

## Article

# The Comparison Analysis of Uniform-and Variable-Rate Fertilizations on Winter Wheat Yield Parameters Using Site-Specific Seeding

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**Abstract:** Wheat is among the world's most important agricultural crops, with winter wheat accounting for approximately 25.5% of the total agricultural crop in Lithuania. The unchangeable goal of crop production is to achieve good and economically beneficial crop yield, but such efforts are often based on conventional agrotechnological solutions, and excessive fertilization, which is uneconomical and negatively affects the soil, the environment, and human health. In order to produce a rich and high-quality cereal crop, scientists and farmers are increasingly focusing on managing the sowing and fertilization processes. Precision technologies based on spectrometric methods of soil and plant characterization can be used to influence the optimization of sowing and fertilizer application rates without compromising crop yield and quality. The aim of this study was to investigate the effect of site-specific seeding and variable-rate precision fertilization technologies on the growth, yield, and quality indicators of winter wheat. Experimental studies were carried out on a 22.4 ha field in two treatments: first (control)—SSS (site-specific seeding) + URF (uniform-rate fertilization); second—SSS + VRF (variable-rate precision fertilization) and 4 repetitions. Before the start of this study, the variability of the soil apparent electrical conductivity (ECa) was determined and the field was divided into five soil fertility zones (FZ-1, FZ-2, FZ-3, FZ-4, and FZ-5). Digital maps of potassium and phosphorus precision fertilization were created based on the soil samples. Optical nitrogen sensors were used for variable-rate supplementary nitrogen fertilization. The variable-rate precision fertilization method in individual soil fertility zones showed a higher (up to 6.74%) tillering coefficient, (up to 14.55%) grain yield, number of ears per square meter (up to 27.6%), grain number in the ear (up to 6.2%), and grain protein content (up to 12.56%), and a lower (up to 8.61%) 1000-grain weight on average than the conventional flat-rate fertilization. In addition, the use of the SSS + VRF method saved approximately 14 kg N ha<sup>-1</sup> of fertilizer compared to the conventional SSS + URF method.

**Keywords:** precision agriculture; maps; variable-rate fertilization; soil; seed; fertilizer



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## 1. Introduction

Wheat is statistically the most popular crop grown in the Baltic Sea Region. Wheat accounts for the largest share of farm finances and is also the crop that is expected to yield the highest profits. However, efforts to produce higher and better-quality yields are often based on irrational agrotechnological decisions, with excessive fertilization, which is uneconomical, and has negative impacts on soil, the environment, and human health [1–3]. Precision-oriented technological change in the agricultural sector is leading to better management practices that make all agricultural technological operations, from tillage to harvesting, more precise, resulting in reduced costs, increased profits, and environmental sustainability [1,4]. Scientists have found, applying variable-rate fertilization,

the grain yield does not decrease when the fertilization rate is reduced [5,6]. Additionally, precision fertilizer systems improve plant quality by increasing crude protein content [7]. Precision agriculture involves a large number of technological processes such as soil testing, variability detection, cartography, yield monitoring and mapping, remote field or crop monitoring, Geographical Information System (GIS) application, variable seeding or fertilizer rate application, and automated driving [1].

The aim of using site-specific seeding and precision variable-rate fertilizer technologies is to take advantage of the inherent variability in the soil and environment of a particular field to increase crop yields in areas where the soil is more productive and has better potential, and to reduce inputs in areas where the soil and crop yield potential are limited. Variable-rate fertilization is key to implementing precision farming and ensuring efficient fertilizer use and soil nutrient management tailored to the conditions of individual field sites [8–10]. This precision-oriented technology also helps to mitigate the environmental damage of intensive farming. Reducing fertilizer application at marginal sites can better protect groundwater resources by reducing the risk of nutrient leaching, where excess synthetic N fertilizer is not taken up by plants and the remainder is leached from the soil as  $\text{NO}_3$  [9,11,12]. Applying a fixed uniform rate of nitrogen to the whole field may not be sustainable from either an economic or ecological point of view, whereas precision fertilization can help to address excess or inappropriate fertilizer use [3].

For precision fertilization, there are three main methods for assessing field variability: measuring plant properties, measuring soil properties, and measuring plant yield [13]. Sensors and mapping provide the basis for the application of key variable-rate technologies. Map-based variable-rate applications rely on the use of digital maps, which are constructed with precise information on the input rates to be applied in individual field areas. Sensor-based variable-rate applications usually do not require maps or positioning systems. Sensors measure soil or plant properties as they pass through the crop in real time. However, in order to use the information obtained to manage future crop zones for specific crops, the sensor data should be recorded and geo-referenced. Plant trait sensors have the greatest potential as they are able to determine in real time the crop's requirements (e.g., nitrogen) during variable-rate fertilization [14–16]. Sensor-based nitrogen management systems compared to conventional farming practices showed an increase in nitrogen fertilizer use efficiency by up to 3.7 fold, which indicates a less negative environmental impact and greater economic profitability [3,5]. Smart sensor systems enabled nitrogen fertilizer savings of 10% to 80%, while residual nitrogen fertilizer levels in the soil were reduced by 30–50% without negatively affecting wheat grain yield and quality [3]. The reduced amount of fertilizers reduced the accumulation of nitrates compared to the uniform-rate fertilizer application method [7].

