agriculture

Review

Variable Rate Seeding in Precision Agriculture: Recent Advances and Future Perspectives

Egidijus Šarauskis [1], Marius Kazlauskas [1], Vilma Naujokienė [1,*], Indrė Bručienė [1], Dainius Steponavičius [1], Kęstutis Romaneckas [2] and Algirdas Jasinskas [1]

[1] Institute of Agricultural Engineering and Safety, Agriculture Academy, Vytautas Magnus University, Studentu Str. 15A, Kaunas Distr., LT-53362 Akademija, Lithuania; egidijus.sarauskis@vdu.lt (E.Š.); marius.kazlauskas@vdu.lt (M.K.); indre.bruciene@vdu.lt (I.B.); dainius.steponavicius@vdu.lt (D.S.); algirdas.jasinskas@vdu.lt (A.J.)

[2] Institute of Agroecosystems and Soil Science, Agriculture Academy, Vytautas Magnus University, Studentu Str. 11, Kaunas Distr., LT-53361 Akademija, Lithuania; kestutis.romaneckas@vdu.lt

* Correspondence: vilma.naujokiene@vdu.lt

Abstract: The main objective of this study was to analyze variable rate seeding (VRS) methods and critically evaluate their suitability and effectiveness for the challenges under field conditions. A search was performed using scientific databases and portals by identifying for analysis and evaluation 92 VRS methodologies, their impact and economic benefits depending on the main parameters of the soil and environment. The results of the review identified that VRS could adapt the appropriate seeding rate for each field zone, which was based on site-specific data layers of soil texture, ECa, pH and yield maps. Then, remotely detected images or other data which identify yield-limiting factors were identified. The site-specific sowing method (with a variable sowing rate for each field area) allows the optimization of crop density to obtain the best agronomic and economic results. Various proximal and remote sensor systems, contact and contactless equipment, mapping and VRS modeling technologies are currently used to determine soil and crop variability. VRS depends on the field characteristics' sowing equipment capabilities, the planned harvest, soil productivity and machine technology interactions with the environment. When forecasting the effective payback of a VRS over the desired period, the farm size should on average be at least 150 ha. In future studies, to achieve the best solutions and optimal methods, it is important to test, evaluate and put into practice the latest methodologies on farms, to perform complex assessments of changes in sensor, soil, plant and environmental parameters.

Keywords: precision farming; site-specific seeding; prescription maps; apparent electrical conductivity; proximal sensing

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1. Introduction

Variable rate seeding (VRS) is a precise agricultural technology that can properly and accurately adjust the seeding rate according to the variability of soil properties, terrain, meteorological conditions and other factors. VRS not only provides better opportunities for the use of variable soil nutrient and water storage capacity characteristics, it can also increase crop yields by reducing seed consumption. Seed germination, crop development and yield potential may vary in different areas of a field, and thus VRS is a method of linking seed quantities to a specific area, thereby increasing crop yields and production profits. By implementing VRS practices, farmers can better manage farm risk and focus more on investing in areas with higher return potential. In most regions of the world, the implementation of VRS in agriculture has been relatively low [1,2]. A prescription map is an electronic data file containing specific information about input rates to be applied in every zone of a field. One of the main reasons for an increased interest in VRS is that VRS technological solutions have been introduced into agricultural machinery and have become easier to implement. In addition, VRS innovations combined with high-precision global navigation satellite systems allow farmers to create and implement VRS prescriptions to optimize seed placement and yield [2,3].

Seeding and planting at a variable rate are particularly useful in very heterogeneous fields, i.e., in fields with very different water retention capacities or soil organic matter levels. Measurements of soil properties, plant condition and yield are performed using a precision farming system. Using the data obtained, the technological parameters of the drill are adjusted, the number of seeds to be inserted is optimized, the yield potential is increased, and the quality of the plants is improved [4]. VRS is likely to work well in changing crop protection and crop nutrition strategies [2].

When developing a VRS application program at the level of a specific farm, a correct choice of precision agricultural technologies for the whole complex and a good understanding of the growth environment of different plants for each field is required. Forming this understanding requires not only good intuition by the farmer himself but also spatial layers of field data that allow the field to be divided into separate soil management zones (MZ) in which each MZs is subject to a unique VRS. General spatial layers of field data should include maps of soil properties, height difference data and yield maps of previously grown crops [5]. Precision agriculture (PA) technologies, variable rate fertilization and liming and seeding operations are applied to individual field MZs [6]. Other authors emphasize that one of the most important tasks for the successful application of PA technology is the assignment of optimal rates of fertilizers, limes or seeding in individual field MZs [7,8]. Modern farmers are well-aware of the differences in their soil productivity and recognize the potential of using variable rate technologies compared to uniform rates. Images depicting highly variable crop growth in the fields are often used to promote the attractiveness of intuitive variable rate farming. However, to recoup the costs of applying a variable rate, it is necessary to use only well-managed and accurately predictable field changes. An element of physical soil inspection will also be required because the relationship with crop establishment is related to stone content and soil texture and so it will not be reliable to use EC maps alone in predicting seed bed quality and establishment. Yield maps have been used to identify zones of different yield potential and planting rates [7].

VRS is a very important, but still emerging, PA technological operation, which has a particularly important impact on the further stages of plant development and the production efficiency of the whole farm. Therefore, it is crucial to have sufficient information for the application of VRS to be successful. Unfortunately, the resources of the scientific literature on the application of VRS to different plants are still quite limited. In particular, few research results have been published on seedings under VRS with one of the most popular plants—winter wheat. Winter wheat is one of the most popular plants in the world and is the most popular plant in Lithuania. In addition, the number of studies conducted with wheat VRS remains limited. The main aim of this study was to review and provide a synthesis of the recent advances in VRS methods and to critically analyze their suitability in view of the challenges posed under field conditions.

2. Search Methods

The review discusses scientific, technical and other documents from a particular time period (the search time duration was from 1998 to 2021). The review was written as a report on the subject of the research area and as an introduction before the planned experimental research. The survey drafting method was a piecemeal and systematic method, rather than impulsive. The scientific literature was analyzed and the review plan was prepared based on information that was clearly divided into sections. These methods were used as they were most convenient for the reader.

The literature search was performed using databases such as ScienceDirect, Wiley Online Library, Springer Link, Scopus and Google Scholar. We refined publications by domain (engineering, life sciences, agriculture, environmental science, earth and planetary sciences, energy, etc.) and publication type (journals, books, etc.). The subjects in the ScienceDirect database were physical sciences and engineering, earth and planetary sciences, energy, engineering, life sciences, agricultural and biological sciences and environmental science. The subjects in the Scopus database were agricultural and biological sciences, environmental science and engineering. The subjects in the Wiley Online Library were life sciences, earth space and environmental sciences, agriculture, aquaculture and food science and technology. The subjects in Springer Link were engineering, environment and life sciences (Figure 1).

