Impact of soil electrical conductivity-based site-specific seeding and uniform rate seeding methods on winter wheat yield parameters and economic benefits

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Abstract

Precision seeding which exploits the variability of soil properties in the field, is one of the most important agrotechnological solutions for smart agriculture, making it possible to increase the agronomic and economic efficiency of the production of one of the world's most popular crops – winter wheat. The aim of this work was to investigate the impact of the site-specific-seeding (SSS) method on winter wheat yield and its productivity parameters and economic benefits compared with the conventional uniform rate seeding (URS) method. The experimental studies were carried out in a 22.4 ha field, which was divided into 5 soil management zones (MZs) based on the measured apparent electrical conductivity (ECa) with an electromagnetic induction sensor. These included MZ1 representing the highest soil ECa zone, MZ2, MZ3, and MZ4 as the medium-high, medium, and medium-low zones, respectively, and finally MZ5 as the lowest ECa zone with the lightest soil texture. The studies were carried out using two seeding methods. Under the conventional URS method, the same seeding rate of 180 kg ha^{-1} was applied in all MZs, while under the precision SSS method different seeding rates ranging from 146 kg ha^{-1} (MZ1) to 214 kg ha^{-1} (MZ5) were applied. Results showed that the SSS method overcome the URS in providing higher average grain yield and its yield components (e.g., the number of ears per square meter, the number of grains per ear, and the weight of 1000 grains). A particularly strong effect of seeding methods was found in the poorest soil fertility zone MZ5, where a significant difference between SSS and URS was obtained concerning plant height, straw-to-grain ratio, number of grains per ear, weight of 1000 grains, and grain yield. The cost-benefit analysis showed that the SSS approach resulted in an 8.3% higher gross margin than the URS approach. Future research is necessary to validate the results obtained in a larger number of fields having different degrees of spatial variability.

Keywords

Precision agriculture, soil fertility, variable rate seeding, wheat, apparent electrical conductivity.

Introduction

Seeding rate and plant density are particularly important factors in wheat production, as they can influence yield and quality (Laghari et al., 2011; Zecevic et al., 2014). In recent years, the average yield of winter wheat in Lithuania has been around 5.35 t ha^{-1} and the country ranks among the top five European Union countries in terms of the quantity of wheat grain exported (Šiuliauskas, 2020). However, the experience of neighboring western European countries shows that winter wheat yields can be significantly increased (1.0–1.5 t ha^{-1}) without significant additional investment if farmers are able to establish crops with optimal productivity parameters that match the fertility of the soils and the intensity of the cultivation technologies used (Šiuliauskas, 2020). The results of previous studies have shown that in some European countries, e.g. in Belgium, Ireland, the Netherlands and in some climatic zones of France, Germany and Sweden, the average yield of winter wheat ranges from 7.4 to 9.6 t ha^{-1} (Schils et al., 2018) while in Lithuania a similar high yield can be achieved only in individual fields. Given that winter wheat is a highly demanding crop in terms of agrotechnical requirements (Gaweda and Haliniarz, 2021), practical experience shows that the importance of crop density and wheat ear productivity are closely interrelated (Šiuliauskas, 2020).

The increasing use of smart farming services is vital to improve the economic performance of farms, meet the growing food needs for the increasing world population and reduce the environmental impact of pollution from agriculture (Saiz-Rubio and Rovira-Mas, 2020; Balafoutis et al., 2017; Šarauskis et al., 2021). Seeding is one of the most important operations of the crop production, as it directly affects growth and yield, influencing the productivity of the crop and the resulting economic benefits (Chen et al., 2022; Holman et al., 2021; Šarauskis et al., 2021). A successful seeding operation is considered when, under good soil moisture conditions, seeds are sown at the desired rate, within row spacing, planter speed, and seed depth (Virk et al., 2019). The determination of these parameters requires advanced sensing, modelling and control technologies that become available during the current decade despite they are underutilized (Munnaf et al., 2020a).

Precision agriculture pioneers became more interested in site-specific seeding (SSS) in the mid-1990s (Fulton, 2019). According to Munnaf et al. (2020a), SSS is a precision agriculture practice that aims to optimize the seeding rate and depth according to the variability of soil fertility and yield potential in a field. The success of a site-specific application of seed placement depends heavily on the accuracy of the measurement of key parameters in the system (e.g., soil, topography, weather), the modeling of management zone (MZ) maps based on soil properties (e.g., ECa, texture, soil fertility) and/or crop yield heterogeneity in the field and the provision of accurate recommendations, and finally the choice of appropriate variable rate technologies and their integrations. Depending on soil characteristics, seed germination, crop development, and yield potential may vary between field sites and even within one field (Munnaf et al., 2020a). Therefore, SSS may therefore be the right key to accurately apply the amount of seed in different zone within a field, each having specific characteristics to increase crop yield and profit (Kazlauskas et al., 2022).

One of the most important steps in implementing variable rate seeding (VRS) is to pinpoint the key factors that have the greatest impact on yield at each specific field location by forming separate seeding zones and assigning different seeding rates to them, resulting in a VRS map (Fulton, 2019; Munnaf et al., 2020a). To optimize yield and other components, it is important to choose the optimal number of plants per unit area when seeding e.g., wheat (Wang et al., 2021). Researchers usually distinguish two important questions for SSS technology, that is, how many seeds should be allocated in the soil and what seed density should be applied to various plants (Munnaf et al., 2020a). Too high a plant population results in a crop that is too dense, an environment that promotes high canopy temperature and humidity. This creates additional difficulties in controlling the crop during the growing season, as a too-dense crop can lead to intensification of disease spread, and consequently higher costs for disease control (Šarauskis et al., 2022). Otherwise, when the number of plants per unit area is too low, yield per unit area reduces due to the lower number of plants that optimum, which also leads to a potentially stronger impact of pests on the crop and a poorer chance of competing with vigorous weeds (Griffin and Hollis, 2013). Therefore, it can be hypothesized that optimizing the number of plants per unit area by SSS boosts yield while reducing the risk of biotic stresses and the subsequent increases in the amount of pesticides needed.

