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The effect of soil tillage and nutrient supply on maize yield based on multi-year experimental results

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Abstract: To optimize maize (Zea mays) yield, soil tillage and nutrient supply play a key role. The application of appropriate soil tillage techniques and the precise application of nutrients can contribute to increasing yield, maintaining plant health, and developing sustainable agricultural practices. The aim of the study was to analyse the long-term yield performance of maize hybrids under different nutrient supply levels and basic tillage methods. According to the repeated measurement model, soil tillage, fertilization, and crop year had a significant ($p<0.001$) effect on maize yield. The integrated approach allows for the optimization of yield and the development of sustainable agricultural practices. Reduced soil tillage methods reduce soil erosion and improve soil biological activity.

Keywords: maize, yield, tillage, strip-tillage, ripping, winter ploughing, fertilization, crop year effect

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1. Introduction

Precision agriculture is a farming concept that optimizes agricultural production by employing the most advanced technologies while reducing environmental impact and increasing economic efficiency [1]. Over the past decades, advancements in digital technologies, satellite positioning, remote sensing, and big data analytics have revolutionized agricultural practices [2].

The essence of precision farming lies in site-specific interventions, where farmers adjust their agricultural practices according to field variability [3]. This includes precise mapping of soil properties, crop conditions, pest presence, and other influencing factors, followed by targeted interventions based on this information [4].

The application of precision agriculture offers numerous benefits. It reduces the amount of inputs used (fertilizers, pesticides, water) while maintaining or even increasing crop yields [5]. Furthermore, it mitigates environmental impacts, contributes to sustainable farming, and improves economic efficiency [6].

In Hungary, the transition towards precision farming practices began in the late 1990s and has been continuously expanding ever since [7]. Domestic research institutes, universities, and enterprises actively participate in developing and adapting precision technologies [8]. International experience shows that implementing precision farming requires significant investment, but it proves profitable in the long run [9].

The technological foundation of precision agriculture comprises global satellite positioning systems (GPS, GLONASS, Galileo), geographic information systems (GIS), remote sensing, sensors, robotics, and artificial intelligence [10]. These tools enable farmers to accurately assess field variability and tailor their agricultural practices accordingly [11]. In precision crop production, farmers apply site-specific seeding, fertilization, plant protection, and irrigation techniques [12].

For optimizing maize (Zea mays) yield, soil cultivation and nutrient management play a crucial role. Based on research by Zagyi et al. [13; 14], selecting the optimal amount and timing of nutrient application is a key agrotechnical factor in supplying nutrients to different maize hybrid genotypes and increasing yield. Implementing appropriate soil cultivation techniques and precision nutrient application can enhance yield, maintain plant health, and support sustainable agricultural practices.

Gombos and Nagy [15] emphasize that weather conditions significantly impact crop yield. Drought years have drastically reduced maize yield, regardless of soil cultivation and nutrient management strategies. In contrast, favorable weather conditions have resulted in significant yield increases.

Hungarian researchers have achieved significant results in applying precision agriculture. Széles et al. [16; 17] examined the effects of nitrogen doses on maize chlorophyll concentration and yield in dry years, as well as the stomatal conductance (Gs), heat-use efficiency (HUE), and water-use efficiency (WUE) of different maize hybrids. These findings are crucial for planning precision nutrient supply and addressing future environmental changes to ensure successful cultivation. Horváth et al. [18] analyzed the effects of drought years on different maize genotypes, reinforcing the fundamentals of no-till soil management systems.

In the future, precision agriculture is expected to have an even greater significance in achieving sustainable food production [19]. Autonomous machines, drones, artificial intelligence, and big data analysis offer further opportunities for optimizing farming practices [20]. However, the widespread adoption of precision farming also presents challenges, such as the cost of technological investments, the need for digital skills development, and data protection issues [21].

Overall, precision agriculture is an innovative approach that leverages modern technologies to contribute to sustainable and efficient food production [22]. It is anticipated that more farmers will begin implementing these technologies in the coming years, fostering both the environmental and economic sustainability of agriculture [23].

2. Materials and Methods

The study was carried out at the Crop Production Experimental Station of the Agricultural Research Institutes and Educational Farm (AKIT) of the University of Debrecen, located at Látókép (N 47°33' E 21°27'). The soil type of the experimental site is loess-based chernozem, with a lime accumulation layer. The long-term experiment involving complex tillage (crop rotation, tillage, fertilization, irrigation, plant density and genotype) was established in 1989 based on the recommendation of academician Béla Győrffy by Prof. Dr. János Nagy, making it unique both in Hungary and in Europe. The objective of the research was to analyze the long-term yield dynamics of maize hybrids under different nutrient supply levels and basic tillage methods. In the experiment, three main factors were examined: the combination of soil tillage methods and nutrient supply, and also the impact of the crop year between 2015 and 2024. In terms of experimental design, combinations of three basic tillage methods and three fertilizer treatments were compared.

The applied soil tillage methods were as follows: Winter ploughing: A traditional agrotechnical method involving soil turning at 28–32 cm depth. Strip tillage: The soil is ripped only in the immediate vicinity of the rows to a depth of 28 cm, thus minimizing soil disturbance. Ripping: Tillage performed at a depth of 55 cm using a subsoiler over the entire surface.

