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Life Cycle Assessment of Winter Wheat Production Using Precision and Conventional Seeding Technologies

Marius Kazlauskas [1], Indrė Bručienė [1], Dainius Savickas [1], Vilma Naujokienė [1], Sidona Buragienė [1], Dainius Steponavičius [1], Kęstutis Romaneckas [2] and Egidijus Šarauskis [1,*]

[1] Department of Agricultural Engineering and Safety, Faculty of Engineering, Agriculture Academy, Vytautas Magnus University, Studentu Str. 15A, LT-53362 Akademija, Kaunas Distr., Lithuania; marius.kazlauskas@vdu.lt (M.K.); indre.bruciene@vdu.lt (I.B.); dainius.savickas@vdu.lt (D.S.); vilma.naujokiene@vdu.lt (V.N.); sidona.buragiene@vdu.lt (S.B.); dainius.steponavicius@vdu.lt (D.S.)

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

* Correspondence: egidijus.sarauskis@vdu.lt; Tel.: +370-37-752357

Abstract: Sustainable and responsible agricultural production is one of the keys to keeping people, animals, soil, and the environment healthy. Precision seeding technologies for winter wheat, exploiting the variability of soil properties and adapting the technological processes of variable rate seeding and variable seeding depths, are essential not only to improving plant productivity and economic benefits but also to cleaner agricultural production. This work aimed to carry out a life cycle assessment (LCA) of winter wheat production and determine the environmental impact of different precision seeding technologies in terms of individual impact categories compared to conventional seeding technology. Experimental studies were carried out between 2020 and 2022 using conventional uniform seeding rate (URS) and several precision seeding technologies: in the first year—VRS for variable seeding rate and VRS + VRF for variable seeding rate and fertilizer rate, and in the second year—VRS and VRSD for variable seeding rate and variable depth, and VRSD + VRF for variable seeding rate, variable depth, and variable fertilizer rate. The results obtained for winter wheat grain yield showed that the effect of precision seeding technology on the increase of grain yield was not significant compared to the URS. A greater influence on grain yield was found in individual soil management zones, especially in the zone with the worst soil fertility. The LCA did not show any significant differences between precision seeding technology and conventional technology in any of the environmental impact categories. The GWP values (0.200–0.236 kg CO_{2eq} kg^{-1}) were most dependent on grain yield, as precision seeding technology had small changes in the amount of inputs (seeds and fertilizers), while all other technological operations were the same as under the URS technology. The amounts of phosphorus and potassium fertilizers decreased by 1.4 and 7.9%, respectively, and the amounts of winter wheat seeds and nitrogen fertilizers increased by 4.1 and 5.4%, respectively, compared to the URS.

Keywords: environmental analysis; variable rate seeding; variable seeding depth; variable rate fertilization; global warming potential; grain yield

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1. Introduction

Wheat is one of the world's oldest crops, with grains used for human food, animal feed, and industry [1,2]. The European Union is one of the largest wheat producers in the world, while in Lithuania, winter wheat is the most popular agricultural crop, with about 6.4 million tons produced in recent years [3].

In recent decades, agriculture has been one of the main factors of environmental pollution [4]. Therefore, in the general context of climate change, agriculture plays a very important role and is one of the key factors that can contribute to reducing the negative impact on the environment [5]. To achieve a more sustainable agricultural production, progress in the development of precise agricultural technological processes is inevitably required, combined with the application of artificial intelligence, the creation of new agricultural solutions, and the implementation of decision support systems [4]. The application and management of variable rate technological processes can bring important benefits in terms of more sustainable farming [5].

To increase the efficiency of crop production, new precision farming technological operations are increasingly being introduced to reduce inputs, optimize their use according to the soil and plant characteristics of the specific field site, save labor time and costs, and generate economic benefits [6]. Another objective of precision agriculture is to reduce the negative environmental impacts of wheat and other crop production [7]. Research in the last decade has shown that variable rate nutrient distribution using management zone (MZ) demarcation methods has increased farming efficiency compared to traditional uniform rate application methods [8]. This improvement in the efficiency of agricultural production has reduced its impact on the environment. This means that the implementation of site-specific application technologies contributes to more sustainable farming and provides financial and environmental benefits [8].

