Effects of NP Fertilizer Placement Depth by Year Interaction on the Number of Maize (Zea mays L.) Plants after Emergence Using the Additive Main Effects and Multiplicative Interaction Model

Piotr Szulc¹,†, Jan Bocianowski²,*†, Kamila Nowosad³, Henryk Bujak³,4, Waldemar Zielewicz⁵ and Barbara Stachowiak⁶

Abstract: Field experiments were carried out at the Department of Agronomy of the Poznań University of Life Sciences to determine the effect of the depth of NP fertilization placement in maize cultivation on the number of plants after emergence. The adopted assumptions were verified based on a six-year field experiment involving four depths of NP fertilizer application (A1—0 cm (broadcast), A2—5 cm (in rows), A3—10 cm (in rows), A4—15 cm (in rows)). The objective of this study was to assess NP fertilizer placement depth, in conjunction with the year, on the number of maize (Zea mays L.) plants after emergence using the additive main effects and multiplicative interaction model. The number of plants after emergence decreased with the depth of NP fertilization in the soil profile, confirming the high dependence of maize on phosphorus and nitrogen availability, as well as greater subsoil loosening during placement. The number of plants after emergence for the experimental NP fertilizer placement depths varied from 7.237 to 8.201 plant m⁻² during six years, with an average of 7.687 plant m⁻². The 61.51% of variation in the total number of plants after emergence was explained by years differences, 23.21% by differences between NP fertilizer placement depths and 4.68% by NP fertilizer placement depths by years interaction. NP fertilizer placement depth 10 cm (A3) was the most stable (ASV = 1.361) in terms of the number of plants after emergence among the studied NP fertilizer placement depths. Assuming that the maize kernels are placed in the soil at a depth of approx. 5 cm, the fertilizer during starter fertilization should be placed 5 cm to the side and below the kernel. Deeper NP fertilizer application in maize cultivation is not recommended. The condition for the use of agriculture progress, represented by localized fertilization, is the simultaneous recognition of the aspects of yielding physiology of new maize varieties and the assessment of their reaction to deeper seed placement during sowing.

Keywords: AMMI model; biplot; fertilization depth; interaction; maize; the number of plants after emergence; stability
1. Introduction

Recently, maize has grown in popularity and importance [1]. This is mainly due to its functional features. Nevertheless, they would not be sufficient to generalize cultivation without breeding participation, which would ensure access to varieties with suitable early maturation. Until recently, maize was mainly cultivated for silage from whole plants, while in recent years, the placement acreage was dominated by grain cultivation [2]. As part of the planned animal feeding systems, maize silage is a cheap source of starch and fiber, which is a good complement to grazing nutrition throughout the year [3]. This is due to maize cultivation for silage that has significantly increased the profitability of dairy production [3]. For the expansion of this species cultivation, it is important to develop a technology that would utilize sustainable technological and biological advances [4]. Domestic and foreign breeding programs led to the creation of many high-yielding and sufficiently early hybrid varieties that were well adapted to soil and climate conditions [5]. Unfortunately, the production potential of this species has not yet been fully exploited [6]. This is due to the lack of sufficient knowledge and skill resources, and frequent underestimation of the importance of punctuality and thoroughness in individual agriculture procedures [7]. Contrary to popular belief, maize, like other cereals, requires careful agriculture practices. Therefore, the primary aspect is to learn and implement a new technology of maize cultivation, and in particular to recognize the impact of the depth of starter (row) fertilization on the number of plants after emergence. This trait is very important in maize cultivation, because it determines the number of production ears per unit area, i.e., one of the elements of grain yield structure [8]. Previous studies clearly showed the beneficial effect of localized nitrogen and phosphorus fertilization on maize’s growth, development, and yielding [9,10]. This influence is particularly high in the early developmental stages, when the weather conditions in the initial growth period are often stressful for maize [11]. The positive effect of starter fertilization on maize in the initial growing season is also reflected in its yield [12].

