 3.06** | 1 888.42 |
| Y × A × C | 9 | 0.36 | 158.86 | 0.21 | 631.19 |
| Y × B × C | 3 | 0.75* | 148.01 | 0.21 | 886.98 |
| A × B × C | 3 | 0.86** | 119.44 | 0.16 | 1 038.39 |
| Y × A × B × C | 9 | 0.26 | 157.77 | 0.15 | 1 294.50 |
| Error 4 | 96 | 0.21 | 250.25 | 0.39 | 1 259.40 |

*$P < 0.05$; **$P < 0.01$; TKW – thousand-kernel weight

Table 4. Mean values of the traits for the years and other factors

| Factor | Factor level | Grain yield (t/ha) | Thousand-kernel weight (g) | Number of productive ears (pcs./m$^2$) | Number of kernels per ear (pcs.) |
|---|---|---|---|---|---|
| Year (Y) | 2015 | 8.68$^{b}$ | 291.14$^{b}$ | 8.94$^{a}$ | 465.76$^{b}$ |
| | 2016 | 10.89$^{a}$ | 316.47$^{a}$ | 8.15$^{a}$ | 499.50$^{ab}$ |
| | 2017 | 10.51$^{a}$ | 302.26$^{ab}$ | 8.55$^{a}$ | 517.90$^{a}$ |
| | 2018 | 6.75$^{c}$ | 289.09$^{b}$ | 6.34$^{b}$ | 471.97$^{b}$ |
| Depths of fertilisation (A) | A1 | 8.61$^{b}$ | 297.05$^{a}$ | 8.11$^{a}$ | 475.51$^{b}$ |
| | A2 | 9.57$^{a}$ | 302.20$^{a}$ | 8.03$^{a}$ | 496.80$^{a}$ |
| | A3 | 9.45$^{ab}$ | 297.22$^{a}$ | 7.84$^{a}$ | 489.50$^{ab}$ |
| | A4 | 9.20$^{ab}$ | 302.48$^{a}$ | 7.99$^{a}$ | 493.32$^{ab}$ |
| Types of nitrogen fertiliser (B) | B1 | 9.15$^{a}$ | 301.92$^{a}$ | 7.98$^{a}$ | 490.83$^{a}$ |
| | B2 | 9.27$^{a}$ | 297.56$^{b}$ | 8.00$^{a}$ | 486.73$^{a}$ |
| Dates of nitrogen application (C) | C1 | 9.31$^{a}$ | 298.60$^{a}$ | 8.04$^{a}$ | 492.40$^{a}$ |
| | C2 | 9.11$^{b}$ | 300.88$^{a}$ | 7.95$^{a}$ | 485.16$^{a}$ |

$^{a, b, c}$homogeneous groups (α = 0.01 or α = 0.05)

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. 2016). 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

**Grain yield of maize and yield components.** The different weather conditions in the study years 2015–2018 were reflected in the maize grain yield and its components (Table 3). Significantly the highest mean yields, not differing from each other, were obtained in 2016 and 2017, and significantly the lowest yield was obtained in 2018 (Table 4). The analysed yield components, i.e., thousand-kernel weight (TKW), number of productive ears and number of kernels per ear, were also found to be highest in the years 2016 and 2017. Analysis of the whole plots (Table 3) showed no interaction of fertilisation depth (A) with study year (Y) for all studied traits. However, regardless of the year and other factors, the effect of depth of fertilisation on the grain yield and the number of kernels per ear proved to be significant. Table 4 shows that the use of fertilisation in each experiment at a depth of at least 5 cm resulted in a significant increase in the mean grain yield and the mean number of kernels per ear, while the depths of 10 cm and 15 cm did not significantly differentiate the