Currently, precision fertilization is probably the most widely studied technological process that allows for the reduction of the use of chemical fertilizers and their environmental impact [9]. However, other technological operations in agricultural production that affect wheat productivity and have an impact on the environment are equally important. One of these technological operations is wheat seeding. The seeding process is one of the most important in wheat production as it directly affects seed germination and growth and influences yield and economic benefits [4,7,10]. Variable rate seeding of cereals is still an understudied subject. To date, several scientific papers have been published summarizing the results of precision variable rate seeding studies on maize [11], potatoes [12], and soybeans [13]. Meanwhile, the number of published studies on precision seeding of winter wheat using variable rate and variable depth seeding methods is very limited [7]. In contrast, no studies could be found assessing the environmental impact of precision seeding of winter wheat. Therefore, to fill this gap and make the necessary scientific contribution to this topic, experimental studies and an environmental assessment were carried out. The aim of this work was to perform a life cycle assessment of winter wheat production and determine the environmental impact of precision seeding technologies, including variable rate and variable depth seeding, in terms of individual impact categories, compared to conventional seeding technology. This kind of scientific research and discussions on the implementation of precise technological operations in agriculture can contribute to the implementation of cleaner production processes for winter wheat, the most widely grown cereal in the world, and provide farmers, extension professionals, policymakers, and other stakeholders with a clearer understanding and useful information for more sustainable farming.

2. Materials and Methods

2.1. Experimental Research Site and Design

Experimental studies were carried out in 2020–2022 on a farm in Panevėžys district, Lithuania (55°40′27.7″ N 24°08′43.9″ E). The experimental research was carried out in an area with an average annual precipitation of 600–650 mm. During the research years, the average annual air temperature was about 7.5 °C. It was more than one degree higher than the long-term annual temperature (about 6.3 °C). Winter wheat was sown for two consecutive years in the same field (22.4 ha) using the no-tillage method according to precision farming technologies. In the first year of the study (2020–2021), three technologies were applied with four replications: URS—uniform rate seeding (as control), VRS—variable rate seeding, and VRS + VRF—variable rate seeding with variable rate fertilization. In the second year of the study (2021–2022), four technologies with three replications were applied: URS—uniform rate seeding (as control), VRS—variable rate seeding, VRSD—

variable rate and depth seeding, and VRSD + VRF—variable rate and depth seeding with variable rate fertilization.

To enable the application of precision farming technologies, a full-field scan of the apparent electrical conductivity (ECa) was carried out before the start of the experimental studies. An EM38-MK2 electromagnetic induction soil scanner (Geonics Ltd., Mississauga, ON, Canada) and a Trimble EZ-Guide 250 global positioning system (GPS) coordinate locating device (Trimble Navigation Ltd., Alpharetta, GA, USA) with a GPS antenna were used for this scan. Based on the soil ECa data and using QGIS (Open-Source Geographic Information Systems) software (version 3.16, Hannover, Germany), the experimental field was divided into 5 soil management zones (MZs): MZ1—>28.6 mS m^{-1}, MZ2—27.3–28.6 mS m^{-1}, MZ3—25.7–27.3 mS m^{-1}, MZ4—24.2–25.7 mS m^{-1}, and MZ5—22.6–24.2 mS m^{-1}. Soil samples were taken from each MZ, and soil texture was determined in the Agrochemical Research Laboratory. The soil texture was sandy loam in the first four zones (MZ1–MZ4) and loamy sand in the last zone (MZ5). In the first year of the study, a regional average rate of 180 kg ha^{-1} of winter wheat (Skagen variety) was applied using the URS and, in the middle zone (MZ3), using the VRS and VRS + VRF variants. In the variable rate variants, the seeding rate was reduced by 10% and 20% in the higher ECa zones MZ2 and MZ1, respectively, while, contrarily, in the lower ECa zones, the seeding rate was increased by 10% and 20% in zones MZ4 and MZ5, respectively. In the second year of the study, the average seeding rate was 162 kg ha^{-1}, while in the other years, the MZ rate was reduced or increased in the same way as in the first year. Since variable seeding depth was also included in the second year, the same principle as that for seeding rate was applied to this technological parameter. Using the URS variant and in zone MZ3, the seeding depth was 3.0 cm; in MZ2 and MZ1, it was 10% and 20% lower; and in MZ4 and MZ5 it was 10% and 20% higher, respectively. Seeding at variable rates and variable depths was carried out using a Horsch Avatar 6.16 SD direct drill.

Using the VRS + VRF and VRSD + VRF precision seeding technologies, precision variable rate fertilization was applied simultaneously. Rates of phosphorus, potassium, and nitrogen fertilizers by year can be seen in the tables in the following subsection. Approximately 60% of the phosphorus fertilizer rate was applied during the seeding process, and the remainder of the phosphorus fertilizer and the total potassium fertilizer rate were applied immediately after seeding, according to the phosphorus and potassium maps obtained from the chemical analysis of soil samples. Fertilization was carried out with a Rauch Axis H50.2 centrifugal mineral fertilizer spreader with a working width of 36 m. Nitrogen fertilizer (180 kg N ha^{-1}) was applied 3 times. The first time, a uniform rate of 60 kg N ha^{-1} was applied on all technologies; the second time, a variable rate of 70 kg N ha^{-1} was applied, and the third time, the remainder of the rate was applied. For the variable rate application, N-uptake and nitrogen fertilizer requirement maps were prepared using a Yara N-Sensor ALS optical nitrogen sensor (Yara International ASA, Norway). Spraying with growth regulators and fungicides was carried out with a Horsch Leeb PT 270 self-propelled sprayer with a working width of 36 m.