After assessing the electrical conductivity of the soil, corrections to the fertilization rate are made. These changes help to equalize the ratio of macro elements in the soil and thus increase the yield potential of the plants. The principle of determining the apparent electrical conductivity (ECa) of soil is widely used to assess the variability of soil properties. One way of estimating soil electrical conductivity is by electromagnetic induction, which can be measured using the commercially available Geonics Limited EM38 m [17]. Another way to measure soil ECa can be the commercially available Veris MSP, which measures ECa while driving. This device uses a set of disc-shaped electrodes that transmit an electrical signal through the soil [9,17,18]. Crop scanning technology can be used for additional fertilization, determining the nitrogen requirement of plants, and spreading nitrogen fertilizers according to the map created by the scanner. For the assessment of nitrogen status in a field crop, Yara N-Sensors are widely used. They are installed on tractors and consist of two spectrometers, one to scan the crop on the side of the tractor and the other to measure the ambient light in order to correct the reflected signal in real time at a selected wavelength [9].

Variable-rate fertilization helps address changes in soil nitrogen (N) availability and crop responses in the field and can be an effective site-specific management tool on the

farm [19]. Other authors, who conducted research on winter wheat grain yield in two growing seasons with a standard N fertilizer rate and a variable rate, obtained data showing that the variant with a variable N fertilizer rate had a higher grain yield within the expected limits [20]. The application of N fertilizer in the case of variable-rate fertilization decreased from 5 to 40% compared to the standard uniform rate, depending on the heterogeneity of the field. However, the same scientists indicated that the prediction of soil N-mineralization and associated plant N uptake still needs to be better understood to further optimize in-season N fertilization [20].

The application of main and supplementary variable-rate fertilizer technologies to winter wheat sown using the SSS method lacks scientific justification for assessing quantitative and qualitative indicators of winter wheat growth and yield. Therefore, the aim of this study was to investigate the effect of site-specific seeding and variable-rate precision fertilization technologies on the growth, yield, and quality indicators of winter wheat.

## 2. Materials and Methods

### 2.1. Site Description

The experimental studies were carried out in 2020–2021 in the northern part of Lithuania, in a 22.4 ha farmer's field with coordinates 55°40'30.9'' N 24°08'39.9'' E. The soil texture in the study field ranged from loamy sand to sandy loam (sand 73.30%, silt 26.70%). Lithuania has a moderately cold climate. During the period of the experimental studies, the average annual precipitation was approximately 467 mm, and the average annual temperature was approximately 7.5 °C.

### 2.2. Experimental Design

On 15 September 2020, the research field was sown with winter wheat, variety Skagen. Sowing using the site-specific seeding method was carried out with a 6 m working width direct drill HORSCH Avatar 6.16 SD with a row spacing of 16 cm.

The experimental studies were carried out in two variants. The first variant was adopted as a control—site-specific seeding + uniform-rate fertilization (SSS + URF). The second variant was site-specific seeding + variable-rate fertilization (SSS + VRF). Each variant was tested in four replications. The width of one replicate was 36 m and corresponded to the width of a one-pass technological fertilizer stripe.

The choice of experimental research methodology was inspired based on the methodologies used by other authors, who evaluated the soil properties of a specific field location and applied site-specific seeding [21] and site-specific fertilization [22] technologies accordingly. Grisso et al. [14] reported that the application of a variable-rate map adjusts the dispensing rate of substances according to an electronic map, sometimes called a prescription map. This previous experience of the authors was applied in developing the methodological guidelines for this study.

Since soil heterogeneity affects soil properties, measurements of the apparent electrical conductivity (ECa) of the soil were carried out in the field prior to the start of the experiment. The EM38-MK2 equipment was used for these measurements. Following the ECa measurements, the entire field was divided into five field (FZ-1, FZ-2, FZ-3, FZ-4, and FZ-5) management zones according to the average ECa values. Based on these data, the SSS method was applied sowing rate to the different field zones.

Fertilization of the winter wheat crop was carried out on the basis of a pre-established soil nutrient map. The potassium fertilizer KCL\_60 (60% K<sub>2</sub>O) and the phosphorus fertilizer NP\_12-52 (52% P<sub>2</sub>O<sub>5</sub>) were applied immediately after sowing. Phosphorous fertilizer NP\_12-52 was inserted near to the seeds in both variants at the rate of 100 kg·ha<sup>-1</sup>. The rest of the phosphorus fertilizer 75 kg·ha<sup>-1</sup> was spread at a uniform rate in the SSS-URS variant and a variable rate according to the phosphorus fertilization map in the SSS-VRF variant. Potassium fertilizer KCL\_60 was spread after seeding at a uniform rate of 90 kg·ha<sup>-1</sup> in the control and the same amount of fertilizer at a variable rate in the SSS-VRF variant. The mineral granular fertilizers were applied with a Rauch Axis H50.2 centrifugal mineral

fertilizer spreader. This spreader was equipped with a hydraulic spreading disc drive and a mass flow monitoring system. The working width was set at 36 m. The spreading was carried out using machines with automatic steering with a theoretical minimum accuracy of 5 cm.

On 16 November 2020, measurements of plant tillering and biomass were carried out by randomly sampling plants from a 50 cm long row. A total of 40 samples were taken, 5 samples from each replicate of both variants. Plant and stem counts and biomass measurements were carried out in the laboratory of the Department of Agricultural Engineering and Safety of Vytautas Magnus University. Plant biomass measurements were carried out with a Kern K8 laboratory balance with an error of 0.01 g. Calculations of the tillering coefficients and biomass measurements for comparison of results were repeated on 16 April 2021.