Table 5. Mean values for the combinations year (Y) × type of nitrogen fertiliser (B) and Y × the date of nitrogen application (C)

| Year | Type of nitrogen fertiliser | Grain yield (t/ha) | Number of kernels per ear (pcs.) | The date of nitrogen application | Grain yield (t/ha) | Number of kernels per ear (pcs.) |
|---|---|---|---|---|---|---|
| 2015 | B1 | 8.80$^{c}$ | 464.69$^{a}$ | C1 | 8.95$^{b}$ | 470.02$^{d}$ |
| | B2 | 8.56$^{c}$ | 466.84$^{a}$ | C2 | 8.41$^{c}$ | 461.50$^{d}$ |
| 2016 | B1 | 10.73$^{ab}$ | 500.54$^{a}$ | C1 | 10.91$^{a}$ | 497.97$^{bc}$ |
| | B2 | 11.06$^{a}$ | 498.45$^{a}$ | C2 | 10.87$^{a}$ | 501.02$^{bc}$ |
| 2017 | B1 | 10.53$^{ab}$ | 522.75$^{a}$ | C1 | 10.51$^{a}$ | 532.50$^{a}$ |
| | B2 | 10.48$^{b}$ | 513.05$^{a}$ | C2 | 10.50$^{a}$ | 503.30$^{b}$ |
| 2018 | B1 | 6.54$^{d}$ | 475.36$^{a}$ | C1 | 6.85$^{d}$ | 469.10$^{d}$ |
| | B2 | 6.96$^{d}$ | 468.58$^{a}$ | C2 | 6.65$^{d}$ | 474.83$^{cd}$ |

$^{a, b, c, d}$homogeneous groups (α = 0.01 or α = 0.05)

https://doi.org/10.17221/644/2019-PSE

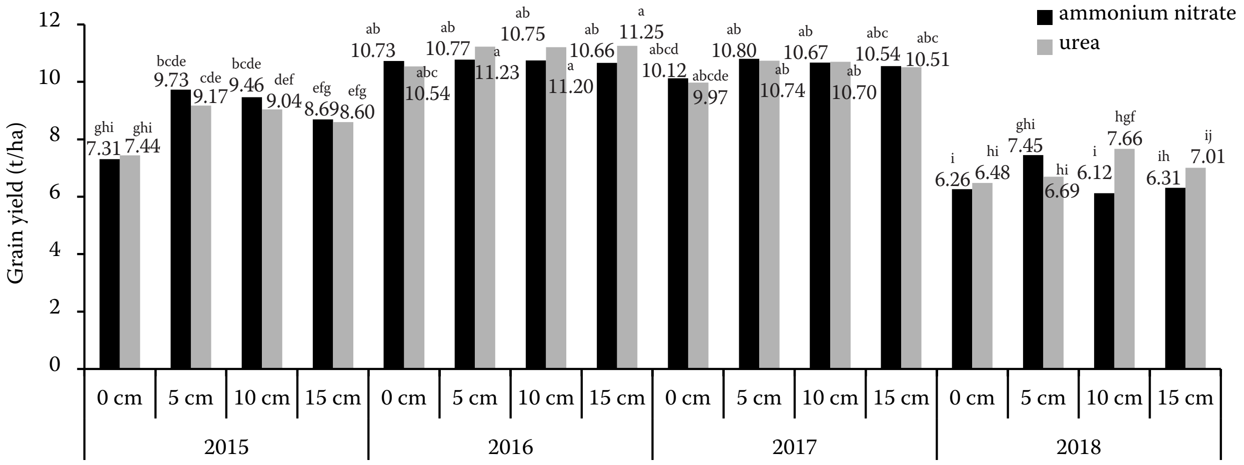

Figure 1. Mean values of the grain yield for the combinations of four years, four depths of fertilisation and two types of nitrogen fertiliser. $^{a, b, c, d, e, f, g, h, i}$homogeneous groups (α = 0.05)

values of either of these two traits. It was also found (Table 5) that the cultivar's response to the types of fertilisation used was uneven during the years of study. Significantly the highest yield was obtained in 2016 using both AN and U. The yields were also high in 2017, regardless of the type of fertilisation. The use of U in 2017 significantly reduced the mean grain yield compared with the previous year. Significantly the lowest grain yields occurred in 2018, regardless of the type of fertilisation used (Table 5).

Irrespective of the study year and other factors, maize fertilised with AN had a significantly larger mean TKW than maize fertilised with U (Table 4). The grain yield also depended on the interaction effect of the type of nitrogen fertiliser with the depth of fertilisation and year. Considering these three factors, significantly, the highest yields occurred in 2016 and 2017, but combinations of fertilisation type and fertilisation depth did not differentiate significantly the mean yields in those years (Figure 1).

