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Functional relationships between yield of maize (*Zea mays* L.) and its components

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SUMMARY

A field experiment was carried out in the years 2017–2019 on the fields of the Experimental Station in Chrząstowo, belonging to the Research Centre for Cultivar Testing in Słupia Wielka. It was carried out for 3 years in the same split-plot design with 2 experimental factors in 3 field replicates. The following factors were studied: A – 1st order factor – maize variety: A1 – ES Bombastic (FAO 230-240) – single cross hybrid (SC), A2 – ES Abakus (FAO 230-240) – three-way cross hybrid (TC, stay-green), A3 – ES Metronom (FAO 240) – single cross hybrid (SC, stay-green + roots power). B – 2nd order factor – type of nitrogen fertilizer: B1 – control (without N application), B2 – ammonium nitrate, B3 – urea, B4 – ammonium nitrate + N-Lock, B5 – urea + N-Lock, B6 – Super N-46, B7 – UltraGran stabilo. In this study, we investigated whether there was a functional relationship between maize grain yield and ear number, TSW (thousand-seed weight), and seed number per ear. Additionally, we investigated whether there was a functional relationship between maize grain yield and ear number, TSW, and seed number per ear for each type of fertilization in a given study year, as well as for each type of fertilization regardless of year.

Key words: linear regression, maize, multiple linear regression, nitrogen, polynomial regression of degree two

1. Introduction

Stabilized nitrogen fertilizers contain nitrification or urease inhibitors (Szulc et al. 2023a). The main purpose of their use is to increase the efficiency of plant fertilization with nitrogen (by reducing the number of applications and enabling

a wider range of application dates), as well as to improve environmental conditions by reducing the risk of releasing excess nitrogen into groundwater and air (Drury et al. 2017). Nitrification inhibitors reduce the intensity of microbial transformations of ammonium ions (NH_4^+) to nitrate ions (NO_3^-) and free nitrogen (gaseous N_2 and nitrous oxide N_2O – greenhouse gases) in the soil (Byrne et al. 2020, Nugrahaeningtyas et al. 2022). A urease inhibitor, on the other hand, is a compound that temporarily slows down the enzymatic conversion of urea to CO_2 and NH_3 due to its inhibitory effect on urease. This is of great importance, especially in alkaline soils, as it reduces nitrogen losses due to ammonia volatilization. A urease inhibitor blocks the conversion of urea to ammonia for one to two weeks. This reduces the risk of losses due to its evaporation and is a major advantage over non-stabilized urea (Bastos 2019; Uzun et al. 2020).

The aim of this study was to develop various types of regression equations to estimate maize grain yield depending on variables such as ear number, TSW (thousand-seed weight), and number of seeds per ear. It was examined whether the relationships could be described by linear regression, polynomial regression of degree two, or multiple linear regression. The study examined whether there was a functional relationship between the traits tested regardless of nitrogen fertilizer type, for each fertilization type in a given study year, and for each fertilization type regardless of year.

2. Methodology

2.1. Experimental field

The field experiment was carried out in the years 2017–2019 on the fields of the Experimental Station for Cultivar Testing in Chrząstowo, belonging to the Research Centre for Cultivar Testing in Słupia Wielka. It was carried out for 3 years in the same random block design (split-plot) with 2 experimental factors in 3 field replicates. The following factors were studied: A – 1st order factor – maize cultivar: A1 – ES Bombastic (FAO 230-240) – single cross hybrid (SC), A2 – ES Abakus (FAO 230-240) – three-way cross hybrid (TC, “stay-green”), A3 – ES