Nitrogen demand measurements for Skagen winter wheat, for the purpose of mapping the variable rate of spring fertilization, were carried out with a Yara nitrogen optical sensor installed on the roof of the tractor and running on the tramlines on 19 November 2020. These measurements provided data on crop nitrogen uptake in  $\text{N}\cdot\text{kg}\cdot\text{ha}^{-1}$ , which were used to generate a field variable-rate fertilization map for first application.

Four additional fertilizer applications were made during the winter wheat-growing season:

- First: liquid nitrogen fertilizer KAS32+TIO10 (40.3% N),  $60 \text{ kg ha}^{-1}$ , BBCH 23, according to the fertilizer map prepared in autumn, Horsch Leeb PT280;
- Second: ammonium sulfate NS 21–24,  $33 \text{ kg ha}^{-1}$ , BBCH 30, YARA N-Sensor ALS, Rauch AXIS H 50.1 EMC+W;
- Third: ammonium nitrate (34.4% N),  $48 \text{ kg ha}^{-1}$ , BBCH 37, YARA N-Sensor ALS, Rauch AXIS H 50.1 EMC+W;
- Fourth: liquid nitrogen fertilizer KAS32+TIO10 (40.3% N),  $47 \text{ kg ha}^{-1}$ , BBCH 47, YARA N-Sensor ALS, Horsch Leeb PT280.

The liquid fertilizer was spread on the crop by a Horsch Leeb PT 270 self-propelled sprayer with a working width of 36 m. This sprayer had 72 working sections, each of which could be individually controlled.

Before harvesting, in the experimental field, plant samples were randomly cut from 1.0 m long rows at 40 locations (5 per replicate) for the determination of winter wheat yields. Wheat grains were extracted from the ears using a Wintersteiger LD350 laboratory combine harvester. The yield was weighed using a Kern KB laboratory scale and the protein content of the wheat grains was determined using a GrainSense manual analyzer.

### 2.3. Statistical Evaluation of Data

The data from the experimental studies are sorted for comparison by variant and by ECa zones of the different soils, in order to identify significant differences between crops grown under different conditions. To compare the sample means of the resulting data, an ANOVA for analysis of variance and a t-test were used, in which the sample volumes (number of replicates) and the dispersion of the replicates are evaluated with Student's t-criterion. The reliability of the data obtained was assessed at the 95% confidence interval.

## 3. Results

### 3.1. The ECa and Field Variable-Rate Fertilization Maps

The ECa map of the field is presented in Figure 1. Following the ECa measurements, the entire field was divided into five field management zones according to the average ECa values: FZ-1— $28.8 \text{ mS m}^{-1}$ ; FZ-2— $27.3 \text{ mS m}^{-1}$ ; FZ-3— $25.7 \text{ mS m}^{-1}$ ; FZ-4— $24.2 \text{ mS m}^{-1}$ ; FZ-5— $22.6 \text{ mS m}^{-1}$ . Based on these data, the SSS method was applied sowing rate to the different field zones: FZ-1— $146 \text{ kg ha}^{-1}$ , FZ-2— $163 \text{ kg ha}^{-1}$ , FZ-3— $180 \text{ kg ha}^{-1}$ , FZ-4— $197 \text{ kg ha}^{-1}$ , and FZ-5— $214 \text{ kg ha}^{-1}$ .

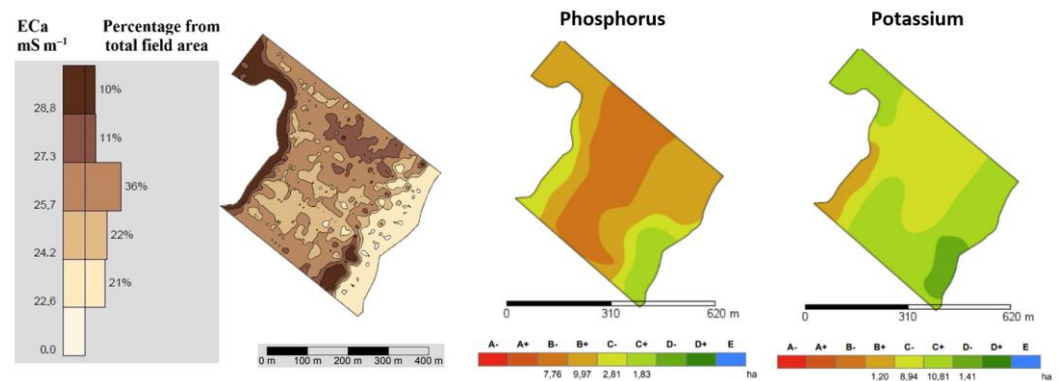


Figure 1. Mapping ECa, phosphorus, and potassium in the soil of experimental field.

After evaluating nitrogen uptake, which varied from 7.3% to 25.1% in the studied field, it was determined that the fertilization rate should vary from 42.3 to 90.3 kg N ha<sup>-1</sup> (Figure 2).