The relationship between wheat grain yield and plant density is not consistent, and the mechanisms that may provide the answers are not always clear. A better understanding of the determinants of this relationship could help to refine plant density recommendations in relation to specific soil and environmental characteristics (Bastos et al., 2020). The recommended increase or decrease in seed rate compared to the average seeding rate depends on the productivity potential of the respective soil MZs (Lovell, 2016). According to Heege (2013), under a SSS practice, seed density should increase on sandy soils and decrease on clay soils. This seeding rate principle should allow for an increase in yield or seed saving. High-fertility soils are assumed to have a much higher percentage of emergence, thus requiring less seed to produce the optimum seed rate per hectare (Fulton, 2019). In addition, sandy soils are usually characterized by lower water capacity and microcapillarity and lower nutrient content, which often results in poorer seed germination, poorer crop growth and development, and therefore a higher seeding rate guarantees a more even and productive crop. Another opinion can also be found in scientific studies that higher seeding rates can be recommended in a more fertile soil zone, with the aim of achieving a higher crop yield, while a low productivity soil zone could give a better yield with a lower seeding rate and with a lower plant population (Hörbe et al., 2013). The latter approach is designated recently as the Kings SSS (Munnaf et al., 2022), and was validated for potato and maize (Munnaf and Mouazen, 2021; Munnaf et al., 2022). However, no work has been found on SSS with Robin Hood approach (feeding the poor), which suggest applying the smallest number of seeds in the highest fertility zone and vice versa for the largest number of seeds. The motivation is that by reducing the number of seeds, the crop canopy size would be reduced in the most fertile zone, hence, the risk for biotic stresses could be reduced, and input cost of pesticides is reduced accordingly.

One of the important proximal soil sensing technology used in SSS is the apparent soil electrical conductivity (ECa) (Griffin and Hollis, 2013; Kazlauskas et al., 2021). Soil ECa measurements correlate with soil physicochemical properties that affect crop productivity, including soil structure, moisture, texture, drainage conditions, salinity, and subsoil properties (Grisso et al., 2011; Munnaf et al., 2020a). Furthermore, a soil ECa map is a product that is commercially available by service providers, and is a simple and inexpensive tool that farmers can use to characterize within field spatial variability quickly and accurately (Gunzenhauser et al., 2012). Lovell (2016) gives a relevant example in maize, if a field has five MZs of different soil fertility, the standard seeding rate should be recommended for the middle zone (e.g., the third zone). He reported that the seeding rate on soils of poorer fertility could be reduced by 10% in zone two and 15% in zone one on one side and increased by 10% and 15%, respectively, in zones four and five where soil fertility is higher. This means that seeding rate applied varied by up to 30% in the same field. However, there is no definite figures given about the percentage increase or decrees in the seeding rate among different MZ.

The effect of seeding rate on winter wheat yield and its components (number of ears per square meter, number of grains per ear, weight of 1000 grains, etc.) has already been studied by researchers from different countries (Zecevic et al., 2014; Wang et al., 2021; Laghari et al., 2011; Iqbal et al., 2012), while ignoring the within field spatial variability of the soil. Several researchers have already published interesting papers summarizing results of SSS of maize (Munnaf et al., 2022), potato (Munnaf et al., 2020b), soybean (da Silva et al., 2022), and other crops, and the impact of seeding methods on yield performance. However, there is a lack of previous work analyzing the impact of variable rate seeding on yield and its productivity parameters in one of the world’s most important crops, winter wheat (Gaweda and Haliniarz, 2021). The lack of such scientific papers and research results inspired a new experimental study to investigate the impact of SSS on yield, productivity parameters and economic benefits of winter wheat, compared with the conventional URS method.

Material and methods

Site and meteorological conditions

The experimental studies were carried out in 2020–2021 cropping season in Lithuania on a 22.4 ha field (55°40'27.7"N 24°08'43.9"E) of a commercial farm in Panevėžys district (Fig. 1). The predominant soil textures in the field ranged between a sandy loam and a loamy sand.