Winter wheat yield was determined by randomly sampling 5 plant samples from each technology and each replication. Depending on the variant and management zone, each sample consisted of 69 to 147 productive stems with ears. The samples were manually cut from a 1.0 m long row, threshed in the laboratory, and weighed, and the grain yield per hectare was calculated.

2.2. Life Cycle Assessment

The utilization of the life cycle assessment (LCA) was involved in assessing the environmental impact of using variable rates of seeding, plant protection products, and fertilizers in the cultivation of winter wheat [14,15]. This assessment did not include the technological operations and materials used, the rate of which did not change across technologies (herbicides, fungicides, diesel, machinery, etc.). The boundary of this LCA system (Figure 1) includes only those materials that were used at a variable rate. To allow for a qualitative comparison between LCA data, a specific functional unit (FU) was selected. In this study, the FU was defined as one kilogram of winter wheat grain.

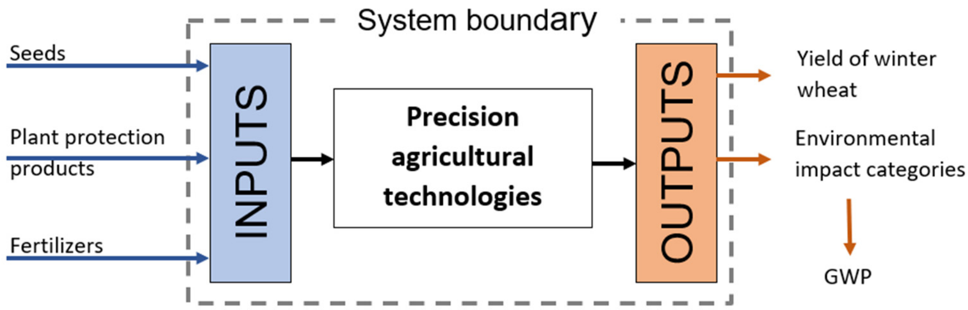

Figure 1. Flowchart and system boundary of the LCA of winter wheat production.

LCA serves as a widely employed instrument for evaluating the potential environmental consequences and resource utilization associated with a product or service system throughout its entire life cycle. This life cycle encompasses activities ranging from the extraction of raw materials to the production and utilization phases, as well as waste management and transportation [16]. The LCA methodology adheres to the standards set by the International Commission of Standardization, specifically ISO 14040 [17] and ISO 14044 [18]. To conduct the LCA analysis in this study, SimaPro 9 software was employed. Data related to materials, as shown in Tables 1 and 2, were obtained from the Ecoinvent V3 database [19].

Table 1. Life cycle inventory of winter wheat production using variable input rates (first year).

Items	URS	VRS	VRS + VRF
Inputs			
Winter wheat seed, kg ha^{-1}	180.0	185.0	182.7
Phosphorus pentoxide (P_2O_5), kg ha^{-1}	91.0	91.0	90.6
Potassium oxide (K_2O), kg ha^{-1}	54.0	54.0	49.7
Nitrogen (N), kg ha^{-1}	180.0	180.0	188.6
Growth regulator, L ha^{-1}	1.10	1.10	1.08
Fungicide, L ha^{-1}	1.75	1.75	1.72

Table 2. Life cycle inventory of winter wheat production using variable input rates (second year).

Items	URS	VRS	VRSD	VRSD + VRF
Inputs				
Winter wheat seed, kg ha^{-1}	162.0	166.9	162.2	168.6
Phosphorus pentoxide (P_2O_5), kg ha^{-1}	91.0	91.0	91.0	89.7
Potassium oxide (K_2O), kg ha^{-1}	54.0	54.0	54.0	51.6
Nitrogen (N), kg ha^{-1}	180.0	180.0	180.0	189.8
Growth regulator, L ha^{-1}	1.40	1.40	1.40	1.35
Fungicide, L ha^{-1}	1.55	1.55	1.55	1.51

The seed rate in kilograms in the tables differed for each year, but the number of seeds was the same (about 4.2 million seeds per ha). In the second year, the seeds were smaller and lighter. Therefore, the seeding rate seems to be lower at first glance, but in reality, the number of seeds and plants was the same. For the same number of seeds and plants, the same amount of chemical fertilizers was used in both years.

The assessment of the environmental impact related to the cultivation of winter wheat was specifically focused on midpoint impacts, utilizing the CML-IA baseline V3.06/EU25 methodology. For evaluation purposes, 11 distinct impact categories were employed, as presented in Table 3. These categories are standard in LCA and help to better understand the impact of activities in different categories. It is also possible to evaluate the differences between different variable rate technologies for different impact categories.