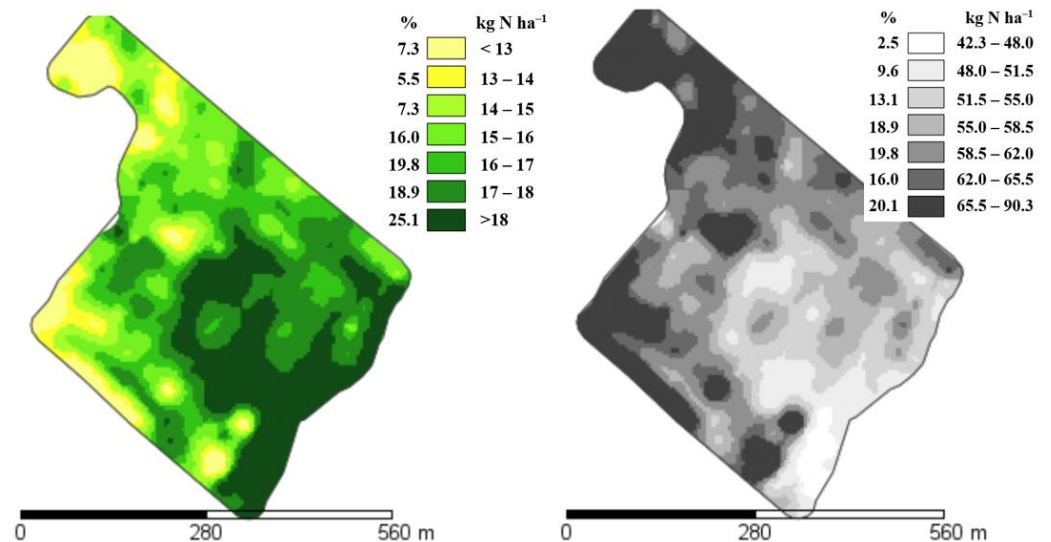
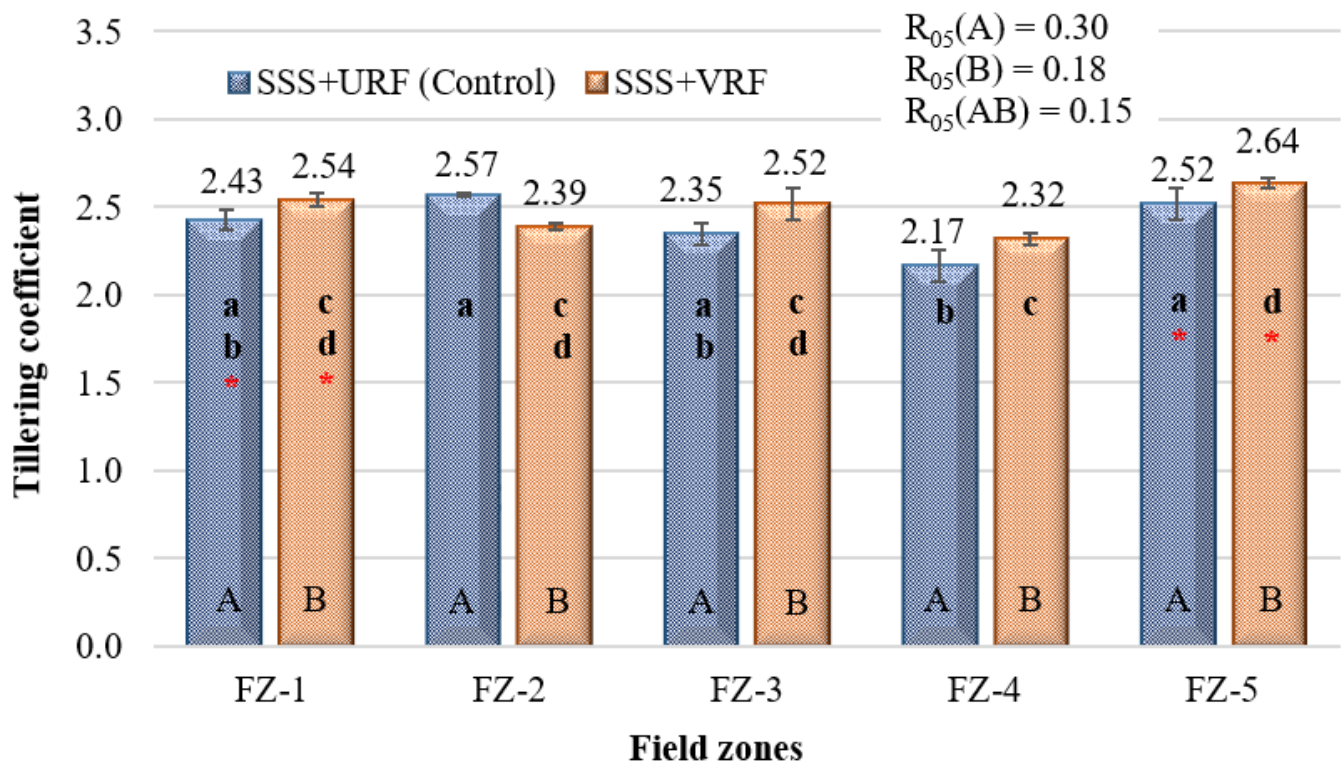


Figure 2. Maps of nitrogen uptake by crops (left) and variable-rate fertilization (right).