The applied fertilizer treatments have been the following:

Control: No nutrient supply.

Treatment 80: 80 kg N ha^{-1}, 60 kg P2O5 ha^{-1}, and 90 kg K2O ha^{-1}.

Treatment 160: 160 kg N ha^{-1}, 60 kg P2O5 ha^{-1}, and 90 kg K2O ha^{-1}.

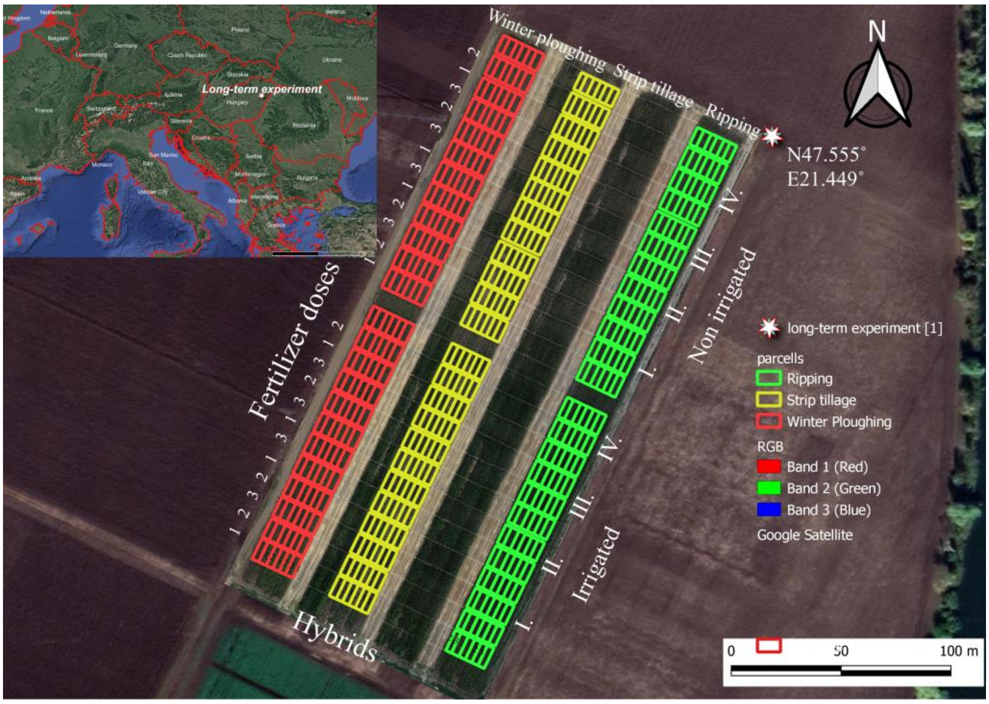

Figure 1. Map of the area with basemap of RGB image and location in Hungary (Tamás et al. 2023)

Note: control, 80kg N ha^{-1} + 60kg P_2O_5 ha^{-1} + 90kg K_2O ha^{-1}, and 160kg N ha^{-1} + 60kg P_2O_5 ha^{-1} + 90kg K_2O ha^{-1} fertilization treatments were randomly distributed across four replications (I–IV), combined with three different tillage approaches

The nutrients were applied in the following forms:

Nitrogen (N): in the form of ammonium nitrate (27%). Phosphorus (P): in superphosphate form (18%). Potassium (K): in potassium chloride form (60%).

In autumn, 30 kg of nitrogen fertilizer was applied as a base fertilizer. The remaining nitrogen was applied as Nitrosol liquid fertilizer, injected into the soil during inter-row tillage.