Table 3. Selected impact categories, their abbreviations, and measurement units.

Impact Category	Abbreviation	Unit
Marine aquatic ecotoxicity	MAE	kg 1,4-DB_{eq}
Abiotic depletion (fossil fuels)	ADf	MJ
Global warming potential	GWP	kg CO_{2eq}
Freshwater aquatic ecotoxicity	FWAe	kg 1,4-DB_{eq}
Human toxicity	HT	kg 1,4-DB_{eq}
Terrestrial ecotoxicity	TE	kg 1,4-DB_{eq}
Eutrophication	ET	kg PO^{3}_{4eq}
Acidification	ACD	kg SO_{2eq}
Photochemical oxidation	PO	kg C_2H_{4eq}
Abiotic depletion	ADn	kg Sb_{eq}
Ozone layer depletion	ODP	kg CFC-11_{eq}

2.3. Statistical Analysis

To allow for a qualitative comparison between LCA data, a specific functional unit (FU) was selected. In this study, the FU was defined as one kilogram of winter wheat grain. In the experimental studies, each seeding technology was carried out in several replications (four in the first year and three in the second year). To ensure higher winter wheat grain yield data accuracy, 5 samples were taken from each replication (60 samples from the field in total). A one-way ANOVA was used to determine the significance of differences between seeding technologies. Data were evaluated by calculating the least significant difference ($LSD_{0.05}$) at the 95% probability level. In Table 4 and Figure 1 and Figure 2, the same letters (a, b) indicate that there is no significant difference between the seeding technologies.

3. Results

3.1. Grain Yield

Knowing the yield performance of crops is crucial for assessing the environmental impact of precision farming technologies in crop production. In 2021, winter wheat was harvested on 22 July, and in 2022, on 3 August. Meteorological conditions were good as there was no precipitation for several days before harvesting. In the first year of the experimental studies, winter wheat grain yield ranged from 7482.3 to 7782.2 kg ha^{-1}, while in the second year, it ranged from 7593.8 to 8744.1 kg ha^{-1} (Table 4).

Table 4. The influence of precision agricultural technologies on winter wheat grain yield.

Year of the Experiment	Precision Agriculture Technologies	Winter Wheat Grain Yield, kg ha^{-1}
First year (2020–2021)	URS	7482.3 a
	VRS	7782.2 a
	VRS + VRF	7773.8 a
	$LSD_{0.05}$	1028.2
Second year (2021–2022)	URS	8178.6 ab
	VRS	7785.1 ab
	VRSD	8744.1 a
	VRSD + VRF	7593.8 b
	$LSD_{0.05}$	1085.1

In the first year, the best winter wheat yield was obtained using VRS technology, and in the second year, using VRSD technology. In the first year, both precision farming technologies showed better grain yield results than the control URS technology. In the second year, only the VRSD technology had a higher grain yield than the control URS, while the other technologies had lower yields.

3.2. The Effect of Winter Wheat Production on Impact Categories

The assessment of the environmental impact of different agricultural technologies depends strongly on the inputs used in the production process and the resulting winter wheat yield. In the first year of the experimental studies, all environmental assessment results for all impact categories were better using precision farming technologies VRS and VRS + VRF than using the control URS technology (Table 5).

Table 5. Results of the environmental assessment of winter wheat precision agricultural technologies by impact categories per FU of 1.0 kg of grain (first year).

Impact Category	Abbreviation	Unit	URS	VRS	VRS + VRF
Abiotic depletion	ADn	kg Sb_{eq}	3.741×10^{-6}	3.616×10^{-6}	3.700×10^{-6}
Abiotic depletion (fossil fuels)	ADf	MJ	2.686	2.595	2.671
Ozone layer depletion	ODP	kg CFC-11_{eq}	1.244×10^{-8}	1.204×10^{-8}	1.233×10^{-8}
Human toxicity	HT	kg 1,4-DB_{eq}	0.176	0.170	0.174
Freshwater aquatic ecotoxicity	FWAe	kg 1,4-DB_{eq}	0.176	0.170	0.171
Marine aquatic ecotoxicity	MAE	kg 1,4-DB_{eq}	231.865	224.065	229.733
Terrestrial ecotoxicity	TE	kg 1,4-DB_{eq}	1.484×10^{-3}	1.451×10^{-3}	1.444×10^{-3}
Photochemical oxidation	PO	kg C_2H_{4eq}	3.512×10^{-5}	3.396×10^{-5}	3.485×10^{-5}
Acidification	ACD	kg SO_{2eq}	1.140×10^{-3}	1.105×10^{-3}	1.129×10^{-3}
Eutrophication	ET	kg PO^3_{4eq}	4.812×10^{-4}	4.684×10^{-4}	4.755×10^{-4}

In the second year of the experimental studies, four different winter wheat cultivation technologies were applied. The environmental assessment showed that not all precision farming technologies improved environmental performance. As in the first year of the experiment, environmental performance in the second year was mainly dependent on grain yield. Only the VRSD technology showed better environmental performance in all impact categories compared to the URS (Table 6). The other precision technologies, VRS and VRS + VRF, demonstrated worse results than the URS.