### 3.2. The Effect of Precision Fertilization on the Tillering of Winter Wheat

Experimental studies showed that the tillering coefficient of winter wheat varied from 2.17 (FZ-4) to 2.57 (FZ-2) in the control variant (Figure 3). Subtle differences were observed between FZ-2 and FZ-4, and between FZ-4 and FZ-5. The resulting tillering coefficient for FZ-4 was 15.57% and 13.89% lower compared to FZ-2 and FZ-5, respectively. The SSS + VRF method resulted in a higher tillering coefficient in most of the field zones, ranging from 2.32 (FZ-4) to 2.64 (FZ-5). A significant difference in tillering coefficient was found between FZ-4 and FZ-5, which was 12.12%. When comparing the control with precision variable-rate fertilization, significant differences were found for FZ-2, FZ-3, and FZ-4. In the average soil electrical conductivity zone FZ-3, it was found that the winter wheat tillering coefficient was 7.94% higher in the SSS + VRF method compared to the control with the same fertilizer rate. In the other field zones, FZ-4 and FZ-5, the coefficient was higher by 6.46% and 4.55%, respectively.

Summarizing the results on tillering of winter wheat, the tillering coefficient was higher in all the field zones except FZ-2 with variable-rate fertilization compared to the control with a uniform rate.



**Figure 3.** The effect of fertilization methods on the tillering coefficient of winter wheat in different field zones. Black letters (a, b, c, and d) indicate no significant difference between field zones for individual fertilization methods; red symbol (\*) indicates no significant difference between fertilization methods in individual field zones.

### 3.3. Winter Wheat Yield and its Productivity Indicators

The experimental studies on winter wheat yield showed that the highest grain yield ( $8878 \text{ kg ha}^{-1}$ ) was found in zone FZ-4 (Table 1). In this zone, as in zone FZ-3, there was no significant difference in grain yield between the control SSS + URS and the precision SSS + VRS fertilization methods. However, when evaluating the differences between the field zones for the same fertilization option, significant differences were obtained. In the case of uniform-rate fertilization, there were no significant differences only between FZ-1 and FZ3 and between FZ-2 and FZ-4, in all other cases, there was a significant difference between the field zones. The SSS + VRS fertilization method resulted in a more homogeneous winter wheat yield between zones FZ-1 and FZ-4. Compared to the other zones, only zone FZ-5 showed a significant difference.

**Table 1.** Winter wheat productivity indicators.

Indicators	Field Zones									
	FZ-1		FZ-2		FZ-3		FZ-4		FZ-5	
	SSS + URF (Control) (A)	SSS + VRF (B)	SSS + URF (Control) (A)	SSS + VRF (B)	SSS + URF (Control) (A)	SSS + VRF (B)	SSS + URF (Control) (A)	SSS + VRF (B)	SSS + URF (Control) (A)	SSS + VRF (B)
<b>Grain yield, kg ha<sup>-1</sup></b>	7325 ± 163.81	8572 ± 178.87	8851 ± 202.88	7976 ± 153.97	7715 ± 278.63	8103 ± 511.38	8756 ± 169.36	8878 ± 111.84	6378 ± 176.26	5609 ± 257.52
<b>T-test<sub>05</sub></b>		R(A) = 609 kg ha <sup>-1</sup>				R(B) = 845 kg ha <sup>-1</sup>			R(AB) = 726 kg ha <sup>-1</sup>	
<b>A, B</b>	a	cd	b	c	a	cd	b	c	-	-
<b>A × B</b>	-	-	-	-	a	a	b	b	-	-
<b>The number of ears, unit m<sup>-2</sup></b>	519 ± 12.30	717 ± 1.27	639 ± 17.39	612 ± 9.33	632 ± 11.60	615 ± 35.06	642 ± 14.42	632 ± 5.46	546 ± 10.00	642 ± 19.88
<b>T-test<sub>05</sub></b>		R(A) = 40 units m <sup>-2</sup>				R(B) = 56.10 units m <sup>-2</sup>			R(AB) = 48.10 units m <sup>-2</sup>	
<b>A, B</b>	a	-	b	c	b	c	b	c	a	c
<b>A × B</b>	-	-	a	a	b	b	c	c	-	-
<b>The grain number in ear, unit</b>	35.68 ± 0.25	37.36 ± 0.38	39.09 ± 0.11	39.93 ± 0.14	36.07 ± 0.39	38.47 ± 0.35	36.51 ± 0.60	38.54 ± 0.30	34.44 ± 0.66	31.82 ± 0.25
<b>T-test<sub>05</sub></b>		R(A) = 0.89 unit				R(B) = 1.37 unit			R(AB) = 1.12 unit	
<b>A, B</b>	a	b	-	-	a	b	a	b	-	-
<b>A × B</b>	-	-	a	a	-	-	-	-	-	-
<b>1000-grain weight, g</b>	34.81 ± 0	31.81 ± 0.36	34.27 ± 0.63	35.27 ± 0.08	35.26 ± 0.59	34.27 ± 1.03	35.95 ± 0.62	36.42 ± 0.05	28.59 ± 0.66	27.48 ± 0.86
<b>T-test<sub>05</sub></b>		R(A) = 1.68 g				R(B) = 1.87 g			R(AB) = 1.52 g	
<b>A, B</b>	a	-	a	bc	a	b	a	c	-	-
<b>A × B</b>	-	-	a	a	b	b	c	c	d	d

Note: The same letters (a, b, c, and d) indicate no significant difference; A, B—between FZ with the same treatment; A × B—between different treatments in the same field zones.

