

Theses for doctoral dissertation (PhD)

**SITE-SPECIFIC VARIABLE RATE SOWING IN THE PRECISION
SUNFLOWER PRODUCTION**

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1. INTRODUCTION

The leap in the quality of agricultural production over the last few decades has also led to a great deal of attention being paid to the level of resources (energy, ecological, human) used. It has become essential to take account of the specific characteristics of the soil, the needs of cultivation technology and the need to harmonise production with environmental concerns.

Extreme weather phenomena - in particular, prolonged periods of drought - are becoming more common. These adverse effects have a major impact on and alter the water cycles and the biological-physical-chemical properties of soils, forcing farmers to rethink the soil management systems they have been using successfully so far. As a consequence of the constantly and rapidly changing climatic factors, research is being conducted to develop cultivation systems and practices that facilitate adaptation to changing environmental conditions and are capable of mitigating or preventing yield losses due to water scarcity.

Sunflowers have an extraordinary ability to use the soil's water resources, but among the factors limiting their yields, if we look at sunflower production in recent years, it is still true that the amount of available water is the primary limiting factor. The optimum number of plants is a site-, environment- and hybrid-specific trait, but also soil productivity, site heterogeneity, expected yield, the potential offered by the seeding technology and the adaptability of the hybrid used can be decisive.

Technological advances in precision farming based on satellite positioning have made available to farmers geo-information applications and cultivation tools that can significantly increase the efficiency of farming. In the precision farming toolbox, site-specific variable rate sowing methods are still new, especially for sunflower, which is less sensitive to changes in plant density due to its high adaptability. Its usefulness and efficiency are based on the ability to increase yields by increasing the amount of seed used for the site or to reduce the cost of sowing to achieve higher profits.

Objectives of research

The main objective of my research is to attempt to clarify the influence of varied management factors on sowing quality and the relationship between management, soil- and environmental variables on yield and to contribute to the improvement of the economics of sunflower production. To conduct a complex study that considers agronomic, technical-technological, soil physical and chemical aspects of sunflower production, as well as the economics of production.

Other objectives of the research were to investigate the impact of management, soil and environmental variables on sowing quality using satellite remote sensing technology and geoinformation tools, meteorological and soil survey data, and precision sowing technology. Investigate the impact of changes in management, soil and environmental factors on crop characteristics using statistical methods and explore the interactions between soil properties based on soil test results from different productivity zones. Find the relationship between the altitude of the growing area (fields) and the nutrient content of the soil and analyse the economics of sunflower production, the influence of factors affecting the income and profit per hectare.

2. MATERIAL AND METHODS

2.1. Basic parameters of the experiment

Due to the specificity of sunflower production, a three-year variable number of sowing experiments was set up for the years 2021-2023, with two different experimental plots per year to avoid the obvious adverse consequences of monoculture production on sunflower. Following the mapping of the field heterogeneity of the experimental areas, the zone areas according to the quality of productivity were determined and the variable rate sowing experiment was designed.

The Szemere-Mag Kft provided the location of the sowing experiments; the farm is located in Mezőszemere (Heves county). The soil type of the experimental areas is typical of the meadow soils of the Borsodi-Mezőségi landscape, which are fully suitable for sunflower production, but also characterised by varying degrees of heterogeneity within the field due to the nature of the water management in the area, which provides excellent opportunities for the application of precision technologies.

The weather phenomena of the period under study (2021-2023) were also suitable for examining the effect of the vintage. It was observed that, depending on the season, there are alternating favourable, average and unfavourable weather conditions for crop production, which can determine the success of farming each year (Table 1).

Table 1. Weather data for the experimental areas in 2021-2023

Year	2021	2022	2023	2021	2022	2023	2021	2022	2023	2021	2022	2023
Month	Precipitation, monthly (mm)			Temperature, monthly (C°)			Number of days up to total precipitation of 5mm			Number of heat days, (T _{max} ≥30°C)		
January	26,8	4,5	90,7	0,05	-0,32	4,07	0	0	8	0	0	0
February	47,8	8,6	9,1	1,57	4,11	2,53	3	0	0	0	0	0
March	10,3	32,0	35,1	5,30	5,40	7,06	1	1	2	0	0	0
April	59,3	40,1	50,8	8,47	9,56	9,61	5	3	2	0	0	0
May	73,7	11,4	65,4	14,21	17,58	16,23	4	0	5	0	1	0
June	41,4	26,9	135,9	22,66	22,98	20,00	1	2	7	13	14	4
July	49,5	20,1	102,3	24,32	24,06	22,97	4	1	4	21	20	16
August	65,7	81,6	72,3	20,71	24,48	22,97	6	3	4	10	20	17
September	11,7	51,3	33,1	17,37	15,76	20,07	1	3	3	0	0	6
October	17,5	6,4	51,8	10,05	12,31	13,29	1	0	4	0	0	0
November	62,0	38,2	102,7	4,95	6,17	5,61	4	2	8	0	0	0
December	45,5	81,5	70,4	0,82	1,97	2,02	1	4	5	0	0	0
Total./Avg.	511,2	402,6	819,6	10,87	12,01	12,20	31	19	52	44	55	43

The cultivation technology of the trials was the same in all three years, only the number of seeds varies as a productivity zone has changed.

2.2. Mapping methodology of the field heterogeneity

When designing the experimental sowings, it was essential that the areas had a sufficient degree of site heterogeneity, and it was possible to identify three distinct productivity categories within the field (low, average, high) and to keep them as separate as possible.

Soil properties data for the determination of the heterogeneity of the experimental plots were provided by the HUN-REN Center for Agricultural Research, Institute for Soil Sciences. Based on the data, the heterogeneity characteristics of the experimental areas could be determined and interpreted spatially.