Metronom (FAO 240) – single hybrid (SC, "stay-green + roots power"). B – 2nd order factor – type of nitrogen fertilizer: B1 – control (without N application), B2 – ammonium nitrate, B3 – urea, B4 – ammonium nitrate + N-Lock, B5 – urea + N-Lock, B6 – Super N-46, B7 – UltraGran stabilo. The same level of mineral fertilization was applied in all experimental plots in amounts of 150 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1} and 130 kg K_2O ha^{-1}. Nitrogen fertilization was not applied in the control combination (B1). Nitrogen fertilizers were applied by broadcasting, directly before the maize was sown. After application, they were mixed with the soil. In combinations with standard nitrogen fertilizers (B4 and B5), N-Lock nitrogen stabilizer was applied as a spray on day 5 after sowing the nitrogen fertilizer at a rate of 1.7 l ha^{-1}. This contains 200 g of nitrapyrin in the form of a microcapsule suspension and is designed to slow down the nitrification process. Fertilization with P and K was carried out before maize sowing at two dates: in the autumn of the previous year (under winter plowing), and in the spring immediately before sowing of the maize (before the combined seed drill). At the first date, the compound fertilizer Lubofos 12 (12% P_2O_5, 20% K_2O) was applied, containing 36 kg ha^{-1} P_2O_5 and 60 kg ha^{-1} K_2O. The remaining dose of P and K was supplied before maize sowing in the form of enriched superphosphate (40% P_2O_5) at 84 kg ha^{-1}, and potassium salt (60% K_2O) at 70 kg ha^{-1}.

2.2. Soil conditions

The analyzed soils of the experimental field belonged to quality class IVa, a very good rye complex (Szulc et al. 2023b). In terms of grain size, the top horizons of the analyzed soils were classified as loamy sands, and the content of the loam fraction was 4%, dust 14%, and sand fraction 83%. The pH determined in the water extract expressed in pH units was about 7.0, while in KCl it was about 0.5 units lower and was in the upper part of the slightly acidic range. The content of assimilable potassium forms was 80.5 mg K kg^{-1}, which lies within the moderate range for this element. The contents of assimilable phosphorus and magnesium (168.2 mg P kg^{-1}, 92.5 mg Mg kg^{-1}) were in the very high range.

2.3. Thermal and moisture conditions

Temperatures and humidity were reported in an earlier study (Szulc et al. 2023c).

2.4. Statistical analysis

The statistical analyses employed in this study involved the use of various regression models, including linear regression, polynomial regression of degree two, and multiple linear regression. These models were utilized to establish functional relationships among maize grain yield (y), ear number (x_1), TSW (x_2), and seed number per ear (x_3).

The Pearson correlation coefficient (r) was used to measure the strength of the statistical relationships between the maize grain yield and the ear number, TSW or seed number per ear (Szulc et al. 2022).

The coefficient of determination (R^2) determines the accuracy of a statistical model in predicting outcomes. In this model, the outcome is represented by the dependent variable (the maize grain yield).

All calculations were carried out using the STATISTICA 13.3 software package (2017). Statistical significance was set at the level $\alpha = 0.05$.

3. Results

3.1. Dependence of maize grain yield on its components

3.1.1. For cultivars (A) regardless of nitrogen fertilizer type (B)

The study investigated whether there was a functional relationship between maize grain yield (y) and ear number (x_1), TSW (x_2), and number of seeds per ear (x_3). For each study year and all observations obtained in 2017–2019, positive linear relationships were obtained between grain yield and TSW (Table 1). This shows that for higher values of TSW, the maize grain yield was also higher. Moreover, it was shown for all observations obtained in 2017–2019 that there was a positive linear relationship between the grain yield and the number of seeds per ear, with higher yields with increasing number of seeds per ear. The coefficient of

Table 1. Functional relationships between grain yield and TSW, or grain yield and grain seed number per ear

Year	Pearson correlation coefficient (r)	Regression equation	Coefficient of determination (R^2)	p-value
2017	0.6477	$y = 1.586 + 0.027x_2$	41.95%	0.0015
2018	0.7065	$y = -1.835 + 0.031x_2$	49.91%	0.0003
2019	0.6239	$y = 2.466 + 0.011x_2$	38.92%	0.0025
All years (2017–2019)	0.3919	$y = -0.737 + 0.028x_2$	15.36%	0.0015
	0.4054	$y = 1.343 + 0.016x_3$	16.43%	0.0010

y – grain yield, x_2 – TSW, x_3 – number of grain seeds per ear

determination of 16.43% means that 16.43% of the total variability of the grain yield was explained by variability in the number of seeds per ear according to the equation $y = 1.343 + 0.016x_3$ (Table 1).