Table 6. Results of the environmental assessment of winter wheat precision agricultural technologies by impact categories per FU of 1.0 kg of grain (second year).

Impact Category	Abbreviation	Unit	URS	VRS	VRSD	VRSD + VRF
Abiotic depletion	ADn	kg Sb_{eq}	3.404×10^{-6}	3.596×10^{-6}	3.172×10^{-6}	3.725×10^{-6}
Abiotic depletion (fossil fuels)	ADf	MJ	2.455	2.592	2.288	2.705
Ozone layer depletion	ODP	kg CFC-11_{eq}	1.138×10^{-8}	1.203×10^{-8}	1.060×10^{-8}	1.249×10^{-8}
Human toxicity	HT	kg 1,4-DB_{eq}	0.159	0.168	0.148	0.174
Freshwater aquatic ecotoxicity	FWAe	kg 1,4-DB_{eq}	0.154	0.163	0.143	0.167
Marine aquatic ecotoxicity	MAE	kg 1,4-DB_{eq}	210.943	222.816	196.570	231.318
Terrestrial ecotoxicity	TE	kg 1,4-DB_{eq}	1.245×10^{-3}	1.334×10^{-3}	1.161×10^{-3}	1.358×10^{-3}
Photochemical oxidation	PO	kg C_2H_{4eq}	3.208×10^{-5}	3.390×10^{-5}	2.989×10^{-5}	3.526×10^{-5}
Acidification	ACD	kg SO_{2eq}	1.030×10^{-3}	1.092×10^{-3}	0.960×10^{-3}	1.131×10^{-3}
Eutrophication	ET	kg PO^3_{4eq}	4.266×10^{-4}	4.542×10^{-4}	3.976×10^{-4}	4.700×10^{-4}

3.3. The Impact of Winter Wheat Production on GWP

Climate change is caused by warming temperatures due to the increasing concentration of pollutants such as methane and carbon dioxide in the atmosphere. Each pollutant has a different life cycle and warming effect. Therefore, specific indicators have been developed to better understand and compare the relative impact of each pollutant. The best-known and most widely used climate indicator today is global warming potential (GWP) [20]. GWP is a key indicator for LCAs, allowing us to compare different agricultural technologies that are influenced by natural and anthropogenic factors. In this study, the determination of GWP required precise amounts of inputs (seeds, fertilizers, growth regulators, and fungicides) used in different seeding technologies. Amounts of other substances, which were the same for all technologies, as mentioned in the previous section, were not included in the GWP assessment.

The LCA analysis of winter wheat showed that in the first year of the experiment, GWP varied between 0.228 and 0.236 kg CO_{2eq} kg^{-1}, with no significant difference between the different seeding technologies (Figure 2). In the second year of the experiment, the variation in GWP was higher, ranging from 0.200 to 0.236 kg CO_{2eq} kg^{-1} (Figure 3), and a significant difference was found between the two precision farming technologies, i.e., between VRSD and VRSD + VRF.

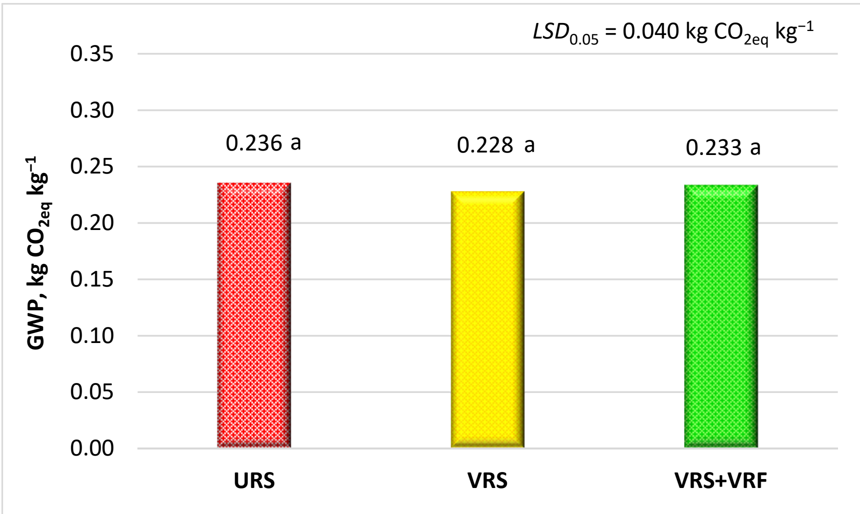

Figure 2. The impact of winter wheat seeding technologies on global warming potential (first year).