In addition to information on the soil heterogeneity of the growing areas, I also collected data on the cropping patterns of crops previously grown in the areas. The thematic information obtained by analysing the space images of the experimental plots and using the data on the production technology of the crops grown between 2017 and 2020 was presented in map form. The main purpose of my studies was to investigate the soil surface vegetation, which is important for farming. The difference or quotient images of arithmetic operations between bands of satellite images, the so-called vegetation indices, are an excellent way to monitor vegetation. Using spectral data from satellite images of the experimental plots taken in each season, I calculated the NDVI index and then averaged the images.

Precision data collection also used yield map data of crops harvested from the experimental plots. In the John Deere S690 combines that I use, John Deere uses the Harvest Monitor and Harvest Doc yield and moisture measurement and yield mapping system. The data collections resulted in a yield map for each crop harvested in previous years (2017-2020).

The 10x10m pixels from the Sentinel-2 satellites provided the basic data for the delineation of the productive zones. I performed zone delineation based on homogeneous productivity pixels on the productivity zone maps based on the multispectral satellite images and yield maps. The pixel with average productivity was assigned a value of 100%, the pixel with higher productivity was assigned a value higher than 100% and the pixel with lower productivity was assigned a value lower than 100%.

In my experiment, the qualitative classification of the productivity was based on the productivity percentage value of the pixels, with the condition that at least 75% of the pixel values include within the given range (Table 2).

Table 2. Values for each productivity class

Field name	Statistical ID	Productivity (%)		
		low	average	high
C14	2021A	≤93,5	99,5-102,5	104,5≤
C4-7	2021B	≤95,5	100,5-103,5	111,5≤
B6	2022A	≤93,65	99,9-106,4	113,4≤
C10	2022B	≤94,83	97,81-101,47	106,64≤
B5	2023A	≤91,5	100,5-106,16	110,84≤
C5	2023B	≤97,5	99,15-101,5	102,5≤

The boundaries of the experimental areas were marked based on field-level heterogeneity maps created after analysing satellite images. Soil samples were taken from ten sampling points in each of the productivity zones from the 0-30 cm layer of soil. A soil sample characteristic of the given productivity zone was prepared from the average sample formed from the soil samples. The Szolnok Soil Protection Laboratory Ltd. conducted the tests.

2.3. Basic principles of the variable rate sowing

Based on the breeder's recommendation, the recommended planting density of the sunflower hybrid SY Bacardi CLP is 55-58,000 ha⁻¹. Accordingly, I have taken the 55,000 ha⁻¹ as the baseline for the trial, which has been used in the company's operational practice in the past. Considering the evaluation criteria of the experiment, I applied three number of units in each productivity zone in four replications.

In the low-quality productivity zone, I applied the basic seeding rate (55,000 ha⁻¹) and the reduced by 20% (44,000 ha⁻¹) and 40% (33,000 ha⁻¹) respectively.

In the average quality productivity zone, I applied the basic seeding rate (55,000 ha⁻¹) and the increased by 20% (66,000 ha⁻¹) and reduced by 20% (44,000 ha⁻¹).

In the high-quality productivity zone, I applied the basic seeding rate (55,000 ha⁻¹) and the increased by 20% (66,000 ha⁻¹) and 40% (77,000 ha⁻¹) respectively.

In the statistical analysis, the number of seeds used for each productivity zone was classified into quality categories according to Table 3.

Table 3. Classification of the number of seeds applied in the different quality productivity zones.

Quality of Productivity Zone	Classification of Seeding Rate		
	Low	Average	High
Seeding Rate (seed ha ⁻¹)			
low	33,000	44,000	55,000
average	44,000	55,000	66,000
high	55,000	66,000	77,000

After mapping the heterogeneity of the experimental fields, the zone areas according to the quality of productivity were determined and the variable seeding rates were designed.

2.4. Requirements for the sowing technology

The sunflowers were sown with a Horsch Maestro 12.75 SV (Horsch, 2024) seed drill, which was adapted for precision sowing, but equipped with a Precision Planting (Precision Planting, 2024) sowing unit mounted on a John Deere 1750 (John Deere, 2024) seed drill wagon to ensure the most accurate sowing possible. I have tried to combine the advantages of the different technical solutions to create the most accurate sowing technology available for sunflower. As a result of building a complete sowing system, I got a seed drill that is capable of high-quality experimental seeding and that can produce this precision at large scale (150-200ha/24h) and under variable soil conditions.

2.5. Verification of plant density

To monitor the number of seeds sown according to the seeding plan and the number of plants hatched, and to check the uniformity of the sowing technique, I conducted a statistical counting of the plant density and the number of plants after hoeing. The number of plants within the sampling areas and the distance between plants in cm (SI) were recorded.

2.6. Measurement of quantitative and qualitative parameters of the crop

The plots of the experimental fields were harvested separately, and the harvested sunflower quantities were individually measured by a mobile weighting unit (Avery Weight-Tronix M640), which was unloaded onto the transport vehicle. The sunflowers harvested as plots were sampled at five points, from which an average sample of approximately 1 kg was taken. The collected sunflower samples were analysed for moisture content, oil content and thousand seed weight.

2.7. Measuring the economics of sunflower production

Within a given year's cost of production, only the cost of seed per plot varied as a function of the number of plants, since the production technology was the same throughout the whole experimental area.

For the calculation of the gross yield, I used the weight per plot at a given moisture content during harvesting, corrected by the purity % of the measured rate (2021: 8m/m%; 2022: 13m/m%; 2023: 5.5m/m%) to obtain the net yield. I also considered the factors affecting the yield quality, which were calculated using the rules of the oil and moisture content bonification system applied by the purchaser.

Data on seed and other production-related costs and selling price were provided by the farmer.