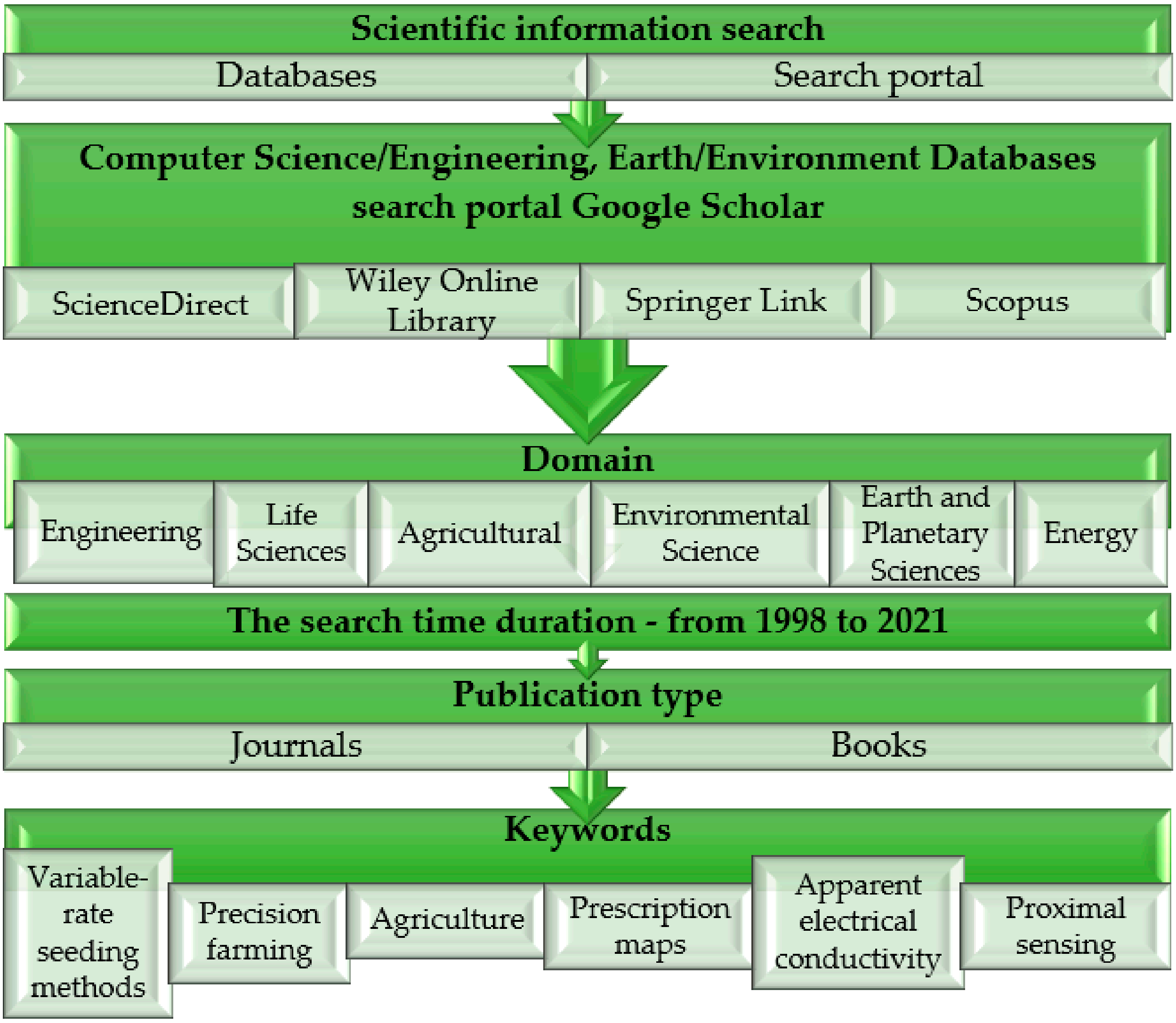

Figure 1. Scientific review information search strategy and enforcement selection process.

The time duration for articles and books was set from 1998 to 2021. Our in-depth analysis and evaluation largely focused on the most recent literature, the most relevant and useful of which was published between 2000 and 2021. Filtering by journal or book title was performed using the query string. We searched for the keywords "variable rate seeding methods", "precision farming", "agriculture", "prescription maps", "apparent electrical conductivity" and "proximal sensing", and a large volume of work from diverse professional fields was retrieved.

The scientific analysis first involved identifying the different techniques and methodologies used and then discussing and abstracting the results obtained by applying different methods depending on the variation of the main parameters of the soil and the environment. The conclusions provide suggestions for practitioners by highlighting the most optimal options that yielded the best results for the improvement of the environment and production (Figure 2).

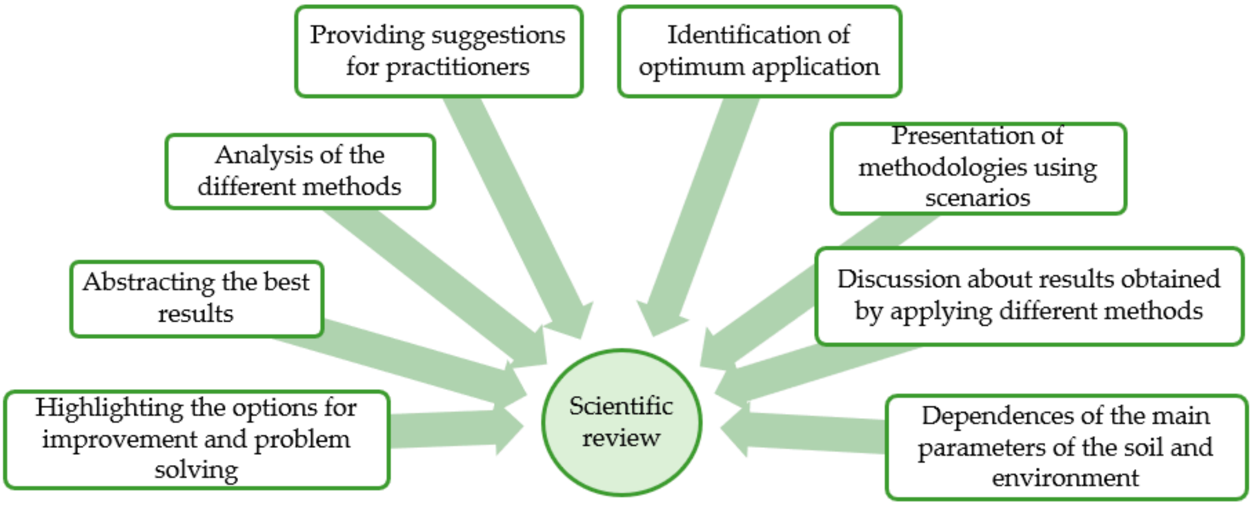

Figure 2. The components of the scientific information selection process of the review. These parts formed our review structure.

Most of the articles focused on general information on seeding and thus the collected information related to soil property maps, soil sensing methods and equipment used for VRS was purposefully concentrated. First, we analyzed the soil sensing methods and equipment used for VRS, then the influence of VRS on wheat growth characteristics and finally, what economic benefits could be obtained. Each document was reviewed and questions, including what soil sensing methods and equipment were used for VRS, how this affected wheat growth characteristics and what economic benefits were obtained, were answered (Figure 3).

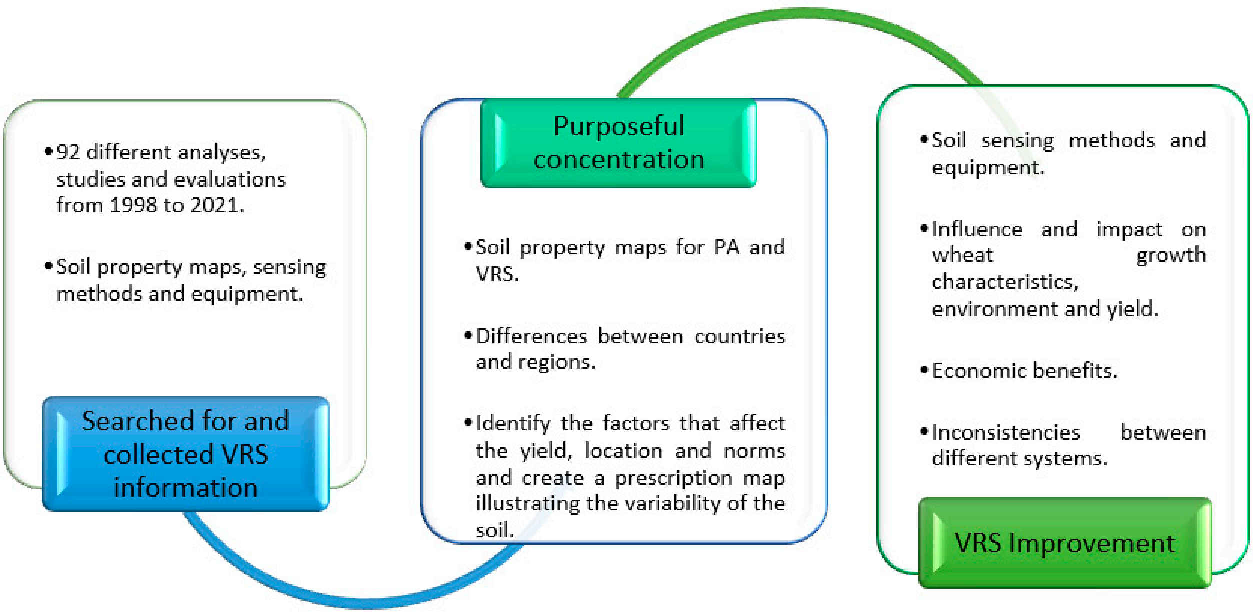

Figure 3. Method of evaluation of variable rate seeding methods and their applications in practice.

In summary, a significant beneficial effect has been identified as a result of the application of certain processes as a multifunctional filter for farmers. The main aim of this analysis was to provide a synthesis of recent advances in VRS methods and to analyze their suitability in view of the challenges posed under field conditions.

3. Findings

3.1. The Assessment of Soil Property Maps for PA and VRS

Depending on the country and the region, different methods are used to develop VRS. An essential element of VRS implementation is to identify the factors influencing the yield and the specific location in order to classify the sowing areas and to assign the necessary norms to them, thus creating a prescription map illustrating the variability of the soil [2]. In order to increase the value of VRS, it is necessary to define appropriate crop management zones or decision zones, in which soil types, topography, irrigation, long-term yield history, apparent electrical conductivity, etc. can be described [9]. A crucial element of VRS implementation is the establishment of site-specific factors impacting yield in order to create seeding zones and assign rates, thus generating a seeding prescription (RX) map. Fundamentally, two main methods are distinguished for the application of variable rate seeding—VRS based on a map and VRS based on sensor data [10,11]. Using the mapping method, soil and crop properties are determined, samples are taken, modeling and mapping are performed and variable rate seeding recommendations are prepared. These steps are performed in advance of the actual use of precision seeding in the field. Meanwhile, in a sensor data-based approach, these different steps mentioned are performed in real time using advanced algorithms, hardware, and software [11]. Recent VRS innovations increase our ability to insert two different plant varieties into the field. This corresponds to a multi-layer seeding method where seeds or two different varieties are distributed differently in the same field at the same time [2].