In 2017, a positive linear relationship was found between the grain yield of the cultivar ES Bombastic and the number of seeds per ear (r = 0.7688) (Table 2). Thus, the higher the number of seeds per ear, the higher the yield of this cultivar. The coefficient of determination of 59.10% means that 59.10% of the total variability of the grain yield of the cultivar ES Bombastic was explained by variability in the number of seeds per ear according to the equation $y = 3.673 + 0.013x_3$. In 2019, a positive linear relationship was demonstrated between grain yield of the cultivar ES Bombastic and TSW (r = 0.8096). Thus, increased TSW

Table 2. Functional relationships for the cultivar ES Bombastic between grain yield and TSW, or grain yield and grain seed number per ear

Year	Pearson correlation coefficient (r)	Regression equation	Coefficient of determination (R^2)	p-value
2017	0.7688	$y = 3.673 + 0.013x_3$	59.10%	0.0434
2019	0.8096	$y = 3.349 + 0.007x_2$	65.54%	0.0274
All years (2017–2019)	0.5336	$y = 1.199 + 0.015x_3$	28.47%	0.0127
	–	$y = -60.080 + 0.461x_2 - 0.001x_2^2$	22.64%	0.0380

y – grain yield, x_2 – TSW, x_3 – number of grain seeds per ear

also indicated higher yield for this cultivar. The coefficient of determination R^2 = 65.54% means that over 65% of the variability in grain yield for this cultivar was explained by variability in TSW according to the equation $y = 3.349 + 0.007x_2$ (Table 2).

In addition, for all observations for the cultivar ES Bombastic recorded in 2017–2019, it was shown that (Table 2):

- There was a positive linear relationship between the grain yield and seed number per ear. The coefficient of determination R^2 = 28.47% means that the variability in the number of grain seeds per ear had an influence on the grain yield variability for this variety according to the equation $y = 1.199 + 0.015x_3$.
- The second-degree non-linear relationship between the grain yield and TSW was significant at the level $\alpha = 0.05$ ($p = 0.0380$).

In 2017 (Table 3):

- The second-degree non-linear relationship between the grain yield for the cultivar Abakus and ear number was significant at the level $\alpha = 0.05$ (p = 0.0278).
- The second-degree non-linear relationship between the grain yield for this cultivar and TSW was significant at the level $\alpha = 0.05$ (p = 0.0129).

Table 3. Functional relationships for the cultivar ES Abakus between grain yield and ear number, grain yield and TSW, or grain yield and grain seed number per ear

Year	Pearson correlation coefficient (r)	Regression equation	Coefficient of determination (R^2)	p-value
2017	–	$y = 311.532 - 70.855x_1 + 4.151x_1^2$	36.84%	0.0278
	–	$y = 30.329 - 0.152x_2 + 0.0003x_2^2$	51.96%	0.0129
2018	0.9542	$y = 2.716 + 0.011x_3$	91.06%	0.0008
2019	0.8671	$y = 2.154 + 0.010x_3$	75.18%	0.0115
All years (2017–2019)	0.4433	$y = -1.374 + 0.030x_2$	19.65%	0.0442
	0.5321	$y = 0.200 + 0.018x_3$	28.32%	0.0130

y – grain yield, x_1 – ear number, x_2 – TSW, x_3 – number of grain seeds per ear

In 2018 and 2019 (Table 3), a positive linear relationship was found between the grain yield of the cultivar ES Abakus and the number of seeds per ear. In 2018, the linear relationship between these characteristics was very strong (r = 0.9542), and in 2019 the linear relationship was significant (r = 0.8671).

For all observations for the cultivar ES Abakus recorded in 2017–2019, it was shown (Table 3) that there was a positive linear relationship between the grain yield and TSW (r = 0.4433), and between the grain yield and the number of seeds per ear (r = 0.5321).

In 2017 (Table 4), a very strong positive linear relationship was found between the grain yield of the cultivar ES Metronom and TSW (r = 0.9037). The value of the regression coefficient (b_1 = 0.036) implies that if TSW increased by one unit, i.e. by 1 g, the grain yield for the cultivar ES Metronom would be higher by an average of 0.036 t ha^{-1}.

