Article

Evaluating relationships between multi-depth EM38-derived soil electrical conductivity and maize yield under contrasting tillage systems in irrigated conditions

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Abstract: Soil spatial variability influences crop productivity and is increasingly assessed using electromagnetic induction technologies. This study investigated the spatial and temporal variability of EM38-derived apparent soil electrical conductivity at 0.5 m and 1.0 m depths and its relationship with maize (Zea mays L.) grain yield under contrasting tillage systems in an irrigated production environment in eastern Hungary during the 2024 and 2025 growing seasons. Conductivity measurements were collected during vegetative and cob formation stages using an EM38 sensor operated in vertical dipole mode. Relationships between ECa and maize yield were examined using descriptive statistics, correlation analysis, and analysis of variance. Significant differences in maize yield were observed among tillage systems in both seasons, with strip tillage producing lower yields than winter ploughing and ripping tillage ($p < 0.05$). Strong positive correlations were found between conductivity measurements at 0.5 m and 1.0 m depths ($r = 0.807–0.928$, $p < 0.001$), indicating consistent spatial conductivity patterns across the soil profile. However, ECa was not significantly correlated with final maize grain yield in either season. These results demonstrate that EM38 sensing effectively characterises soil spatial variability but has limited value as a stand-alone predictor of maize yield under uniformly irrigated conditions.

Keywords: EM38; apparent soil electrical conductivity; maize yield; tillage systems; precision agriculture; soil spatial variability; electromagnetic induction; irrigated maize

Academic Editor: Adrienn Széles

Received: 2026.04.15.
Revised: 2026.06.02.
Accepted: 2026.07.28.
Published: 2026.08.19.

1. Introduction

Soil spatial variability is a major factor influencing crop productivity, nutrient dynamics, and water distribution within agricultural systems, particularly under irrigated and conservation-oriented management practices [1]. Understanding this variability is essential for developing precision agriculture strategies capable of improving resource-use efficiency and sustaining crop yields under changing climatic conditions [2]. Among the available approaches for assessing within-field variability, proximal soil sensing technologies have gained considerable attention because they provide rapid, non-destructive, and cost-effective measurements over large areas [3,4].

Electromagnetic induction (EMI) sensors, especially the EM38 instrument, are widely used to estimate apparent soil electrical conductivity (ECa), which is strongly associated with soil texture, salinity, moisture content, organic matter, and cation exchange capacity [5,6].

The EM38 electromagnetic induction sensor has been extensively applied in agricultural research because of its capability to capture subsurface soil variability at different measurement depths under field conditions [7]. In vertical dipole mode, the sensor provides conductivity information from shallow and deeper soil layers, commonly represented as effective depths of approximately 0.5 m and 1.0 m [8]. Variations in conductivity across these depths may reflect differences in root-zone water availability, compaction, salinity distribution, and nutrient retention, all of which influence crop development and final yield [9]. Previous studies have demonstrated strong correlations between ECa patterns and crop performance, especially in cereals such as maize, wheat, and barley grown under variable moisture regimes [10,11,12,13,14]. However, the magnitude and direction of these relationships often differ depending on climate, soil type, irrigation management, and tillage practice, indicating the need for site-specific investigations [14].

Tillage systems significantly influence soil physical and hydraulic properties, thereby affecting crop growth and the spatial distribution of soil electrical conductivity [15]. Conventional intensive tillage practices can alter soil structure, disturb aggregate stability, and increase variability in water movement, whereas reduced or conservation tillage systems generally improve soil moisture retention and organic matter accumulation [16]. In irrigated production systems, these effects become even more pronounced because irrigation modifies soil moisture dynamics and can interact with tillage-induced changes in soil porosity and compaction [17]. Such interactions may influence EM38-derived conductivity measurements and their relationship with crop productivity across seasons [18]. Despite increasing adoption of precision agriculture technologies, few studies have integrated the combined effects of multi-depth (0.5 m versus 1.0 m) temporal variability, irrigation conditions, and tillage systems on EM38-derived soil electrical conductivity-maize yield relationships under Central European agroecological conditions [19].

Temporal monitoring of soil electrical conductivity is increasingly recognised as an important approach for understanding seasonal changes in soil conditions and crop response [18]. Soil moisture fluctuations, root activity, evapotranspiration, and climatic variability can all contribute to changes in ECa values during the growing season [20]. Measurements taken at different crop growth stages may therefore provide complementary information regarding the evolving soil-plant relationship and support the interpretation of soil-crop relationships throughout the growing season [21]. For maize production systems, critical phenological stages such as vegetative growth and cob formation are particularly sensitive to soil water availability and nutrient uptake [22]. Repeated EM38 assessments across these stages may help identify stable and transient conductivity patterns associated with crop performance [23]. Nevertheless, research addressing the temporal consistency of multi-depth conductivity measurements under irrigated management remains relatively limited, especially in long-term experimental fields [24].

Therefore, this study aimed to investigate the spatial and temporal variability of EM38-derived soil electrical conductivity at two effective depths under irrigated conditions and contrasting tillage systems in maize production systems. The research specifically evaluated conductivity measurements obtained during different growth stages over two consecutive growing seasons and examined their relationships with final maize grain yield [25]. Particular emphasis was placed on depth-specific (0.5 m and

1.0 m) and stage-dependent (vegetative and cob-formation) conductivity-yield relationships under contrasting tillage systems in irrigated maize fields. By integrating multi-depth conductivity data with seasonal yield information, the study seeks to improve understanding of the relationship between soil heterogeneity and maize productivity under irrigated conditions [26]. These findings are expected to contribute to precision agriculture research by improving understanding of spatial soil variability and informing site-specific irrigation and soil management decisions [27]. In addition, the study provides valuable information regarding the applicability of EM38 sensing technology for monitoring soil variability in temperate agroecosystems of Eastern Europe [5,28], particularly under managed irrigation and contrasting tillage regimes where soil-water dynamics are highly variable.

2. Materials and Methods

2.1. Study Area

The study was conducted at the Látókép Experimental Station located in Debrecen, Hungary (47^{0}05′55′′ N, 21^{0}04′49′′ E), at an elevation of 118.6 m above sea level. The experimental station is located in the eastern part of Hungary and is characterised by a temperate continental climate with moderately warm summers and relatively low annual precipitation [29]. During the study period, the minimum and maximum mean daily air temperatures were 7.5 ^{0}C and 18.3 ^{0}C, respectively. The average daily precipitation was 1.26 mm, while the mean daily wind speed was 2.6 m s^{-1}. Daily global solar radiation averaged 13.6 MJ m^{-2} throughout the cropping period. The present study was conducted exclusively on the irrigated maize (Zea mays L.) block of the experimental field. Soil and climatic conditions at the experimental station have previously been described in earlier agronomic and soil management studies conducted in the region [30,31,32]. Figure 1 presents the geographical location of the experimental study area.