With the development of PA technologies, variable rate application technologies are increasingly used. They are often based not only on previous crop performance but also on soil productivity, soil structure, organic matter, landscape position, topography, or some combination of these [12]. Kaspar et al. [13] found that the yield potential of higher landscapes and steep slopes was lower than that of lower landscape positions in years when precipitation was below average. Griffin and Hollis [14] used landscape position elevation maps to identify areas of different yields in the field. Another common way to produce a variable rate seed plan is to start with a soil electrical conductivity survey that, along with other soil properties, identifies changes in soil texture. Figure 4 shows a map of the field terrain highlighting the difference in altitude at different locations in the field.

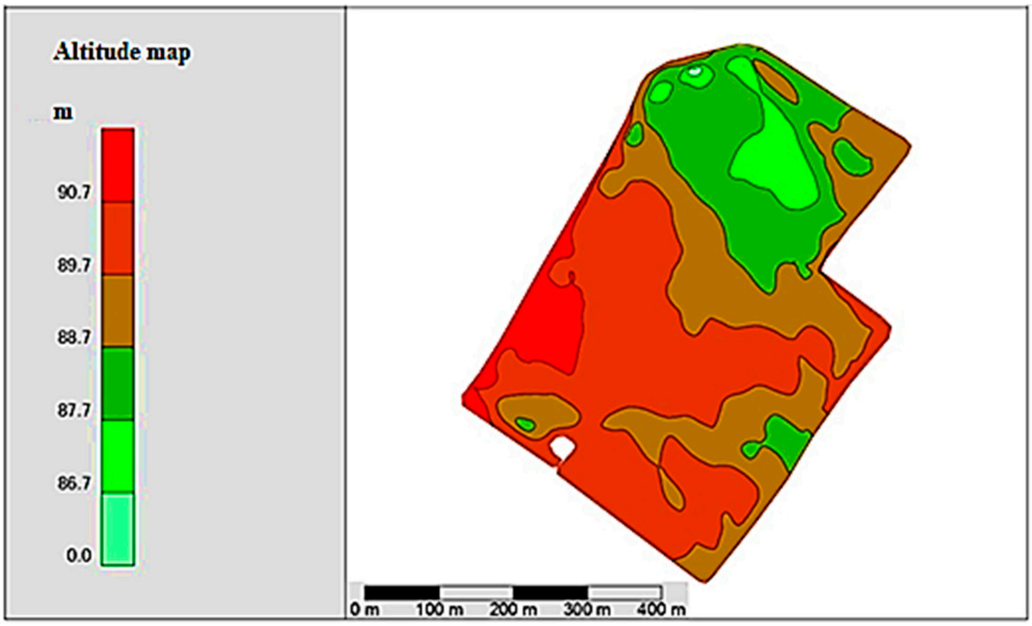

Figure 4. Elevation map representing relief differences in the field. The colored parameter variation internal maps were created by the authors using a Veris MSP 3150.

Soil property maps are probably the most important datasets used for the implementation of PA technologies. Table 1 provides a summary of the analysis of scientific sources showing the main soil properties applied to PA technologies by other authors.

Table 1. The main soil properties applicable to PA technologies.

Soil Properties	Application of PA Technologies	Reference
Organic matter, pH	Variable-rate seeding application on farms	[15]
pH	An on-the-go sensor used for mapping	[16]
SOC, soil texture	Exploring the driving forces and digital mapping using remote sensing	[17]
Soil texture	Electromagnetic induction for regional data coordination	[18]
	Radar and optical data from Sentinel-1 and Sentinel-2	[19]
Apparent electrical conductivity (ECa)	Applications of soil electrical conductivity mapping	[20]
	Scientific equipment and measurements in agriculture	[21]
	Effect of variable rate seeding on seedbed and germination parameters	[22]
Bulk density	Novel electromechanical system application	[23]

Soil productivity is defined as the ability of soil to provide plants with the necessary nutrients [24] and sufficient water. The ability of soil to perform various functions of biological productivity, such as ensuring the function of ecosystems, maintaining environmental sustainability and promoting plant and animal habitats, is often understood as soil quality [25]. The soil quality indicator is sensitive to any changes in the soil [11].

Soil pH affects the availability of nutrients important to plants, such as phosphorus and trace elements and herbicide activity. With the field area divided according to soil pH, lime and other sources of calcium can be used more accurately. This increases the likelihood that the amount required by the right product will be accurately distributed in the right places, which can increase the utility and efficiency of the product used as well as the crop yield [15]. Soil fertility and pH influence crop yield potential, and with precision soil management, can provide information that can be used for generating VRS RX maps. This soil information could reveal opportunities around determining high and low yield potential areas in a field depending on water availability; water represents the most important driver of crop yield.

Soil organic matter is another very important soil property, which has a significant effect on crop productivity. Organic matter (OM) is one of the main components of soil structure and porosity, influencing soil water retention capacity, biodiversity, the activity of soil organisms and the availability of plant nutrients, especially nitrogen [15]. The amounts of OM can vary significantly in different field areas, which is perfectly demonstrated by the field study performed in Lithuania with Veris MSP 3150 and the OM map presented in Figure 5.

PA technologies are increasingly being implemented using the variability of apparent electrical conductivity. Apparent electrical conductivity (ECa) is a property of soil that indicates its ability to conduct electricity. ECa field measurements started with soil salinity measurements, which were linked to the irrigation of arid agricultural areas [21]. This electrical soil property is influenced by a combination of physical and chemical properties, including soluble salts, clay content, soil water content, soil temperature, organic matter content and bulk density [21]. ECa varies depending on the amount of moisture retained by the soil particles. Thus, ECa strongly correlates with the size and the structure of soil particles. Saline soils and clay have high conductivity, silt has medium conductivity and sand has low conductivity [2,26].

ECa measurements, together with other soil properties, determine the changes in soil structure. Another common way to produce a variable rate seed plan is to start with a soil electrical conductivity survey that, along with other soil properties, identifies changes in soil texture [20]. Apparent electrical conductivity is related to soil structure and previous studies are mainly based on higher ECa values associated with higher yield areas, so these areas can grow a larger plant population. This method has been used mainly for corn crops in North America, but it is not necessarily the correct method for winter wheat or other crops that, due to their ability to bush, do not show a linear relationship between number plants and yield [14]. Experimental studies were carried out in Lithuania when an ECa map (Figure 6) was prepared after estimating the differences in soil granulometric composition, according to which the winter wheat seeding map of the study field was created. For winter wheat sowing, an average seeding rate of 180 kg ha^{-1}, typical for this region [27], was chosen. Then, variable rate seeding was applied to each of the five soil management zones (MZ), varying between the zones by about 20%—from a minimum of 146 kg ha^{-1} to a maximum of 214 kg ha^{-1} [22].

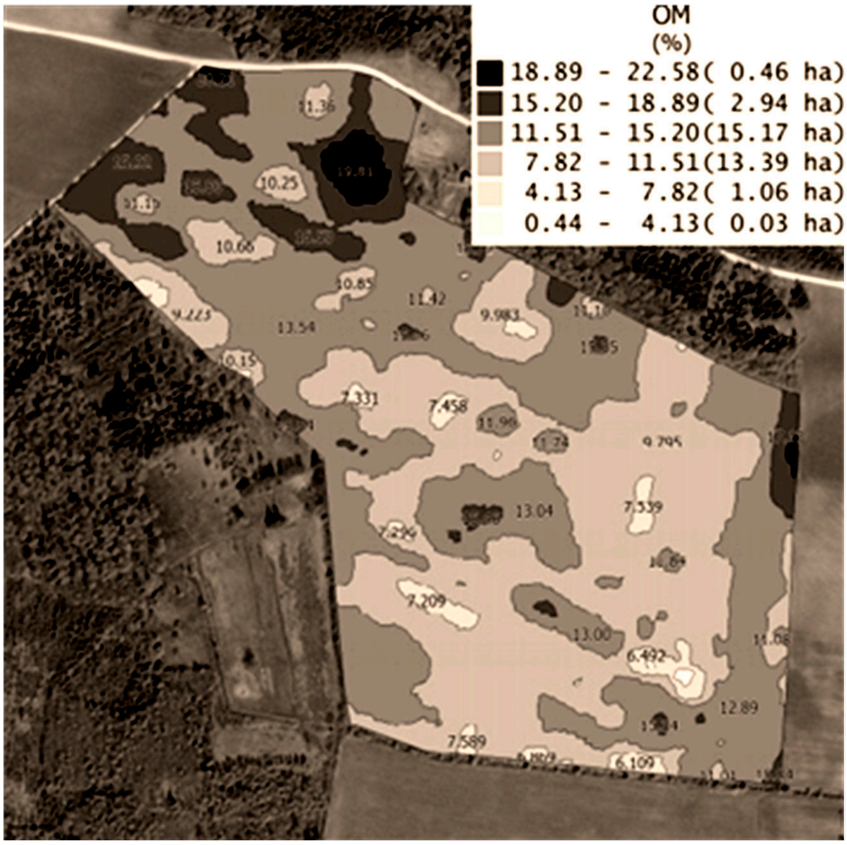

Figure 5. Map of soil organic matter differences. Colored parameter variation internal maps were created by the authors using a Veris MSP 3150; as a background layer, we used an ORT10LT digital raster orthophoto map of a territory in the Republic of Lithuania, M 1:10,000 (compiled 2012–2013) in the precision farming software AgLeader SMS Advanced.