2.8. Statistical analysis

The measured plant distances showed a normal distribution for any plant densities. Double and missing sowing rates were determined by the difference from the required plant distance. In the next step, the ratio of double and missing sowing was calculated for each parcel ($n = 216$). For the determination of sowing uniformity, the relative difference (%) between the measured plant distance and the required plant distance based on the nominal plant density was calculated - excluding cases of missing or double sowing - for each plant ($n = 41,829$) using the following formula:

$$D_r = \left| \frac{d_m - d_n}{d_n} \right|$$

where D_r means the relative difference in plant distance, d_m means the measured plant distance, and d_n means the required plant distance.

Yield data were converted to one hectare (kg ha^{-1}) and corrected to 8% moisture content. All variables related to yield were analysed separately per plot ($n=216$).

For the economic variables (income and profit), the same other production-related costs (Ft ha^{-1}) were incurred each year, only the seed cost (Ft ha^{-1}) related to the variable rate seeding used varied. The evolution of revenue (Ft ha^{-1}) was determined by the actual net yield per plot (kg ha^{-1}), the variation in moisture and oil content (m/m%) (bonification) and the actual selling price per tonne. The profit (Ft ha^{-1}) was the difference between revenue and net production cost. In the first step of the statistical analysis, the effect of the field ($n = 6$), productivity zone (low, average, high), and plant density level (low, average, high) were tested by Multiway Analysis of Variance (Multiway ANOVA) separately on the yield, seed oil content, seed moisture, thousand seed weight, double sowing, missing sowing at the parcel level ($n = 216$), and sowing uniformity - excluding cases of missing or double sowing - at the plant level ($n = 41,829$) (Yates, 1934). Significant cases were also assessed by Tukey's post hoc test (Tukey, 1949). It was originally planned to include the year of the survey as a separate factor in the analysis, but only

the field was included as a factor after realising that there was a high proportion of significant differences between the pairs of fields within the same year.

The connections among the soil and environmental variables, and between the group of soil and environmental variables and the group of the yield variables, as well as the group of sowing quality variables, were also tested by Pearson's correlation (R) analysis at the parcel level (n = 216) (Pearson, 1895). To measure the additional explanatory effect of the relationships between management, sowing technique, crop, and economic variables, I also calculated partial eta squared (η_p^2) values (Adams et al., 2021).

All independent and dependent variables are listed in Table 4.

The next step was to conduct Principal Component Analysis (PCA) to describe the relationships among the fields, as well as the soil and environmental variables and datasets were tested with Analysis of Covariance (ANCOVA) to measure the effect of the Field, covariating by PC₁₋₄ separately on the yield (yield, moisture, seed oil content, and thousand seed weight) and sowing quality factors (double and missing sowing) at the parcel level (n = 216), and on the sowing uniformity at the plant level (n = 41,829) (Keselman et al., 1998).

Table 4. Independent and Dependent variables of analyses.

Variables (Unit)	Range/Categories
Independent (Input) variables	
Management variables	
Field	2021A, 2021B, 2022A 2022B, 2023A, 2023B
Productivity zone	Low, medium, high
Plant density	Low, medium, high
Soil variables	
Soil pH (KCl)	4.87 - 6.87
Soil plasticity (K_{ARANY})	42 - 60
Soil properties (m/m %)	
Salt	0.06 - 0.16
CaCO ₃	0 - 10.9
Humus	2.66 - 4.71
Soil properties (mg kg ⁻¹)	
N	11.3 - 109
P ₂ O ₅	72.5 - 2230
K ₂ O	214 - 1230
Mg	288 - 2430
Na	14 - 70.1
Zn	1.81 - 4.87
Cu	4.43 - 11.8
Mn	105 - 733
S	3.93 - 18.1
Environmental variables	
Altitude (m, AASL)	92.8 - 114.2
Total precipitation (mm) ^A	225.2 - 561.6
Number of days with precipitation above 5 mm ^A	10 - 32
Average temperature (°C) ^B	18.07 - 19.73
Number of hot days ^{B C}	37 - 55
Dependent (Output) variables	
Sowing variables	
Double sowing (%) ^D	0 - 9.06
Missing sowing (%) ^{D E}	0.69 - 26.50
Sowing uniformity (Relative deviation of plant spacing, %) ^F	1.1 - 48.5
Crop variables	
Yield (kg ha ⁻¹) ^G	1466 - 5679
Moisture (%)	4.69 - 7.53
Oil content (% in dry matter)	40.6 - 53.8
Thousand kernel weight (g)	26.1 - 91.4
Economics variables	
Revenue (Ft ha ⁻¹)	326534 - 826695
Profit (Ft ha ⁻¹)	-26999 - 575962

^A Total value between January and August; ^B Average or total value between April and August; ^C Days with maximum temperature of 30 °C or above; ^D Average distribution per plot (n = 216); ^E No distinction was made between the cases of missing sowing due to sowing or incomplete seed germination, ^F Relative difference between the required and measured plant distance. Calculation based on each plant spacing, cases determined as double or missing sowing were excluded (n = 41.829), ^G Calculated on 8% of moisture.

3. RESULTS

3.1. Description of sowing technology

A key feature of the Horsch Maestro seed drill is that it has a large central seed hopper (2000 l), fertilizer hopper (6000 l) and microgranule hopper, ensuring high area coverage. The double-disc V-shaped coulter mounted on the John Deere 1750 seed drill is an excellent solution for preparing the necessary seedbeds. Variable rate seeding control and section control were performed by the Precision Planting system's own on-board computer (20|20™ Monitor).

I constructed the structural elements for applying nutrients and soil-insecticide myself. As a result of developing the entire sowing technology system, I obtained a sowing machine that is suitable for high-quality experimental sowing and is capable of producing this level of precision on a large scale, with high area performance (150-200 ha/24 h) and under varying soil conditions.