The analysis of the results for the number of ears per square meter of winter wheat showed that there were no significant differences between the control and the precision SSS + VRF method in field zones FZ-2, FZ-3, and FZ-4. In contrast, in field zones FZ-1 and FZ-5, a significantly lower number of ears was found in the control treatment, 27.62% and 14.95%, respectively, compared to the variable-rate treatment. Both the highest (717 units  $m^{-2}$ ) and the lowest (519 units  $m^{-2}$ ) number of winter wheat ears were obtained in zone FZ-1 when the SSS + VRF and SSS + URF fertilization methods were applied, respectively. Looking at the results of the control variant between the zones, it was found that the number of ears varied from 519 units  $m^{-2}$  (FZ-1) to 642 units  $m^{-2}$  (FZ-4). Significant differences in the number of ears were observed between FZ-1 and FZ-2, between FZ-1 and FZ-3, between FZ-1 and FZ-4, and also between FZ-5 and FZ-2, between FZ-5 and FZ-3, and between FZ-5 and FZ-4. As regards the precision fertilization method of SSS + VRF, the results showed that the number of ears varied from 612 units  $m^{-2}$  to 717 units  $m^{-2}$ . Compared to the other field zones, a significantly higher number of approximately 12.80% of ears was obtained in zone FZ-1. No significant differences were found when comparing the results obtained in zones FZ-2, FZ-3, FZ-4, and FZ-5 with each other.

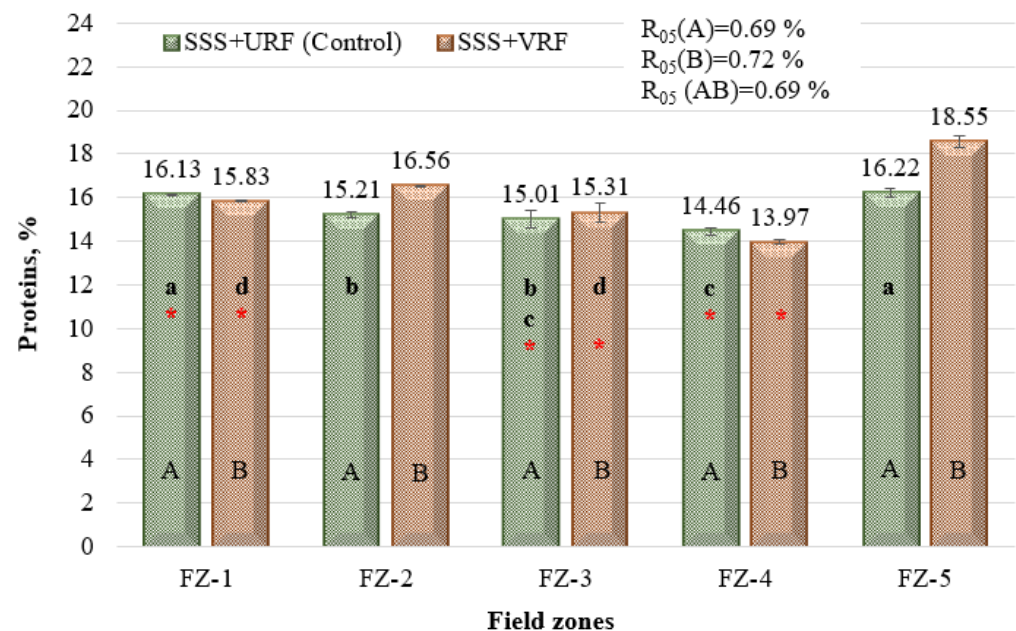
The highest number of grains in the ear was found in zone FZ-2, both in the control (39.01 units) and in the precision fertilization method (39.93 units). Although this zone showed the best results, no significant difference was found between the different fertilization methods. In all other field zones, significant differences were found between the different fertilization methods. In zones FZ-1, FZ-3, and FZ-4, significantly higher grain numbers in the ear (4.50%, 6.23%, and 5.27%, respectively) were found in the precision fertilizer variant compared to the control. Only in zone FZ-5, on the contrary, a significantly lower number of grains per ear (7.60%) was found with the precision fertilization method. When the results of the control SSS + URF method were analyzed in the different field zones, it was found that the number of grains per ear varied from 34.44 units (FZ-5) to 39.01 units (FZ-2). The number of grains per ear was significantly lower in zone FZ-5 and significantly higher in zone FZ-2 compared to the other field zones. When comparing the number of grains in the ear between FZ-1, FZ-3, and FZ-4, there were no significant differences in either the control or the SSS + VRF variants.

Among the very important indicators of the 1000-grain weight is the difference in the weight of grains produced in different field zones and under different fertilizer technologies. The study showed that the highest 1000-grain weight in both the control (35.95 g) and the precision fertilizer variant (36.42 g) was obtained in zone FZ-4. In this field zone, no significant differences were found between the different variants. When analyzing the results for all field zones, significant differences between fertilization variants were obtained in zone FZ-1. In this zone, comparing the control and the precision fertilization methods SSS + VRF, it was found that a significantly higher 1000-grain weight (8.62%) was obtained with the control method of uniform-rate fertilization. When comparing the results of this indicator between the different field zones when precision fertilization was applied, a significantly higher 1000-grain weight was found in zone FZ-4 compared to FZ-1 and FZ-3, by 12.66% and 5.90%, respectively, and a significantly lower weight was found in zone FZ-5, by 13.61% to 24.55%, when compared to the rest of the field zones.