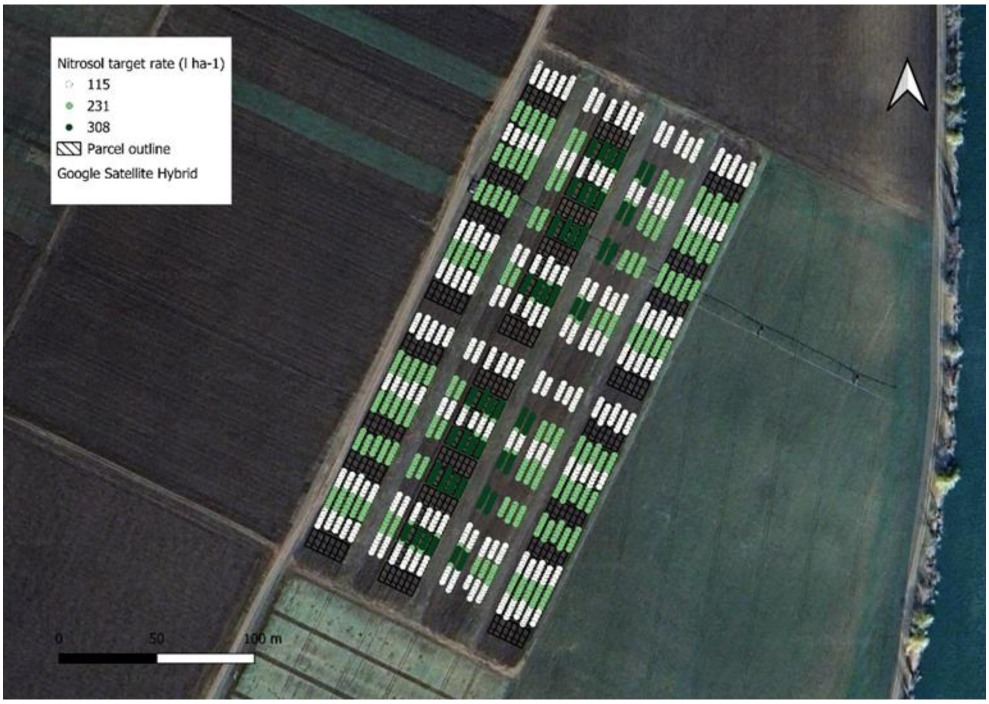

Figure 2. Field map with basemap of google satellite hybrid image

Note: Nitrosol target rates: control, 80kg N ha^{-1} + 60kg P2O5 ha^{-1} + 90kg K2O ha^{-1}, and 160kg N ha^{-1} + 60kg P2O5 ha^{-1} + 90kg K2O ha^{-1} fertilization treatments

In the case of strip-tillage, the base fertilizer was applied using an Orthmann 1tRIPr strip-tillage machine. Sowing was carried out with a John Deere 1755 NT electric-powered sowing machine with two different plant density levels (60,000 and 80,000 plants ha^{-1}).

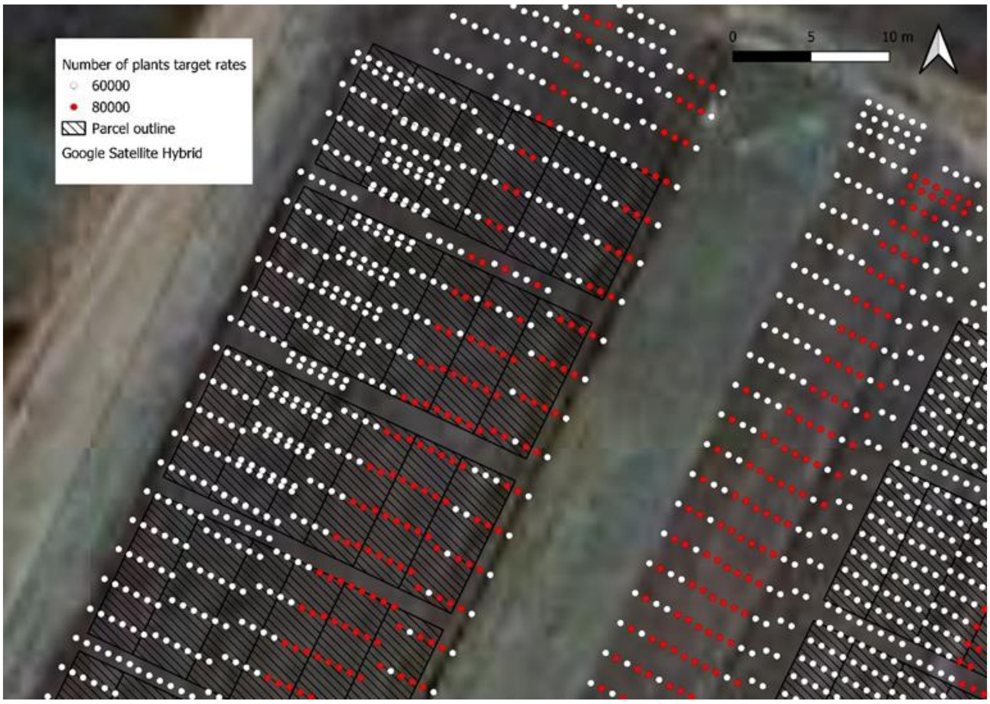

Figure 3. Sowing map with basemap of google satellite hybrid image

Note: number of plants target rates: 60,000 and 80,000 number of plants ha^{-1}

Table 1. Soil characteristics of the trial area (Debrecen-Látókép)

	Winter ploughing	Strip tillage	Deep ripping
pH (KCl 1:2,5)	4.68	4.76	4.67
K_A	45.5	46	46
Humus (%)	2.86	3.09	2.11
$NO_3 + NO_2$ (mg kg^{-1})	5.07	3.53	2.77
P_2O5 (AL) (mg kg^{-1})	133.6	202.2	263.9
K_2O (AL) (mg kg^{-1})	249.4	280.3	308.2
Ca (AL) (mg kg^{-1})	2424	2105	1630
Mg (AL) (mg kg^{-1})	301.8	285.7	239.9

Note: KA: Arany's plasticity index; AL: ammonium lactate-soluble

2.1. Meteorological properties at the trial location (2015-2024)

Table 2. Temperature and precipitation characteristics of the trial location

	Year		Crop season (april - september)	
	temp (C)	prec. (mm)	temp (C)	prec. (mm)
2015	11.9	517	19	299
2016	11.3	818	18.6	453
2017	11.4	641	18.7	354
2018	11.8	552	19.7	318
2019	11.5	578	17.7	364
2020	11.1	708	17.7	482
2021	10.6	365	17.6	182
2022	11.4	490	18.5	268
2023	12.1	700	18.4	336
2024	13.4	478	19.9	312
1981-2010	10.8	560	17.5	346