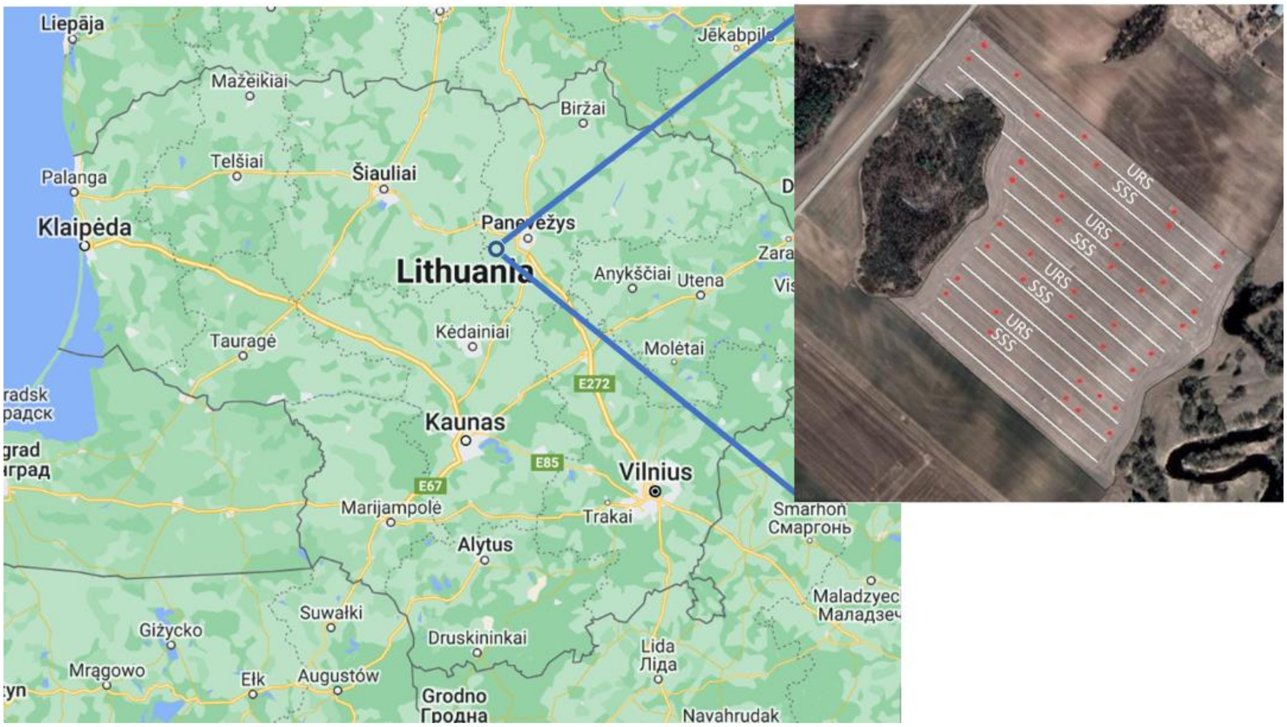

Fig.1. Location of the experimental field in Panevėžys district in Lithuania. The red dots in the figure indicate the sampling locations.

During the experimental period, the average annual air temperature in the region was 7.47 °C, which was more than one degree higher than the long-term annual temperature (6.25 °C). The highest average daily temperature was on 16 July (27.1 °C) and the lowest was on 17 January (-20.6 °C). The total precipitation during the reporting period was 468 mm, compared with the long-term average annual precipitation of 545 mm. Despite the month of May, when about 28% of the total annual precipitation fell (Fig. 2), many months had very low precipitation. The highest daily precipitation was 48.9 mm on 3rd of May. In summary, the year of the study was drier and warmer than the long-term meteorological data.

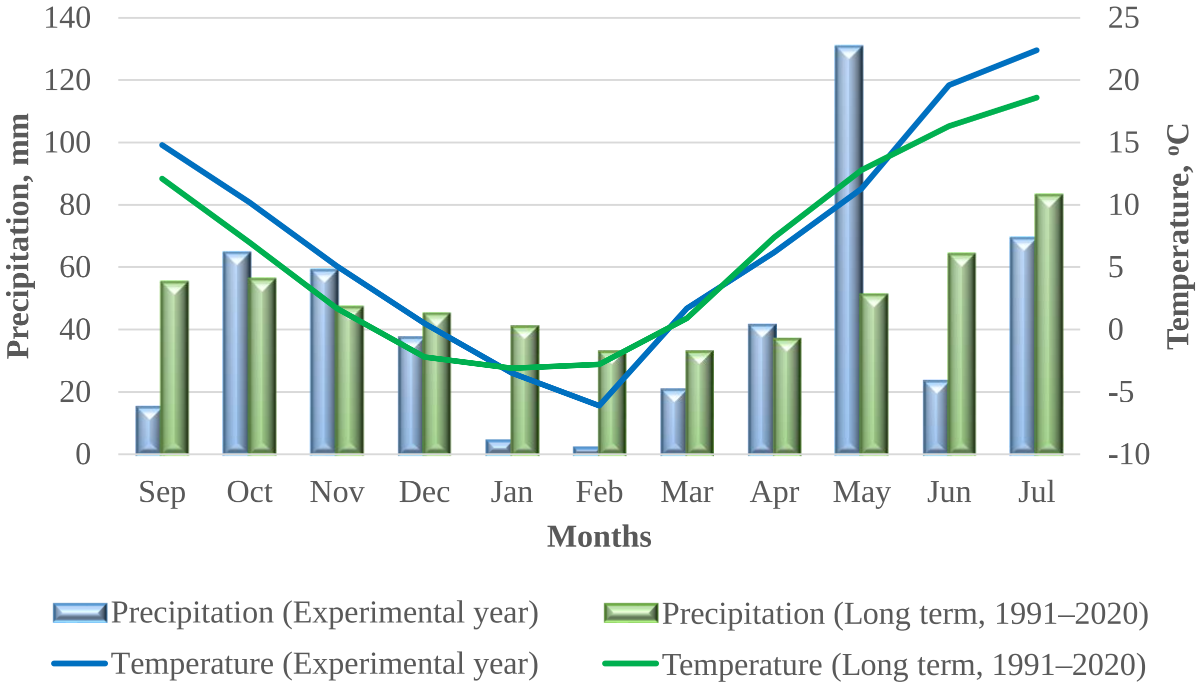

Fig. 2. Dynamics of the weather condition recorded over the experimental period compared with long-term average monthly temperature and precipitation

Determination of soil variability

It is well documented in the literature that ECa is an important parameter to indicate and map variability in soil properties (Mouazen et al., 2020). Therefore, before the precision seeding experiments, a soil scan was carried out using an EM38-MK2 ECa scanner (Geonics Ltd, Canada). ECa measurements (mS m^{-1}) in the soil layer from 0 to 1.5 m depth were performed by driving a Toyota Hilux (Toyota Motor Corporation, Toyota, Japan), which was equipped with a Trimble EZ-Guide 250 global positioning system (GPS) (Trimble Navigation Ltd., Alpharetta, USA) with a GPS antenna (Trimble Navigation Ltd., Alpharetta, USA). The EM38-MK2 scanner mounted on a plastic sled was dragged along the measurement tracks at 24 m intervals. An Open-Source Geographic Information Systems (QGIS) software was used to divide the entire field area into 5 soil MZs, according to the ECa results obtained. An average of 8 samples (from 0–20 cm soil layer) were taken from each soil MZ and the soil texture was determined in the Agrochemical Research Laboratory of the Lithuanian Research Centre for Agriculture and Forestry using the method by sieving and sedimentation (ISO 11277:2020). The soil properties of the entire experimental field were also studied. It was determined that the average pH of the field soil was 7.3 (varied from 6.6 to 7.5), the average phosphorus content was 4.2 mg 100 g^{-1} (3.1–5.5 mg 100 g^{-1}), potassium was 12.1 mg 100 g^{-1} (10.4–13.9 mg 100 g^{-1}), magnesium – 14.9 mg 100 g^{-1} (12.1–16.7 mg 100 g^{-1}), organic matter – 2.0% (1.6–2.3%).