In turn, analysis of sub-subplots (Table 3) showed that the date of nitrogen application, interacting with the year, had a significant impact on the yield of the studied maize cultivar and the number of kernels per ear. The highest mean grain yields were obtained in 2016 and 2017, but the date of application – before sowing or top-dressing at BBCH 15/16 – was not significant. Also, in 2018, when the mean grain yields were significantly the lowest, the date of nitrogen application was not significant (Table 5). The date of application of nitrogen fertiliser had a large impact on the number of kernels per ear in 2017 when significantly the highest mean number of kernels per ear was obtained using fertilisation before sowing (Table 5).

The analysis in Table 3 also shows a highly significant interaction effect of the type of nitrogen fertilisation and the date of fertiliser application, but only for the number of productive ears. For the other variables, no significant interaction between these factors was demonstrated. Detailed analysis (Figure 2) shows that the pre-sowing application of AN significantly increases the number of productive ears in comparison with top-dressing at BBCH 15/16. In turn, the use of U did not significantly affect the mean value of the number of productive ears. The date of application of this nitrogen fertiliser was not relevant, either.

A significant interaction was, however, found for the date of nitrogen application and type of nitrogen fertiliser with the year of research (Table 3).

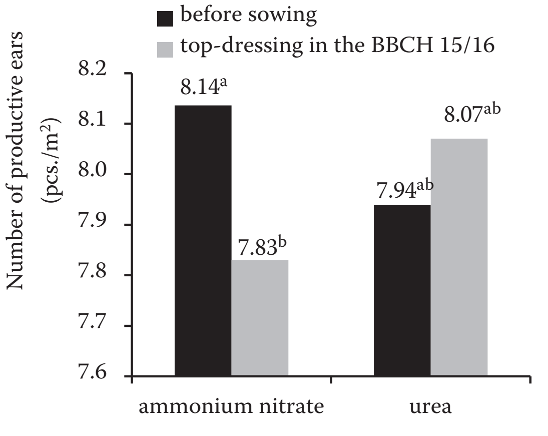

Figure 2. Mean values of the number of productive ears for the combinations of two types of nitrogen fertiliser and two dates of nitrogen application. $^{a, b}$homogeneous groups (α = 0.05)

https://doi.org/10.17221/644/2019-PSE

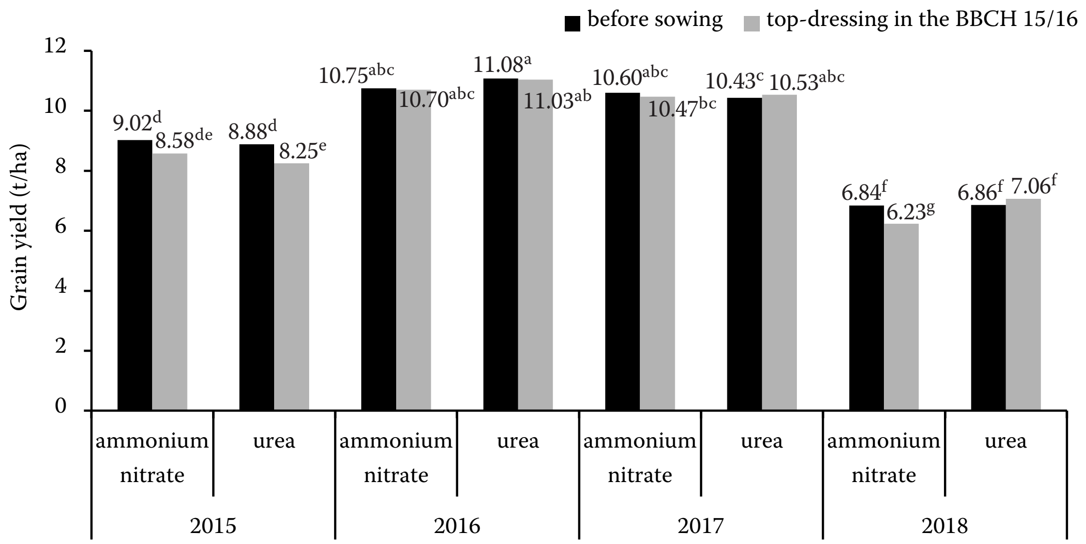

Figure 3. Mean values of the grain yield for the combinations of four years, two types of nitrogen fertiliser and two dates of nitrogen application. [a, b, c, d, e, f, g]homogeneous groups (α = 0.05)

In 2016, significantly higher mean grain yields were obtained for each combination of levels of both these factors compared with the other years of research. It was also noted that significantly the highest mean grain yield was obtained using the U fertilisation before sowing in 2016 (Figure 3). A highly significant interaction effect was also found between the three considered agrotechnical factors, regardless of the year of research (Table 3). A detailed analysis (Figure 4) showed a noticeable grain yield increase when any type of fertilisation was applied at a depth of at least 5 cm before sowing. Significantly the highest mean grain yield was obtained using U at a depth of 10 cm before sowing (9.85 t/ha).