Note: average temperature and precipitation data; yearly average and growing period average

At the experimental site, meteorological data are collected using several instruments: air temperature is monitored with a P100 platinum resistance sensor, global radiation is recorded by a Kipp & Zonen SP Lite2 pyranometer, and precipitation is measured with a PG200 rain gauge (Hungarian-made), functioning based on the gravimetric method. Compared to the 30-year average, the average growing season temperature was 0.1–2.4°C higher, while the amount of precipitation has shown a decreasing trend in recent years.

2.2. Measurement and calculation methodology

Harvesting was performed using a Sampo 2010 plot harvester, which measures yields by plot. To determine the content parameters, a Perten grain analyzer was used, as the calculation of plot yields requires the measurement of harvest-time moisture content, which is not measured by the combine.

The numerical database, including the geoinformatics database and maps, was created using Quantum GIS [24] geoinformatics software.

The effect of tillage, fertilization, and crop year on yield of maize was examined using a repeated measurement model with the 'agricolae' package in RStudio [25]. For the comparison of data means, an LSD test was performed.

3. Results

The maize grain yield data for the examined period were visualized on a map, with the same yield categories marked in the same colour each year. The effect of fertilization is clearly observable on the time-series map, as the control plots were separated from the fertilized plots in almost every case. In 2015, 25.7% of the plots fell into the 0–6 t ha-1 category, while 45.3% of the data belonged to the 8–10 t ha-1 category. In 2016, 50.7% of the data exceeded the 12 t ha-1 category. In 2017, 27.5% of the data fell into the 0–6 t ha-1 category, while 44.2% of the data fell into the 8–12 t ha-1 category. In the 2018 crop year, 31.5% of the data belonged to the 10–12 t ha-1 category. In 2019, 20.9% of the data were in the 6–8 t ha-1 category, 26.4% of the data were in the 8–10 t ha-1 category, and 30.8% of the data fell into the 10–12 t ha-1 category. In 2020, 23.8% of the data belonged to the 0–6 t ha-1 category, while 21.3% of the data fell into the 12–14 t ha-1 category. The impact of the crop year on yield of maize can be observed, particularly highlighting the drought year of 2021 and the record drought year of 2022. In 2021, 39% of the yield fell into the 0–6 t ha-1 category, 27% of the data belonged to the 6–8 t ha-1 category, and 20.8% of the data were in the 8–10 t ha-1 category. In 2022, 91.9% of the data fell into the 0–6 t ha-1 category. In the 2023 season, 20.6% of the data were in the 10–12 t ha-1 category, 42.8% of the data were in the 12–14 t ha-1 category, and 17.4% of the data were in the 14–20 t ha-1 category. In 2024, 31.9% of the data belonged to the 10–14 t ha-1 category.