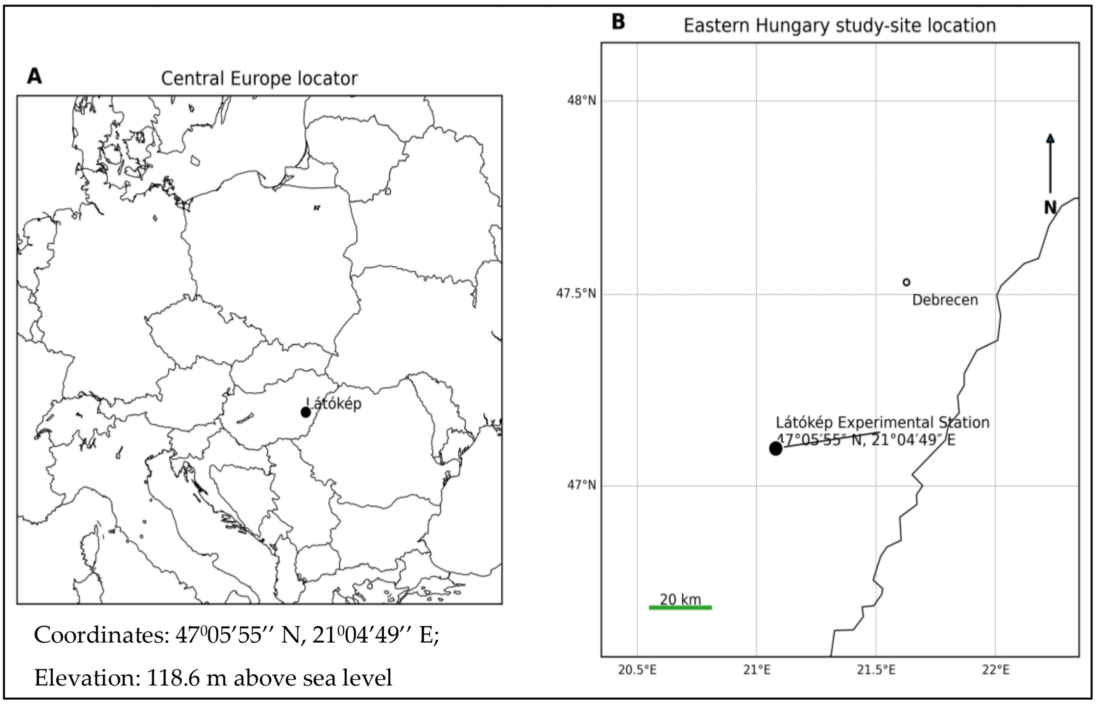

Figure 1. Location of the study site of the Látókép Experimental Station, Debrecen, Hungary. **Source:** Author-generated based on the geographic coordinates of the experimental station.

2.2. Experimental design and Crop management

The field experiment was conducted under irrigated conditions using three tillage systems: winter ploughing, strip tillage, and ripping tillage. The three systems were established as part of a long-term field experiment, within which the present study was conducted during the 2024 and 2025 growing seasons, to evaluate their effects on soil-crop interactions under irrigated maize production.

The experimental area consisted of an irrigated block measuring approximately 140 m x 109.5 m, which was divided into three adjacent sub-blocks of approximately 140 x 36.5 m. Each sub-block represented one tillage treatment: winter ploughing, strip tillage, and ripping tillage (Figure 2). Thus, each tillage treatment was represented by a single field-level sub-block rather than by replicated sub-blocks.

Maize was planted at standard agronomic densities recommended for irrigated maize production in Hungary [33]. Fertilisation, irrigation scheduling, and weed management, were carried out according to local best management guidelines for maize cultivation [34]. The tillage system was intended to be the principal management difference among the experimantal sub-blocks.

Soil and crop measurements were conducted along predefined field survey paths within each tillage sub-block. The survey paths were not georeferenced using Global Positioning System (GPS). The experimental layout and the location of the three tillage sub-blocks are shown in Figure 2.

An operational constraint affected the implementation of the strip-tillage treatment in both growing seasons. In both 2024 and 2025, the contracted strip-tillage implement was not available at the intended time, resulting in a two-week delay in the execution of strip tillage relative to the planned field operation. Consequently, although the experimental comparison was maintained, the strip-tillage treatment included an additional operational difference that should be considered when interpreting the results. The delayed timing of the tillage operation may have influenced soil conditions and crop establishment in addition to the effects associated with the tillage system itself. The tillage operation prior to planting is illustrated in Figure 3.

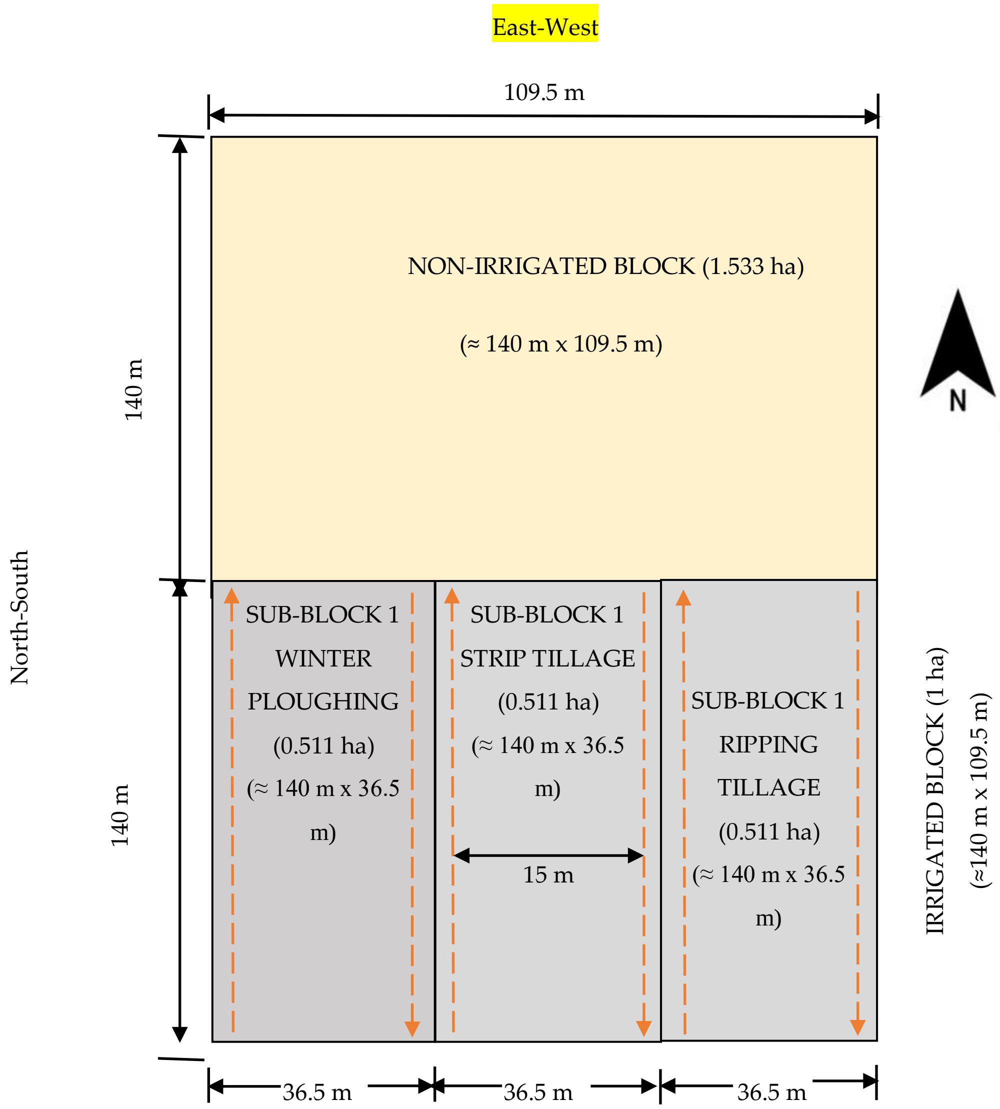

Figure 2. Schematic layout of the experimental field showing the irrigated and non-irrigated blocks, the three tillage treatments, field dimesnions, and survey paths. **Source:** Author-generated based on the established experimental layout and field measurements. The experimental field of study (south, irrigated) measured 140 m (North-South) by 109.5 m (East-West) as one block of the whole experimental field. The irrigated block was divided into three sub-blocks (0.511 ha each) with different tillage treatments: winter ploughing, strip tillage, and ripping tillage. Two length-wise survey paths in each block were established 15 m apart. EM38 measurements started from one end and side along the first path to the other end, turned back to the starting end along the second path, then proceeded to the next sub-block following the same format.