Table 4. Functional relationships for the cultivar ES Metronom between grain yield and TSW, or grain yield, TSW and grain seed number per ear

Year	Pearson correlation coefficient (r)	Regression equation	Coefficient of determination (R^2)	p-value
2017	0.9037	$y = -0.262 + 0.036x_2$	81.67%	0.0052
2018	0.9558	$y = -28.569 + 0.084x_3$	91.36%	0.0008
2019	–	$y = 1.892 + 0.025x_2 - 0.009x_3$	91.98%	$p_2 = 0.0028$ $p_3 = 0.0276$
All years (2017–2019)	0.4757	$y = -4.440 + 0.042x_2$	22.63%	0.0293

y – grain yield, x_2 – TSW, x_3 – number of grain seeds per ear

In 2018 (Table 4), a very strong positive linear relationship was found between the grain yield of the cultivar ES Metronom and seed number per ear (r = 0.9558). The value of the regression coefficient (b_1 = 0.084) implies that if seed number per ear increased by one unit, i.e. by 1 seed, the grain yield for the cultivar ES Metronom would be higher by an average of 0.084 t ha^{-1}.

In 2019, the grain yield for the cultivar ES Metronom was significantly affected by TSW and by the number of grain seeds per ear.

For all observations for the cultivar ES Metronom recorded in 2017–2019, it was shown (Table 4) that the linear relationship between the grain yield and TSW was positive ($r = 0.4757$).

3.1.2. For nitrogen fertilizers (B) irrespective of maize cultivar (A)

The study also examined whether there was a functional relationship between maize grain yield (y) ear number (x_1), TSW (x_2) and seed number per ear (x_3) for each fertilization type in a given study year, and for each fertilization type regardless of year.

For fertilizer 1 (control plot), a functional relationship for maize yield was proven only when all observations obtained in 2017–2019 were considered. A positive linear relationship was demonstrated for grain yield and TSW ($r = 0.4836$), and for grain yield and seed number per ear ($r = 0.6246$) (Table 5).

Table 5. Functional relationships for the control plot between grain yield and TSW, or grain yield and grain seed number per ear

Year	Pearson correlation coefficient (r)	Regression equation	Coefficient of determination (R^2)	p-value
All years (2017–2019)	0.4836	$y = -1.794 + 0.033x_2$	23.39%	0.0420
	0.6246	$y = 2.688 + 0.011x_3$	39.01%	0.0056

y – grain yield, x_2 – TSW, x_3 – number of grain seeds per ear

For ammonium nitrate, a significant non-linear relationship of second degree was shown only for the data from 2019, between the grain yield and seed number per ear ($p = 0.0465 < \alpha = 0.05$) (Table 6).

For urea fertilizer (Table 7):

- In 2018, the number of ears and TSW had a significant impact on grain yield. The coefficient of determination $R^2 = 89.95\%$ means that nearly 90% of the variation in grain yield can be attributed to the variability in the number of ears and TSW, as described by the equation $y = 8.155 - 1.238x_1 + 0.031x_2$.

Table 6. Functional relationship for ammonium nitrate between grain yield and grain seed number per ear

Year	Regression equation	Coefficient of determination (R^2)	p-value
2019	$y = 146.061 - 0.844x_3 + 0.001x_3^2$	78.18%	0.0465

y – grain yield, x_3 – number of grain seeds per ear

Table 7. Functional relationships for urea fertilizer between grain yield and ear number and TSW, grain yield and TSW, or grain yield and grain seed number per ear

Year	Regression equation	Coefficient of determination (R^2)	p-value
2018	$y = 8.155 - 1.238x_1 + 0.031x_2$	89.95%	$p_1 = 0.0466$ $p_2 = 0.0155$
2019	$y = -126.854 + 0.961x_2 - 0.002x_2^2$	90.43%	0.0146
All years (2017–2019)	$y = 84.072 - 0.381x_3 + 0.001x_3^2$	54.37%	0.0007

y – grain yield, x_1 – ear number, x_2 – TSW, x_3 – number of grain seeds per ear