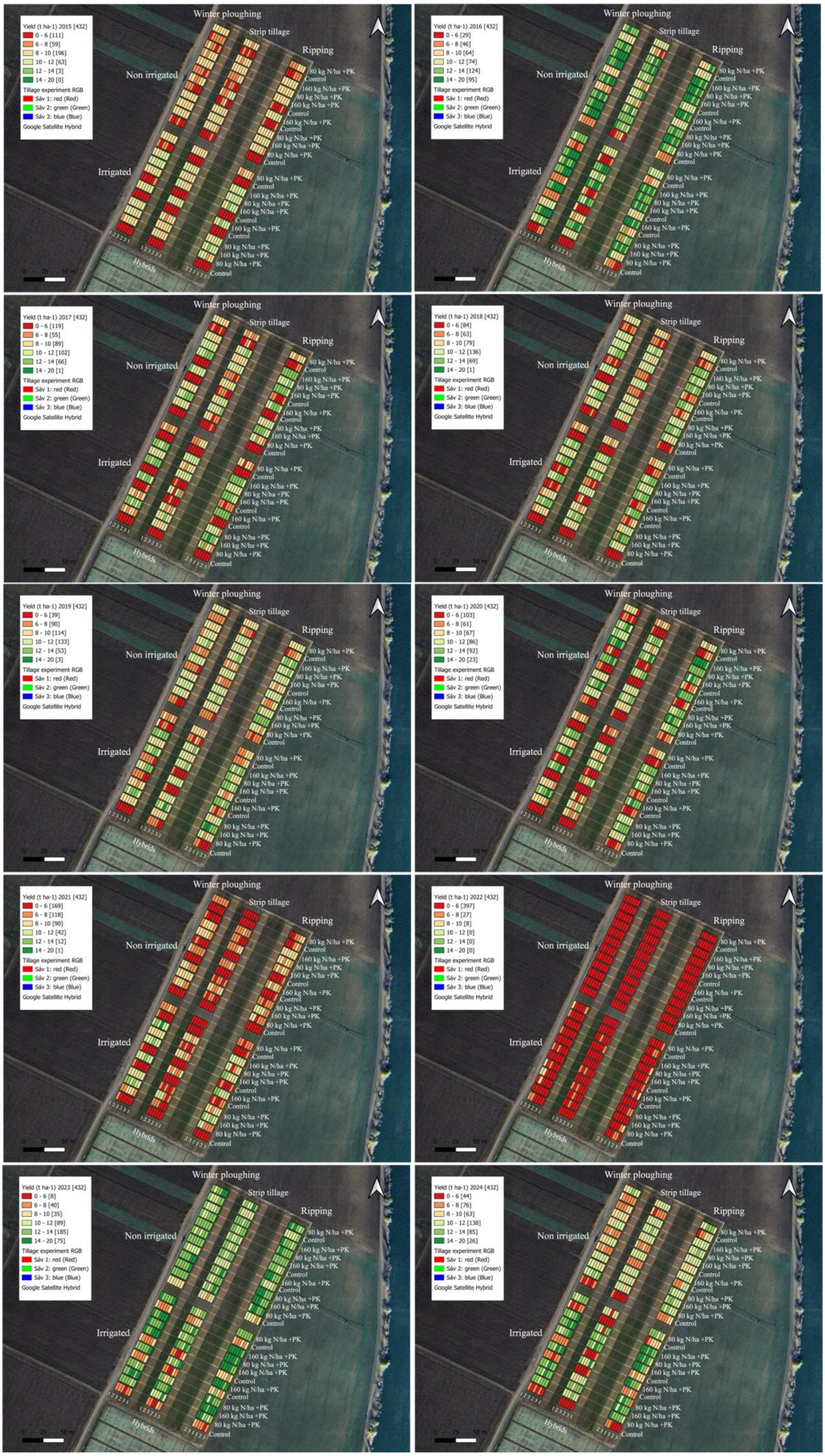

Figure 4. Average yield by plot (t ha^{-1}) (2015–2024)

The repeated measures analysis indicated that maize yield was notably affected by the applied tillage methods, fertilization regimes, and the specific crop year. Soil tillage combined with crop year, fertilization combined with crop year, as well as the three treatments together demonstrated a significant statistical influence on maize yield.

Over the 10 years examined and across all treatment variations, the maize yield of the small plots under ripping was notably higher than that of the other two tillage methods. The average maize yield under ripping over the 10 years and across all treatments was 9.14 t ha-1. The lowest maize yield was measured under strip tillage (8.26 t ha-1)

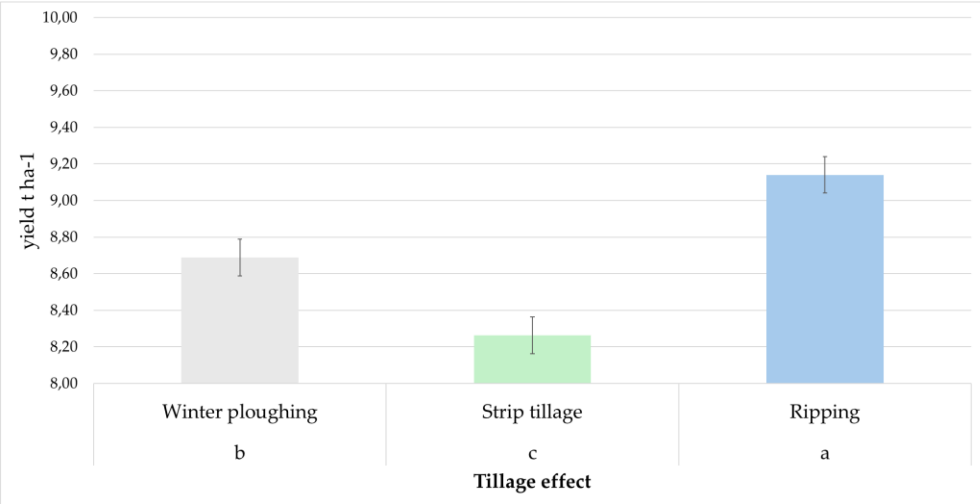

Figure 5. Impact of soil tillage on yield results in the average of the examined years
Note: Different letters indicate significant differences

Increasing fertilizer levels significantly increased maize yield. In comparison with the control plots, the 80 kg N/ha dose increased maize yield by 3.04 t ha-1, while the 160 kg N/ha dose increased maize yield by 3.71 t ha-1.