Figure 3. Field preparation using ripping tillage before maize planting. S**ource:** Author (2024–2025).

2.3. EM38 Soil Electrical Conductivity Measurements

Apparent soil electrical conductivity (ECa) measurements were collected using an EM38 electromagnetic induction sensor manufactured by Geonics Limited. The EM38 sensor is widely used for rapid and non-destructive assessment of spatial soil variability because conductivity measurements are strongly influenced by soil texture, moisture content, salinity, clay content, and bulk density [7]. Prior to field measurements, the instrument was calibrated according to the manufacturer's recommendations to ensure measurement accuracy and consistency [35].

Measurements were collected using a metal-free sledge system, with the EM38 sensor towed along predefined transects within the experimental field under vertical dipole orientation (Figure 4). Vertical conductivity (CV) readings were recorded at two effective investigation depths, namely 0.5 m (CV-0.5m) and 1.0 m (CV-1.0m), representing shallow and deeper root-zone soil conditions [36].

Data collection was initiated one month after planting and repeated at monthly intervals throughout both growing seasons (2024 and 2025), including at the cob formation stage. This temporal sampling strategy enabled assessment of both spatial and seasonal variability of soil electrical conductivity under irrigation conditions [37].

Each tillage treatment plot was surveyed systematically to ensure spatial coverage. Conductivity data were recorded at 108 sampling locations per treatment, resulting in 324 observations per growth stage across all treatments. Raw EM38 outputs were organised by depth and sampling period for subsequent statistical analysis (Table 1). Data preprocessing involved sorting and tabulating conductivity readings [38].

Figure 4. EM38 electromagnetic induction sensor mounted on a metal-free sledge during field measurements.

The dataset was structured according to year, tillage treatment, crop growth stage, measurement depth, and crop yield. A representative sample of the raw observations is presented in Table 1. The complete dataset was used for subsequent statistical analyses.

Year	Tillage	Growth stage	CV-1.0m	CV-0.5m	Yield
2024	Winter ploughing	Vegetative	24.739	62.202	7.304
2024	Strip tillage	Vegetative	23.874	61.521	5.315
2024	Ripping tillage	Vegetative	29.483	64.438	10.167
2024	Winter ploughing	Cob formation	27.900	63.198	7.304
2024	Strip tillage	Cob formation	24.202	54.712	5.315
2024	Ripping tillage	Cob formation	28.018	62.873	10.167
2025	Winter ploughing	Vegetative	34.348	85.964	5.140
2025	Strip tillage	Vegetative	30.303	71.083	3.892
2025	Ripping tillage	Vegetative	23.341	66.055	4.217
2025	Winter ploughing	Cob formation	23.822	57.746	5.140
2025	Strip tillage	Cob formation	20.014	54.670	3.892
2025	Ripping tillage	Cob formation	23.249	57.051	4.217

Table 1. Representative sample of the raw soil electrical conductivity dataset, organised by year, tillage treatment, crop growth stage, and measurement depth.

2.4. Yield Data Collection

Maize grain yield data were collected at physiological maturity during harvesting. Yield observations were recorded for the experimental plot and subsequently matched with the EM38 conductivity measurements obtained at different depths and growth stages across different tillage systems. The dataset was spatially and temporally integrated to evaluate relationships between soil electrical conductivity and maize yield variability [39]. The final maize grain yield measured at harvest was linked to EM38-derived conductivity measurements collected during the vegetative and cob formation stages. This approach enabled assessment of the relationship between measured soil conductivity at different crop growth stages and depths and the resultant maize yield at maturity [40]. Because maize grain yield was measured only once at harvest, the same final yield observations were linked separately to conductivity measurements obtained during the vegetative and cob formation stages for growth-stage comparisons [41].

2.5. Statistical Analysis

The compiled dataset containing conductivity and yield information was entered into Microsoft Excel 2016 for preliminary organisation and quality checking. Statistical analyses were subsequently performed using IBM SPSS Statistics 20 software, while graphical visualisations were generated using PAST4.11 (Paleontological Statistical Software Package). Descriptive statistical parameters, including mean, minimum, maximum, and standard deviation, were computed to characterise variability in conductivity and yield measurements [42].

Correlation analyses were conducted to determine the relationships between EM38-derived conductivity values and maize grain yield at different depths and measurement periods [43]. Descriptive statistics were computed separately for tillage systems and growth stages using the 'split file' feature. One-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) test was used to determine whether mean maize yield differed among tillage systems. Independent-samples t-tests were used to compare the final maize yield datasets associated with conductivity measurements obtained during the vegetative and cob formation stages. Pearson correlation analysis was used to examine relationships between conductivity measurements obtained at 0.5 m and 1.0 m depths and the final maize grain yield.

A two-way ANOVA was performed to evaluate the main effects of tillage system and growth stage, as well as their interaction, on final maize grain yield. In the growth-stage analyses, the yield variable represented the final harvested grain yield associated with soil conductivity measurements taken at each respective growth stage. Differences among tillage systems and the relationships between soil conductivity and final maize grain yield were assessed using the selected statistical procedures at a significance level of $p < 0.05$.

3. Results

Results are presented separately for the 2024 and 2025 growing seasons because all analyses were conducted independently for each season.

3.1. Results from the 2024 Growing Season

3.1.1. Effect of Tillage System on Maize Yield

Descriptive statistics of EM38-derived conductivity measurements and maize grain yield under the three tillage systems are presented in Table 2. Maize yield varied among tillage systems, with ripping tillage recording the highest mean yield (11.960 t ha^{-1}), followed by winter ploughing (11.570 t ha^{-1}), while strip tillage produced the lowest mean yield (10.410 t ha^{-1}).

A one-way ANOVA revealed a statistically significant effect of tillage system on maize yield ($F(2, 645) = 13.54$, $p < 0.001$). Tukey's HSD post hoc test indicated that strip tillage produced significantly lower yields than both winter ploughing and ripping tillage ($p < 0.05$), while no significant difference was observed between winter ploughing and ripping tillage. These findings suggest that winter ploughing and ripping tillage provided similarly favourable conditions for maize production during the 2024 growing season. Mean maize yields and Tukey grouping letters are presented in Table 3.

Table 2. Descriptive statistics of EM38-derived conductivity measurements and maize grain yield under different tillage systems during the 2024 growing season.