Grain yields are significantly higher for the localized fertilizer placements performed concurrently with seed placement compared to traditional broadcast fertilization over the entire soil surface [13]. Grain moisture during harvest is a very important trait that determines the profitability of maize cultivation [14,15]. All studies carried out at the Department of Agronomy of the Pozna ń University of Life Sciences demonstrated that row application of fertilizers, compared to the traditional (broadcast) application, lowered water content in the grain [16]. Moreover, the row method of fertilizer placement allowed to reduce the level of mineral fertilization and extend maize placement period, especially by accelerating the placement, which is important in periodic soil moisture shortages in the early spring [17–19]. Therefore, the present results are of great applicatory importance and can improve the economy and organization of maize cultivation.

In published studies [20–22], the effectiveness of starter fertilization was usually assessed by placing the fertilizer at a distance of 5 cm to the side and below the seeds. Hence, a comparison of different depths of fertilizer placement in soil in relation to kernel and soil surface could suggest a deeper placement of the fertilizer in drought conditions that occur almost every year.

The number of plants after emergence is influenced by NP fertilizer placement depth (D), year (Y) and NP fertilizer placement depth-by-year (DY) interaction, but also many other climatic, biologic, and terrestrial factors.

Hence, phenotyping should be carried out in replicated, multi-year field trials to accurately assess this trait. DY interaction in the field trials of agricultural crops can be analyzed using the Additive Main effects and Multiplicative Interaction (AMMI) model [23]. The AMMI model determines NP fertilizer placement depths characterized by a high mean value of the observed trait and high adaptability to the desired area using the analysis of variance (ANOVA) and mega-year delineation. This model combines ANOVA with additive parameters and principal component analysis (PCA) with multiplicative parameters in a single analysis. As a result, the AMMI biplot simultaneously displays both the main and interaction effects for NP fertilizer placement depths and years, thereby
enabling a single analysis of DY interaction. For this reason, AMMI is also known as interaction PCA (IPCA) [24,25]. The advantages of the AMMI model are that they use overall fitting, impose no restrictions on the multiplicative terms, and result in a least squares fit; within limits, any model may also be expected to fit data from which it was derived. The AMMI method is used for three main purposes. The first is that the model diagnoses other models; secondly, AMMI clarifies treatment × environment interaction and summarizes patterns and relationships of treatment and environment [23,26], and the third use is the accuracy of trait estimates [23,26]. The AMMI method is widely used in stability and adaptability analyses because it (i) provides an initial diagnosis of the model and is well-suited for data analysis with many environmental influences, (ii) allows greater unfolding of the treatment × environment interaction and summarizes the patterns and relationships between treatments [27–33].

Field studies at the Department of Agronomy of the Poznań University of Life Sciences were carried out to determine the effect of the depth of NP fertilization placement in maize cultivation on the number of plants after emergence. The objective of this study was to assess NP fertilizer placement depths by years interaction on the number of maize (Zea mays L.) plants after emergence using the additive main effects and multiplicative interaction model.