When analyzing the influence of VRS on winter wheat production indicators, it was found that the unevenness of the field soil had a significant impact on the quality of seed placement, germination and plant tillering [22]. Using the same winter wheat seeding rate of 180 kg ha^{-1}, the germination of winter wheat seeds was significantly lower (MZ1—62.7% and MZ2—72.6%) in the two MZs with the highest soil ECa than in the remaining three soil MZs. There were no significant differences between MZs in the application of VRS. Changes in seed germination may have been influenced by soil structure and seedbed quality [14].

Soil ECa maps can be created for a variety of soil depths, from 5 to 150 cm. Figure 7 shows two ECa field maps drawn at the depths of 30 and 90 cm using a Veris MSP 3150 machine. These images illustrate that the apparent electrical conductivity was higher over the entire field as the measurement depth was increased but the differences between the zones remained similar.

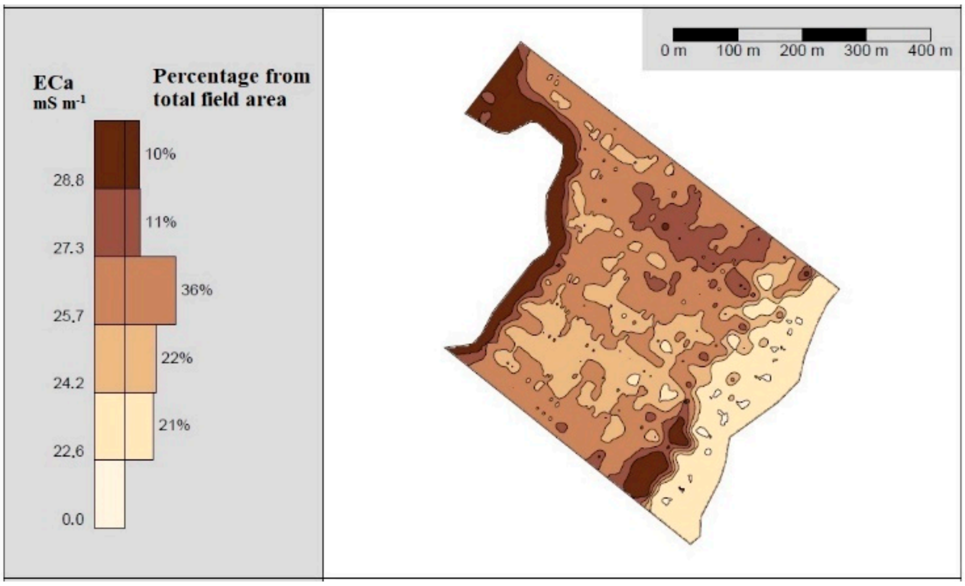

Figure 6. ECa map representing differences in soil properties in the field. The colored parameter variations were created by the authors using an EM38-MK2 device [22].

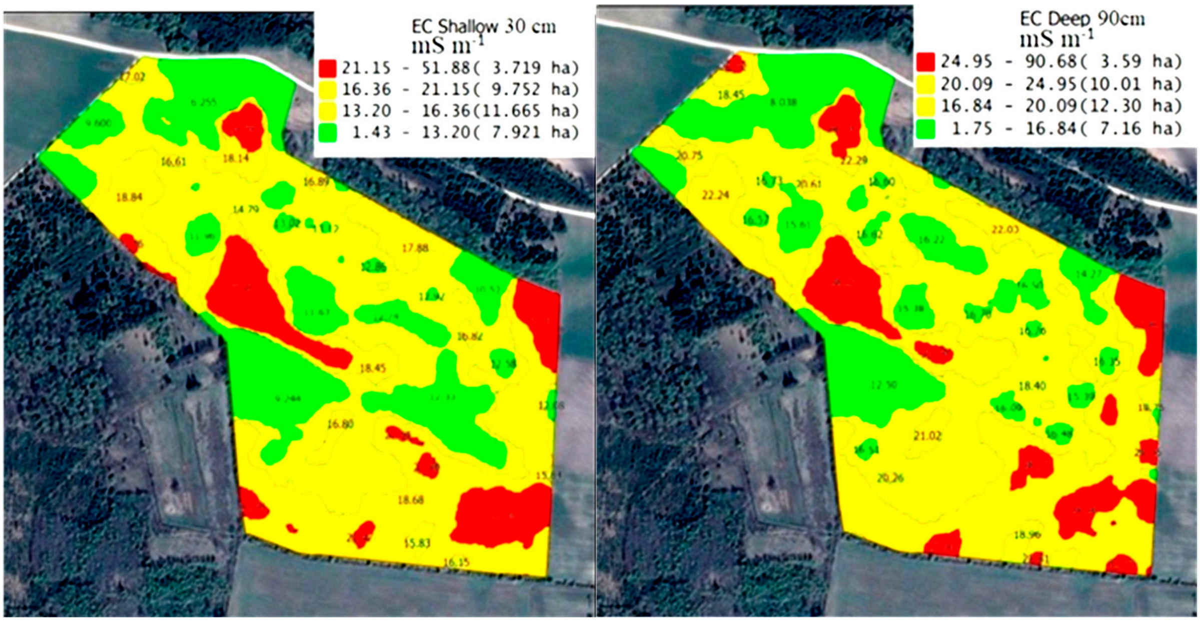

Figure 7. ECa maps of soil surface structure differences at the depth of 30 cm (**left**) and 90 cm (**right**). The colored parameter variation internal maps were created by the authors using a Veris MSP 3150; as a background layer, we used an ORT10LT digital raster orthophoto map of a territory in the Republic of Lithuania, M 1:10,000 (compiled 2012–2013) in the precision farming software AgLeader SMS Advanced.

Chemical and physical soil properties and topographical features are highly interrelated. As one soil characteristic changes, it can cause changes to other characteristics [28]. Soil organic carbon, pH, phosphorus, bulk density, water accumulation and other physical, chemical and biological properties are the most often reflected soil quality indicators [11,29]. It is not possible to assess soil functionality based on the individual soil property responsible for regulating crop yields [30], as changes in crop yields are influenced by a number of biotic and abiotic factors [31–34].

Studies by Reining et al. [35] with winter wheat showed that factors such as soil quality and precipitation had the greatest influence on the change in sowing rate. In order to optimize the seeding rate in VRS technologies, it is necessary to have as much information as possible about the properties of the soil and the crop. The seeding rate is optimized based on measurements such as soil ECa, soil pH, crop nitrogen content, previous yield and grain protein indices [36]. Water availability and accumulation are important parameters for determining the yield potential and optimal seeding rate in specific field areas, especially in dry weather conditions [12]. It is generally accepted that the specific optimal sowing rate depends on soil conditions, such as texture. However, optimal seeding rates can almost never be accurately known [37].

The mapping of soil properties such as pH and organic matter also holds great potential for delineating spatial variation in fields. Soil organic matter maps can be used to develop management zones for variable nitrogen and seeding rates. It is generally thought that areas of higher organic matter can support higher seeding rates. Soil sensing tools can better characterize the within-field variability into MZ and perhaps serves as a better source of information than soil surveys for deriving variable rate prescriptions of crop inputs.

3.2. The Assessment of Soil Sensing Methods and Equipment Used for VRS

The use of actual small-area data from a number of locations can provide an approximation of a variable rate seeding plan in order to increase the economic return on agricultural production. However, determining the optimal seeding rate for each field remains a challenge. The definition of specific control zones may be possible using different soil properties [12], but it may take time to establish consistent models under different crop rotations or tillage regimes [38–40].

Based on soil ECa, Taylor et al. [41] created VRS maps and evaluated them using GIS global information systems. In their study, soil ECa was considered an indicator of soil quality, which showed a different (positive and negative) correlation between the crop yield and the seeding rate in different years. ECa data collected using Veris or electromagnetic EM devices show soil productivity zones. The elevation and the slope of the terrain, collected using real-time kinematics (RTK), is also valuable information. All these data help to determine the MZs of the soil and allow us to establish the appropriate plant density and yield potential for each of these zones. This should result in the identification of the maximum yield for each zone. Topography and landscape position often have a significant impact on soil properties and, consequently, crop productivity, and can therefore enhance proximal and remote soil sensing. VRS has been proven to be profitable for fields with highly variable levels of productivity [42].

Munnaf et al. [43] argue that uniform rate seeding (URS), where field characteristics differ, is an inappropriate approach to the sustainable management of farm resources. They performed a study using field scanning online visible and near-infrared (vis-NIR) spectroscopy and an electromagnetic induction (EMI) sensor. The uniform rate seeding method was compared with two VRS methods, the first based on a soil MZs map generated using EMI data and the second treatment based on the fusion of vis-NIR measured soil data with the Sentinel-2-derived normalized difference vegetation index (vis-NIRsen). The latter method makes it possible to assess the interrelationships between the main characteristics of the soil and the yield using different seeding intervals. The research results obtained showed that both VRS methods resulted in higher yields of potato tubers and higher economic returns compared to URS [43].