Tillage system	Variable	N	Minimum	Maximum	Mean	Standard deviation
Winter ploughing	CV-1.0 m	216	21.190	31.771	27.850	2.000
	CV-0.5 m	216	55.467	66.664	61.940	2.060
	Yield	216	4.928	16.109	11.570	2.970
Strip tillage	CV-1.0 m	216	23.874	31.362	28.460	1.270
	CV-0.5 m	216	54.712	66.305	63.060	1.870
	Yield	216	2.923	16.147	10.410	3.480
Ripping tillage	CV-1.0 m	216	23.563	31.215	26.860	1.650
	CV-0.5 m	216	58.140	66.667	61.260	1.710
	Yield	216	4.682	16.528	11.960	3.220

Table 3. Mean maize yield under different tillage systems during the 2024 growing season.

Tillage system	Mean yield (t ha^{-1})	Tukey group
Ripping tillage	11.962	A
Winter ploughing	11.566	A
Strip tillage	10.406	B

Means sharing the same letter are not significantly different at $p < 0.05$.

3.1.2. Relationship between Growth-Stage Conductivity Measurements and Final Maize Yield

Descriptive statistics for conductivity measurements obtained during the vegetative and cob formation stages, along with corresponding final maize yield values, are presented in Table 4.

The mean maize yield associated with conductivity measurements collected during the vegetative stage was identical to that associated with measurements collected during the cob formation stage (11.310 t ha^{-1}). An independent samples t-test revealed no significant difference in maize yield between the two growth stages ($p > 0.05$). Because the same final harvested yield dataset was linked to conductivity measurements obtained at both growth stages, no significant differences in yield were expected between stages.

Table 4. Descriptive statistics of conductivity measurements obtained at different crop growth stages and corresponding maize yield during the 2024 growing season.

Tillage system	Variable	N	Minimum	Maximum	Mean	Standard deviation
Vegetative	CV-1.0 m	324	23.874	31.771	28.370	1.210
	CV-0.5 m	324	59.797	66.667	62.780	1.210
	Yield	324	2.923	16.528	11.310	3.290
Cob formation	CV-1.0 m	324	21.190	31.746	27.080	2.030
	CV-0.5 m	324	54.712	66.305	61.390	2.400
	Yield	324	2.923	16.528	11.310	3.290

3.1.3. Relationship between Conductivity Depth and Maize Yield

Pearson correlation analysis was conducted to examine relationships among conductivity measurements obtained at 0.5 m and 1.0 m depths and the final maize grain yield. The results are presented in Table 5.

A strong positive correlation was observed between conductivity measured at 0.5 m and conductivity measured at 1.0 m ($r = 0.807$, $p < 0.001$), indicating substantial consistency between measurements obtained at the two depths. However, neither conductivity measured at 1.0 m ($r = -0.030$, $p = 0.451$) nor conductivity measured at 0.5 m ($r = -0.021$, $p = 0.601$) was significantly correlated with final maize yield. These scenarios are indicated in Figures 5 and 6.

These results suggest that while conductivity measurements were strongly related across depths, conductivity-derived variability was not significantly associated with maize yield during the 2024 growing season. The weak and non-significant correlations indicate that factors other than soil electrical conductivity may have played a greater role in determining maize yield variability under the experimental conditions.

Table 5. Pearson correlation coefficients among conductivity measurements at different depths and maize grain yield during the 2024 growing season.

Variable		CV-1.0m	CV-0.5m	Yield
CV-1.0m	Pearson Correlation	1	0.807***	-0.030
	Sig. (2-tailed)	-	0.000	0.451
	N	648	648	648
CV-0.5m	Pearson Correlation	0.807***	1	-0.021
	Sig. (2-tailed)	0.000	-	0.601
	N	648	648	648
Yield	Pearson Correlation	-0.030	-0.021	1
	Sig. (2-tailed)	0.451	0.601	-
	N	648	648	648

*** Correlation significant at $p < 0.001$.

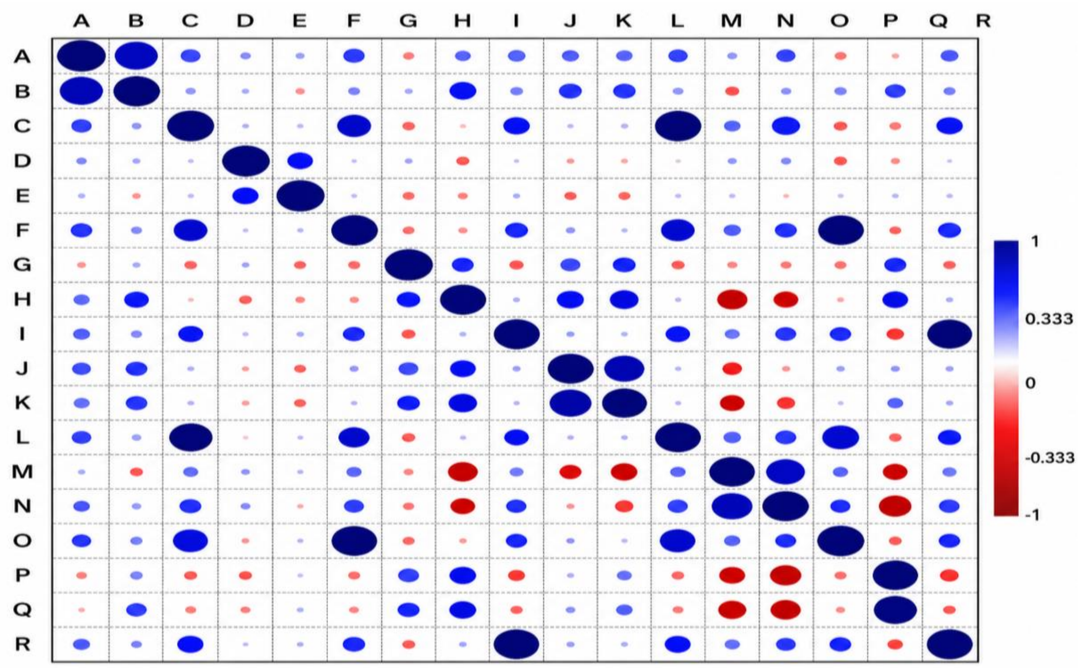

Figure 5. Pairwise correlation matrix of soil conductivity (CV-1.0 m and CV-0.5 m) and maize yield under winter ploughing (WP), strip tillage (ST), and ripping tillage (RT) systems at vegetative (V) and cob formation (CF) growth stages in 2024. **Source:** Author (2024). Panels A–C = WP at V stage; D–F = ST at V stage; G–I = RT at V stage; J–L = WP at CF stage; M–O = ST at CF stage; and P–R = RT at CF stage. Within each panel group, the variables are presented in the following order: CV-1.0 m, CV-0.5 m, and yield respectively.

The correlation matrix showed variability in the relationships between EM38-derived soil ECa measured at 0.5 m and 1.0 m depths and maize yield across tillage systems and growth stages under irrigated conditions. Strong positive correlations were observed between conductivity measurements within the same tillage treatment and depth, whereas several ECa-yield relationships were weak or negative. The significance-filtered matrix indicates that the strength and direction of associations varied among winter ploughing, strip tillage, and ripping treatments, as well as between vegetative and cob formation stages.