3.2. Impact of management variables on sowing quality characteristics

The results showed significant differences in the rate of double sowing in different fields and vintages. The Tukey test comparison also confirmed that these groups were statistically different from each other, emphasizing the variability of sowing quality from year to year, but the effect of the site (field) proved to be weak on the occurrence of double sowing ($\eta_p^2=0.26$).

When analysing the productivity zones, the average rate of double sowing in the high productivity zones was 4.58% compared to 2.71% in the low productivity zones, which resulted in a significantly higher value in the high productivity zones compared to the average productivity zone (-1.11%) and the low productivity zone (-1.87%). However, the effect of the quality of the productivity zones was also weak for this variable ($\eta_p^2=0.31$).

The results also show that the plant density influenced the double sowing rate, which resulted in a lower value in the low-density strips (3.21%), than in the average (3.77%) and high (3.78%) density strips, but the explanatory effect was very weak ($\eta_p^2=0.05$).

The analysis of missing sowing showed even greater differences, with the highest average percentage of 17.2% for the 2022A field and the lowest for the 2023B field at 5.9%. The field variable had a strong effect on incomplete sowing every year ($\eta_p^2=0.75$).

Analysis of the effect of the productivity zone showed that the high productivity zone had an average of 11.36%, while the average zone had a lower average of 9.77%. I measured significant differences only between the average and high productivity zones ($p < 0.001$), but the explanatory effect of the productivity zone proved to be very weak ($\eta_p^2=0.10$).

When examining the correlations with plant density, it can be concluded that the proportion of incomplete sowing increases significantly with increasing plant density ($\eta_p^2=0.49$).

The analysis also showed that the average relative deviation of plant spacing ratio in the high productivity zone was the highest (18.17%), which is significantly higher than the values for the average productivity zone (16.37%) and also higher than the average for the low productivity zone (14.46%).

The results of calculations examining the effect of plant density also showed that in the high-density group, the relative deviation of plant spacing was significantly higher, an average of 17.63%, than in the average (16.29%) and low (15.46%) density groups, which shows the correlation between higher density and higher relative deviation of plant spacing.

The effect of individual management variables on the uniformity of tree spacing proved to be very weak in all three cases ($\eta_p^2=0.01-0.02$).

3.3. The impact of management variables on crop characteristics

The results show that plot 2021A achieved the highest average yield (4262 kg ha⁻¹), while plot 2022B achieved the lowest average yield (2575 kg ha⁻¹). This significant difference highlights the impact of field variables on yield variability ($\eta_p^2=0.88$). The high productivity zone resulted in an average yield that was 41.8% higher (4044 kg ha⁻¹) than the average for the low-yield zones (2852 kg ha⁻¹), a difference that was also confirmed when examining the effect of the variable ($\eta_p^2=0.82$).

Changes in the crop production area (field) resulted in significant differences in each vintage. The effect of plant density was significant, but the average yield was 3490 kg ha⁻¹ for the low plant density group, 3509 kg ha⁻¹ for the average group, and 3522 kg ha⁻¹ for the high plant density group, resulting in a difference of only 32 kg ha⁻¹ between the groups ($\eta_p^2=0.03$).

In terms of the moisture content of the harvested sunflower kernels, the results show that the moisture content of the crop harvested from field 2023A was the highest (6.99 m/m%), compared to field 2023B, which had the lowest moisture content (5.74 m/m%). The analysis revealed that the moisture content of the cashew was significantly influenced by the effect of the field ($\eta_p^2=0.9$) and that the characteristics of the different zones also played a key role ($\eta_p^2=0.57$). The effect of the plant density was significantly the same on the moisture content of the sunflower kernel in all cases examined, and the size of the effect was also very weak ($\eta_p^2=0.02$).

When analysing the oil content of harvested sunflower kernels, significant differences between fields highlight the strength of the explanatory effect of field variation ($\eta_p^2=0.79$). The productivity zones had a significant ($p < 0.001$) effect on oil content, resulting in lower oil content in the low-productivity zone (45.79 m/m%) than in the average (46.39 m/m%) and high productivity zones (46.68 m/m%). However, there was no significant difference between the average and high productivity zones. A significant difference in oil content was only found between the low (46.08 m/m%) and high plant density (46.54 m/m%) groups. This result suggests that the explanatory effect of the quality of the productivity zone ($\eta_p^2=0.15$) and the increase in plant density per hectare ($\eta_p^2=0.05$) on the oil content of sunflower kernels is also very weak.

The thousand kernel weight varied significantly between the sunflowers harvested from the individual fields ($\eta_p^2=0.95$). In the 2021 crop year, I measured significantly similar data on the two fields included in the research (2021A: 54.96 g; 2021B: 55.41 g), while the results measured in 2022 and 2023 showed significant differences within the vintage for each field, which again suggests that environmental effects and site characteristics also play a major role in the development of thousand kernel weight. The productivity zones also had a significantly detectable ($p < 0.001$) effect on thousand kernel weight ($\eta_p^2=0.58$), which was lowest on average in low-yield zones (55.03 g).

An increase in plant density resulted in a significant decrease in thousand kernel weight. Changes in plant density had a moderately strong effect ($\eta_p^2=0.61$) on sunflower thousand kernel weight.

3.4. Examination of soil variables and altitude, as well as the relationships between soil variables

I conducted the analyses using Pearson's correlation method, which found a correlation between altitude above sea level (AASL) and several soil variables. One of the strongest correlations was measured in relation to salt content, where the correlation was negative ($R = -0,52$), meaning that salt content tended to decrease as AASL increased.