Seeding methods

Soil granulometric composition and its apparent electrical conductivity are closely correlated parameters. Differences in these properties were applied to the site-specific seeding of winter wheat. Based on the results of the field soil granulometric composition and ECa (Table 1), all MZs were assigned a soil fertility class, ranging from the highest soil fertility in MZ1 to the lowest in MZ5. The seeding experiment compared between two methods e.g., URS and SSS. For the conventional URS method, a seeding rate of 180 kg ha^{-1} of winter wheat (variety Skagen) specific to the region was applied. For the SSS method, the Robin Hood seeding system (Munnaf et al., 2021) was adopted, where the seeding rate is increased in the MZ of poorer-yielding soils and reduced in the MZ of higher-yielding soils. In our study, the variation between the highest (214 kg ha^{-1}) and the lowest (146 kg ha^{-1}) seeding rate was around 30%, as reported by other researchers (Lovell, 2016). Winter wheat (*Triticum aestivum* L.) was sown after pea harvest, following the no tillage practice. A Horsch Avatar 6.16 SD (HORSCH Industrietechnik GmbH, Germany) direct seeder with a working width of 6 m, was used for seeding, with 167 mm row spacing, an average depth of 30 mm, and a speed of 10 km h^{-1}. The seeding rate was changed automatically. A map of variable rate seeding in shape format was uploaded to the tractor terminal, and the information of the specific seeding location and seeding rate was transferred from the terminal to the work computer of the seeder.

Determining yield indicators

To determine the biological yield of winter wheat, 40 locations (red dots in Fig. 1) were randomly selected, in which crop sampled were collected by cutting the plants along one-meter row 5 days before harvest. The individual samples were then threshed in the laboratory using a laboratory thresher (Wintersteiger LD 350, Austria), weighed using a laboratory balance Kern KB 3600 – 2N (Germany), and converted to yield per hectare at a uniform grain moisture content (13.0 %). An average of 8 samples (40 in total) were taken from each soil MZ. Sampling location was also linked to different seeding methods, which allowed a broad analysis of yield parameters. Plant height, straw-to-grain ratio, the number of ears per unit area, the number of grains per ear, the weight of 1000 grains, and grain protein content were determined. Straw to grain ratio (%) in each MZ for both seeding methods was calculated from straw weight and grain weight per unit area. Grain protein content was determined using a GrainSense hand-held spectrometer (GrainSense Oy, Finland).

Cost-benefit assessment

After determining the winter wheat yield, the potential revenue (hereafter referred to as "revenue") from the sale of the grain was calculated. The average market price for winter wheat during the harvest rime was 240 Eur t^{-1} (Overview of food prices…, 2022), whereas the average market price of seeds at the time of seeding was 370 Eur t^{-1}. According to these prices the gross margin for the SSS and URS was calculated. Fuel costs, costs of technological operations for crop maintenance and harvesting, costs of materials used, labor, and other costs were not included in the calculation, as these costs were the same for both seeding methods and in all MZs. Relative gross margin and an increase in gross margin were calculated by comparing the values obtained from the SSS treatment with that of the URS average. Using SSS, a different seeding rate was applied in each MZ area, so a relative gross margin comparison was also calculated between both seeding methods in each MZ.

Statistical analysis

To ensure the reliability of the results, the experimental studies were carried out in 4 replications for each seeding method. In each replication, 5 samples were taken for the determination of winter wheat grain yield and its productivity and quality parameters (height of stems, straw-to-grain, number of ears, number of grains per ear, weight of 1000 grains, and grain protein content) resulting in a total of 40 samples, 20 for SSS and 20 for URS treatment. The data between soil zones (MZ) were processed using one-way ANOVA. Differences between URS and SSS seeding methods were analyzed by two-way ANOVA. The means of the data were compared by calculating the least significant difference ($LSD_{0.05}$) using a T-test at the 95% confidence level. The same letters (*a*, *b*, *c*, etc.) in the tables indicate that there is no significant difference between soil MZs. A symbol "*" in the tables indicates that there is significant difference between the URS and SSS (*URS vs SSS*) seeding methods in a particular MZ.

Results and discussions

Soil ECa, texture and granulometric composition

The soil ECa in the field ranged from 22.6 to over 28.6 mS m^{-1} (Table 1). The highest proportion of clay (14.8%) was found in the MZ1, where the highest electrical conductivity was determined. The soil texture was very similar in all management zones of the experimental studies. The sand was the predominant texture fraction in all MZs. In the first four zones MZ1–MZ4, the percentage of sand varied from 60.8 to 73.3%. In these MZs the soil texture was a sandy loam, while in MZ5 the percentage of sand was even higher, and the soil texture was a loamy sand according to the United States Department of Agriculture (USDA) texture classification. Considering the soil ECa and granulometric composition, a comparative soil fertility and seeding rate for SSS method were assigned to each MZ.

Table 1. Soil properties and average seeding rate for each MZ

Management zone	ECa, mS m^{-1}	Granulometric composition of soil				Soil fertility*	Seeding rate, kg ha^{-1}	
		Texture	Sand, %	Silt, %	Clay, %		URS	SSS
MZ1	>28.6	sandy loam	60.8	24.4	14.8	highest	180	146
MZ2	27.3–28.6	sandy loam	73.3	17.4	9.3	medium-high	180	153
MZ3	25.7–27.3	sandy loam	69.0	19.4	11.6	medium	180	180
MZ4	24.2–25.7	sandy loam	70.6	18.7	10.7	medium-low	180	197
MZ5	22.6–24.2	loamy sand	81.4	12.0	6.6	lowest	180	214

Note: *comparative soil fertility from highest to lowest.