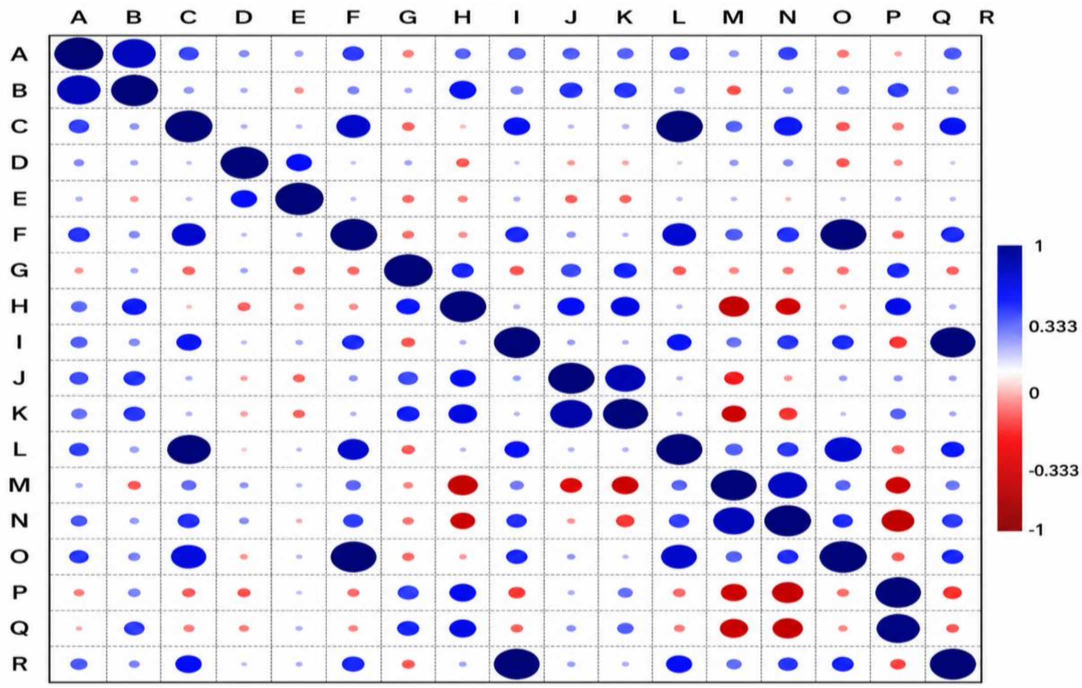

Figure 6. Pairwise correlation matrix of soil conductivity (CV-1.0 m and CV-0.5 m) and maize yield under winter ploughing (WP), strip tillage (ST), and ripping tillage (RT) systems at vegetative (V) and cob formation (CF) growth stages in 2025. **Source:** Author (2025). Panels A–C = WP at V stage; D–F = ST at V stage; G–I = RT at V stage; J–L = WP at CF stage; M–O = ST at CF stage; and P–R = RT at CF stage. Within each panel group, the variables are presented in the following order: CV-1.0 m, CV-0.5 m, and yield respectively.

Similar to 2024, the 2025 correlation matrix demonstrated variable relationships among soil conductivity measurements and maize yield across tillage systems and growth stages. Conductivity meaasurements at 0.5 m and 1.0 m depths were generally positively correlated within individual tillage treatments, whereas correlations between ECa and yield were less consistent and ranged from positive to negative. The significance-filtered matrix indicated that the strength and direction of associations differed among tillage systems and between vegetative and cob formation stages.

The relationship between soil electrical conductivity (CV-1.0m and CV-0.5m) at the vegetative and cob formation stages and final maize yield under winter ploughing tillage, strip tillage, and ripping tillage in 2024 is shown in figures 7a, 7b, 7c, 8a, 8b, and 8c respectively.

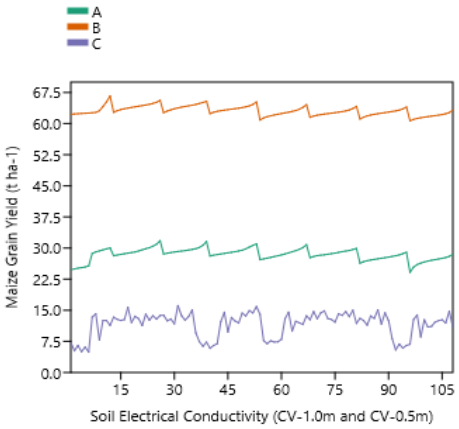

Figure 7a. Vegetative stage under winter ploughing tillage in 2024.

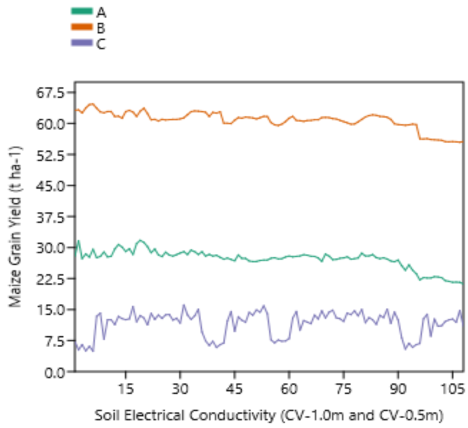

Figure 8a. Cob formation stage under winter ploughing tillage in 2024.

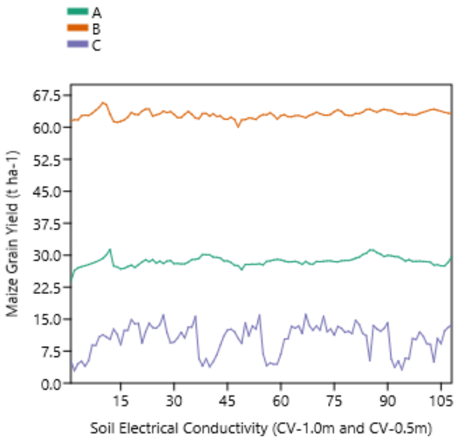

Figure 7b. Vegetative stage under strip tillage in 2024.

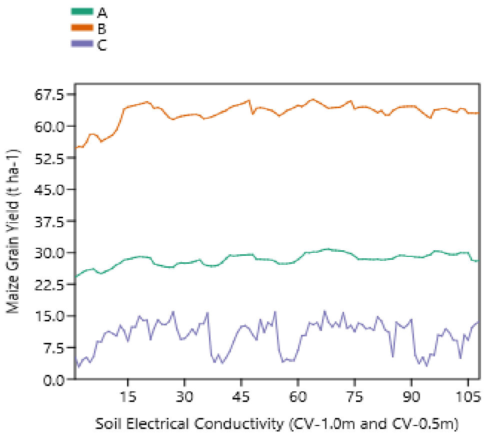

Figure 8b. Cob formation stage under strip tillage in 2024.

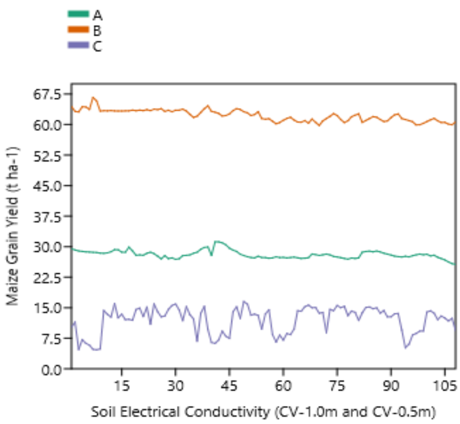

Figure 7c. Vegetative stage under ripping tillage in 2024.