2. Materials and Methods
2.1. Soil and Climate Information

Maize placement was performed using a precision seeder, with a built-in granular fertilizer applicator (Monosem). Gross plot size was 24.5 m² (length—8.75 m, width—2.8 m), while the plot size used to observe the number of plants after emergence was 12.25 m². In the 3-leaf stage (BBCH 13), the plants in each row of the plot were carefully counted, and subsequently their sum was divided by its size, thus establishing the number of plants after emergence. The structure of the experimental field morphology was characteristic of the bottom moraine of the North Polish (Baltic) glaciation, the Poznań stadium. Sandy-loam formations constituted parental materials of the soil. Terrain configuration was slightly diversified, and the dominant area was flat and slightly undulating. Typologically, the soils in the test field were of the black-earth type, the cambic black-earth subtype that belonged to the black-earth order. These soils should be classified as Phaeozemes according to the international WRB classification [34], and as Mollisols according to the US Soil Taxonomy [35]. Humic horizon was homogeneous on the entire experimental field. The percentage content of the sand fraction of the Ap level showed little differentiation and ranged from 77–79%, while the average values for individual fertilization objects were almost identical for the depths of 0–0.15 m and 0.15–0.30 m. Dust content in these levels was also not very diverse and was within 17–18% for both depths. Clay content, relatively low, fluctuated in the top and deeper soil layers in a narrow range of 4–5%. Granulometric composition of the soils from the experimental field in the arable-humic horizons (Ap) was even in all the tested fertilization objects in this experimental field. All analyzed samples from the experimental objects belonged to one grain size group, i.e., loamy sands [36]. The experimental field was valuated as class IIIb. The black earth type are soils with direct impact of groundwater or heavy rainfall on the lower and partly central portions of the soil profile. Precipitation and water management dominate in the surface horizons and it can be somewhat modified through changes of water properties in the deeper parts of the soil profile (0–0.30 m, genetic horizon Ap). Soil abundance in nutrients and soil pH before establishing the experiment in maize growing seasons are presented in Table 1.
Table 1. Nutrient contents and soil pH before establishing the experiment in maize growing seasons.

| Specification                          | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|----------------------------------------|------|------|------|------|------|------|
| P [mg P kg\(^{-1}\) dm of soil]        | 40.0 | 104.0| 73.0 | 49.0 | 155.0| 115.0|
| K [mg K kg\(^{-1}\) dm of soil]        | 111.0| 97.0 | 108.0| 116.0| 122.0| 103.4|
| Mg [mg Mg kg\(^{-1}\) dm of soil]      | 29.0 | 44.0 | 53.0 | 53.0 | 69.0 | 58.0 |
| pH [1 mol dm\(^{-3}\) KCl]             | 4.5  | 4.6  | 5.6  | 5.1  | 5.8  | 5.9  |
| \(N_{\text{min}}\) [kg ha\(^{-1}\)] in soil, layer 0.0–0.6 m | 68.5 | 79.2 | 71.4 | 65.7 | 69.3 | 73.8 |
| C, org. [%]                            | 1.01 | 0.99 | 0.99 | 0.98 | 1.02 | 1.00 |

Air temperature and rainfall in the maize growing seasons are presented in Table 2. Definitely the warmest and driest growing season was recorded in 2018. In turn, the largest sum of precipitation in the initial period of maize growth was recorded in 2016. The lowest average daily temperature at the level of 12.8 °C was recorded in 2017. Generally, it should be said that thermal and rainfall in the initial maize vegetation varied considerably in individual growing seasons. The effect of temperature and humidity factors is best described in a comprehensive manner by the hydrothermal water supply index \([K]\) according to Szulc et al. [37].

\[
K = \frac{10 \cdot \text{monthly precipitation total [mm]}}{\text{Number of days} \cdot \text{mean daily air temperature in a given month [°C]}}
\]

Table 2. Average monthly air temperatures and monthly total precipitation in individual growing season.

| Years | Temperature [°C] | April | May | June | Average/Sum |
|-------|------------------|-------|-----|------|-------------|
| 2015  | 9.3              | 13.9  | 16.9| 13.4 |
| 2016  | 9.6              | 16.3  | 19.9| 15.3 |
| 2017  | 7.3              | 13.7  | 17.4| 12.8 |
| 2018  | 12.9             | 16.9  | 18.5| 16.1 |
| 2019  | 10.5             | 11.9  | 22.0| 14.8 |
| 2020  | 9.4              | 11.8  | 18.3| 13.2 |

| Years | Rainfall [mm]    | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|-------|-----------------|------|------|------|------|------|------|
| 2015  | 17.6            | 27.2 | 66.6 | 111.4|      |      |      |
| 2016  | 47.3            | 47.3 | 12.8 | 107.4|      |      |      |
| 2017  | 40.6            | 56.8 | 68.2 | 165.6|      |      |      |
| 2018  | 36.2            | 17.4 | 25.6 | 79.2 |      |      |      |
| 2019  | 8.6             | 94.4 | 7.2  | 110.2|      |      |      |
| 2020  | 2.0             | 52.8 | 42.8 | 97.6 |      |      |      |