I measured a similar negative correlation between AASL and K_2O ($R = -0,59$), Mg ($R = -0,45$), and Zn ($R = -0,45$).

When examining the relationships between soil variables, I measured the highest correlation between pH and $CaCO_3$ content. The correlation was positive, with a medium level of significance ($R = 0,53$).

The strongest correlation was measured between soil plasticity (K_{ARANY}) and salt content ($R = 0.64$) and Cu content ($R = 0.60$), while a moderate correlation was measured between Mg content ($R = 0.57$) ($p < 0.01$). A moderately strong negative correlation was found between soil plasticity and Mn content ($R = -0.55$) ($p < 0.05$).

A moderate positive correlation was found between soil salt content and humus ($R = 0.51$), N ($R = 0.47$), Mg ($R = 0.53$), and Na content ($R = 0.50$) ($p < 0.01$).

When analysing the $CaCO_3$ content of the soil, I observed the strongest correlation values for two factors. There was a strong positive correlation with humus content ($R = 0.71$) and an equally strong negative correlation with Mn content ($R = -0.72$) ($p < 0.01$).

I measured a moderate positive correlation between N and K_2O content ($R = 0.50$).

Similar to nitrogen, I measured a strong correlation between P_2O_5 and K_2O ($R = 0.69$).

During the correlation analysis, I measured a strong positive correlation between K_2O and Zn content, where the R value was 0.83 ($p < 0.01$), and a strong negative correlation between Na and Mn content ($R = -0.75$) ($p < 0.01$).

3.5. The effect of soil and environmental variables on crop characteristics, and the effect of soil variables on sowing quality

During the analysis, I observed that the correlation between moisture content and soil plasticity (K_{ARANY}) was moderate ($R = -0.56$), as was the case with N ($R = 0.52$) and Cu content ($R = -0.52$) ($p < 0.01$).

The variables showing a significant correlation between sunflower oil content and the variables examined were all negatively correlated, with the strongest correlation being between $CaCO_3$ ($R = -0.61$) and Cu ($R = -0.52$).

The thousand seed weight showed a moderate positive correlation with soil N ($R = 0.51$), Zn ($R = -0.40$) and Mn ($R = -0.44$) content, and a moderate negative correlation with Na content ($R = 0.38$) ($p < 0.01$).

When examining the quality parameters of sowing, missing sowing was more influenced by individual soil variables than double sowing. Accordingly, a moderately strong positive correlation was found between missing sowing and soil $CaCO_3$ ($R = 0.55$) and humus content ($R = 0.48$). In the case of Mn and missing sowing, I measured an opposite but similarly strong correlation ($R = -0.43$) ($p < 0.01$).

As annual total precipitation increased, yield also increased, showing a moderately strong positive correlation ($R = 0.47$). Similarly, I measured a moderately strong correlation with

precipitation in relation to thousand seed weight ($R = 0.43$) and sunflower seed oil content ($R = 0.41$) ($p < 0.01$).

In the case of total annual precipitation, the same significantly moderate positive correlation was observed for all crop variables ($R = 0.40-0.47$). In the case of the variable number of days with precipitation above 5 mm, a significantly moderate positive correlation was observed for yield ($R = 0.50$), moisture content ($R = 0.41$), and oil content ($R = 0.49$). Based on these results, it can be concluded that not only the amount of precipitation but also its distribution had a similar effect on crop variables. The annual average temperature and yield ($R = -0.48$) as well as sunflower oil content ($R = -0.57$) showed a significantly negative moderate correlation. There was a significant negative correlation between the number of hot days and the crop variables examined in all cases, with the strongest correlation being with yield ($R = -0.48$), but the oil content ($R = -0.48$), moisture content ($R = -0.41$), but a weak correlation in the case of thousand seed weight ($R = -0.39$) ($p < 0.01$).

3.6. Impact of the field characteristics influenced by the soil and environmental variables

The principal component analysis (PCA) diagram showed a close correlation between soil variables such as soil plasticity (K_{ARANY}), Na and Mg content, humus content, lime ($CaCO_3$) and salt content, soil N and S content, and soil K and P content. Within the environmental variables, I found a close relationship between annual total precipitation and the number of days with precipitation above 5 mm, as well as between annual average temperature and the number of hot days.

The PCA diagram also described the weather variability between years, comparing the differences between productivity zones within a field and between fields, the difference between productivity zones within the field is smaller than the difference between productivity zones of similar quality in different fields, except for field 2021A and, to a lesser extent, field 2021B.

3.7. The impact of management variables on the profitability of sunflower production

Based on the results of the Tukey post hoc test, the field variable had a significantly detectable effect ($p < 0.001$) on revenue development. Obviously, the sales price of sunflowers each year also played a key role in revenue development. The extreme drought in 2022 resulted in low yields, but due to the higher sales price, field 2022A showed the same level of significance in terms of revenue per hectare as field 2021A, while field 2022B showed the same level of significance as field 2023A.

The effect of the productivity zone on revenue was also significantly different ($p < 0.001$). The lowest average revenue was measured in the low productivity zone (496 038 HUF ha⁻¹), while revenue increased significantly with increasing quality of zone productivity. During the analysis, the variables of the table ($\eta_p^2=0.75$) and the productivity zone ($\eta_p^2=0.8$) also had a strong explanatory effect on revenue development.

The correlation between revenue and plant density was significant but based on the results of the Tukey post hoc test, no difference could be demonstrated, and the effect was also very weak ($\eta_p^2=0.11$).

In terms of profit, the field explanatory variable showed a significant effect, with major differences in profit levels between fields within and between vintages, which also had a strong explanatory effect ($\eta_p^2=0.75$).