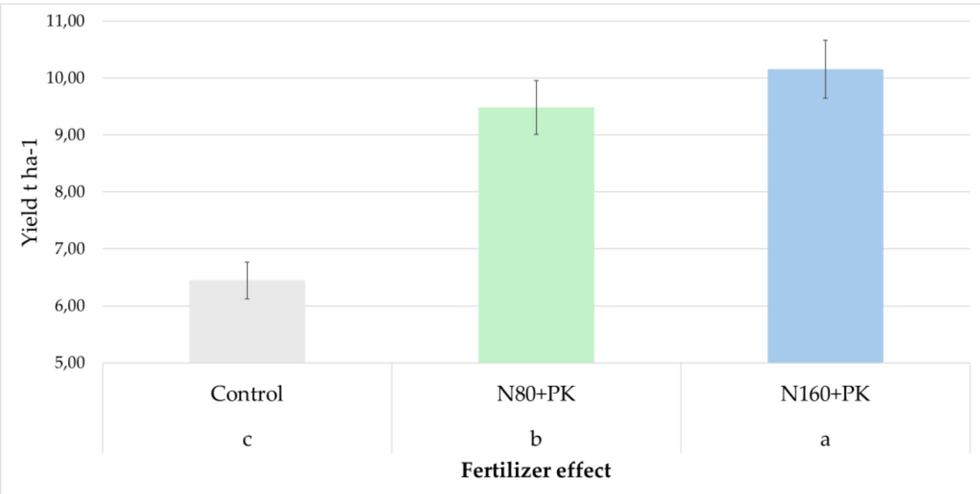

Figure 6. Impact of fertilization on yield results over the examined years
Note: Different letters indicate significant differences

Among the 10 examined years, the 2023 season was the most favourable for maize (12.42 t ha-1). The lowest amount of harvested grain yield (1.18 t ha-1) was measured in

2022. The yield of 2024 did not differ from 2020 or 2019. The other years differed significantly in maize yield compared to 2019, 2022, and 2024.

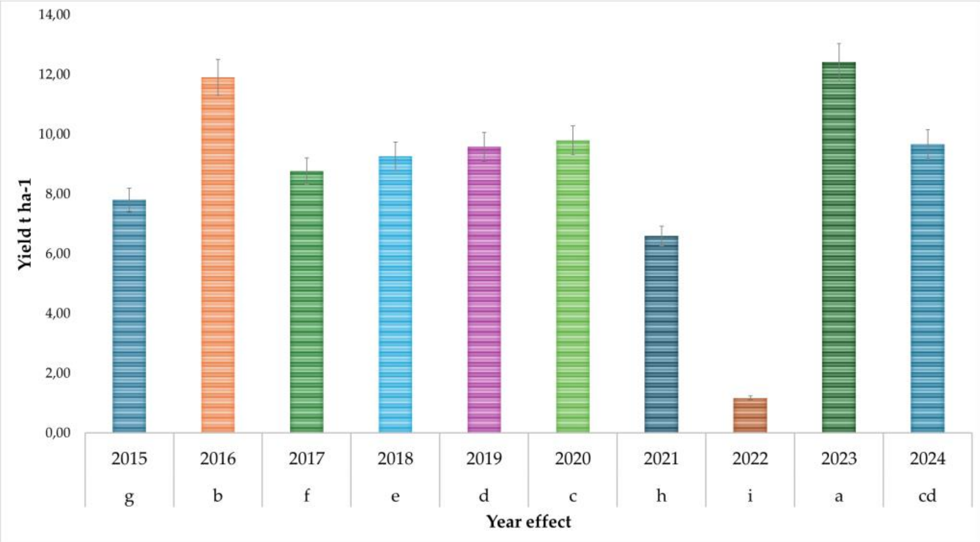

Figure 7. Effect of crop year on yield results

Note: Different letters indicate significant differences

The combined effect of soil tillage and crop year also influenced maize yield. In the first examined year (2015), maize yield did not vary significantly among the three basic tillage methods. In the following year, in comparison with the previous year, the yield increased substantially for all three tillage methods. In the 2016 season, the yields from all three tillage methods differed from each other. In that year, the second largest maize grain yield of the surveyed period (12.47 t ha-1) was measured under ripping, which was only 0.3 t ha-1 lower than the highest yield (12.78 t ha-1) observed during the examined period. Statistically, however, the two treatment combinations did not differ from each other (LSD = 0.31 t ha-1). In 2017, the yield of all three basic tillage methods decreased in contrast with with the last year. In that season, there was no significant difference between the yields of winter ploughing and strip tillage, but under ripping, maize yield was notably higher. In 2018, the yield of winter ploughing (9.02 t ha-1) increased compared to the previous year, the yield of strip tillage (8.82 t ha-1) did not deviate statistically from the previous crop year, and maize yield increased under ripping (9.97 t ha-1) in comparison with the year before. In that year, maize yield under winter ploughing and strip tillage did not differ significantly from each other; however, in that crop year, ripping produced higher yields than the other two methods. In 2019, compared to the previous year, maize yield under winter ploughing did not change significantly (+0.25 t ha-1).