| Years | Values of hydrothermal coefficient of water preservation [K] | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|-------|------------------------------------------------------------|------|------|------|------|------|------|
| 2015  | 0.63                                                       | 0.63 | 1.31 | 0.85 |      |      |      |
| 2016  | 1.64                                                       | 0.93 | 2.07 | 1.54 |      |      |      |
| 2017  | 1.85                                                       | 1.33 | 1.30 | 1.49 |      |      |      |
| 2018  | 0.93                                                       | 0.33 | 0.46 | 0.57 |      |      |      |
| 2019  | 0.27                                                       | 2.55 | 0.11 | 0.97 |      |      |      |
| 2020  | 0.07                                                       | 1.44 | 0.77 | 0.76 |      |      |      |

\(^1\) according to Sielianinow [37].

Interpretation of the hydrothermal index according to Sielianinow: \(K > 1.5\)—excessive moisture for most plants, \(1 < K < 1.5\)—sufficient moisture for most plants, \(0.5 < K < 1.0\)—insufficient moisture for most plants, \(K < 0.5\)—drought.
2.2. Field Experiment

Field trial was carried out at the Department of Agronomy of the Poznań University of Life Sciences on the fields of the Gorzyń Experimental and Educational Unit, branch in Złotniki (52°26′ N; 16°45′ E), in the years 2015–2020. The experiments were carried out for six years as single-factor experiments in four field replications. The following variable was tested: A—NP fertilizer placement depth (A1—0 cm (broadcast), A2—5 cm (in rows), A3—10 cm (in rows), A4—15 cm (in rows)). The same level of mineral fertilization (100 kg N ha\(^{-1}\), 70 kg P\(_2\)O\(_5\) ha\(^{-1}\) and 130 kg K\(_2\)O ha\(^{-1}\)) was applied in all experimental objects. Fertilization was balanced against phosphorus, which was applied at the whole required concentration in the form of ammonium phosphate (18% N, 46% P\(_2\)O\(_5\)). N and K fertilization was performed before maize placement using urea (46% N) and potassium salt (60%). Fertilizer coulters (on objects with starter fertilization) were set 5 cm aside from the seeds. The depth of NP fertilization application was regulated on the seeder frame (Figure 1). The maize variety P7905 was used in the experiment. Is this a commercial hybrid.

![Setting the depth of NP fertilizer placement (photo taken by Szulc P.).](image1)

2.3. Statistical Analysis

Two-way analysis of variance was applied to determine the magnitude of the main effects of NP fertilizer placement depth and years as well as NP fertilizer placement depth by years interaction on the number of plants after emergence. The main effects of NP fertilizer placement depths and years were fixed; however, the effect of NP fertilizer placement depth by year interaction was random. In parallel, least-squares means were calculated for the AMMI model. The model first fitted the additive main effects of NP fertilizer placement depths (D) and years (Y), followed by the multiplicative effects of DY interaction by PCA. The AMMI model [24,38] was defined by the following equation:

\[
y_{de} = \mu + \alpha_d + \beta_e + \sum_{n=1}^{N} \lambda_n y_{dn} \delta_e + Q_{de},
\]

(1)
where $y_{de}$ is the mean of NP fertilizer placement depth $d$ in the year $e$, $\mu$ is the grand mean of the number of plants after emergence, $\alpha_d$ is the mean deviation of NP fertilizer placement depth, $\beta_e$ is the year mean deviation, $N$ is the number of PCA axes retained in the adjusted model, $\lambda_n$ is the eigenvalue of the PCA axis $n$, $\gamma_{dn}$ is NP fertilizer placement depth score for the PCA axis $n$, $\delta_{en}$ is the eigenvector score for the PCA axis $n$, and $Q_{de}$ is the residual, which includes AMMI noise and pooled experimental error. The expected distribution of $Q_{de}$ was found to be normal. The AMMI stability values (ASVs) were used to compare the stability of NP fertilizer placement depths as described by [39]:

$$ASV = \sqrt{\frac{SS_{IPCA1}}{SS_{IPCA2}} (IPCA_1)^2 + (IPCA_2)^2},$$

(2)

where $SS$ is the sum of squares, IPCA$_1$ and IPCA$_2$ are the first and the second interaction principal component axes, respectively; and the IPCA$_1$ and IPCA$_2$ scores were the NP fertilizer placement depth scores in the AMMI model. ASV is the distance from zero in a two-dimensional scatterplot of IPCA$_1$ scores against IPCA$_2$ scores. Since the IPCA$_1$ score contributes more to the NP fertilizer placement depth by year sum of squares, it has to be weighted by the proportional difference between IPCA$_1$ and IPCA$_2$ scores to compensate for the difference in contribution. The distance from zero is then determined using Pythagoras’s theorem. The greater the IPCA score, either negative or positive, the more specifically adapted the NP fertilizer placement depth is to certain years. The higher the IPCA score (which can be negative or positive), the more accurately selected NP fertilizer placement depth in an individual year. Lower ASV score indicates more stable NP fertilizer placement depth across the year [29,31,33,38,40]. The level of significance in PCA analysis was tested with the $F$ test.

The level of significance of PCA analysis was tested using the $F$ test according to Gollob [41]. In the biplot, which is an efficient representation of the AMMI model, DY interactions are plotted on the vertical axis (IPCA 1), while means of NP fertilizer placement depth and year are plotted on the horizontal axis. The applied analytical procedures and result interpretation were based on the protocol of Gauch and Zobel [24]. All statistical analyses were conducted using the GenStat software package (v. 18) [42].

3. Results

Three sources of variation (NP fertilizer placement depth, year and DY interaction), were found to be significant for the number of plants after emergence. In ANOVA, the sum of squares for the main effect of the year represented 61.51% of the total variation in the number of plants after emergence, and this factor had the highest effect on the number of plants after emergence. The differences between NP fertilizer placement depths explained 23.21% of the total variation in the number of plants after emergence, while the effects of the DY interaction explained 4.68% of the variation (Table 3). The values of the two principal components were also statistically significant and jointly accounted for 91.87% of the whole effect on the variation in the number of plants after emergence. The first principal component (IPCA 1) explained 80.21% of the variation caused by interaction, while the second component (IPCA 2) accounted for 11.66% of the variation in the number of plants after emergence (Figure 2). Among the tested NP fertilizer placement depths, the A4 had the highest IPCA 1 value of 0.882, while the lowest value of IPCA 1 was $-0.251$ for A1. The values of IPCA 2 ranged from $-0.147$ (for A1) to 0.153 (for A3) (Figure 2, Table 4). Among the years of study, the 2018 had the highest IPCA 1 value of 0.231, while the lowest value of IPCA 1 was $-0.360$ in 2016. The values of IPCA 2 ranged from $-0.249$ (in 2019) to 0.125 (in 2018) (Figure 2, Table 4).
Table 3. Results of main effects and interaction from analysis of variance for the number of plants after emergence in relation to NP fertilizer placement depths as well as variability explained (in %). Coefficient of variation of the number of plants after emergence is equal to 3.28%.

| Source of Variation          | d.f. | Sum of Squares | Mean Squares | F Statistic | Variability Explained (%) |
|------------------------------|------|----------------|--------------|-------------|---------------------------|
| Treatments                   | 23   | 5.404          | 0.2349       | 24.09 ***   | 89.40                     |
| NP Fertilizer Placement Depth (D) | 3    | 1.403          | 0.4678       | 47.96 ***   | 23.21                     |
| Year (Y)                     | 5    | 3.718          | 0.7435       | 117.19 ***  | 61.51                     |
| DY Interaction               | 15   | 0.283          | 0.0189       | 1.93 *      | 4.68                      |
| IPCA 1                       | 7    | 0.227          | 0.0324       | 3.32 **     | 80.21                     |
| IPCA 2                       | 5    | 0.033          | 0.0066       | 0.67 *      | 11.66                     |
| Residuals                    | 3    | 0.023          | 0.0078       | 0.8 *       | 8.13                      |
| Error                        | 54   | 0.527          | 0.0098       |             |                           |

*p < 0.05, ** p < 0.01, *** p < 0.001, d.f.—the number of degrees of freedom.