The explanatory effect of productivity zones on profit was significant ($p < 0.001$). The level of profit increased steadily in line with the improvement in the quality of the productivity zones. The difference in profit between low and high productivity zones (193 759 HUF ha⁻¹) was significant, with a difference of 114 296 HUF ha⁻¹ between low and average productivity zones and 79 463 HUF ha⁻¹ between average and high productivity zones.

The effect of plant density used in the sowing experiment on profit was significant, but the profit levels for each plant density group were statistically identical. The explanatory effect of the plant density on profit development showed the weakest correlation even when examining the complete statistical analysis ($\eta_p^2 < 0.01$).

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Assessment of factors affecting sowing quality

The double sowing rate also showed significant differences between different years and fields. Based on the Tukey test, the results between fields were significantly similar in 2021, but significantly different in 2022 and 2023. The data examined by productivity zone show that the double sowing rate increases significantly with the improvement of zone quality. The same significant increase can be seen in relation to the increase in plant density. This finding suggests that as productivity increases, soil variables may contribute to more frequent double sowing, but Pearson's correlation showed only a very weak correlation when examining relationships with soil variables. I measured a closer relationship only in relation to soil plasticity (K_{ARANY}), salt content, and Mn content, but the correlation was weak here as well.

At the same time, it can be observed that with the improvement in the quality of the productivity zones, the actual plant density used has increased, since the names of the plant density groups used in each zone are the same (low, average, high), yet the number of sunflower seeds sown in each group increases with the improvement in the quality of the productivity zones. This suggests that during sowing, at a constant forward speed, the sowing disc rotating in the sowing unit housing rotates at a higher speed when the seed rate is higher. As the speed increases, the operation of the stripping unit may become less accurate, potentially increasing the chance of sowing two (double) sunflower seeds at the same time. In this case, I recommend considering reducing the forward speed by increasing the number of seeds, which may improve the uniformity of the seed spacing while reducing the double sowing rate. I recommend further investigation to evaluate the causes of double sowing in terms of sowing technology.

The examination of the proportion of missing sowing showed even greater significant differences between vintages and between fields within vintages. I measured an outstanding 17.2% for field 2022A. When examining the effect of the productivity zone, the average quality zone resulted in the lowest value, while I measured a higher rate of missing sowing in both the low- and high-quality zones. When examining the effect of the plant density, a significantly increasing rate was observed with an increase in the plant density. Based on Pearson's correlation analysis, I demonstrated that $CaCO_3$ and humus content showed a significantly moderate correlation with the rate of missing sowing. Among the soil test results, it can be observed that the humus and $CaCO_3$ content measured in the average productivity zone of field 2022A is the highest among the zones examined. These results suggest that higher levels of humus and $CaCO_3$ content reduce the extent of missing sowing. I also observed that the winter-

spring weather conditions in 2022 were the least optimal for sunflower germination. Based on the results obtained, I recommend considering the humus and CaCO_3 content and winter recharge precipitation when determining the number of seeds sown per hectare.

According to my research, the sowing uniformity varies between fields within and between vintages (14.61%–18.72%), as well as depending on the quality of the productivity zones (14.46%–18.17%) and the plant density used (15.46%–17.63%). Since the Pearson correlation was significant for each variable when analysing the effect of soil variables on the sowing uniformity but showed only a very weak correlation ($R = -0.09-0.09$). The effect of the management variables was also very weak ($\eta_p^2=0.01-0.02$).

The direct effect of spatial variability in soil variables on sowing quality, seed germination, and emergence dynamics was also observed by Bakanogullari et al. (2018).

In addition to soil variables, sowing technology adapted to crop production systems can play a key role in achieving the most accurate sowing uniformity, which depends on the technical solutions of the seed drill used and its precise adjustment (Aikins et al., 2020). The no-till production system I use requires higher-level sowing technology and technical solutions (Morrison et al., 1988) (Lekavičienė et al., 2019). In this cultivation system, seed drills must simultaneously manage crop residues on the soil surface, prepare a seedbed suitable for sunflowers, ensure optimal seed-soil contact, and ensure the most uniform plant spacing possible (Godwin, 1990). Badua et al. (2021) found that high-speed sowing causes significant seed bounce within the seed drill and in the seed furrows, which significantly affects the uniformity of plant spacing. I recommend further studies to evaluate the effect of the sowing technology and seed drill settings used on sowing uniformity.

4.2. Assessment of factors affecting sunflower yield and quality

Changes in weather conditions and site characteristics (field) had a significant impact on yield. The explanatory effect of the field was particularly strong ($\eta_p^2=0.88$).

The quality of the productivity zones also greatly influenced yield ($\eta_p^2=0,82$), with high-productivity zones achieving an average yield 41.8% higher than low-productivity zones. In contrast, although changes in plant density had a significant effect on yield, no quantitative difference was found between plant densities. Allam et al. (2003) came to the opposite conclusion. Soil humus content ($R = -0.42$) had a significant moderate negative effect on yield. It should be noted that the extremely dry weather experienced during the 2022 growing season had a significant moderate effect (annual total precipitation: $R = 0.47$; annual average temperature: $R = -0.50$) on the low yield results measured in the same year. However, the four

highest humus content values measured in the productivity zones of the three vintages included in the experiment all came from the zones of the 2022 fields, so most of the low yield results came from the zones with the highest humus content. Orehovacki (2009) also investigated the relationship between soil humus content and yield. In his studies, higher humus content was associated with lower yields in some cases, and he concluded that the effect of the vintage on yield is stronger than the effect of the humus content of the crop production area. Demydenko et al. (2018) came to a similar conclusion, finding that crop rotation, the effect of different seasons, the use of fertilizers, and different soil cultivation systems strongly influenced soil humus content and showed a strong correlation with achievable crop yields. Antal (1978) concluded in his research that water shortage is a limiting factor in achieving high yields, and Visic (1991) also found that the average temperature from the beginning of flowering to full maturity shows a negative correlation with yield. The results show that, among the management variables, changes in plant density (in the case of the plant densities used in the experiment) had a lesser effect on yield, while the impact of the field and the quality of the production zones, as well as environmental variables, had a decisive influence on yield. Szabó et al. (2005) came to a similar conclusion, describing the hybrid used, environmental conditions, and plant density per hectare as complex influencing factors.