## DISCUSSION

Weather conditions in the growing season are a factor that largely determines grain yields (Paponov et al. 2005). Two years of research, i.e., 2016 and 2017, were favourable in this respect for the development of maize, which was confirmed by high grain yields exceeding 10 t of grain/ha. In 2015, periodic soil moisture deficits occurred almost during the entire maize growing season (Table 2). Moisture content was optimal only in June and July. However, the last year (2018) was the worst one in terms of the precipitation sum. In this year, only July was characterized by optimal soil moisture, while soil

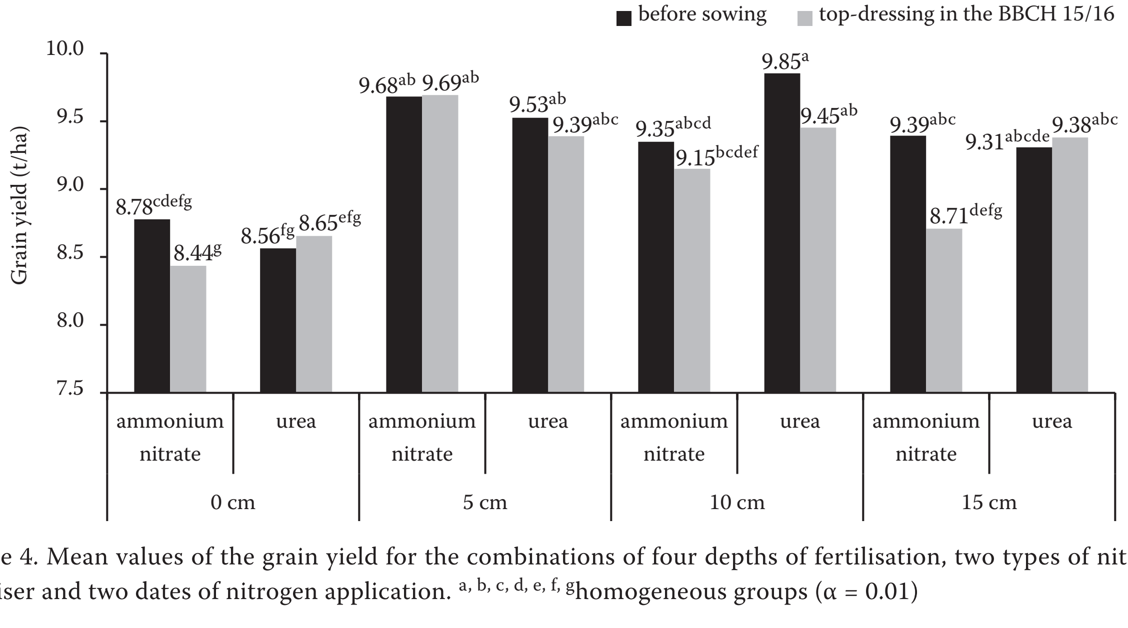

Figure 4. Mean values of the grain yield for the combinations of four depths of fertilisation, two types of nitrogen fertiliser and two dates of nitrogen application. [a, b, c, d, e, f, g]homogeneous groups (α = 0.01)