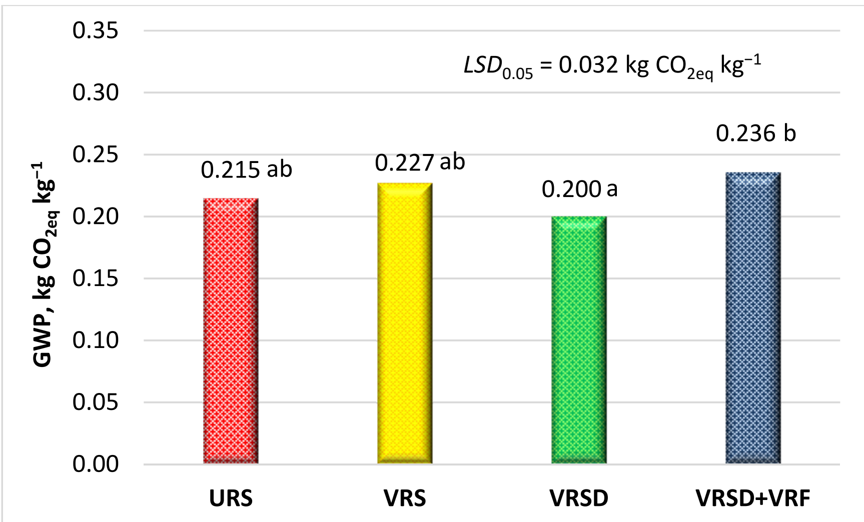

Figure 3. The impact of winter wheat seeding technologies on global warming potential (second year).

4. Discussion

4.1. Grain Yield

Agricultural efficiency depends to a large extent on the level of mechanization-automation of production processes, direct and indirect inputs, and crop yield. In both conventional and precision farming technologies for winter wheat production, grain yield is the most important parameter affecting economic and environmental performance. Our experimental studies showed that, in the first year, there was no significant difference in grain yield between the different seeding technologies, while in the second year, there was only a difference between the two seeding technologies with different seeding depths and fertilizer application methods. Soil variability is a key factor in precision seeding and fertilization technologies [4,21]. The greater the variability of soil properties, the more likely we are to observe a significant effect of precision technologies on crop yield. In our case, one of the most widely used soil properties, electrical conductivity (ECa), was applied to determine the variability of soil properties in the field (Figure 4).

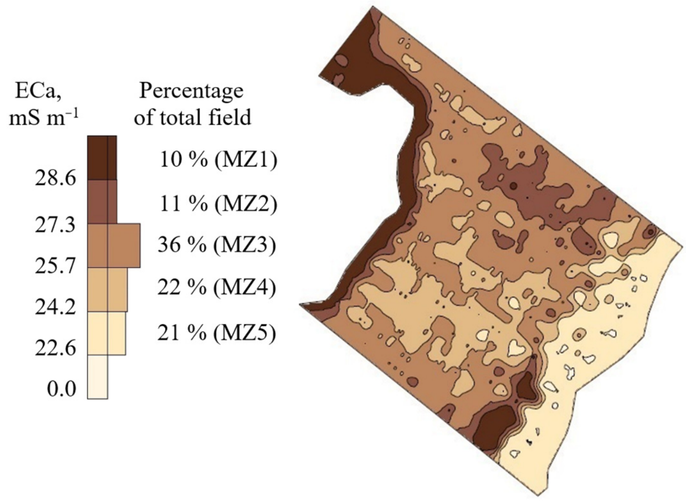

Figure 4. Field soil variability based on ECa.

As the field was not uniform, each seeding technology included soil with different soil properties. Two maps were used to ensure the variability of seeding rate and seeding depth. These maps were uploaded to the tractor's computer and, with additional telematic automatic control tools, the seeder was able to accurately implement precision seeding in each MZ. For precise depth control, the hydraulic system DepthXControl (Geoprospectors GmbH, Austria), additionally installed on the frame of the seeder, was used.