The moisture content of the harvested sunflowers varied, with the highest average value (6.99%) measured in field 2023A. In my analysis, I showed that the explanatory effect of the field variable was particularly strong ($\eta_p^2=0.9$).

The moisture content was significantly positively influenced by the soil N content and negatively by the soil plasticity (K_{ARANY}) and Cu content, which is similar to the results measured by Tahoun et al. (2022). Among the environmental variables, annual total precipitation and the number of hot days also resulted in a significant moderate negative correlation with moisture content. It is also noticeable that moisture content decreased with increasing productivity zone quality. The moisture content remained significantly at the same level with changes in the plant density. The results obtained suggest that, in relation to moisture content, the combined effect of individual soil variables and environmental variables influences the ripening of sunflower seeds and the water release of sunflower heads.

The oil content showed a significantly strong negative correlation with $CaCO_3$ content and a moderate negative correlation with soil pH, humus content, and Mn content. There was also a significant moderate positive correlation with annual total precipitation and the number of days with precipitation above 5 mm, and a negative correlation with annual average temperature and the number of hot days. Related results were obtained by Wang et al. (1997a) (1997b), who

found in their research that the daily average temperature during the flowering and seed development period has a significant effect on oil content. Among the management variables, increasing the plant density significantly increased the oil content of the harvested sunflower seeds. In the case of oil content, it can also be concluded that the combined effect of individual soil and environmental variables and an increase in the plant density influences the oil content of sunflower seeds.

When examining the correlation between thousand seed weight and environmental variables, I measured a significantly moderate positive correlation with annual total precipitation and a weak negative correlation with the number of hot days. When examining the effects of management variables, the effect of the field variable is strong ($\eta_p^2=0.95$), while the effect of the productivity zone and the plant density has a moderate influence on the development of thousand-kernel weight.

These results suggest that the amount of precipitation during the winter recharge and growing seasons, as well as plant density, fundamentally influence the weight of the seeds developing in the sunflower head.

4.3. Assessment of correlations between soil variables

I observed a significant moderate positive correlation between soil pH and CaCO_3 , indicating that higher CaCO_3 concentrations may lead to an increase in soil pH due to the buffering capacity of carbonate minerals. This relationship affects the availability of microelements, as increased pH can reduce the solubility of elements such as Fe, Mn, Cu, and Zn, thereby reducing their availability to plants. The significantly strong positive correlation between soil texture, salt content and Mg content suggests that finer-textured, higher clay content soils can retain more salt and magnesium. This finding is supported by studies showing that soils with higher clay and organic matter content have significantly higher concentrations of micronutrients, including magnesium (Choudhury et al., 2021).

In contrast, the significantly moderate negative correlation between soil plasticity (K_{ARANY}) and Mn content may indicate that soils with a coarser texture and lower clay content have a reduced Mn retention capacity (Clark et al., 2020). Mn content showed a significantly strong or moderate negative correlation with several soil variables, such as pH, soil plasticity, salt, humus, CaCO_3 , Zn and Na content. Saniga et al. (2005) found a similar relationship between soil plasticity and nutrient content in relation to plant development. Among the soil variables grouped by the PCA diagram, soil plasticity showed a significant relationship between Na, Mg, humus, CaCO_3 , and salt, N, S, K_2O , and P_2O_5 content. When examining the relationship

between soil pH and yield, I measured a significantly weak negative correlation. This is supported by Láng's (1967) research, according to which sunflowers are indifferent to soil pH. Gyulai et al. (1995) showed that sunflowers produced the highest yield on chernozem loam soil with a pH between 6.5 and 7.5.

The correlations revealed between soil variables indicate that, in most cases, the quantitative and qualitative parameters of the yield depend not only on the effects of management and environmental variables, but also largely on the nature of the physiological and biological relationships between soil variables.

4.4. The role of altitude above sea level

The negative correlation observed between altitude and soil salinity, as well as K₂O, Mg, and Zn content, is consistent with the results of numerous studies examining the effect of altitude on soil properties. Egyptian researchers have demonstrated a significantly strong negative relationship between surface elevation and soil salinity, with lower electrical conductivity (EC) values at higher elevations. This trend was quantified using regression models, which yielded values as high as $R^2 = 0.94$, indicating that altitude is a significant predictor of soil salinity (Bakr et al., 2019). Similarly, a study examining the effect of altitude on soil texture found that soil EC values decreased with increasing altitude, suggesting that salt accumulation is lower at higher altitudes. This finding was attributed to the fact that at higher altitudes, the accumulation of base-forming cations (e.g., Ca²⁺, Mg²⁺, K⁺) decreased and soil CaCO₃ levels were also lower (Kamal et al., 2023). These results are consistent with the negative correlations between altitude and K₂O, Mg, and Zn content observed in the present study.

After examining the effect of altitude on crop variables, I concluded that there is no significant difference in the altitude and location of the fields included in the experiment that would affect yield, moisture content, oil content, or thousand seed weight.

4.5. Assessment of factors determining the profitability of sunflower production

When examining the effects of management variables, it is important to note that although the field variable has a significant effect on both revenue and profit, external market processes also played a key role in the development of revenue and profit levels. The annually varying input material and sunflower sales prices had a decisive influence on the revenue and profit levels of individual fields in each vintage. Sales prices were particularly volatile. The differences in crop variables between fields within a given year highlight the importance of growing conditions in terms of economical sunflower production.