water deficit was recorded in the remaining months of the growing season. August turned out to be the worst month in this respect. Only 11 mm of rainfall was recorded during that month, with an average daily air temperature over 21 °C (Table 2). Hence, the lowest maize grain yield of 6.74 t/ha can be explained by weather conditions prevailing in the last year of research. When fertilising maize using row method, the fertiliser was applied in a dense, moist soil layer, while in broadcasting, the fertiliser remains in a loosened top layer, and thus nutrient uptake during drought periods is limited. According to Barber (1984), diffusion is the decisive process in transporting phosphorus to the roots. This process occurs faster in a moist rather than dry environment. Therefore, in the drought period, row fertilisation of plants is more effective than broadcasting in terms of uptake, especially of low-mobility components such as phosphorus. Soil richness determines the strength of the impact of deeper initial fertilisation on plant yielding (Pabin et al. 2004). In soil with lower phosphorus content (2015 and 2018), the application of this component in the form of mineral fertiliser enriches the soil and contributes to a significant yield increase. However, the efficiency of the localized application of phosphorus is definitely lower in rich soil (2016 and 2017). Penetrating plant roots have access to more nutrients and the effect of additional fertilisation does not have a strong yield-forming significance as is the case with low natural soil richness in this component. In the present study, the increase in grain yield as a result of row application of NP fertiliser in relation to broadcast fertilisation was at the following level regardless of the depth of application: 2015 – 23%; 2016 – 3.2%; 2017 – 6.1%, 2018 – 7.8%. Maize grain yield is largely determined by the availability of water. Water shortages in the plant limit the supply of leaf assimilates, which in the form of starch are deposited already at the early stages of grain development, leading to ovary necrosis and shedding of young grains. Water deficits also affect nitrogen transformations in the soil. Uptake of nitrate ion, which is only mobile in the aquatic environment, depends on the water content available in the soil. The number of grains in the ear is determined during the florescence of female flowers (Cirilo and Andrade 1994), while conditions just before their flowering play the main role in shaping this grain yield component. Both water stress and the shortage of nutrients in the plant extend the period between full pollination and florescence of female flowers. According to Borras et al. (2003), the rate of assimilate inflow to grains after the florescence of female flowers at the grain filling stage determines their final weight. Nevertheless, in the present study, row fertilisation was on average more effective compared to broadcast fertilisation during 4 years of research. The grain yield increase was recorded at the following level: 5 cm – 11.2%; 10 cm – 9.8%; 15 cm – 6.8%. Higher grain yields obtained under row fertilisation were also obtained by Mascagni and Boquet (1996) and Szulc et al. (2016). Ochal et al. (2015) examined the effect of maize fertilisation method on the growth and development of the maize root system and found that the best results were obtained in the object where the initial dose was located at a depth of 5 cm and or 2 cm below the maize grain. In turn, Pabin et al. (2004) found that a positive correlation between the depth of placing the fertiliser in the soil and crop yields was mainly determined by the weather, especially rainfall. In the case of its deficit, there is a clear positive impact of the deeper placement of NPK fertilisers in the soil profile. The results obtained in the present study confirm earlier literature reports (Su et al. 2015). According to these authors, it is not recommended to apply surface fertilisers under drought stress. Only deep application of the fertiliser reduces the effects of drought, thereby increasing plant productivity. However, according to these authors, such fertiliser application requires increased expenditure on the application of the component itself.

## REFERENCES

Andraski T.W., Bundy L.G., Brye K.R. (2000): Crop management and corn nitrogen rate effects on nitrate leaching. Journal of Environmental Quality, 29: 1095–1103.

Barber S.A. (1984): Soil Nutrient Bioavailability. A Mechanistic Approach. New York, Wiley, 90–251.

Bélanger G., Claessens A., Ziadi N. (2011): Relationship between P and N concentration in maize and wheat leaves. Field Crops Research, 123: 28–37.

Bocianowski J., Szulc P., Tratwal A., Nowosad K., Piesik D. (2016): The influence of potassium to mineral fertilizers on the maize health. Journal of Integrative Agriculture, 15: 1286–1292.

Borras L., Westgate M.E., Otegui M.E. (2003): Control of kernel weight and kernel weight relations by post flowering source-sink ratio in maize. Annals of Botany, 91: 857–867.

Ciampitti I.A., Murrell T.S., Camberato J.J., Vyn T.J. (2013): Maize nutrient accumulation and partitioning in response to plant density and nitrogen rate: I. Macronutrients. Agronomy Journal, 105: 783–795.

https://doi.org/10.17221/644/2019-PSE

Ciampitti I.A., Vyn T.J. (2013): Maize nutrient accumulation and partitioning in response to plant density and nitrogen rate: II. Calcium, magnesium, and micronutrients. Agronomy Journal, 105: 1645–1657.