Maps of soil ECa and SSS rate

The soil ECa map in Fig. 3, clearly shows that the largest part of the field (36%) was composed of ECa, which varied between 25.7 and 27.3 mS m^{-1}. This ECa was assigned to the middle soil management zone MZ3, and it was assumed that the soil fertility in this MZ was average. This was subsequently used to produce an SSS map, which assigned an average seeding rate of 180 kg ha^{-1} to this MZ, the same as the one used under the URS method. The Robin Hood seeding approach (feeding the poor) intends to reduce the seeding rate in the relatively higher soil fertility zones and increase the seeding rate in the poorer soil fertility zones, while maintaining an overall difference of around 30% between the highest and the lowest seeding rate.

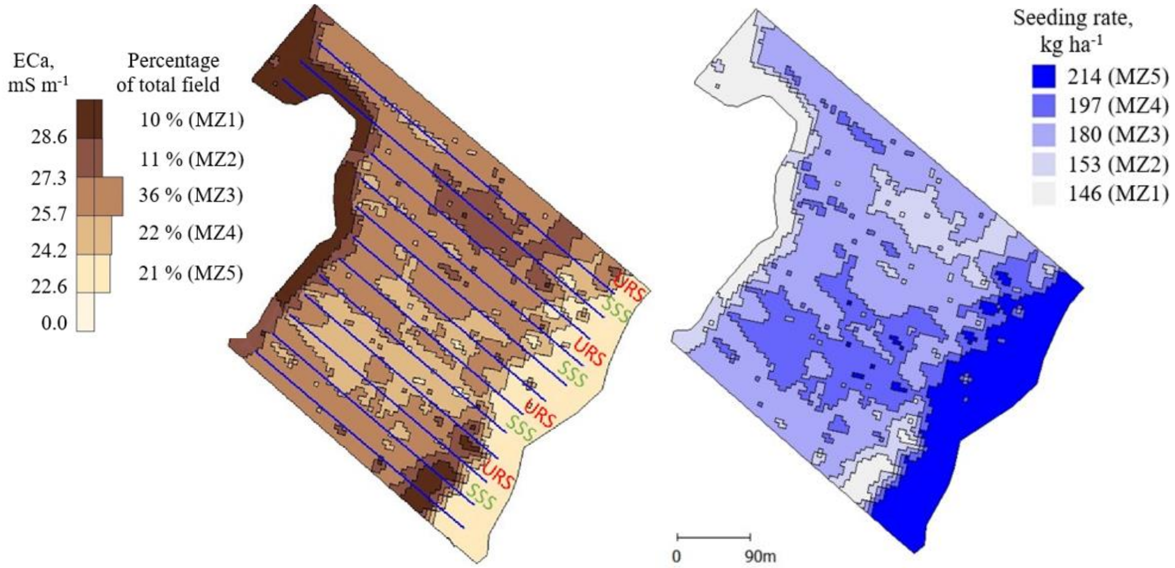

Fig. 3. Maps of the apparent electrical conductivity (ECa – left) and site-specific seeding recommended rate (right) of the experimental field soil

Stem height and straw-to-grain ratio

Pre-harvest measurements of the stem height of productive winter wheat with a ruler showed that the average stem height was higher, although not significantly, under the SSS method (Table 2). Significant differences in stem height between the URS and SSS methods were obtained in zones MZ1 and MZ5, where SSS resulted in significantly higher heights compared to URS. In the other zones, there was no significant difference. When evaluating the stem height between MZs under the same seeding method, it was found that for URS there were significant differences between all soil MZs except MZ3 and MZ4. In the SSS method, the poorest zone MZ5 had the significantly lowest winter wheat stems (83.4 cm). A significant difference was also found in MZ4 compared to MZ1 and MZ2. Previous research has suggested that stem height and seeding rate may be correlated. Iqbal et al. (2012) found that as the seeding rate increased from 150 to 175 kg ha^{-1}, plant height decreased. The results obtained in the current study confirm this inverse relationship, as plant height was the lowest in zone MZ5, having the highest seeding rate. However, when the research results were obtained in relation to ECa, it was observed that the height of winter wheat stems increased with increasing ECa in both URS and SSS treatments, except in MZ1, where there may have been a headland effect characterized as being highly compacted.

Table 2. Stem height and the straw-to-grain ratio of winter wheat as a function of soil management (MZ) and seeding method [e.g., site specific seeding (SSS) and uniform rate seeding (URS)]

Management zones	Height of stems, cm		Straw-to-grain ratio	
	URS	SSS	URS	SSS
MZ1	86.20 *b* *	90.40 *e**	0.85 *b*	0.84 *cd*
MZ2	93.07 *c*	91.05 *e*	0.88 *b*	0.84 *cd*
MZ3	90.43 *a*	89.45 *ef*	0.87 *b*	0.89 *e*
MZ4	89.53 *a*	88.46 *f*	0.83 *b*	0.81 *c*
MZ5	79.67 *d* *	83.40 *g* *	1.09 *a* *	0.87 *de* *
Average	87.78	89.35	0.90 *	0.85 *
$LSD_{0.05}$	*2.50*	*1.76*	0.05	0.03
$LSD_{0.05}$ *(URS vs SSS)*	*2.13*		0.04	

Notes: the same letters (*a*, *b*, *c*, etc.) indicate that there is no significant difference between soil MZs. A symbol "*" indicates that there is significant difference between the URS and SSS seeding methods in a particular MZ.

When analyzing the effect of the seeding density treatment on the straw-to-grain ratio, it was found that there was a significant difference in the average straw-to-grain ratios between the URS and SSS methods. A significant difference was observed for MZ5 only, where grain yields differed. The SSS method showed a significantly higher grain yield in this zone compared to the URS, although the straw biomass was quite similar. The analysis of the straw-to-grain ratio between the individual zones in the URS method revealed that zone MZ5 showed a significant difference compared to all other zones. The SSS method did not show such a significant difference in the values of this ratio between individual MZs, but a significant difference was also found between MZ4 and MZ3 and between MZ4 and MZ5. Significant differences were also found between MZ1 and MZ3 and between MZ2 and MZ3. Previous studies reported that this straw-to-grain ratio is 0.8 for barley and wheat, 0.9 for rye and triticale, and 1.1 for oats (Gauder et al., 2011). In contrast, Samireddypalle et al. (2019) reported straw-to-grain ratios in the range of 1.0 to 1.1. The straw-to-grain ratio obtained in our study fell within the range reported by other authors and varied from 0.83 to 1.09 in the URS and from 0.81 to 0.87 in the SSS method.