Figure 2. Biplot for NP fertilizer placement depth by year interaction of the number of plants after emergence for four NP fertilizer placement depths of maize (Zea mays L.) during six years, showing the effects of primary and secondary components (IPCA 1 and IPCA 2, respectively) (A1—0 cm (broadcast), A2—5 cm (in rows), A3—10 cm (in rows), A4—15 cm (in rows)).
Table 4. Average number of maize (Zea mays L.) plants after emergence (plant m$^{-2}$), for NP fertilizer placement depths and years, principal component analysis values (IPCAg1, IPCAg2) and AMMI stability value (ASV).

| Year | NP Fertilizer Placement Depth | IPCA 1 | IPCA 2 |
|------|-------------------------------|--------|--------|
|      | A1 $^1$| A2 | A3 | A4 | Mean | Standard Deviation | Coefficient of Variation | A1 | A2 | A3 | A4 | Mean | Standard Deviation | Coefficient of Variation |
| 2015 | 8.201 a | 8.147 ab | 8.022 ab | 7.835 b | 8.051 | 0.161 | 2.00 | −0.073 | −0.034 |
| 2016 | 7.911 a | 7.862 a | 7.598 b | 7.402 b | 7.693 | 0.233 | 3.03 | −0.360 | 0.012 |
| 2017 | 7.446 a | 7.432 a | 7.384 b | 7.237 c | 7.375 | 0.114 | 1.55 | 0.173 | 0.053 |
| 2018 | 7.710 a | 7.688 ab | 7.637 ab | 7.548 b | 7.646 | 0.103 | 1.34 | 0.231 | 0.125 |
| 2019 | 7.821 a | 7.665 b | 7.688 b | 7.496 c | 7.667 | 0.153 | 2.00 | 0.113 | −0.249 |
| 2020 | 7.867 a | 7.770 a | 7.590 b | 7.522 b | 7.688 | 0.168 | 2.18 | −0.085 | 0.093 |

Mean 7.826 a 7.761 ab 7.653 ab 7.507 b 7.687 0.252 3.28

Coefficient of variation 3.17 3.08 2.78 2.59

IPCA 1 $^2$ IPCA 2 $^2$

A1—0 cm (broadcast), A2—5 cm (in rows), A3—10 cm (in rows), A4—15 cm (in rows). $^2$ Means in rows followed by the same letters are not significantly different.

The number of plants after emergence for the tested NP fertilizer placement depths varied from 7.237 plant m$^{-2}$ (for A4 in 2017) to 8.201 plant m$^{-2}$ (for A1 in 2015) over the six years, with an average of 7.687 plant m$^{-2}$ (Table 4). NP fertilizer placement depth A1 (0 cm—broadcast) had the highest average number of plants after emergence (7.828 plant m$^{-2}$), while NP fertilizer placement depth A4 (15 cm in rows) resulted in the lowest number of plants after emergence (7.507 plants m$^{-2}$). In addition, the average number of plants after emergence per year varied from 7.375 in 2017 to 8.051 plant m$^{-2}$ in 2015 (Table 4). Variation of the number of plants after emergence, measured coefficient of variation—CV, was equal to 3.28%, across all four NP fertilizer placement depth and six years of study (Table 3). The highest variation of the number of plants after emergence was observed for A1 (CV = 3.17%), while the lowest for A3 (2.78%) (Table 4). Values of coefficient of variation for particular years of study varied from 1.34% (in 2018) to 3.03 (in 2016) (Table 4).