A soil permeability map is a simple, inexpensive tool that farmers can use to describe soil differences in farm fields quickly and accurately. Soil ECa is the ability of a soil to transfer or transmit an electric current in units of millisiemens per meter [26,44–46].

In the agricultural industry, crop yield and seeding maps are becoming increasingly important as these two-parameter data layers help us to better understand the feasibility of VRS. The variable rate seeding strategy for each soil MZs is based on the following data: long-term yield history, field productivity, soil dryness and moisture, apparent electrical conductivity, environmental response units, soil type, topography, landscape, slope, drainage and color, crop, soil and plant vegetation index [9]. Site-specific field data, such as digital soil maps, aerial photographs, apparent electrical conductivity maps, or previous-year yield maps, are the basis for calculating the optimal site-specific seeding rate. In this way, VRS application maps are created, showing differences in the seeding rate due to different conditions related to location, cultivation system and short-term parameters (Figure 8). This means that the generated VRS maps describe the situation only at a certain point in time [47]. Prepared VRS prescription maps are recognized by most seed drills [8].

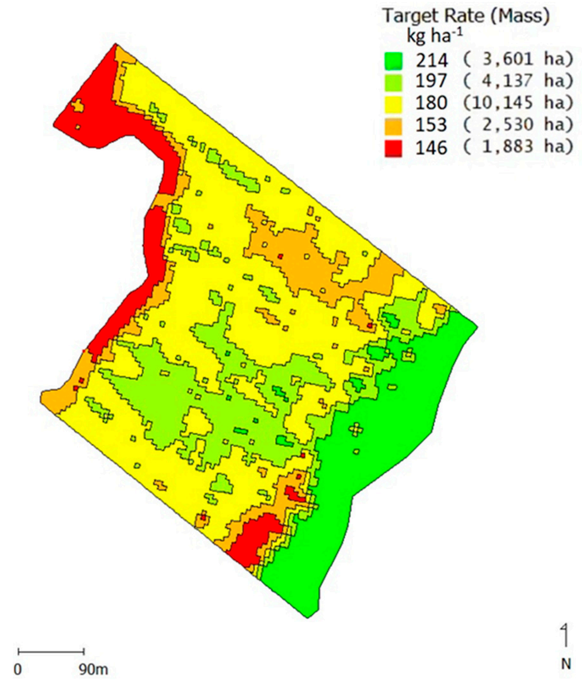

Figure 8. Winter wheat VRS map. The colored parameter variation was created by the authors using SMS software with the data received from an ECa map.

In heterogeneous fields, it is useful to change the number of seeds according to the soil potential. In precision agriculture, machinery makes it possible to adapt the optimal number of seeds, thus saving farm resources and achieving more environmentally friendly agricultural production [47]. The main process of VRS is the creation of a pre-scription map for individual fields. Research has shown that the development of such prognostic maps needs to be managed separately due to differences in the unique variability and historical management of each field. When designing zones, it is necessary to consider around four to five variables (yield, soil, terrain, etc.), paying attention to those that limit the yield [2].

When creating a prescription map, the number and diversity of plant populations in each area must be determined before loading the map onto the tractor cab screen. In most cases, there can be around four to five variables to consider in designing zones (yield, soil, terrain, organic matter, etc.), with attention being paid to those that are yield-limiting factors. When working with a population (seeds per hectare), a different zoning rate of at least 15–20% must be maintained in order to maximize the yields in response to VRS. In general, higher seed populations will be found in soil areas with higher yield potential and in lower yield areas seed population rates are lower [48]. Methods for zoning may include assessments of aerial imagery [49], soil type, farmers' knowledge of fields [50], soil characteristics [51], crop history, water availability, terrain, yield maps or remote sensing [52].

Mapping systems are not suitable for large variations in soil conditions that are highly dependent on weather conditions. Therefore, future advanced farming requires systems that overcome the limitations of a map-based approach. Sensor-based, real-time, site-specific seeding (SSS) requires high-resolution data collected using advanced sensor technology. This continuous flow of sensor data is consistently translated into information and recommendations to be implemented by the right controller, all in real time [10].

Seeding by sensor makes it possible to overcome the limitations of the map method. The design of the sensing and control device is very important, as the incorrect design of the system can sometimes cause problems [11]. SSS is an accurate application method that takes into account inherent soil heterogeneity to maximize crop yields and to minimize seed yields. Most SSS program practices are based on management zone (MZ) maps generated using different inputs [11], which include total field productivity, land and moisture, soil and crop vegetation, environmental response index [9], terrain attributes [2], soil fertility status, structure, [53], color [9], apparent electrical conductivity [53,54] and historical yields [35,55,56].

The main requirements for the implementation of the VRS system are to have the right technology, the right prescription mapping process and trained specialists. Key VRS technologies include a GPS receiver and a cab display with the ability to load and execute prescription maps, collect data and provide real-time feedback to the tractor operator on drill performance and VRS drill capabilities. VRS options include a hydraulic drive that allows the seeding rate of the seeding machine to be changed throughout the crop rotation [2]. With the development of real-time kinematic (RTK) and other high-grade GPS receivers, accurate topographic measurements can be obtained simultaneously with proximal readings of soil sensors [44]. Variable rate sowing adjustment technologies can operate on prescription maps or real-time (online) sensor readings, which can be adapted to change the sowing rate according to certain algorithms. Site-specific properties in the field (soil properties, OM, landscape differences, etc.) can be detected during the sowing of cereals or before sowing using various sensors. Optical sensors detect the proportion of organic matter and/or moisture in the soil, non-contact EC sensors detect electromagnetic induction, electromagnetic induction sensors detect the electrical conductivity or moisture of the soil (e.g., EM38 TopSoil Mapper GEM-2 and DUALEM), electrical resistance sensors determine the electrical conductivity of the soil from which the soil moisture is determined and gamma ray sensors determine the proportion of organic matter in the soil and texture (e.g., SoilOptix) [45]. Research has shown that the real-time sensor on Veris' multi-sensor platform (MSP) accurately matches the spatial models of organic matter (OM) and cation exchange capacity (CEC). Veris OpticMapper can register the values of soil OM and CEC in real time using a dual wavelength optical sensor mounted on a specially configured row unit [44]. This allows plant residues to be removed and the sapphire window at the bottom of the sensor to adhere to the soil, recording readings every second. Conventional soil samples are obtained from the field after passing with OpticMapper, with soil sample sites monitored by OpticMapper measurements [15,44].

Integration of automatic sensing, modeling and control systems is a complex task. The "VRfertilizer" program and the application of the pesticide Chlorpyriphos can be distinguished as examples of sensor-based site-specific applications [57]. SSSs also have the potential to apply similar principles and thus future research should focus on the development and evaluation of sensor-based SSSs in a variety of soil qualities and crop, local and weather conditions [11].

Measurements of apparent electrical conductivity correlate with soil properties that affect crop productivity, including soil structure, cation exchange capacity, drainage conditions, salinity and subsoil properties [26,58]. The contact method for mapping the soil ECa uses coulters that are in direct contact with the soil to measure its ECa. Another non-contact method uses electromagnetic (EM) induction to measure soil ECa [42]. The latter method can be used to determine the differences in soil properties in the field. To create an accurate soil sampling plan and variable rate seeding map an EM-38 MK-2 scanner can be used (Figure 9). When mounted on plastic sleds, ECa measures from 0 to 150 cm soil depth [22].

Veris Technologies' commercial soil ECa mapping system measures ECa at two depths (0–30 cm, 0–90 cm) when the device is pulled through the field. The ability to measure and obtain results from approximately 25 sample sites per hectare provides the farmer or consultant with a higher resolution dataset to measure the changes in field pH. The usual grid soil sampling practice can provide pH values for each 2.5–4.0 ha area. The sampling resolution of Veris Soil pH Manager is 25 to 40 times higher than that provided by a conventional soil grid. The pH controller can be paired with a soil ECa array to simultaneously capture soil pH, soil ECa and soil color [15]. The sensor operates by lowering the sampling mechanical arm into the soil to take the sample and then lift the sample in front of the electrode set to measure the pH before repeating the process. Studies have shown that one-hectare grids have a wide range of pH values, often ranging from soil that requires lime to soil with a particularly high pH [59].

Figure 9. EM38-MK2 remote sensing device constructed on a plastic sledge [22].

Veris Technologies' Soil pH Manager is equipped with a sensor for real-time determination of soil pH (Figure 10). It automatically collects soil samples and measures soil pH from direct contact with soil material along the way [16].