### 3.4. Protein Content in Grains

Experimental studies showed that the SSS + VRF method resulted in the highest (18.55%) protein content of winter wheat grain in zone FZ-5 and the lowest (13.97%) in FZ-4 (Figure 4). In the control SSS + URF variant, the protein content varied from 14.46% (FZ-4) to 16.22% (FZ-5) in all field zones. In zones FZ-1, FZ-3, and FZ-4, the protein content of winter wheat grain was similar when comparing the control with the precision variable-rate fertilizer. Significant differences between fertilization methods were observed in the two field zones FZ-2 and FZ-5. Significantly higher protein content in winter wheat grain (8.15% in FZ-2 and 12.56% in FZ-5) was found for SSS + VRF. In the control method SSS + URF, it was observed that the protein content of the grain was significantly higher in zones

FZ-1, FZ-2, and FZ-5 compared to FZ-4. For SSS + URF, a significantly higher grain protein content was obtained in FZ-2, and FZ-5 compared to the other zones. There was also a significant difference of 10.73% between FZ-5 and FZ-2.



**Figure 4.** Dependence of winter wheat grain proteins on field zones in different fertilization treatments. Black letters (a, b, c, and d) indicate no significant difference between field zones for individual fertilization methods; red symbol (\*) indicates no significant difference between fertilization methods in individual field zones.

To summarize the results on the grain protein content of winter wheat, the variable-rate precision fertilization option 3 of the five field zones produced a higher grain protein content than the uniform-rate control.

## 4. Discussion

### 4.1. The ECa and VRF Maps

The processes from field data collection to computer processing and fertilizer mapping are the foundation of fertilization in precision agriculture. Remote sensing data and methods have an important role to play in improving fertilization in precision agriculture today and will be increasingly important in the future [23]. Variable-rate methods are among the main options for precision fertilizer management and require spatial information [5]. Variable-rate fertilization reduces fertilizer surplus [24]. Our studies have shown benefits in fertilizer quantity, yield, and qualitative indicators when fertilizer application is based on a field map. Technological innovation plays an important role in making agriculture more efficient and sustainable. Among the main objectives of precision farming is to optimize yield and quality, minimizing environmental impact by improving resource efficiency [5,25]. During the experimental studies, the field was divided into five control zones after the soil ECa measurements, when the ECa varied from 22.6 (FZ-5) to 28.8  $\text{mS m}^{-1}$  (FZ-1). Based on these data, the adjusted seeding rate varied from 146  $\text{kg ha}^{-1}$  (FZ-1) to 214  $\text{kg ha}^{-1}$  (FZ-5). Nitrogen uptake was evaluated in this study, which ranged from 7.3% to 25.1% in different field zones. Taking into account these data, variable nitrogen fertilization was selected accordingly, which ranged from 42.3 to 90.3  $\text{kg N ha}^{-1}$  and reduced the amount of nitrogen fertilizers used.

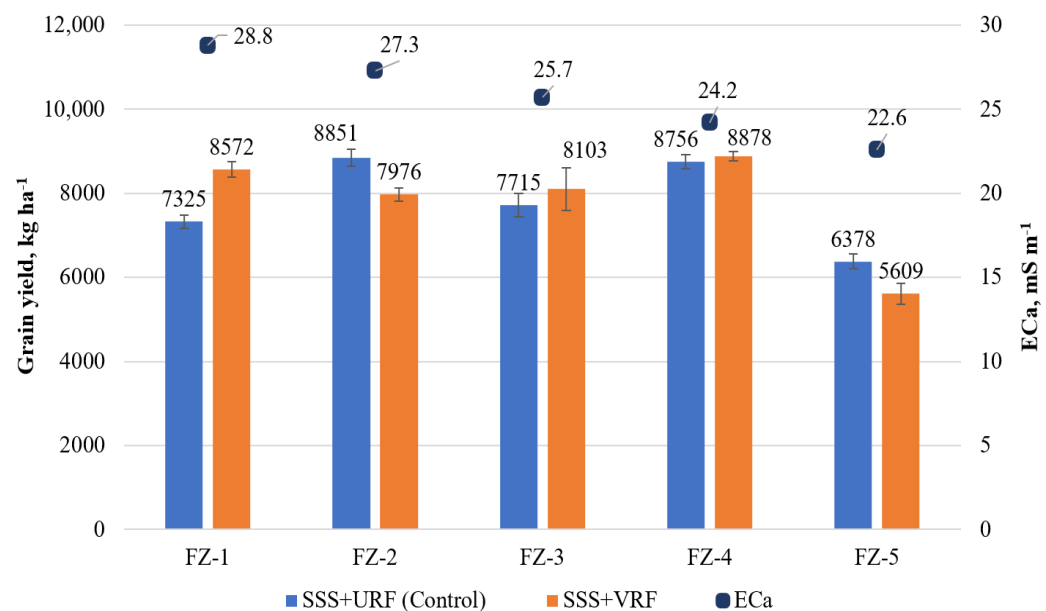
### 4.2. The Tillering Coefficient

The tillering coefficient is an important factor influencing wheat productivity parameters [26]. In our case, precision variable-rate fertilization showed that in all field zones

except FZ-2, the tillering coefficient of winter wheat was on average approximately 5.26% higher compared to the control when the same fertilization rate was applied. Fan et al. [27] report that plant height, leaf area index, aboveground biomass, and yield were not significantly reduced due to the reduced fertilizer application rate in variable-rate fertilization. Research by Gaile et al. [26] found that tillering coefficient had an influence on the number and weight of grain per ear, although 1000-grain weight and grain quality indicator (crude protein) were not influenced.