Ear and grain parameters

Pre-harvest samples of winter wheat provided an opportunity to evaluate the dependence of important yield components on the seeding method and field soil zone. The analysis of the number of ears showed that the URS method had the highest number of ears in zones MZ4, MZ3, and MZ2 (Table 2), of 609.4, 607.0, and 602.0 ears m^{-2}, respectively. There was no significant difference in the number of ears between these zones. Compared to the best-performing soil zones, significantly fewer ears were found in zones MZ1 and MZ5 in both the URS and SSS methods. Although on average more ears were found in the SSS variant when comparing seeding methods, the differences were not significant. When analyzing the results of the SSS variant, it was observed that although in zones MZ1 and MZ5 different numbers of seeds per square meter were sown, e.g., 326 and 478 seeds m^{-2}, respectively, a similar number of ears were found at harvest e.g., 519 and 546 ears m^{-2}, respectively. This indicates that the ratio of ears to seeds was better in zone MZ1 than in zone MZ5, e.g., 1.59 versus 1.14, respectively.

The average crop density is usually determined by the amount of space and land per plant required to support plant growth and development. The area of space is determined by the availability of sunlight to the individual organs of the plant, and the area of land is determined by the ability to feed and water the plant. Judging by the space requirement, under the Baltic climate conditions and high soil productivity, a winter wheat plant needs an average space of 15–16 cm^2 per plant, or 625 productive stems per square meter. This would be the maximum density of the winter wheat crop, which could be problematic if exceeded (Šiuliauskas, 2020). Poškus et al. (2022) analyzed the impact of fertilizer application on the yield of winter wheat, reporting that the number of productive stems per square meter varied from 587 to 676. In our study, similar results were obtained compared to previous works, as the number of ears varied from 516 to 609 ears m^{-2} in the URS and from 519 to 642 ears m^{-2} in the SSS method. Kühling et al. (2017) indicated that seeding rate affected two components of spring wheat yield, namely, number of ears per square meter and number of grains per ear. A higher seeding rate resulted in more reproductive ears per square meter, while a lower seeding rate produced more grain per ear.

The number of grains per ear is an important parameter that can determine the final yield of wheat (Iqbal et al., 2012). The current study shows that although there were significant differences between the individual MZs, the number of grains per ear in the SSS method was significantly more uniform than in the control URS method (Table 3). Significantly the lowest average number of grains per ear (28.59) in the URS method was found in the least fertile MZ5 (Table 3). In this zone, yield was the lowest, which may be attributed to the lower moisture reserves (e.g., lower water holding capacity) of the lightest soil texture of this zones and the earlier onset of grain maturity. Significant differences between URS and SSS were found in MZ1, MZ4, and MZ5. In the URS and SSS methods, the number of grains per ear ranged from 28.59 to 37.96 and from 34.44 to 39.01, respectively. This corresponds to the results of Šuliauskas (2020), who points out that the average number of grains per ear of winter wheat is around 32–35 grains, which can increase to up to 45 grains per ear with modern technology. Other researchers have demonstrated that the number of grains per ear depends on the seeding rate (Iqbal et al., 2012). Increasing the seeding rate from 125 to 175 kg ha^{-1} increased the number of grains per ear from 36 to 40.

Table 3. Ear and grain parameters of winter wheat in different management zones (MZs) obtained under the uniform rate seeding (URS) and site-specific seeding (SSS) methods

Management zones	Number of ears per m^2		Number of grains per ear		Weight of 1000 grains, g	
	URS	SSS	URS	SSS	URS	SSS
MZ1	516.0 *a*	519.0 *c*	36.86 *ab* *	35.68 *d* *	34.81 *a*	35.68 *c*
MZ2	602.0 *b*	639.0 *d*	37.96 *b*	39.01 *e*	34.27 *a*	35.72 *c*
MZ3	607.0 *b*	632.6 *d*	36.14 *a*	36.07 *d*	35.26 *a*	33.72 *d*
MZ4	609.4 *b*	642.0 *d*	37.72 *b* *	36.51 *d* *	35.95 *a*	37.44 *e*
MZ5	552.0 *a*	546.0 *c*	28.59 *c* *	34.44 *f* *	28.59 *b* *	33.86 *d* *
Average	577.4	595.7	35.45	36.34	33.77	35.28
$LSD_{0.05}$	*38.73*	*40.02*	*1.31*	*0.90*	*1.68*	*1.39*
$LSD_{0.05}$ *(URS vs SSS)*	*38.93*		*1.10*		*1.68*	

Notes: the same letters (*a*, *b*, *c*, etc.) in the tables indicate that there is no significant difference between soil MZs. A symbol "*" in the tables indicates that there is significant difference between the URS and SSS seeding methods in a particular MZ.

The analysis of the yield parameters showed that the SSS method led to a higher average weight of 1000 grains than the URS method. The largest and most significant difference between the two seeding methods was obtained in the lowest fertility MZ5. Comparisons between zones showed that the URS method had the highest grain weight in MZ4 and the lowest in MZ5. While there was no significant difference between the first four zones, the results obtained for MZ5 were significantly different from all the other zones. In the SSS treatment, the weight of 1000 grains varied from 33.72 to 37.44 g and in the URS ranged from 28.59 to 35.95 g. The MZ4 (SSS) had the highest grain weight and was significantly different from the other zones. There were no significant differences only between MZ1 and MZ2 and between MZ3 and MZ5. Independent studies have shown that the weight of 1000 grains of winter wheat in the Baltic region applying the URS method can range between 36 and 41 g (Poškus et al., 2022) or between 42 and 45 g (Šuliauskas, 2020). In the current study, however, increasing the seeding rate did not lead to significant changes in the weight of 1000 grains. However, previous research has demonstrated that an increase in seeding rate can both increase (Zecevic et al., 2014) and decrease (Laghari et al., 2011) the weight of 1000 grains. Holman et al. (2021) concluded that the seeding rate of winter wheat did not have a significant effect on grain weight.