In that year, the yield under strip tillage increased significantly (+0.62 t ha-1) compared to the previous year. Maize grain yield under ripping did not change significantly compared to the previous year. In this crop year, maize yields did not differ significantly under winter ploughing and strip tillage; however, ripping produced outstanding yields again in this year. In the 2020 crop year, maize yield under winter ploughing increased significantly (+0.42 t ha-1) relative to the prior year, while the yield under strip tillage decreased significantly (−0.37 t ha-1) as opposed to the year before. In this crop year, maize yield under ripping increased significantly (+0.59 t ha-1). In this season, the highest maize yield (10.03 t ha-1) was produced under ripping, while the lowest (9.07 t ha-1) was produced under strip tillage. In the 2021 crop year, due to drought, the yields of all three tillage methods decreased significantly in contrast to the preceding year, and the yields of the three tillage methods differed significantly from each other. In this crop year, the lowest yield was observed under strip tillage (5.93 t ha-1), while the highest was measured under ripping (7.10 t ha-1). The yield under winter ploughing was 6.74 t ha-1. In the record drought year of 2022, the maize yield from all three tillage methods decreased significantly compared to the previous year, and the yield deviations of the three tillage methods were confirmed. In this crop year, the lowest statistically confirmed maize yield of the examined period (0.63 t ha-1) was measured under strip tillage. In this crop year, the largest yield was measured under winter ploughing (1.94 t ha-1), while maize yield under ripping was 0.96 t ha-1. In the favorable 2023 crop year, maize yield from all three tillage methods increased significantly compared to the previous year. The yield under winter ploughing increased to 10.48 t ha-1, the yield under strip tillage increased to 11.42 t ha-1, and the yield under ripping increased to 11.82 t ha-1 compared to the year before. In this crop year, the three tillage methods differed significantly from each other. The highest maize yield of the 10-year examined period (12.78 t ha-1) was observed under ripping in this crop year. In 2024, maize yield under all three tillage methods decreased compared to the previous year. In this crop year, maize yield under winter ploughing (9.16 t ha-1) and strip tillage (9.38 t ha-1) did not differ; however, in this crop year, the largest yield (10.46 t ha-1) was produced under ripping.

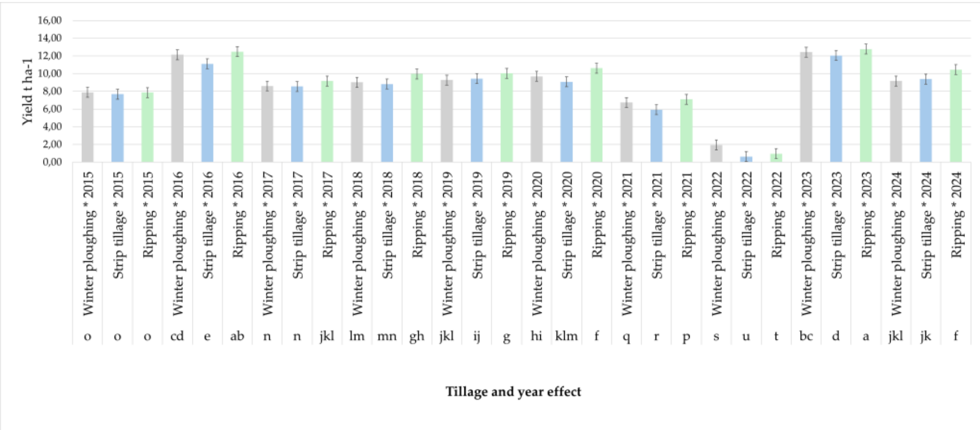

Figure 8. Interaction of tillage methods and crop year on the dynamics of yield
Note: Different letters indicate significant differences

In 2015, compared to the control (5.73 t ha-1), fertilization increased maize yield; however, there was no confirmed difference among the lower (8.96 t ha-1) and higher (8.72 t ha-1) fertilizer levels. In 2016, in comarison with the prior crop year, the yield increased at all three nutrient levels. In this crop year, all three fertilizer levels differed significantly from each other, and the highest yield of the 10-year examined period (13.81 t ha-1) was measured under the 160 kg N/ha + PK treatment. In the 2016 crop year, the yield of control area was 3.21 t ha-1 higher, the yield of 80 kg N/ha + PK plots was 4.01 t ha-1 higher, and the yield of 160 kg N/ha + PK plots was 5.09 t ha-1 larger than the prior year. In 2016, the yield of control plots (5.38 t ha-1) surpassed the yield of 160 kg N/ha + PK plots (8.72 t ha-1) from the prior year. The 2017 crop year was less favourable for maize, as the maize grain yield under all three fertilizer treatments decreased significantly in comparison with the preceding year. In this crop year, increasing the fertilizer level significantly increased maize yield. In 2018, compared to the previous year, the yield of the control plots (+0.65 t ha-1) and the 80 kg N/ha + PK treatment (+0.56 t ha-1) increased significantly; however, the yield measured in the 160 kg N/ha + PK treatment did not increase significantly. In 2018, increasing fertilizer levels significantly increased maize grain yield, meaning that the yield differences among the three fertilizer levels were statistically significant. In 2019, the yield of the control plots increased significantly (+1.34 t ha-1), the yield of the 80 kg