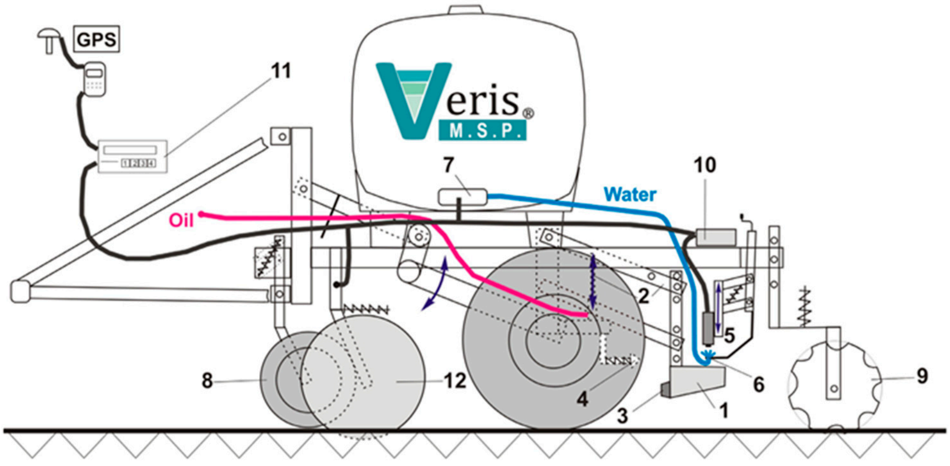

Figure 10. Veris multi sensor platform (MSP) with the Soil pH Manager: 1—soil sampler shoe; 2—parallel linkage; 3—adapter; 4—scraper; 5—pH sensors; 6—water supply with nozzles; 7—water pump; 8—row cleaner; 9—furrow closer; 10—controller; 11—data recorder; 12—sensor of apparent electrical conductivity [16].

As mentioned earlier, two main SSS methods based on maps and touch systems are distinguished. [10]. According to the mapping method, soil and crop identification and sampling, modeling, mapping and the preparation of SSS recommendations are performed in advance of the actual field use and in a sensor-based SSS these different steps are realistically performed by algorithms, hardware and software [11]. The map-based SSS is related to the adjustment of the sowing rate according to the previously created and loaded prescription map in the virtual terminal of the precision seeding machine. GIS and geostatistical analysis allow for the linking of the measured attributes. Based on the yield status of the different field zones, the field is divided into several smaller zones that are assigned a certain seeding rate to create a program application map (AM) or management map. Once the AM is generated, it is converted into a machine-compatible form file and uploaded to the virtual terminal [60]. When working in the field, the variable rate seeding controller delivers the seeding rate according to the optimal quantity and the corresponding location as specified in the AM. A positive aspect of this system is the time it takes to conduct research and then apply VRS. This improves controller responses and smooths out transitional VRS processes. To work under this principle, the equipment uses on-the-go sensors for variable rate seeding (Figure 11). Soil organic matter sensors detect different levels of organic matter and adjust the number of seeds accordingly. There are also soil moisture meters that can be used to adjust the depth and to change the seeding rates [10].

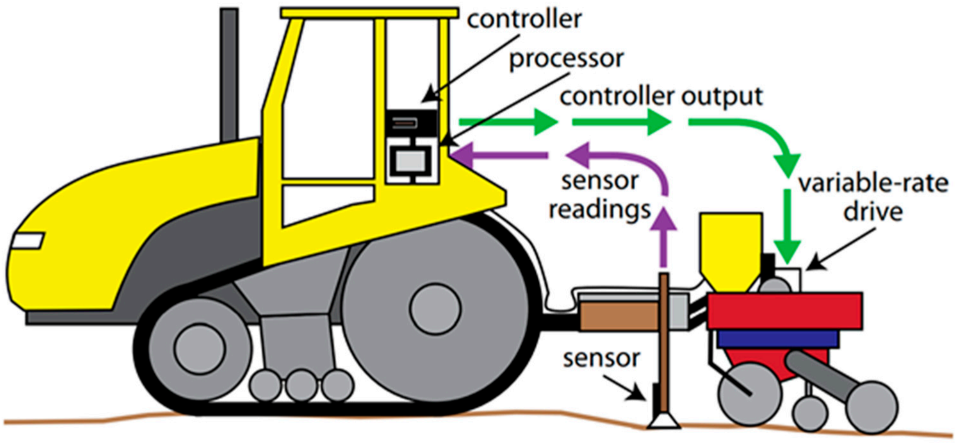

Figure 11. On-the-go soil properties sensor measurement before seeding and adjustment of seeding rate [10].

Another modern soil sensor is the SoilXplorer, which uses innovative methods for real-time soil structure analysis. This is a non-contact sensor that uses electromagnetic signals to measure the soil ECa and is used to justify variable tillage depth, variable seeding depth and variable seeding rate. Soil ECa is highly correlated with the size of soil particles and soil structure. For example, sandy soils have larger particles and low water retention capacity, resulting in lower ECa, while ECa is higher in clay and organic soils. Therefore, the soil sensor can detect compacted areas and readjust the working depth accordingly. Based on this measurement principle, soil type zones, relative water content and compaction zones can be determined. As a result of its four reception coils, ECa can be measured in four different soil layers (0–25 cm, 15–60 cm, 55–95 cm and 85–115 cm) at the same time [61,62].

The SoilXplorer sensor (Figure 12) is installed at a height of 30–40 cm in front of the tractor or other machine so that the drill or tillage machine can be attached at the rear [60]. The sensor autonomously identifies different soil properties, and in real time, the ISOBUS seed drills adjust the seeding rate according to the soil texture and the relative amount of soil water. The highest seeding rate applies to the best soil conditions and the lowest to poor conditions, although the opposite may be the case. With the SoilXplorer sensor, farmers can deepen their knowledge of the soil and increase the efficiency of the tillage and seeding processes. Field tests have shown that reducing the tillage depth from 18 to 10 cm reduces energy expenditure during the tillage process by 45%. Additionally, during the same process, wheel slip can be reduced by about 53% and output can be increased by about 20% [61].

Figure 12. SoilXplorer device for measuring soil structure differences [60].

VRS technology requires the preparation of a prescription map showing how the electronic controller of seed drill should change the gaps between the seeds in a row to make it as convenient as possible to change the seeding rate. Indeed, VRS can be performed by commercial seed drills with electronic seed metering disc controllers that can change the seeding rate by changing the seed distance along the row [63]. There are two main ways to adapt uniform rate seed drills for variable rate seeding, i.e., by changing the active feed-roll length or by changing the seed meter drive shaft speed [62]. With the addition of a controller to a conventional seed drill, it is possible to change the drive speed of the seed metering unit on-the-go. Jafari et al. (2010) presented a system for modifying a conventional seed drill into a variable rate seed drill. It consisted of a DC motor with a fixed speed gearbox, encoders for determining the drive wheel and motor speed of the seed drill, a GPS receiver, a DC electric motor controller and a laptop. The results of the research using different seeding rates from 87.5 (low) to 262.5 (high) kg ha^{-1} showed that the seeding transition rate time from low-to-high and from high-to-low was 7.4 and 5.2 s, respectively [64].

Currently, seed drill manufacturers have adapted to the needs of precision farming and offer farmers a wide range of seed drill models for seeding cereal at a variable rate. Kazlauskas et al. [22] carried out winter wheat seeding at a variable rate with a Horsch Avatar 6.16 SD direct seed drill and the seeding rate varied from 146 to 214 kg ha^{-1}. Cereal seeding at a variable rate can also be conducted with a Vaderstad Spirit 400C, a Horsch Focus 6TD and other seed drills (Figure 13).

(**a**) (**b**) (**c**)

Figure 13. Seed drills for VRS winter wheat seeding: (**a**) Vaderstad Spirit 400C; (**b**) Horsch Focus 6TD; (**c**) Horsch Avatar 6.16 SD.

4. The Influence of VRS on Wheat Growth Characteristics

Differences in seeding rates depend on the field characteristics, capabilities of the seeding equipment, yield objectives, variability of the field, productivity of the soil and understanding of the interaction with the environment. From an agronomic point of view, the seeding rate should vary by at least 4000 seeds per acre (4046.86 m^2 or about 0.4 ha) [9]. The growing number of farmers using VRS and the widespread use of GPS technology on farms are facilitating the implementation of VRS strategies. Farmers need to be well-aware of the variability of their fields in order to apply the right seeding rates [9]. Too low a seeding rate can increase the risk of yield decrease, and too high a seeding rate can increase the total cost of production [65,66].

Precision agricultural technologies can improve the performance of field operations, as errors in the study of field soil characteristics can be very costly depending on the cost of seeds and seeding.

Plant density is a particularly important factor in wheat production systems because it can be controlled. The seeding rate affects the grain yield and is expressed as having a linear and quadratic dependence [67]. The studies of Chen et al. [68] with hard red spring wheat showed that row spacing and seeding rate do not affect each other, i.e., an increase in yield in narrow rows could not be achieved by increasing the seeding rate. Seed density control at a specific field location can be based on soil texture maps. The seeding rate should increase in sandy soils and decrease in clay soils. This principle may allow for an increase in the yield or the preservation of seeds [53].

Ayalew et al. [69] showed that an increasing number of seeds contributes to a lower number of wheat stalks. This could be because a higher seeding rate could increase competition for space, resulting in fewer stems per plant. It was also found that different seeding rates influenced different plant heights, i.e., a higher seeding rate resulted in a higher plant height, and vice versa. Higher plant density increased plant height due to reduced space for horizontal plant development and increased plant competition for light. The decrease in wheat yield with increasing seed yields can be explained by the fact that a denser wheat population forces plants to compete for production resources, which can lead to lower grain yields. Wiesehoff et al. [45] investigated the effect of different seeding rates on the germination of winter wheat in Germany. The results showed that germination decreased with an increase in seeding rate. The main reason for this effect may have been the poor distribution of grains, which led to grains being closely spaced in the soil and competing with each other. Most winter wheat cultivars allow us to compensate for the reduced plant density with higher tillering [45].