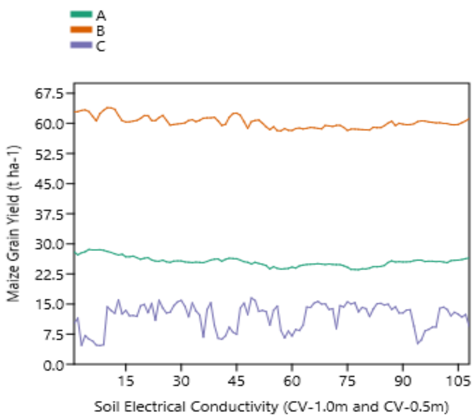

Figure 8c. Cob formation stage under ripping tillage in 2024.

The relationship between soil electrical conductivity (CV-1.0m and CV-0.5m) at the vegetative and cob formation stages and final maize yield under winter ploughing tillage, strip tillage, and ripping tillage in 2025 is shown in figures 9a, 9b, 9c, 10a, 10b, and 10c respectively.

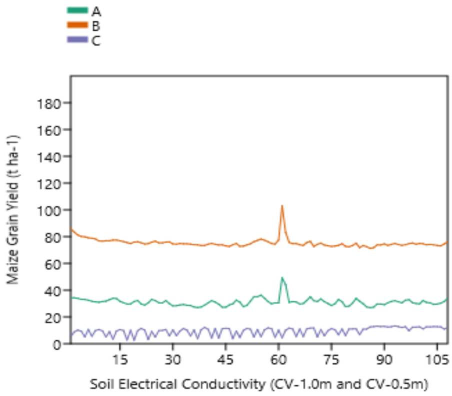

Figure 9a. Vegetative stage under winter ploughing tillage in 2025.

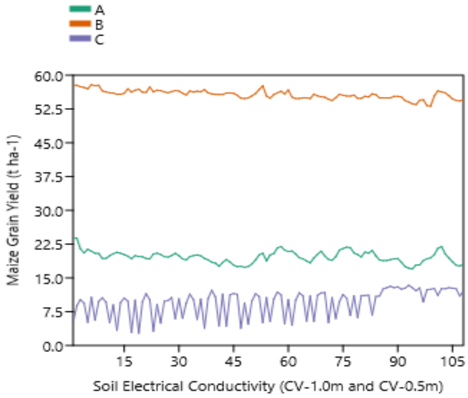

Figure 10a. Cob formation stage under winter ploughing tillage in 2025.

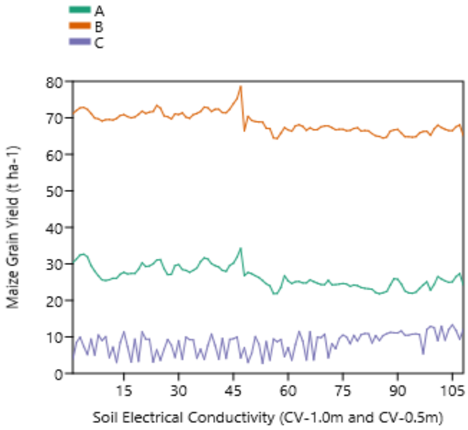

Figure 9b. Vegetative stage under strip tillage in 2025.

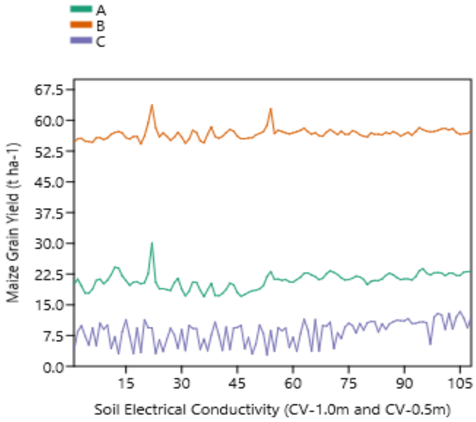

Figure 10b. Cob formation stage under strip tillage in 2025.

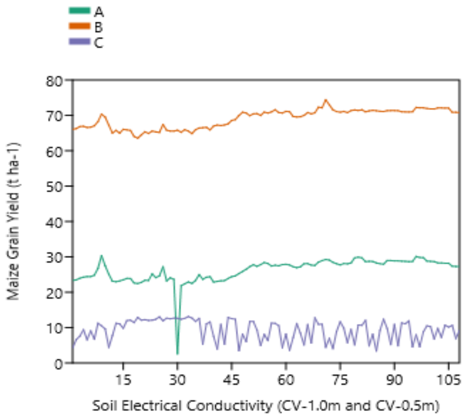

Figure 9c. Vegetative stage under ripping tillage in 2025.

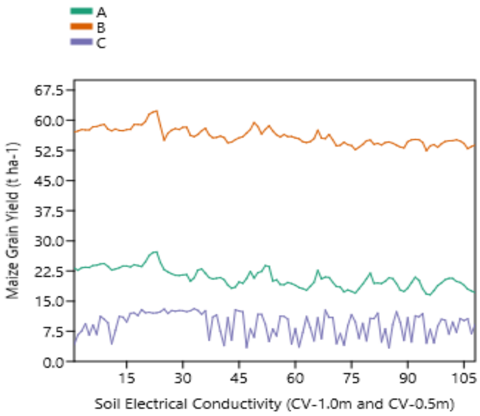

Figure 10c. Cob formation stage under ripping tillage in 2025.

3.1.4. Interaction Effects of Tillage System and Growth Stage on Maize Yield

A two-way mixed ANOVA was performed to evaluate the effects of tillage system (between-subject factor), growth stage of conductivity measurement (within-subject factor), and their interaction on maize grain yield.

The analysis revealed a significant main effect of tillage system on maize yield ($F(2, 642) = 13.475$, $p < 0.001$), indicating significant yield differences among tillage treatments. In contrast, the main effect of growth stage was not significant ($F(1, 642) = 0.000$, $p = 1.000$). Similarly, the interaction between tillage system and growth stage was not significant (F(2, 642) = 0.000, p = 1.000). These results, presented in Table 6, indicate that maize yield differences were primarily associated with tillage system rather than the timing of conductivity measurements.

Table 6. Two-way mixed ANOVA examining the effects of tillage system (between-subject factor), growth stage (within subject factor), and their interaction on maize grain yield during the 2024 growing season.

Source	df	SS	MS	F	p-value
Tillage system (between)	2	282.297	141.149	13.475	<0.001
Growth stage (within)	1	0.000	0.000	0.000	1.000
Tillage x Growth stage	2	0.000	0.000	0.000	1.000
Residual	642	6724.944	10.475	-	-
Corrected Total	647	7007.241	-	-	-

3.2. Results from the 2025 Growing Season

3.2.1. Effect of Tillage System on Maize Yield

Descriptive statistics of EM38-derived conductivity measurements and maize grain yield under the three tillage systems are presented in Table 7. Maize yield varied among tillage systems, with ripping tillage producing the highest mean yield (9.503 t ha^{-1}), followed by winter ploughing (9.279 t ha^{-1}), while strip tillage produced the lowest mean yield (8.321 t ha^{-1}).

A one-way ANOVA showed a significant effect of tillage system on maize yield (F(2, 645) = 10.150, p < 0.001). Tukey's HSD post hoc test indicated that strip tillage produced significantly lower yields than both winter ploughing and ripping tillage (p < 0.05), whereas no significant difference was detected between ripping tillage and winter ploughing. Similar to the 2024 season, strip tillage consistently produced lower maize yields than the other tillage systems. Mean maize yields and Tukey grouping letters are presented in Table 8.