N/ha + PK treatment remained practically unchanged, while the yield of the 160 kg N/ha + PK treatment decreased significantly (−0.52 t ha-1) compared to the previous year. In 2020, the yield of the control plots decreased significantly (−1.45 t ha-1), the yield under the 80 kg N/ha + PK treatment showed no statistically significant change, the 160 kg N/ha + PK treatment resulted in a notable increase of 1.83 t ha^{-1} relative to the preceding year. However, in the 2021 growing season—characterized by unfavourable conditions for maize production—yields declined across all treatments. Specifically, the control plots produced 1.21 t ha^{-1} less, the 80 kg N/ha + PK treatment decreased by 3.47 t ha^{-1}, and the 160 kg N/ha + PK treatment dropped by 4.93 t ha^{-1} compared to the prior year. In the record drought year of 2022, maize yield decreased further compared to the previous year. Yield measured in the control area decreased by 3 t ha-1, the yield of the 80 kg N/ha plots decreased by 5.9 t ha-1, and the yield of the 160 kg N/ha + PK plots decreased by 7.34 t ha^{-1}. In this crop year, increasing fertilizer levels significantly reduced maize yield. The lowest yield of the 10-year examined period (0.68 t ha-1) was measured under the 160 kg N/ha + PK treatment. The 2023 crop year was favourable for maize; after the record drought, maize was able to utilize a significant part of the nutrients remaining in the soil, which resulted in an increase in the yield of the 80 kg N/ha + PK treatment by 12.02 t ha-1 and the 160 kg N/ha + PK treatment by 12.12 t ha-1 compared to the previous year. In 2023, the yield of the control plots was 11.28 t ha-1. In this year, fertilization significantly increased maize yield. The last year of the study was 2024, where compared to the previous year, yield measured in the control area decreased by 3.83 t ha-1, the yield of the 80 kg N/ha + PK treatment decreased by 2.09 t ha-1, and the yield measured in the 160 kg N/ha + PK treatment decreased by 2.34 t ha-1. In this crop year, the largest yield (11.18 t ha-1) was measured under the 80 kg N/ha + PK treatment, but the higher fertilization dosage resulted in a reduced yield (−0.61 t ha-1) than the 80 kg N/ha + PK treatment.

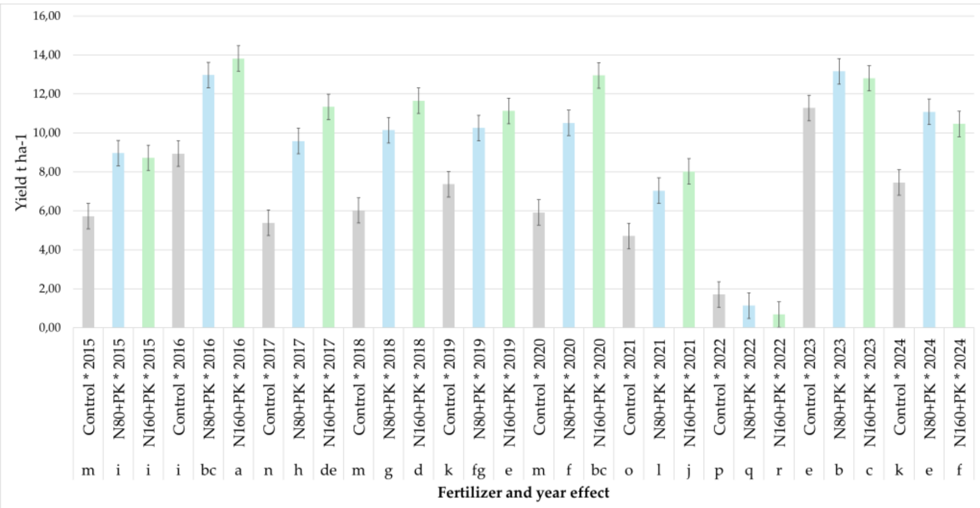

Figure 9. Interaction of fertilization and crop year on yield development

Note: Different letters indicate significant differences

4. Discussion

The results of the examined study highlight that maize yield responds to various agronomic factors, among which tillage methods, fertilization, and the impact of the growing season are particularly significant. The applied loosened primary tillage system resulted in significantly higher yields, which is consistent with findings from other studies with similar objectives, emphasizing the improvement of soil structure and the optimization of water and nutrient management [26; 27].

Fertilization had a notable positive effect on maize growth, especially with increasing nitrogen doses. This observation reinforces previous studies that underscored the importance of adequate nutrient supply in maize production [28; 29].

The growing season also proved to be a decisive factor. Favorable weather conditions, particularly in 2023, significantly contributed to higher yields. In contrast, the extreme drought conditions in 2022 clearly reduced yields, aligning with findings from other studies addressing similar climatic risks [30; 31].

Overall, the study reinforces previous research findings that the combined effects of tillage methods, nutrient supply, and growing season conditions are crucial for optimizing maize yield.

5. Conclusions

Ripping-based soil tillage significantly increased maize yield; therefore, the wider application of these techniques is recommended. Ripping improves soil structure and water retention capacity, which is especially important under changing climatic conditions. Reduced soil tillage methods decrease soil erosion and improve soil biological activity. These methods can be particularly beneficial in areas where soil erosion is a major problem. To avoid excessive nitrogen application, it is important to regularly conduct soil tests and accurately determine nitrogen requirements. An oversupply of nitrogen can not only reduce yield but also increase environmental impact. The integration of different soil tillage and nutrient supply strategies allows for yield enhancement while contributing to the advancement of sustainable agriculture. The integrated approach can help farmers reduce production costs and minimize environmental impacts.

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