Yield and protein content of winter wheat

The most important indicator of crop production in terms of efficiency is crop yield. Results of this work reveals that the average grain yield for the entire field using the SSS method was 7805 kg ha^{-1}, 7.85% higher than that of the conventional URS method with a fixed seeding rate (Table 4). Out of the five MZs, the yield of four MZs of SSS was higher than that of the URS by 5.85 – 13.43%. In two soil zones, MZ2 and MZ5, significantly higher grain yields were found with the SSS method. The lowest grain yield was obtained in MZ5, where the soil was also the lightest and poorest compared to the other zones. However, examining the effect of seeding methods on grain yields, the largest increase (13.43%) in grain yield due to SSS was observed in the lowest soil fertility MZ5. A similar result was reported by Munnaf et al. (2020) for potato. The smallest non-significant difference between URS and SSS was in zone MZ3, which is quite logical since this is the zone where the seeding rate of the two seeding methods coincided, at 180 kg ha^{-1}. Iqbal et al. (2012) found that an increase in wheat seeding rate from 125 to 150 kg ha^{-1} resulted in a significant increase in grain yield from 3949 to 4242 kg ha^{-1}, although a further increase in the seeding rate of 175 kg ha^{-1} resulted in a decrease in grain yield to be 4055 kg ha^{-1}. Similar findings were reported by Wang et al. (2021), who found that increasing the seeding rate of winter wheat from 150 to 300 kg ha^{-1} increased the grain yield from 7285 to 8456 kg ha^{-1}, while further increases led to a decrease in grain yield. The results of current study demonstrated that in MZ4 and MZ5, increasing the seeding rate in the SSS method resulted in higher grain yields, which is a similar result to the that reported by Bhatta et al. (2017) that wheat grain yield increases with increasing seeding rate. In MZ1 and MZ2 having the lowest seeding rate was applied, it was observed that a higher tillering coefficient was achieved as reported by Kazlauskas et al. (2021).

The URS method resulted in the highest grain yield (8272 kg ha^{-1}) in MZ4, while the significantly lowest (5623 kg ha^{-1}) was obtained in MZ5 (Table 4). In this treatment, a significant difference was also found in MZ1. In this zone, the grain yield of winter wheat was significantly higher than in MZ5, but significantly lower than in other field areas MZ2-MZ4. Although MZ5 had the poorest soil and MZ1 had the highest fertility soil, both zones were mostly located on the field headlands, which may have negatively affected the grain yield. If the areas of both headlands were eliminated, the grain yield would vary from 7775 to 8272 kg ha^{-1} and there would be no significant difference between the MZ areas.

The highest grain yield by the SSS method was 8851 kg ha^{-1}, which is 579 kg ha^{-1} higher than the highest yield by the URS method. Although the difference in yield was clearly visible, it was not significant. The analysis of grain yield in different MZs showed that the highest yield was obtained in MZ2 and MZ4, the lowest, as in the case of URS, was in the MZ5 area. Although the soil with the poorest fertility had the highest sowing rate, the grain yield of winter wheat in the zone of the poorest soil was 6378 kg ha^{-1} and was significantly lower than in other MZs. However, comparing the seeding methods with each other it was found that a significant increase in the grain yield (13.43%) was obtained in this MZ5 zone. A significant increase in grain yield by the SSS method compared to URS was also found in the MZ2 area, while in other MZs the increase was noticeable, but it was not significant.

The variation in the seeding rate influenced the yield variation in individual MZs, but a clear direct dependence of the apparent electrical conductivity of the soil on the winter wheat grain yield and its components could not be seen. Data from previous studies by other authors (Ehsani et al., 2005) showed weak relationships between soil ECa and yield, indicating that an increase in ECa could lead to increased yield potential, whereas increased seeding rate showed fluctuating trends in yield potential. The conclusions of another work (Kostic et al., 2021) indicate that soil ECa did not meet a certain correlation with wheat properties and cannot be characterized as a significant parameter. The analysis of the impact of the seeding rate on the yield in this study showed that the application of the SSS method had a particularly good effect on the areas of light sandy soil with poor fertility, where soil ECa was the lowest.

The grain protein content is one of the most important quality indicators for winter wheat, as the protein content of the grain determines the suitability to produce bread. Zhao et al. (2019) indicated that the cereal protein content for bread production should be above 12.5%. The results obtained in our study showed that irrespective of the seeding method, the grain protein content varied from 14.23 to 18.12% (Table 4). The highest protein content in both seeding methods was found in the MZ5, where yields were the lowest. Analysis of the grain protein content in relation to the seeding method revealed that the URS method had a slightly higher average protein content than the SSS method. This is true for all MZs except MZ1. This inverse relationship between winter wheat yield and grain protein content was also confirmed by other authors (Sieling and Kage, 2021; Ayadi et al., 2022). Shah et al. (2020) reported that an increased seeding rate resulted in a higher grain protein content compared to the normal seeding rate, although the difference was not statistically significant.

Table 4. Winter wheat yield and grain protein content obtained from the site-specific seeding (SSS) and uniform rate seeding (URS) treatments, shown for individual management zone (MZ) and average per seeding treatment.

Management zones	Grain yield, kg ha^{-1}			Grain protein content, %		
	URS	SSS	Difference between SSS and URS, %	URS	SSS	Difference between SSS and URS, %
MZ1	6621 *b*	7325 *d*	10.63	14.23 *b* *	16.13 *e* *	13.35
MZ2	7893 *a* *	8851 *e* *	12.13	16.48 *c* *	15.21 *f* *	-7.71
MZ3	7775 *a*	7715 *d*	-0.77	15.09 *a*	15.01 *fg*	-0.53
MZ4	8272 *a*	8756 *e*	5.85	15.23 *a* *	14.46 *g* *	-5.06
MZ5	5623 *c* *	6378 *f* *	13.43	18.12 *d* *	16.22 *e* *	-10.48
Average	7237	7805	7.85	15.83	15.41	-2,65
LSD$_{0.05}$	*808*	*609*		*0.79*	*0.69*	
LSD$_{0.05}$ *(URS vs SSS)*	*705*			*0.73*		

Notes: the same letters (*a*, *b*, *c*, etc.) in the tables indicate that there is no significant difference between soil MZs. A symbol "*" in the tables indicates that there is significant difference between the URS and SSS seeding methods in a particular MZ.