Some seeding technologies dominated in MZ3, others dominated in MZ4 or MZ2. In MZ1, the highest grain yield was achieved using VRSD (8372 kg ha^{-1}), and the lowest was achieved using VRSD + VRF (5089 kg ha^{-1}); in MZ2, the highest grain yield was achieved using VRSD + VRF (9709 kg ha^{-1}), and the lowest was achieved using URS (8074 kg ha^{-1}); in MZ3, the highest grain yield was achieved using VRSD (8817 kg ha^{-1}), and the lowest was achieved using VRSD + VRF (7757 kg ha^{-1}); and in MZ4, the highest grain yield was achieved using URS (9932 kg ha^{-1}), and the lowest was achieved using VRSD + VRF (7503 kg ha^{-1}). All seeding technologies were included in the lowest fertility soil in zone MZ5. In this zone, the methodology resulted in the highest (20%) increase in seeding rate and seeding depth. Although this zone had the lowest grain yield compared to the other MZs, all precision seeding technologies produced a higher grain yield (VRS—6494 kg ha^{-1}, VRSD—7958 kg ha^{-1}, and VRSD + VRF—7518 kg ha^{-1}) than the URS (6231 kg ha^{-1}). Other authors [22–24] who studied the effect of wheat seeding rate on grain yield also obtained similar results. The results of Bhatta et al. [22] showed that wheat grain yield increased with an increase in seeding rates. Iqbal et al. [23] found that when the seeding rate of wheat was increased by 20% from 125 to 150 kg ha^{-1}, the grain yield increased significantly from 3949 to 4242 kg ha^{-1}.

4.2. The Effect of Winter Wheat Production on Impact Categories

The main objective of LCA is to assess the magnitude of the potential environmental impacts of an agricultural product. To achieve this, environmental impact categories, linked to four damage categories in a work published by other authors [25], are used. The human health category is associated with human toxicity (HT), ozone layer depletion (ODP), photochemical oxidation (PO), and abiotic depletion (ADn and ADf); ecosystem quality is associated with ODP, PO, ADn, and ADf, freshwater aquatic ecotoxicity (FWAe), marine aquatic ecotoxicity (MAE), terrestrial ecotoxicity (TE), acidification (ACD), and eutrophication (ET); the climate change category is associated with GWP; and the resources category is associated with ADn and ADf.

The LCA showed that the differences in environmental impacts between the different precision seeding technologies are not significant. In the ADn impact category, related to phosphate and pesticide inputs, the lowest impact (3.616×10^{-6} kg Sb_{eq}) in the first year of the experiment was achieved using VRS technology and the highest impact (3.741×10^{-6} kg Sb_{eq}) was achieved using the conventional URS technology. In the second year, the lowest ADn (3.172×10^{-6} kg Sb_{eq}) was achieved using VRSD technology, and the highest (3.725×10^{-6} kg Sb_{eq}) was achieved using VRSD + VRF technology, which had the lowest winter wheat grain yield. Abiotic depletion is divided into two separate impact categories. The second category of ADf impacts is associated with fossil fuel use and is measured in MJ [26]. In the first year, the lowest ADf (2.595 MJ) was achieved using VRS technology, in the second year—using VRSD (2.288 MJ), and the highest was achieved using URS (2.686 MJ) and VRSD + VRF (2.705 MJ), respectively.

The HT category describes the exposure of humans to toxic substances and is expressed in terms of the substance 1,4 dichlorobenzene (1,4-DB) [27]. In our study, HT ranged from 0.170 to 0.176 kg 1,4-DB_{eq} in the first year and from 0.148 to 0.174 kg 1,4-DB_{eq} in the second year. Without repetition, it can be stressed that in all impact categories, URS had the highest exposure in the first year and VRS had the lowest exposure in the second year for URS + VRF and VRSD, respectively. Other authors indicate that in LCAs of whole wheat production, the HT effects ranged from 0.173 [28] to 0.229 kg 1,4-DB_{eq} [29].

When other impact categories (ACD, ET, PO, TE, etc.) were analyzed, the results showed that the application of precision seeding technologies did not have any specific positive or negative environmental impact. The inputs used were similar for all technologies so there were only some minor differences in winter wheat yield. In our study, the TE impact category, representing the potential toxicant influence on terrestrial ecosystems, varied from 1.444×10^{-3} (VRS + VRF) to 1.484×10^{-3} kg 1,4-DB_{eq} (URS) in the first year and from 1.161×10^{-3} (VRSD) to 1.358×10^{-3} kg 1,4-DB_{eq} (VRSD + VRF). Another important environmental impact category, ET, describes the process by which bodies of water are enriched with dissolved chemicals that then promote the growth of aquatic plants, typically depleting dissolved oxygen. The value of ET also depended on the fluctuations of winter wheat grain yield; in the first year, it was in the range from 4.684×10^{-4} (VRS) to 4.812×10^{-4} kg PO^{3}_{4eq} (URS), and in the second year—from 3.976×10^{-4} (VRSD) to 4.700×10^{-4} kg PO^{3}_{4eq} (VRSD + VRF). These results show that the influence of one technological operation, such as seeding, which does not require high energy and material costs, on impact categories is not significant. More significant differences are found when more energy-intensive processes, such as tillage, are included in the LCA. Holka and Bienkowski [30] found a 63% difference in ET effects between conventional tillage and no tillage for winter wheat.