- In 2019, a significant non-linear relationship of second degree was found between the grain yield and TSW ($p = 0.0146 < \alpha = 0.05$). The coefficient of determination $R^2 = 90.43\%$ means that over 90% of the variability in grain yield was explained by variability in TSW according to the non-linear equation $y = -126.854 + 0.961x_2 - 0.002x_2^2$.
- For all observations obtained in 2017–2019, a significant non-linear relationship of second degree was demonstrated between the grain yield and seed number per ear ($p = 0.0007 < \alpha = 0.05$). The coefficient of determination $R^2 = 54.37\%$ means that over 54% of the variability in grain yield was explained by variability in seed number per ear according to the non-linear equation $y = 84.072 - 0.381x_3 + 0.001x_3^2$.

For ammonium nitrate + N-Lock fertilizer (Table 8):

- In 2017, a significant non-linear relationship of second degree was found between the grain yield and seed number per ear ($p = 0.0339 < \alpha = 0.05$). The coefficient of determination $R^2 = 82.34\%$ means that over 82% of the

variability in grain yield was explained by variability in seed number per ear according to the non-linear equation $y = -25.8398 + 0.1796x_3 - 0.0002x_3^2$.

Table 8. Functional relationship for ammonium nitrate + N-Lock between grain yield and grain seed number per ear

Year	Regression equation	Coefficient of determination (R^2)	*p*-value
2017	$y = -25.8398 + 0.1796x_3 - 0.0002x_3^2$	82.34%	0.0339
2019	$y = -77.4634 + 0.4512x_3 - 0.0006x_3^2$	88.40%	0.0271

y – grain yield, x_3 – number of grain seeds per ear

- In 2019, a significant non-linear relationship of second degree was also observed between the grain yield and seed number per ear ($p = 0.0271 < \alpha = 0.05$). The coefficient of determination $R^2 = 88.40\%$ means that over 88% of the variability in grain yield was explained by variability in the seed number per ear according to the non-linear equation $y = -77.4634 + 0.4512x_3 - 0.0006x_3^2$.

For urea + N-Lock fertilizer (Table 9):

- In 2019, a significant non-linear relationship of second degree was found between the grain yield and TSW ($p = 0.0392 < \alpha = 0.05$). The coefficient of determination of 82.98% means that almost 83% of the total variability of the grain yield was explained by variability in TWS according to the non-linear equation $y = 2404.426 - 16.106x_2 + 0.027x_2^2$.
- For all observations obtained in 2017–2019, a significant non-linear relationship of second degree was also demonstrated between the grain yield and TSW ($p = 0.0374 < \alpha = 0.05$). The coefficient of determination of 41.61% means that over 41% of the total variability of the grain yield was explained by variability in TWS according to the non-linear equation $y = 111.687 - 0.711x_2 + 0.001x_2^2$.

For Super N-46 fertilizer (Table 10):

Table 9. Functional relationships for urea + N-Lock between grain yield and TSW

Year	Regression equation	Coefficient of determination (R^2)	*p*-value
2019	$y = 2404.426 - 16.106x_2 + 0.027x_2^2$	82.98%	0.0392
All years (2017–2019)	$y = 111.687 - 0.711x_2 + 0.001x_2^2$	41.61%	0.0374

y – grain yield, x_2 – TSW

Table 10. Functional relationships for Super N-46 between grain yield and TSW and grain seed number per ear, or grain yield and ear number

Year	Regression equation	Coefficient of determination (R^2)	*p*-value
2017	$y = -9.601 + 0.073x_2 - 0.008x_3$	97.90%	$p_2 = 0.0014$ $p_3 = 0.0208$
2018	$y = -835.78 + 198.74x_1 - 11.68x_1^2$	87.36%	0.0234

y – grain yield, x_1 – ear number, x_2 – TSW, x_3 – number of grain seeds per ear

- In 2017, the grain yield was significantly affected by TSW and the number of grain seeds per ear. The coefficient of determination $R^2 = 97.90\%$ means that nearly 98% of the variability in grain yield can be attributed to variability in the number of grain seeds per ear and TSW, as described by the equation $y = -9.601 + 0.073x_2 - 0.008x_3$.
- In 2018, a significant non-linear relationship of second degree was established between the grain yield and ear number ($p = 0.0234 < \alpha = 0.05$). The coefficient of determination $R^2 = 87.36\%$ means that over 87% of the variability in grain yield was explained by variability in ear number according to the non-linear equation $y = -835.78 + 198.74x_1 - 11.68x_1^2$.