The analysis based on the quality of the productivity zones shows a more nuanced picture, as zone groups of the same quality were compared across all three years. The analysis showed that although sunflower is a crop that compensates well for differences in growing conditions, in zones with different productivity levels defined on the basis of long-term productivity zone classification, I measured a significantly increasing correlation in both yield and oil content increased significantly in line with the improvement in productivity zone quality. The higher yield and oil content per hectare resulted in higher profits at the same cost level.

Changing the plant density resulted in significantly identical levels of revenue and profit. If we examine the effect of the plant density on each crop variable separately, we can see that it had a significantly identical effect on yield and moisture content. There is a significant difference in oil content and thousand seed weight, but thousand seed weight does not affect either revenue or profit, and the bonus for oil content alone could not significantly influence the balancing effect of the other factors on profitability.

5. NEW SCIENTIFIC RESULTS

1. I found that in the areas included in the open field experiment between 2017 and 2020, based on images collected by satellite remote sensing during the vegetation periods, the average yield of harvested sunflowers (4044 kg ha^{-1}) in high productivity zones was significantly higher than in average productivity (3625 kg ha^{-1}) and low productivity (2852 kg ha^{-1}) zones.
2. My investigations have shown that in the open field experiment, there is a significant positive correlation between the annual precipitation (mm) measured by my own meteorological station during the years of the experiment and the average yields (kg ha^{-1}) for each year (2021: $511.2 \text{ mm} / 3724.5 \text{ kg ha}^{-1}$; 2022: $402.6 \text{ mm} / 2824.5 \text{ kg ha}^{-1}$; 2023: $819.6 \text{ mm} / 3972.5 \text{ kg ha}^{-1}$).
3. I found that in the open field experiment, with an increase in annual precipitation (mm) in the years studied, the average thousand kernel weight (g) of sunflowers harvested per year increased significantly (2021: $511.2 \text{ mm} / 55.19 \text{ g}$; 2022: $402.6 \text{ mm} / 54.28 \text{ g}$; 2023: $819.6 \text{ mm} / 68.79 \text{ g}$).
4. I have determined that, based on images collected from experimental fields between 2017 and 2020 during the growing seasons using satellite remote sensing, the average revenue (R) and profit (P) per hectare from sunflower production in high-productivity zone (R: $701,732 \text{ HUF ha}^{-1}$; P: $350,926 \text{ HUF ha}^{-1}$) was significantly higher than the average (R: $616,301 \text{ HUF ha}^{-1}$; P: $271,463 \text{ HUF ha}^{-1}$) and in low-productivity zone (R: $496,038 \text{ HUF}$; P: $157,167 \text{ HUF}$).
5. The results of my research proved that, in the variable rate sunflower sowing experiment using precision sowing technology, there was no significant difference in the profit per hectare from sunflower production due to the plant density (low: $259,221 \text{ HUF ha}^{-1}$; average: $260,055 \text{ HUF ha}^{-1}$; high: $260,280 \text{ HUF ha}^{-1}$).

6. PRACTICAL USE OF THE RESULTS

1. According to the results of sowing technique tests, increasing the number of seeds per unit area resulted in a decrease in the sowing uniformity. The values of the plant density groups used in the productivity zones vary in each zone because I used an increasing number of seeds as the productivity increased. At a constant forward speed, the increasing number of seeds causes the seed disc in the seeding unit of the seed drill to rotate at an increasingly higher speed. As the speed increases, the operation of the seed drill unit may become less accurate, potentially increasing the chance of sowing two seeds at once. I recommend reducing the forward speed when increasing the number of seeds to prevent double and missing sowing and an increase in the relative deviation of plant spacing ratio. Excessive forward speed can also cause increased seed bounce in the seed drill and seed tube, which can lead to inaccurate seed placement and further deterioration in seed spacing uniformity. When sowing sunflowers, it is essential to set the seed drill correctly and select the correct forward speed.
2. Weather conditions have a significant impact on the success of sunflower production, with winter precipitation being particularly important. When planning the sowing, it is advisable to take winter precipitation into account and carefully select the number of seeds sown per hectare.
3. My research has shown that increasing the plant density has a positive effect on the oil content of the harvested sunflower. In practice, it is worth considering increasing the plant density in high productivity areas to obtain the bonus premium that comes with higher oil content.
4. According to the results of studies examining soil properties, nitrogen, and potassium, as well as phosphorus and potassium, are interrelated in the soil. Based on this, it is worth considering the nutrient supply of sunflowers, as they make excellent use of the nutrient reserves of different soil types, since the sunflower roots enable them to efficiently absorb macroelements from deeper layers of the soil. Sunflowers are among the plants that are less sensitive to soil pH, but in soils with higher CaCO₃ content (pH 6.5<), attention must be paid to the replenishment of microelements.

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List of publications related to the dissertation

Hungarian scientific articles in Hungarian journals (1)

1. Monoki, S. I.: A napraforgó (*Helianthus annuus* L.) tőszámreakciójának vizsgálata heterogén termőképességű termőterületeken.
Növénytermelés. 72 (2), 87-95, 2023. ISSN: 0546-8191.

Foreign language scientific articles in Hungarian journals (2)

2. Monoki, S. I., Csomai, G., Zalai, M., Nagy, J.: Economics of site specific crop density in precision sunflower (*Helianthus annuus* L.) production.
Acta agrar. Debr. 2023 (1), 91-96, 2023. ISSN: 1587-1282.
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4. Monoki, S. I., Nagy, J.: Az évjárat, a termőhely és a tőszám változásának hatása a napraforgó (*Helianthus annuus* L.) termesztésének eredményességére.
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