Cost-benefit analysis

The cost-benefit analysis revealed that the economic benefits depend on the seeding method and MZ. The best gross margins for the URS were achieved in zones MZ2–MZ4. The gross margins of individual MZs 2, 3 and 4 were higher than that of the average of the URS seeding, ranging between 7.73% and 14.88% (Table 5). The lowest yield (revenue) and gross margin were obtained in zone MZ5 [-387.31 Eur ha^{-1} (-23.19%)] having the lowest soil fertility, followed by MZ1 [-147.79 Eur ha^{-1} (-8.85%)], compared to the URS average.

Table 5. Comparative cost-benefit analysis of seeding winter wheat of uniform rate seeding (URS) and site-specific seeding (SSS) methods

Seeding method	MZ	Seed rate, t ha^{-1}	Seeding cost, Eur ha^{-1}	Yield, t ha^{-1}	Revenue, Eur ha^{-1}	Gross margin, Eur ha^{-1}	Relative gross margin*, Eur ha^{-1}	Increase in gross margin*, %
URS	MZ1	0.180	66.60	6.621	1589.04	1522.44	-147.79	-8.85
	MZ2	0.180	66.60	7.893	1894.32	1827.72	157.49	9.43
	MZ3	0.180	66.60	7.775	1866.00	1799.40	129.17	7.73
	MZ4	0.180	66.60	8.272	1985.28	1918.68	248.45	14.88
	MZ5	0.180	66.60	5.623	1349.52	1282.92	-387.31	-23.19
	Average		66.60	7.237	1736.83	1670.23	-	-
SSS	MZ1	0.146	54.02	7.325	1758.00	1703.98	33.75	2.02
	MZ2	0.153	56.61	8.851	2124.24	2067.63	397.40	23.79
	MZ3	0.180	66.60	7.745	1858.80	1792.20	121.97	7.30
	MZ4	0.197	72.89	8.756	2101.44	2028.55	358.32	21.45
	MZ5	0.214	79.18	6.378	1530.72	1451.54	-218.69	-13.09
	Average		65.86	7.810	1874.64	1808.78	138.55	8.30

Notes: MZ – management zone. The average market price of winter wheat seed used for calculations was 370 Eur t^{-1} (2020); the average market price of winter wheat grains was 240 Eur t^{-1} (2021); * Gross margin values were calculated for the URS and SSS relative to the URS average.

The analysis of the economic benefits of the SSS method showed that the average gross margin was 138.55 Eur ha^{-1} or 8.3% higher than that of the URS method. This is also true for the per MZ gross margin, where SSS resulted in increasing the gross margin (2.02 – 23.79%) for all MZs except for MZ5, where a loss of -218.69 Eur ha^{-1} was recorded compared to the average URS gross margin (Table 5). The gross margin of SSS was higher than that of the corresponding MZ under the URS method in all MZs, except for MZ3, where results were very similar. The relative gross margin between SSS and URS in MZ1 area was 181.54, MZ2 – 239.91, MZ4 – 109.87 and MZ5 –168.62 Eur ha^{-1}, or the increase in gross margin in the SSS method was 11.92%, 13.13%, 5.73% and 13.14% respectively. The gross margin of MZ5 was the lowest, followed by MZ1 as both were under soil compaction effect. The results of the cost-benefit analysis of this study showed that although the SSS-Robin Hood method was applied, when applying a higher seeding rate in poorer soils, the SSS method has both yield and economic benefits compared to URS. The findings of other authors, who applied different SSS methods to different crops, demonstrated that the Kings-SSS method, with higher seeding rates on higher fertility soils, yielded greater benefits. Other researchers reported relative increases in the gross margin of Kings-SSS compared to URS ranging between 5.35 and 56.0% for potato (Munnaf et al., 2020b), between 26.7 and 92.67 Eur ha^{-1} for maize (Munnaf et al., 2022) and 3.95% for winter wheat (Kazlauskas et al., 2022). However, the cost-benefit analysis in this work and majority of previous work did not account for the costs of soil scanning and mapping, which can reach up to 25 Eur ha^{-1} per year (Munnaf et al., 2021). Accounting of these costs in the cost-benefit analysis may reduce the economic return accordingly but does not negate the positive cost-benefit trends of the SSS approach.

Conclusions

Choosing the right seeding method is one of the most important decisions for field operation when growing winter wheat. However, the relationship between seeding rate and yield parameters in winter wheat is a complex one that depends on many factors, including differences in soil properties and yields. The spatial variability in soil properties and soil fertility has a strong effect in this, which needs to be managed site specifically. The site-specific seeding (SSS) method contributes to the correct management of these spatial variabilities, leading to higher yield and productivity parameters of winter wheat. Several of yield performance parameters such as the number of ears per area, number of grains per ear, and weight of 1000 grains also showed better results in the SSS method than in the conventional URS method. The higher grain weight in SSS resulted in a significantly lower straw-to-grain ratio compared to URS. Despite this the grain protein content was lower in the SSS than in the USR treatment. The cost-benefit analysis showed an increase in the SSS gross margin of 8.3% (e.g., 138.55 Eur ha^{-1}), compared to the USR treatment. The current work also revealed that future studies should avoid the headlands as the yield is affected by soil compaction from repeated pass of heavy agricultural machinery. To assess the prospects of precision seeding, it is necessary to include variable seeding depth alongside SSS, which can provide new insights into the possibilities of optimizing seeding according to vertical and spatial variabilities.

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