Cirilo A.G., Andrade F.H. (1994): Sowing date and maize productivity: I. Crop growth and dry matter partitioning. Crop Science, 34: 1039–1043.

Fageria V.D. (2001): Nutrient interactions in crop plants. Journal of Plant Nutrition, 24: 1269–1290.

Grant C.A., Flaten D.N., Tomasiewicz D.J., Sheppard S.C. (2001): The importance of early season phosphorus nutrition. Canadian Journal of Plant Science, 81: 211–224.

Jagła M., Szulc P., Ambroży-Deręgowska K., Mejza I., Kobus-Cisowska J. (2019): Yielding of two types of maize cultivars in relation to selected agrotechnical factors. Plant, Soil and Environment, 65: 416–423.

Ladha J.K., Pathak H., Krupnik T.J., Six J., van Kessel C. (2005): Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. Advances in Agronomy, 87: 85–156.

Lègére A., Shirtliffe S.J., Vanasse A., Gulden R.H. (2013): Extreme grain-based cropping systems: when herbicide-free weed management meets conservation tillage in northern climates. Weed Technology, 27: 204–211.

Mascagni J.H., Boquet J.D. (1996): Starter fertilizer and planting date effects on corn rotated with cotton. Agronomy Journal, 88: 975–981.

Ochal P., Jadczyszyn T., Jurga B. (2015): Maize root development depending on the depth of fertilizer application to the soil. Polish Journal of Agronomy, 23: 74–81. (In Polish)

Pabin J., Biskupski A., Włodek S. (2004): The effect of the depth of placing a multicomponent fertilizer in soil on the yield of crops. Annales Universitatis Mariae Curie-Sklodowska. Sectio E Agricultura (Poland), 59: 493–500. (In Polish)

Paponov I.A., Sambo P., Erley G.S., Presterl T., Geiger H.H., Engels C. (2005): Grain yield and kernel weight of two maize genotypes differing in nitrogen use efficiency at various levels on nitrogen and carbohydrate availability during flowering and grain filling. Plant and Soil, 272: 111–123.

Scharf P.C., Wiebold W.J., Lory J.A. (2002): Corn yield response to nitrogen fertilizer timing and deficiency level. Agronomy Journal, 94: 435–441.

Setiyono T.D., Walters D.T., Cassman K.G., Witt C., Dobermann A. (2010): Estimating maize nutrient uptake requirements. Field Crops Research, 118: 158–168.

Su W., Liu B., Liu X.W., Li X.K., Ren T., Cong R.H., Lu J.W. (2015): Effect of depth of fertilizer banded-placement on growth, nutrient uptake and yield of oilseed rape (*Brassica napus* L.). European Journal of Agronomy, 62: 38–45.

Szulc P., Bocianowski J. (2013): Monitoring of biogenic element concentrations in drainage water of the production field. Bulgarian Journal Agricultural Sciences, 19: 472–478.

Szulc P., Mejza I., Ambroży-Deręgowska K., Nowosad K., Bocianowski J. (2016): The comparison of three models applied to the analysis of a three-factor trial on hybrid maize (*Zea mays* L.) cultivars. Biometrical Letters, 53: 47–57.

Szulc P., Rybus-Zając M., Jagła M. (2015): Influence of maize hybrid type (*Zea mays* L.) and N dose on nitrogen eutrophication of the environment. Electronic Journal of Polish Agricultural Universities, 18: 1–10.

Szulc P., Waligóra H., Michalski T., Bocianowski J., Rybus-Zając M., Wilczewska W. (2018): The size of the $N_{min}$ soil pool as a factor impacting nitrogen utilization efficiency in maize (*Zea mays* L.). Pakistan Journal of Botany, 50: 189–198.

Szulc P., Waligóra H., Michalski T., Rybus-Zając M., Olejarski P. (2016): Efficiency of nitrogen fertilization based on the fertilizer application method and type of maize cultivar (*Zea mays* L.). Plant, Soil and Environment, 62: 135–142.

TIBCO Software Inc. (2017): Statistica (data analysis software system), version 13. Krakow, StatSoft Polska. Available at: http://statistica.io

Ziadi N., Bélanger G., Cambourus A.N., Tremblay N., Nolin M.C., Claessens A. (2007): Relationship between P and N concentrations in corn. Agronomy Journal, 99: 833–841.

Received: August 26, 2019
Accepted: December 2, 2019