Stability of the analyzed NP fertilizer placement depths during six years with respect to the number of plants after emergence was visualized as a biplot (Figure 3). NP fertilizer placement depth A1 interacted positively with the year 2015, but negatively with the years 2017 and 2018 (Figure 2), while NP fertilizer placement depth A2 interacted positively with the years 2016 and 2020, but negatively with 2019. NP fertilizer placement depth A3 interacted positively with the years 2017 and 2018, but negatively with the year 2015, while NP fertilizer placement depth A4 interacted positively with the year 2019, but negatively with 2020 (Figure 2). The analysis indicated that some NP fertilizer placement depths exhibited a high level of adaptation; however, most of them showed a specific adaptation. The ASVs varied in the number of plants after emergence between four NP fertilizer placement depths tested (Table 4). NP fertilizer placement depths A3 and A2 with the ASV of 1.361 and 1.615, respectively, were the most stable, while NP fertilizer placement depths A4 and A1 with the ASV amounting to 1.999 and 1.745, respectively, were the least stable (Table 4).
Figure 3. Biplot for the interaction principal component (IPCA 1) and average number of plants after emergence (plants m$^{-2}$). Vertical line in the biplot center is the grand mean (A1—0 cm (broadcast), A2—5 cm (in rows), A3—10 cm (in rows), A4—15 cm (in rows)).

4. Discussion

The number of plants after emergence per unit area is one of the most important agriculture factors in the cultivation of this plant for grain [43]. According to current recommendations, the number of plants after emergence in grain cultivation ranges from 8 to 10 pcs. m$^{-2}$. In the present study, the number of plants after emergence decreased along with the increase of NP fertilizer placement depth in each of the six years of research. In turn, Szulc and Kruczek [44] showed no significant effect of the method of placement phosphorus and phosphorus-nitrogen fertilizers on plant emergence. Nevertheless, many authors have indicated that too high a concentration of the component in the immediate vicinity of the seeds can cause disturbances in germinating seeds [10,12,45,46]. However, the latter authors have not provided the maximum nutrient concentration that can be used in the immediate vicinity of germinating seeds. The confirmation obtained in these studies [45] that even the maximum concentration of 130 kg P$_2$O$_5$ ha$^{-1}$, applied in the immediate vicinity of the seeds, did not affect maize emergence, seemed to be a positive result. Consistent reproducibility of the lack of influence of fertilization of the on maize emergence in the following days of observation indicated that relationship [45]. To obtain more general conclusions, these authors standardized the intermediate values of subsequent emergence days to the average period of emergence, uniform for individual years. Logarithmic function most optimally reflected the emergence of maize, and its course for the tested fertilization methods was almost identical. Hence, the result obtained in these studies confirmed that the fertilization method did not differentiate maize by the number of plants after emergence. One can ask why the application of a lower phosphorus concentration of 70 kg P$_2$O$_5$ ha$^{-1}$ (30.8 kg P ha$^{-1}$) in the immediate vicinity of the seeds in the current study resulted in a reduction in plants’ quantity after emergence and before maize harvest along with an increase in depth fertilizer application. The increase in fertilizer
placement depth using a fertilizer coulter most likely worked in the same manner as the use of a subsoiler (Figures 4 and 5). Most probably, the subsoil was too loosened and water penetration was interrupted. Therefore, placing the seeds in such soil did not occur at the planned depth (4–5 cm), but deeper. This was confirmed by maize plant losses during the vegetation period that were in fact the lowest in objects with deep (15 cm) fertilizer placement during seed placement.

Figure 4. View of the field after placement. A trace of a seed coulter is visible on the left, and a fertilizer coulter on the right (20 cm from kernels, depth—15 cm) (photo taken by Szulc P.).