Iqbal et al. [70] found that the interaction between seeding rate and nitrogen level does not affect wheat height, number of tillers, spike length or number of spikelets in spike of 1000-grain weight but does affect the number of grains in spike, grain yield and harvest index. Kühling et al. [71] showed that the seeding rate affected two components of the spring wheat harvest—the number of ears per square meter and the number of grains per year in opposite directions. In the areas with a higher seeding rate, the predominant yield was mainly due to the number of ears, and in the areas with a lower seeding rate, there were more grains in each ear.

Optimal VRS recommendations based on a mathematical model are presented according to a predefined mathematical formula of the input seeding rate, taking into account soil quality indicators and/or yield potential. VRS recommendations are generated in real time by identifying and measuring the required soil and crop properties. Real-time optimization of seed input distribution can provide the best yield potential for a given field [12,41,72]. After examining the relationship between maize plant population and yield, a stronger relationship was found between the final number of stems and the yield than between the precision seeding rate and the number of stems. Researchers attempted to incorporate more soil parameters into yield models adjacent to plant populations in order to develop more universal models for seeding rate determination [12,41,72]. In order to obtain higher yields, it may be advisable to use a higher seeding rate in the higher-yielding soil zone, while in lower-yielding soil MZs, better yields may be achieved at lower seeding rates or plant populations [73]. In soils with higher yields and/or higher moisture content, the optimal seeding rate is higher [58]. As the soil moisture content (w) is a deterministic factor for site-specific irrigation, seeding, transplanting and compaction detection, an online measurement system will bring these applications into practice. A fiber-type visible (VIS) and near-infrared (NIR) spectrophotometer with a light reflectance measurement range of 306.5–1710.9 nm was used to measure w during a field operation [22,23]. Seed viability, germination, prevalence of pests, diseases and meteorological conditions all determine the germination and establishment of the crop, i.e., how many plants survive from 100 seeds. Different types of soil MZs based on ECa maps can be used to improve germination and establishment of wheat crops. Field inspection of the soil is also necessary before seeding, as crop germination and establishment are related to the number of stones on the soil surface and soil structure, so predicting seedbed quality and seeding using ECa maps alone will not be reliable [14].

As the plant population in the field increases, the yield per plant decreases, but the increased number of plants may be sufficient to compensate for the decrease in yield per plant [33,74]. However, at higher than optimal seeding rates, the increase in yield due to more plants may not be sufficient to compensate for the losses of one plant [40]. Optimal plant density is a function of the interaction between variety and environment, which varies between different agronomic zones [75]. The influence of plant cultivar on grain yield varies greatly depending on seeding, and the change in the seeding rate has an effect on yield components, especially stem density and the number of ears per m^2 [63,76]. As the seeding rate increases, the number of germinated plants [77] and the crop density increases [63,76], but the grain weight decreases [65,75,78], partly due to the lower efficiency of lighting [67,77]. Varieties have different abilities and adaptations to compensate for low or high seeding rate by modifying crop components such as the number of ears, the number of stems per m^2 [76], the number of grains per ear and the grain weight [65,67]. Geleta et al. [75] and Xue et al. [78] did not find a significant effect of the seeding rate on the grain yield from 65 (245 seeds m^2) to 130 kg ha^{-1} (489 seeds m^2). Stapper and Fischer [79] recorded an increased plant height due to an increase in seeding rate from 50 to 200 kg ha^{-1} (188–753 seeds m^2). It was found that increasing the seeding rate decreases the relative greenery of the leaves [66]. In addition, the highest biomass and N utilization efficiency of common white winter wheat could be achieved by reducing the standard seeding rate by 34–68% [80].

Fang et al. [81] studied the effects of different seeding rates and root pruning on winter wheat grain yield and its components before and after overwintering under field conditions. The aim of the experiment was to determine whether root pruning increased or maintained winter wheat yields at above-optimal seeding densities when growing wheat under semi-dry environmental conditions. The results showed that the yield response of the crop to the seeding rate depends on precipitation, especially on rain in the spring, which coincides with the grain-filling period. In dry years, the decrease in the yields due to higher seeding rate may have been caused by an increased competition for soil water, as more soil water was used before stem elongation due to higher seeding rate, which in turn reduced dry matter production and thus the yield. Many studies have found a positive correlation between the seeding rate, the grain yield and the average kernel weight [75,82], but Fang et al. [81] showed that this correlation depends on the availability of moisture.

In cereal crops, the yield curve is a useful statistical tool for analyzing the effect of seeding rates on plants. The effect of seeding rate on the yield was found to generally correspond to a quadratic response curve. As the seeding rate increases, the yield curve rises abruptly to the optimal seeding rate and then descends slowly [83,84]. Canadian researchers found that the seeding rate had an effect on plant density and the number of ears. Under ecological conditions, the yield increased by 10% when the seeding rate was doubled in wheat and barley cultivars [80]. Other studies have found that when wheat seeding rates were doubled at weed presence/competition locations, yields increased from

23% to 27% [85,86]. In order to optimize the wheat yield, it is important to determine the optimal number of plants per square meter. If the plant population is too large, then the crop will be too dense. This leads to difficulties in crop management and can lead to outbreaks, higher disease prevalence and higher costs. If the number of plants per m^{-2} is too low, the yield will not be optimized due to grain shortages and plants will be vulnerable to pests and will not be able to compete with weeds [14].

Wheat growth and yield depend on environmental conditions and can be regulated to some extent by selecting the right seeding time and seeding rate. Wheat yields increase due to higher seeding rates during the spring seeding [87]. Higher grain yields at higher seeding rates are associated with a higher number of ears per square meter. Therefore, the number of ears per square meter is considered to be the most important component in determining the grain yield. When calculating winter wheat seeding rate in a specific field MZ, Reining et al. [35] took into account the yield obtained from historical records for several years. The GIS-based software module calculated the seeding rate for different yield zones and transformed it directly into the seeding map. The seeding rate can be considered a factor in obtaining higher grain yields and nitrogen efficiency in winter wheat [88]. By optimizing the seeding rate, the yield and N uptake efficiency increased. The increase in N uptake efficiency was mainly due to the optimization of root length density and the synchronous increase in N from the fertilizer and N from the soil. The seeding rate had a significant effect on the number of plants, stems and ears, as well as the leaf area index.

5. The Assessment of Economic Benefits of VRS

VRS has been shown to be profitable for fields with very diverse soil productivity. Quantitative assessments of field variability should be taken into account when deciding whether to use VRS. We concluded that VRT may be of minimal value for fields with maize yields averaging from 9415 to 16,477 kg/ha. If soil types and characteristics do not vary substantially across the field, VRS may not prove to be profitable using currently available technology and agronomic knowledge [2,89]. Researchers in southern Brazil evaluated VRS by creating zones based on data from the producer on field productivity levels, as well as eight-year yield data [73]. The seeding rate of low-yield potential areas decreased and productivity increased by 1197–1900 kg ha^{-1} depending on the yield [73]. The population level of potential MZs with high soil fertility increased and productivity increased by 888–942 kg ha^{-1}, depending on the yield [73].

Economic return is a key issue for farmers interested in VRS. Lowenberg-DeBoer [90] assessed the VRS economic return using zones of yield potential. Potential VRS savings could be around USD 6.25 ha^{-1} in the fields of various seeding populations [6]. These savings from VRS can be effective in the face of rising seed prices. With digital tools and field-based data collection, VRS can enable farmers to explore and fully implement VRS and reap the economic benefits of doing so [2].

The data from the economic analysis of wheat show the effect of different seed quantities and different N levels. It is clear from the data that seeding 120 kg ha^{-1} yields the highest net income while 60 kg ha^{-1} yields the lowest net income. The highest net profit was observed by combining the 120 kg ha^{-1} seeding rate and 120 kg N ha^{-1} quantity of fertilizer, while the minimum profit was obtained when the seeding rate of 120 kg ha^{-1} was applied and nitrogen fertilizer was not used. The highest marginal rate of return was observed by combining 120 kg N ha^{-1} and 120 kg ha^{-1} seeding rate and the lowest marginal rate of return was found in control plots seeded at 60 kg ha^{-1} [91].

Several researchers have analyzed the economics of SSS in terms of economic plant population, degree of field variability, cost-effectiveness of VRS technologies, seed consumption and yield. Bullock et al. [5] found that the optimal density of SSS maize seeds ranged from 44,000 to 104,000 seeds ha^{-1}, and the yields ranged from 5.1 to 18.3 Mg ha^{-1}. A positive Pearson correlation coefficient was found between the soil quality of a particular field area and the optimal seeding rate. Modeling showed that by practicing VRS, farmers could increase their income up to USD 12 ha^{-1} compared to a uniform seeding rate. Robert et al. [92] assessed the economic consequences of maize seeding for a specific area. Their study identified several combinations of different yield options (low, medium and high) and included the costs of seeds and VRS technologies used in the cost–benefit analysis. Two separate strategies were used to provide SSS recommendations, namely agronomic and economic seeding rate recommendations that considered the yield potential of each MZ. According to the agronomic recommendation, the maize seeding rate was 44,460, 69,160 and 74,100 seeds ha^{-1}, and according to the economic recommendation, in low, medium and high yield MZs it was 49,400, 64,220 and 74,100 seeds ha^{-1}, respectively [11].