For UltraGran stabilo fertilizer (Table 11):

- In 2018, the number of ears and TSW had a significant impact on grain yield. The coefficient of determination $R^2 = 94.42\%$ means that over 94% of the variation in grain yield can be attributed to the variation in the number of ears and TSW, as described by the equation $y = -24.162 + 1.750x_1 + 0.054x_2$.

Table 11. Functional relationships for UltraGran stabilo between grain yield, ear number and TSW, grain yield and ear number, or grain yield and grain seed number per ear

Year	Pearson correlation coefficient (r)	Regression equation	Coefficient of determination (R^2)	*p*-value
2018	–	$y = -24.162 + 1.750x_1 + 0.054x_2$	94.42%	$p_1 = 0.0135$ $p_2 = 0.0104$
2019	–	$y = 1060.92 - 244.59x_1 + 14.17x_1^2$	85%	0.0259
	– 0.8801	$y = 13.751 - 0.019x_3$	77.46%	0.0207

y – grain yield, x_1 – ear number, x_2 – TSW, x_3 – number of grain seeds per ear

- In 2019, a significant non-linear relationship of second degree was established between the grain yield and ear number ($p = 0.0259 < \alpha = 0.05$). The coefficient of determination $R^2 = 85\%$ means that 85% of the variability in grain yield was explained by variability in ear number according to the non-linear equation $y = 1060.92 - 244.59x_1 + 14.17x_1^2$.
- In 2019, a negative linear relationship was also shown between the grain yield and number of seeds per ear ($r = 0.8801$). Thus, the higher was the number of seeds per ear, the lower was the yield. The value of the regression coefficient ($b_1 = 0.019$) implies that if seed number per ear increased by one unit, i.e. by 1 seed, grain yield would be lower by an average of 0.019 t ha^{-1}. The coefficient of determination $R^2 = 77.46\%$ means that over 77% of the variability in grain yield was explained by variability in the number of seeds per ear according to the equation $y = 13.751 - 0.019x_3$.

4. Conclusions

Most often, simple correlation coefficients are used to determine the relationship between grain yield and the yield components. Many authors indicate that the relationships occurring between plant traits revealed during ontogeny are better described by the method of path coefficient analysis (Szulc et al. 2017; Aman et al. 2020). Another method to determine the effect of individual plant yield

components on differences in grain yield between two compared objects is proposed by Beruski et al. (2020).

Our own research for all parameters for ES Bombastic obtained in the years 2017–2019 showed that a positive relationship appears between grain yields and seeds per ear. The coefficient of determination R^2 = 28.47% means that the variability in the number of grain seeds per ear had an influence on the grain yield for this variety according to the equation $y = 1.199 + 0.015x_3$. For this variety, there was a significant non-linear relationship of second degree between the grain yield and TSW at the significance level $\alpha = 0.05$ ($p = 0.0380$).

In turn, for all observations of the ES Abakus variety obtained in the years 2017–2019, it was shown that there was a positive linear relationship between the grain yield and TSW ($r = 0.4433$), and between the grain yield and the number of seeds per ear ($r = 0.5321$).

In the case of all observations for the ES Metronom variety obtained in the years 2017–2019, it was found that there was a positive linear relationship between the grain yield and TSW ($r = 0.4757$).

Moreover, significant multiple regression was demonstrated in the following cases:

- In 2019, the grain yield for the cultivar ES Metronom was significantly affected by TSW and the number of grain seeds per ear.
- In 2018, the number of ears and the thousand-seed weight (TSW) had a significant influence on grain yield in the case of urea fertilizer application.
- In 2017, the grain yield was significantly affected by TSW and the number of grain seeds per ear in the case of Super N-46 fertilizer application.
- In 2018, the number of ears and TSW had a significant impact on grain yield in the case of UltraGran stabilo fertilizer application.

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