Figure 5. View of the field after placement. A trace of a seed coulter is visible on the left, and a fertilizer coulter on the right (10 cm from kernels, depth—5 cm) (photo taken by Szulc P.).
Other authors argued [47] that deeper sowing should be a common practice in the development of sustainable agriculture in arid and semi-arid areas of our globe. Nevertheless, most commercial maize varieties are not adapted to deeper sowing (>5 cm), which results in a disturbance of emergence dynamics [47] and reduction of the planned plant density. Therefore, scientists determined a recommended sowing depth, which is dependent on the type of soil, texture, pH and moisture conditions that vary for each crop species. However, arable fields are not uniform, therefore deeper sowing becomes a difficult task to solve. Deeper sowing is an alternative agricultural practice that has a strong influence on maize germination rate and consequently the final yield [48]. Hence, research should be focused on the selection of tolerant maize varieties in terms of increasing depth of their sowing. Strong hydrotropic reactions of new varieties should be the highest for its implementation in sustainable agriculture in times of the impending drought caused by the climate crisis [49]. This feature varies greatly from strong (>40°) to weak (<40°), which confirms the large genetic diversity among commercial maize varieties [50]. Therefore, the selection should use the genetic diversity of native, local maize varieties, which show a strong hydrotropic response and a greater mesocotyl elongation coefficient in deeper seed placement in soil during sowing [51].

In addition to the most important DY interactions, the AMMI biplot allows to visualize the major effects of NP fertilizer placement depths and individual years of cultivation. The present study found that the largest difference in the number of plants after emergence between A1 and A4 was obtained in 2016, which was characterized by the highest sum of atmospheric precipitation (218.4 mm) in the initial period of maize vegetation. On the other hand, the lowest difference between A1 and A4 in the number of plants after emergence occurred in 2018, which was characterized by the highest average daily air temperature (16.1 °C). The AMMI model has been extensively used in studies on numerous species [52–64]. The AMMI is more appropriate in the initial statistical analysis of yield trials because it provides an analytical tool to diagnose other models, such as subcases, when these are better for particular data sets and also have a good chance of predicting new depths and years, this is a real advance [65]. To our knowledge, this is the first report about using the additive main effects and multiplicative interaction model to analysis of NP fertilizer placement depth by year interaction on the number of maize (Zea mays L.) plants after emergence. The results obtained from AMMI analyses are very important in terms of the development and recommendation of most optimal NP fertilizer placement depths concerning the productivity in a specific year. The AMMI model is a useful tool for diagnosing DY interaction patterns and improving the accuracy of reaction assessments. It allows to group NP fertilizer placement depths based on the similarity of response features and determine potential trends over the years. The proposed strategy could extract more information from DY interactions, thereby helping researchers to determine specific NP fertilizer placement depths, which would contribute to competitive yields in different years.

The AMMI model does not provide for a quantitative stability measure and such a measure is essential to quantify and rank genotypes in terms of observed trait stability [66,67]. Therefore, the AMMI stability value (ASV) was proposed by Purchase et al. [39] to quantify and rank objects according to their observed trait stability. The AMMI stability value (ASV) identified NP fertilizer placement depth A3 (10 cm in rows) as a more stable depth, which also had high mean performance. Such an outcome could be regularly employed in the future to delineate predictive, more rigorous recommendation strategies, as well as to help define stability concepts for recommendations for maize.

5. Conclusions

The number of plants after emergence decreased with the depth of NP fertilization in the soil profile. Most probably, the main reason for this relationship was too deep placement, caused by excessive loosening of the subsoil during placement. NP fertilizer placement depths of 10 cm in rows (A3) and 5 cm in rows (A2) were found to be the most
stable, while 15 cm in rows (A4) and 0 cm in broadcast (A1) were the least stable in terms of the number of plants after emergence. Based on the experiment, it seems reasonable to place the NP fertilizer granules at a maximum depth of 10 cm. A deeper application of fertilizer >10 cm can only be advisable with thin coulters that do not disturb the soil structure under the seed. Maize varieties for deeper application of mineral fertilizer in the soil profile >10 cm (row fertilization) should be more tolerant to deeper seed placement during sowing. AMMI analysis proved to be effective for determining DY interactions with respect to the number of plants after emergence. In order to most efficiently utilize the biological progress, represented by new maize varieties, it is very important to assess the correct depth of mineral fertilizer application and develop plant nutrition on this basis.

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