Table 7. Descriptive statistics of EM38-derived conductivity measurements and maize grain yield under different tillage systems during the 2025 growing season.

Tillage system	Variable	N	Minimum	Maximum	Mean	Standard deviation
Winter ploughing	CV-1.0 m	216	16.992	49.219	25.425	6.194
	CV-0.5 m	216	53.121	102.956	65.577	10.218
	Yield	216	2.755	13.361	9.503	2.929
Strip tillage	CV-1.0 m	216	16.997	34.232	23.701	3.716
	CV-0.5 m	216	54.248	78.558	62.750	6.392
	Yield	216	2.769	13.341	8.322	2.833
Ripping tillage	CV-1.0 m	216	2.582	30.349	23.518	3.950
	CV-0.5 m	216	52.447	74.418	62.598	6.937
	Yield	216	3.384	13.142	9.279	2.900

Table 8. Mean maize yield under different tillage systems during the 2025 growing season.

Tillage system	Mean yield (t ha^{-1})	Tukey group
Ripping tillage	9.50	A
Winter ploughing	9.28	A
Strip tillage	8.32	B

Means sharing the same letter are not significantly different at p < 0.05 (Tukey HSD test).

3.2.2. Relationship between Growth-Stage Conductivity Measurements and Final Maize Yield

Descriptive statistics for conductivity measurements obtained during vegetative and cob formation stages and the corresponding maize grain yield are presented in Table 9.

Mean maize yield was identical for conductivity measurements obtained during the vegetative and cob formation stages (9.03 t ha^{-1}). Independent samples t-test results indicated no significant difference in maize grain yield between the two growth stages ($p > 0.05$). Because the same final harvested yield dataset was associated with conductivity measurements from both growth stages, no differences in mean yield were observed between stages.

Table 9. Descriptive statistics of conductivity measurements obtained at different crop growth stages and corresponding maize yield during the 2025 growing season.

Tillage system	Variable	N	Minimum	Maximum	Mean	Standard deviation
Vegetative	CV-1.0 m	324	2.582	49.219	27.958	3.805
	CV-0.5 m	324	63.548	102.956	71.096	4.308
	Yield	324	2.755	13.361	9.035	2.931
Cob formation	CV-1.0 m	324	16.591	30.098	20.471	2.003
	CV-0.5 m	324	52.447	63.716	56.187	1.566
	Yield	324	2.755	13.361	9.035	2.931

3.2.3. Relationship between Conductivity Depth and Maize Yield

Pearson correlation analysis was conducted to determine relationships among conductivity measurements obtained at 0.5 m and 1.0 m depths and maize grain yield. The results are presented in Table 10.

A very strong positive correlation was observed between conductivity measured at 0.5 m and conductivity measured at 1.0 m ($r = 0.928$, $p < 0.001$), indicating a high degree of consistency between conductivity measurements obtained at the two depths. However, maize yield was not significantly correlated with conductivity measured at either 1.0 m ($r = -0.037$, $p = 0.345$) or 0.5 m ($r = -0.034$, $p = 0.390$). Neither conductivity measurement depth showed a statistically significant relationship with final maize grain yield.

These results indicate that conductivity variability measured at either depth was not a significant predictor of maize grain yield during the 2025 growing season. Despite the strong correspondence between conductivity measurements at the two depths, their ability to explain yield variation remained limited.

Table 10. Pearson correlation coefficients among conductivity measurements at different depths and maize grain yield during the 2025 growing season.

Variable		CV-1.0m	CV-0.5m	Yield
CV-1.0m	Pearson Correlation	1	0.928***	-0.037
	Sig. (2-tailed)	-	0.000	0.345
	N	648	648	648
CV-0.5m	Pearson Correlation	0.928***	1	-0.034
	Sig. (2-tailed)	0.000	-	0.390
	N	648	648	648
Yield	Pearson Correlation	-0.037	-0.034	1
	Sig. (2-tailed)	0.345	0.390	-
	N	648	648	648

*** Correlation significant at $p < 0.001$ (2-tailed).

3.2.4. Interaction Effects of Tillage System and Growth Stage on Maize Yield

A two-way mixed ANOVA, represented by Table 11, was performed to evaluate the effects of tillage system (between-subject factor), growth stage of conductivity measurement (within-subject factor), and their interaction on maize grain yield.

The analysis revealed a significant main effect of tillage system on maize yield ($F(2, 642) = 10.150$, $p < 0.001$). In contrast, the main effect of growth stage was not significant ($F(1, 642) = 0.000$, $p = 1.000$). Likewise, the interaction between tillage system and growth stage was not significant ($F(2, 642) = 0.000$, $p = 1.000$). These findings confirm that yield differences among treatments were attributable to tillage effects rather than the growth stage associated with conductivity measurements.

Table 11. Two-way ANOVA examining the effects of tillage system, growth stage, and their interaction on maize grain yield during the 2025 growing season.

Source	Df	SS	MS	F	p-value
Tillage system (between)	2	170.07	85.035	10.150	<0.001
Growth stage (within)	1	0.000	0.000	0.000	1.000
Tillage x Growth stage	2	0.000	0.000	0.000	1.000
Residual	642	5378.832	8.378	-	-
Corrected Total	647	5548.902	-	-	-

4. Discussion

The study investigated the spatial and temporal variability of EM38-derived soil ECa at two effective depths and evaluated its relationship with maize grain yield under different tillage systems in an irrigated production environment over two consecutive growing seasons. The results provide insights into (i) the influence of tillage practices on maize yield, (ii) the consistency of multi-depth conductivity measurements, and (iii) the relationship between soil electrical conductivity and final crop productivity.

4.1. Effects of Tillage Systems on Maize Yield

The results demonstrated a significant effect of tillage treatment on maize yield in both growing seasons, with strip tillage producing lower yields than winter ploughing and ripping tillage, while no significant difference was observed between winter ploughing and ripping tillage. However, interpretation of the lower yield observed under strip tillage requires caution because the strip tillage operation was delayed in both study years due to the late availability of the contracted implement. This operational delay represents an important experimental limitation because differences in the timing of tillage may have affected soil conditions and crop establishment independently of the tillage system itself. Therefore, the observed yield reduction should not be attributed exclusively to the strip tillage system itself.

The lower yield under the delayed strip-tillage treatment may reflect a combination of tillage-related effects and the consequences of late field operation. Reduced or delayed soil disturbance may have influenced physical conditions such as soil structure, seedbed conditions, root penetration, water distribution, or nutrient accessibility, but these mechanisms cannot be separated from the effect of the operational delay within the present experimental design [44,45]. Similar responses have been reported in studies showing that tillage-induced differences in soil structure, rooting conditions, and water availability can influence maize productivity, particularly during periods of high crop water demand [46,47,48]. Thus, the present results demonstrate an association between the implemented strip-tillage treatment and lower maize yield under the conditions of this experiment, rather than providing conclusive evidence that strip tillage itself inherently reduces maize yield.

The absence of a significant yield difference between winter ploughing and ripping tillage indicates that both conventional and deep loosening practices may provide comparable conditions for maize growth under the studied irrigated environment. This is consistent with the general understanding that tillage effects on yield can be site-specific and strongly influenced by soil type, moisture availability, and management history [49].

4.2. Multi-depth Consistency of EM38 Conductivity Measurements

A strong and consistent positive correlation was observed between conductivity measurements at 0.5 m and 1.0 m depths across both growing seasons. This indicates that EM38-derived conductivity captured a stable spatial pattern within the soil profile, suggesting a high degree of vertical consistency in soil properties influencing electrical conductivity [7,50].