Taylor et al. [41] assessed the potential of SSS in eastern Kansas, USA for three years and revealed that SSS is not profitable under the cultivation conditions studied. They also suggested looking for a cheaper method to make SSS economically feasible. Elmore and Abendroth [93] critically reviewed several studies and concluded that SSS is an uneconomical technology. The reports show that the total maize sowing rate of 86,450 seeds ha^{-1} is a good field-testing rate but is not necessarily economically ideal. The optimal density of maize plants in a given year can range from 12,350 to 29,640 plants ha^{-1}, depending on the purpose of the crop (i.e., grain, silage) and growing conditions [11].

It is generally accepted that too high or too low a seeding rate is sub-optimal, so there must be some economically justified optimal seeding rate value or range of values [37]. An economic analysis by Holmes [56] revealed that the highest gross yield per hectare is obtained at a lower seeding rate than the one with the highest yield. In the high-yield zone, the optimal seeding rate to maximize gross yields was several thousand lower than the seeding rate at which the highest yields were achieved. The research results also showed that VRS is a valuable tool for reducing losses due to excess nutrients in poor quality crops, i.e., seeding at a variable rate ensures optimal use of other agricultural raw materials, such as fertilizers.

VRS eliminates double sowing in headlands and point rows and redistributes the optimal number of seeds in very heterogeneous fields. In very uniform fields, the return on investment of VRS will be low, while in heterogeneous fields with differentiated soil productivity zones, the return on investment will be much higher [8,36]. Automatic technology for the control of seeding rows (sections) enables automatic control of the seeding sections using the seeding map to reduce the field areas that can be seeded twice due to overlap. Automatic section control can on average save 4.3% of seeds, as well as reduce maize yield losses by 17% compared to seeding methods that inevitably cause double-sown areas [94].

With VRS, the total number of seeds used in the field can be lower, leading to lower GHG emissions from seed production [36]. The positive impact of VRS on GHG emissions may also be due to higher yields [73]. Another GHG reduction measure is related to the lower amount of fuel required to produce the same yield [36].

Summarizing the literature analysis, personal experience and unpublished assessments allows us to conclude that the application of VRS pays off when the field variability is more than 10%. According to German researchers, it is effective to apply VRS when the apparent electrical conductivity changes in the field on average every 25 m and for NPK (nitrogen phosphorus potassium), when the pH changes on average every 50 m. Sowing at a variable rate is worth 10 percent. Variability in apparent electrical conductivity, organic matter and terrain leads to variability in plant density. It is therefore useful to apply a variable rate of nitrogen. The payback of VRS is such that if one earns an average of 100 EUR per ha, then working on 400 ha will pay off in 1 year. Thus, the conclusion is that it is most efficient and most profitable to apply VRS when the farm size is larger than an average of 150 ha. However, this also depends on the crops grown (possibly smaller) as well as the satellite maps used. Due to meteorological conditions, if satellite maps are used, it is often cloudy in Lithuania, which can cause problems. Therefore, it is better to apply remote and proximal sensors close to the ground, which are effective in all meteorological conditions. This increases the use of non-contact apparent electrical conductivity assessment devices due to the unnecessary need for certain conditions. The key conclusion is that the higher the field variability (altitude, terrain, sand, etc.), the higher the VRS efficiency and payback. In Lithuania, the variability of most fields is due to the current cultural, political, historical and climatic situation, so VRS pays off and is effective all over the country.

There are a variety of VRA technologies available that can be used with or without a GPS system. The two basic technologies for VRA are: map-based and sensor-based. Sensor-based VRA requires no map or positioning system. Sensors on the applicator measure soil properties or crop characteristics "on the go." Based on this continuous stream of information, a control system calculates the input needs of the soil or plants and transfers the information to a controller, which delivers the input to the location measured by the sensor. Because map-based and sensor-based VRA have unique benefits and limitations, some SSCM (site-specific crop management) systems have been developed to take advantage of the benefits of both methods. The map-based method uses maps of previously measured items and can be implemented using a number of different strategies. Crop producers and consultants have crafted strategies for varying inputs based on soil type, soil color and texture, topography (high ground, low ground), crop yield, field scouting data, remotely sensed images and numerous other information sources that can be crop- and location-specific. Some strategies are based on a single information source while others involve a combination of sources. Regardless of the actual strategy, the user is ultimately in control of the application rate. These systems must have the ability to determine machine location within the field and relate the position to a desired application rate by "reading" the prescription map. The sensor-based method provides the capability to vary the application rate of inputs with no prior mapping or data collection involved. Real-time sensors measure the desired properties—usually soil properties or crop characteristics—while on the go. Measurements made by such a system are then processed and used immediately to control a variable-rate applicator. The sensor method does not necessarily require the use of a positioning system, nor does it require extensive data analysis prior to making variable-rate applications. However, if the sensor data are recorded and geo-referenced, the information can be used in future site-specific crop management exercises for creating a prescription map for other and future operations, as well as to provide an "as applied" application record for the grower [10].

6. Conclusions and Future Prospects

Precision agricultural technologies allow agricultural producers to improve the management of specific crop resources in crop production. Advances in seeding technology for the implementation of VRS make it possible to make better use of soil variability. VRS allows the population to be adapted to the variability of the field and helps to ensure precision production in the field in order to reduce errors in the seeding process. Another important aspect is that interest in VRS around the world is growing due to the interaction of these technologies with current seed prices. An optimal plant population can improve crop yields while maximizing farm profits. A site-specific seeding (SSS) method, where a variable seeding rate is applied to each field area separately, makes it possible to optimize crop density in anticipation of the best agronomic and economic effect. Various proximal and remote sensor systems, contact and contactless equipment, and mapping and VRS modeling technologies are currently used to determine soil and crop variability. The VRS depends on a good knowledge of the field characteristics, the capabilities of the seeding equipment, the planned crop yield, soil productivity and an understanding of the interaction of machine technology with the environment. Remote and proximal sensors, mounted on tractors or off-road vehicles, help to create field maps of variable properties. The accuracy of these maps and the good assignment of field soil management zones are the successful outcomes of VRS.

The use of VRS equipment pays for itself in one year when it is applied to 400 ha of arable land, and the average benefit is about 100 EUR per ha. By predicting payback over a period of time, it can be concluded that VRS is effective when the farm size is on average at least 150 ha. However, it also depends on the crop and the satellite maps used. The use of satellite maps can be problematic, as it is often cloudy in the Baltic region (where Lithuania is located). It is therefore advisable to make better use of sensory remote and proximal sensors that are effective in all meteorological conditions. One of the least sensitive to meteorological conditions is non-contact devices for apparent electrical conductivity. One of the most important conclusions is that the higher the variability of field and soil properties, the higher the efficiency of the VRS and the faster the payback.

The application of VRS to the seeding of various crops shows positive agro-economic trends, additional yields and higher economic returns. In particular, there is a lack of an optimal VRS index model that would allow for the application of precision seeding depending on various soil and plant productivity factors. It is not clear what the minimum differences between outdoor areas must be for the SSS method to generate a positive return. Therefore, with a view to the near future, scientists, promoters of precision farming, machinery manufacturers and VRS practitioners in agriculture face important challenges in justifying the application of VRS for different crops, considering the variability in soil, crop as well as the environmental. The Baltic States and other countries in the region need to conduct research into the technological operations of VRS of the most common crops, such as winter wheat and winter rapeseed, considering agronomic, technological, energy, environmental and economic indicators.

The prescription map tells the user how much seed to use depending on the location of the seeding equipment in the field. Future research needs to answer the question of which VRS method is most suitable for different regions, as there are two views on seeding with VRS. The first holds that it is better to distribute more seeds in high-productivity soils and less in low-productivity areas. The second, however, posits that it is better to use VRS in reverse, i.e., to distribute more seeds in poor soils and less in high-productivity soils. There is still a lack of knowledge as to which method is more suitable for the most popular plants in the Baltic region.

Our main future aspiration is to present research schemes and methodologies of VRS and seed placement depth control models that provide precise control and allow for the organization of the seeding process. The research methodology should be developed while considering soil heterogeneity using telemetry systems and multifunctional ultraviolet (UV), optical (VIS) and near-infrared (NIR) spectroscopy methods to optimize the number of seeds per unit area and depth of insertion during seeding. The multifunctional model for sustainable precision seed technology control based on UV–VIS–NIR spectrometry will allow us to save seed, to make better use of soil, to increase plant productivity, to protect the environment and to reduce energy consumption and economic costs.

Therefore, in all future studies, it is especially important to test and evaluate the latest methodologies in practice on farms and then to make complex assessments of the soil, plant and environmental parameters, and changes in the proposed methods in order to find the best solution and the most optimal methods for farmers. In the future, we plan to carry out and publish the results of research on various evaluation spectra and to provide accurate instructions and recommendations for farmers and entrepreneurs.

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