#### 4.3. The Yield and Its Indicators

In our case, the results showed that the SSS + VRS method increased yields in almost all field zones, with a yield increase of approximately 5.5% and a fertilizer saving of approximately  $14 \text{ kg N ha}^{-1}$  compared to the control technology at a constant fertilizer rate. The results of XueMei et al. [28] confirm that variable-rate fertilization can effectively reduce the accumulation and use of N, P, and K fertilizers, and can increase grain yield and N use efficiency of the growing plants. Ameer et al. [29] found that the results of the correlation matrix showed a significant relationship between crop yield and soil properties. Research has shown that the yield was determined the lowest in the field zone, where the ECa was lowest ( $22.6 \text{ mS m}^{-1}$ ) (Figure 5).



**Figure 5.** Interface of grain yield with electrical conductivity in different field zones.

Brambilla et al. [30] argue that improvements in crop yields can be planned and achieved through, for example, variable fertilizer rate allocations. Denora et al. [5] found that variable-rate fertilizer application resulted in a 25% reduction in nitrogen fertilizer application, while wheat yields were the same when compared to conventional technology with a constant fertilizer rate. Vizzari et al. [6] found that there was no reduction in grain yield with variable-rate fertilization methods, but a reduction fertilizer application. The variable-rate application can reduce the total amount of nitrogen, phosphorus, and potassium fertilizers by 24.9% while reducing the total crop input by an average of  $168.0 \text{ € ha}^{-1}$  compared to a constant fertilizer rate [31]. Fan et al. [27] found that in the first year, precision fertilization reduces nitrogen and phosphorus requirements by 8% and 10%, but increases potassium by 15%. In the second year, nitrogen, phosphorus, and potassium reserves are reduced by 9%, 25%, and 17%, respectively. Meena et al. [32] argue that precision farming is a good tool to increase yields on the farm, increase income by reducing inputs, and improve fertilizer management. The use of farm management information systems enables crop management, an efficient increase in quality and quantity of yields, and decision support for farmers [30]. A field study conducted by Diacono et al. [3],

which compared sensor-based N management systems with farmers' common practices, showed an increase in N use efficiency of up to 3.68%. The lower N fertilizer application in the precision variable-rate technology resulted in higher N use efficiency than the control, indicating lower negative environmental impacts and higher economic profitability [5].

#### 4.4. Protein Content in Grains

In addition to the higher average winter wheat grain yield, the number of ears per square meter, and the number of grains in the ear for all field zones in the precision SSS + VRF method, the experimental studies also showed an average increase in winter wheat protein content of approximately 0.63% in the SSS + VRF variant compared to the control, which had a protein content of 15.41%. Other authors have also confirmed that the protein content of wheat grain can be higher in the variable-rate technology than in the uniform-rate technology. In our study, the highest protein content was obtained in the zones where soil electrical conductivity, soil fertility, and winter wheat grain yield were the lowest.

Summarizing the obtained research results, it can be stated that reducing over-fertilization with mineral fertilizers in crop production is a very important factor. Reducing mineral fertilizers is associated with healthier soil, healthier food and more economical, efficient and cleaner agricultural production [31]. In addition to the results already mentioned, other authors have noted further advantages of variable-rate fertilization. Raun et al. [33] reported that the variable-rate method improved nitrogen use efficiency by 15% compared to a uniform-rate method. Other authors found that the precision fertilizer system improved plant quality with a 19% increase in crude protein. Lower fertilizer application resulted in less nitrate accumulation compared to the uniform-rate fertilizer application method [7].

## 5. Conclusions

The success of variable-rate precision fertilization depends on the variability of soil properties in the field. When the soil is very uniform, the potency of precision fertilization is not very high. In our case, where the soil varied from sandy loam to loamy sand, the application of the map-based variable-rate fertilization method has led to positive results in winter wheat production and yield. The precision variable-rate fertilization process resulted in an average increase in winter wheat tillering of approximately 5.5% in four out of the five field zones compared to the conventional flat-rate fertilization. The highest yield increase (14.55%) was achieved in zone FZ-1, where the most fertile soil was predominant, while on the poorest soil, precision variable-rate fertilization showed a lower yield than conventional uniform-rate fertilization. Positive significant differences were also obtained for the number of ears per square meter with variable-rate fertilization. This trend was particularly strong for soil fertility in the extreme field zones FZ-1 and FZ-5. In all field zones, the average grain number in the ear was also higher in the variant with variable-rate fertilization. The precision fertilization method also resulted in a higher average protein content in winter wheat grains. In addition to these positive trends, there was also a saving of approximately 14 kg N ha<sup>-1</sup> of fertilizer for additional fertilization compared with the flat-rate technology.

The results show that the technological process of precision variable-rate fertilization, based on predetermined soil characterization maps and plant scanning data from optical sensors, demonstrates a positive trend in the field areas where site-specific seeding technology has been applied in advance. Looking to the future, variable-rate fertilization could be used in addition to SSS. In addition to site-specific seeding and site-specific fertilization, it is very important to continue scientific research not only in the directions of precise spreading of mineral fertilizers, but also of spreading organic fertilizers, as well as precise spraying and harvesting. It is necessary to achieve that all technological operations of grain production are precise, as this could provide the best conditions for obtaining the greatest economic benefits and the strongest contribution to the reduction in environmental pollution in agriculture.

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