The stronger correlation observed in 2025 compared to 2024 may reflect greater uniformity in soil moisture or improved consistency in field conditions during that season [51]. Overall, these findings indicate that EM38 measurements were capable of identifying coherent spatial conductivity patterns across multiple effective depths despite seasonal variation between years.

4.3. Growth-stage Variability in Conductivity Measurements

Conductivity measurements collected during the vegetative and cob formation stages showed similar mean yield values when linked to final harvest yield, and no significant differences were detected in yield between the two growth-stage datasets. Additionally, no significant main or interaction effects of growth stage were observed in the two-way ANOVA. Because the same final harvested yield dataset was linked to conductivity measurements obtained at both growth stages, the absence of significant yield differences between stages was expected. Therefore, interpretation should focus primarily on temporal changes in conductivity measurements rather than differences in final yield values.

The higher standard deviations observed during cob formation stage suggest increased spatial heterogeneity. Similar increases in ECa variability during later crop growth stages have been attributed to differential root water uptake, changing soil water distribution, and crop growth dynamics [52,53,54]. Conversely, other studies have reported relatively stable ECa patterns throughout the growing season, suggesting that site-specific soil properties may influence temporal ECa dynamics [55,56].

These results indicate that, within the context of this study, the timing of EM38 measurements during the growing season did not significantly influence the relationship with final maize yield. While soil electrical conductivity is known to vary with soil moisture dynamics, root activity, and seasonal weather conditions [57,58,59], the present findings suggest that such temporal variability did not translate into measurable differences in yield response.

4.4. Relationship between Soil Electrical Conductivity and Maize Yield

Despite strong correlations between conductivity measurements at different depths, no significant relationships were found between EM38-derived conductivity values and final maize grain yield in either growing season. This indicates that while EM38 measurements captured a consistent and stable pattern of soil spatial variability, this variability was not expressed in yield response under the irrigated conditions of the study. This suggests that, under the conditions of this study, soil electrical conductivity was not a reliable predictor of maize yield variability.

Several explanations may account for this lack of association. First, conductivity is influenced by multiple soil properties such as texture, salinity, and moisture content [60], which may not directly translate into yield variability in a well-managed irrigated system where water and nutrients are not strongly limiting. Second, the relatively uniform irrigation management applied across treatments may have reduced yield variability, thereby weakening potential relationships with spatial soil variability indicators [61]. Third, maize yield is a complex trait influenced by numerous interacting factors, including plant genetics, weather variability, and management practices [62], which may mask soil conductivity effects at the field scale.

Previous studies have similarly reported weak or inconsistent ECa-yield relationships in environments where irrigation, fertilisation, or other management practices reduce the influence of soil-related constraints on crop performance [14,63,64].

4.5. Implications for Precision Agriculture

The strong spatial consistency of EM38 measurements across depths suggests that EMI sensors remain valuable tools for characterising soil spatial variability in irrigated agricultural systems. However, the lack of a significant relationship between conductivity and yield suggests that EM38-derived ECa reflects both soil properties and management practices such as fertilisation, potentially obscuring direct yield relationships.

Instead, EM38 data may be more effectively used for delineating soil variability patterns and supporting site-specific management decisions when integrated with additional agronomic, hydrological, or soil physical datasets [65]. This highlights the importance of multi-source data integration in precision agriculture applications, particularly in systems where yield variability is influenced by multiple non-soil factors [66].

Consequently, EM38 measurements may be most effective when used as part of an integrated decision-support framework rather than as a stand-alone indicator of crop productivity.

4.6. Study Limitations and Future Research

A key limitation of this study is the absence of strong yield variability linked to conductivity patterns, which may be influenced by the relatively uniform irrigated management system [67].

Another concern is the unavailability of the contracted implement which resulted in strip tillage being implemented two weeks later than originally planned in both growing seasons. Because tillage timing can influence soil physical conditions and the subsequent crop development [68], the observed lower yield under strip tillage may reflect both the tillage treatment and the operational delay. The experimental design therefore does not allow these two effects to be completely separated. Future experiments should ensure that all tillage treatments are implemented within the same planned operational period and, also, include replicated trials in which tillage timing is controlled independently from tillage type.

Another limitation is that only apparent electrical conductivity measurements were evaluated, whereas additional soil attributes such as soil moisture, bulk density, penetration resistance, nutrient availability, and organic matter content were not simultaneously incorporated into the analysis. Future research should consider integrating additional soil properties such as moisture content, nutrient status, and compaction measurements to better explain yield variability.

Furthermore, combining EM38 data with remote sensing indices or crop physiological measurements may improve the ability to interpret spatial and temporal variability in crop performance [69]. Expanding the analysis across more diverse soil types and management regimes would also help clarify the conditions under which EM38 conductivity is most strongly related to yield outcomes.

Longer-term investigations covering multiple seasons with contrasting climatic conditions may further improve understanding of the temporal stability of ECa-yield relationships in irrigated maize production systems.

5. Conclusions

This study evaluated the spatial and temporal variability of EM38-derived apparent soil electrical conductivity (ECa) at two measurement depths and its relationship with maize grain yield under contrasting tillage systems in an irrigated production environment. Strip tillage was associated with significantly lower maize yields than winter ploughing and ripping tillage, while no yield difference was observed between winter ploughing and ripping tillage. However, this response should be interpreted cautiously because strip tillage was implemented later than planned in both growing seasons, and the effects of tillage type and operational timing could not be completely separated. Strong correlations between conductivity measurements at 0.5 m and 1.0 m depths demonstrated the strong spatial consistency of EM38-derived spatial patterns across the soil profile.

Although ECa measurements remained relatively consistent across growth stages, no significant relationship was found between soil conductivity and final maize yield. These findings suggest that EM38 is a useful tool for characterising soil spatial variability but may have limited value as a stand-alone predictor of maize yield in uniformly irrigated systems. The absence of significant ECa-yield relationships in either growing season indicates that soil conductivity variability alone did not explain maize yield variability under the management and environmental conditions of this study. Future studies should integrate ECa data with additional soil, crop, and remote sensing information to improve the understanding and prediction of spatial yield variability in precision agriculture.

Overall, the results demonstrate that EM38 sensing technology can effectively characterise within-field soil variability; however, its application for yield prediction is likely to be enhanced when combined with complementary biophysical and agronomic datasets.

Funding: This research was funded by *VÍZZEL KAPCSOLATOS KUTATÁSOK*, grant number *TKP2021-NKTA-32* and NATIONAL RESEARCH, DEVELOPMENT AND INNOVATION FUND, grant number *TKP2021-NKTA*, and JÁNOS BOLYAI RESEARCH SCHOLARSHIP, grant number BO/00068/23/4, all implemented in the University of Debrecen Institute of Land Use, Engineering and Precision Farming Technology.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the author.

Acknowledgments: The author would like to express his sincere gratitude to Dr. Péter Ragán (Supervisor) and Dr. András Tamás for their valuable technical assistance and active involvement in field data collection that led to the successful execution of this study. Special thanks are extended to the Head of the Institute, Prof. Dr. Kakuszi-Széles Adrienn, for facilitating access to these facilities and supporting the fieldwork activities.

Conflicts of Interest: The author declares no conflicts of interest.

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