4.3. The Impact of Winter Wheat Production on GWP

Precision agriculture technologies, including variable rate seeding, variable depth seeding, and variable rate fertilization, can contribute to GWP reduction. This largely depends on the extent to which inputs can be reduced in winter wheat production and on the extent to which grain yield can be increased. Other researchers [31,32] have pointed out that one of the main factors contributing to GWP is the diesel fuel used in agricultural machinery for technological operations. In our study, diesel fuel consumption was the same for all seeding technologies, as all mechanized technological operations were carried out in the same way, using the same seeding, fertilizing, and spraying machines. Another very important factor that can have a decisive impact on GWP reduction is the reduction in the consumption of chemicals (fertilizers and pesticides) [25,31,32]. In our experiment, the reduction in phosphorus fertilizer inputs was marginal (0.4 kg ha^{-1} in the first year and 1.3 kg ha^{-1} in the second year) using VRS + VRF and VRSD + VRF technologies, compared to the other winter wheat seeding technologies (URS, VRS, and VRSD). A similar reduction in fertilizer use was observed with potassium fertilizer (4.3 kg ha^{-1} in the first year and 2.4 kg ha^{-1} in the second). In contrast, nitrogen fertilizer consumption even increased using technologies in which variable rate fertilization was applied in combination with precision seeding (8.6 kg ha^{-1} in the first year and 9.8 kg ha^{-1} in the second). There was also no significant reduction in the use of growth regulators and fungicides. Therefore, the strongest factor was winter wheat grain yield. As there was no significant difference between the seeding technologies in the first year of the experiment, the LCA did not show a significant difference in GWP between the technologies. In the second year, a significant difference in grain yield was found between the VRSD and VRSD + VRF technologies. This significant difference also remained after the environmental GWP assessment. In our study, GWP ranged from 0.200 to 0.236 kg CO_{2eq} kg^{-1} when only the technologies used were evaluated, while other authors evaluating the whole wheat production process reported GWPs ranging from 0.317 [25] and 0.381 [28] to 0.400 kg CO_{2eq} kg^{-1} [30].

A precise seeding process based on the conditions of soil variability has the advantage of making efficient use of the conditions in each area. This means that in poor soils, by increasing the seeding rate and seeding depth, it is possible to significantly increase the number of plants and the yield of winter wheat grains and to use the field area more efficiently. Meanwhile, in soils with higher productivity, winter wheat tillering is increased by reducing the seeding rate. These factors contribute to a more sustainable production of winter wheat.

Looking into future research perspectives, this type of research should be continued to include an even wider range of precision farming technological operations on different crops. Only a combination of precision agricultural technologies, soil properties, plant rotation, meteorological conditions, and farm management systems can improve the sustainability of winter wheat production.

5. Conclusions

Agriculture is one of the main sectors that strongly influence environmental pollution. Therefore, the implementation of new agrotechnological solutions that allow for a reduction in resource and energy costs is expected. Precision agricultural technological operations, including seeding and fertilizing, contribute to the optimization of resources according to the variability of soil and plant properties and at the same time contribute to a more sustainable agricultural production.

We found that the effect of precision seeding technologies on winter wheat grain yield was not significant. Two years of experimental studies showed that precision seeding technologies with variable rate seeding and variable depth seeding produced similar grain yield to conventional technology with the same seeding rates. Significant yield differences were found when assessing winter wheat grain yield in different soil management zones. A particularly positive effect of all the precision seeding technologies was found in the zone with the poorest soil fertility, which was dominated by the sand fraction. This zone accounted for only 21% of the whole field, so it was not enough to influence the total grain yield among the variants in the whole field. On the other hand, a very high level of soil uniformity would reduce the effect of variable technologies.

Life cycle assessment of the different environmental impact categories allows us to compare different winter wheat seeding technologies. Comparing precision seeding technologies with variable rate and variable depth with conventional technology, which maintains the same technological parameters of rate and depth throughout the field, and the impact categories related to human health, ecosystem quality, and resources did not show any significant differences between the technologies.

A reduction in global warming potential depends on a reduction in inputs in precision seeding technologies and changes in winter wheat grain yield. In our study, precision farming technologies did not reduce material inputs in the production of winter wheat, so GWP mostly depended on grain yield. Significant reductions in GWP were found only among those precision farming technologies that showed a significant increase in grain yield.

Finally, LCA showed that the environmental impact of precision seeding technologies is related to winter wheat grain productivity performance, which depends on the variability of field soil properties. Therefore, the proper application of this factor in agriculture can lead to a more efficient use of resources and make precision agriculture more productive and sustainable. To develop innovative and environmentally, economically, and socially sustainable agricultural production, it is very important to maintain the right balance between the benefits for the farmer and damage to the environment. Sustainability does not depend on a single technological solution; it requires a whole complex of measures to make all agricultural production more resilient to the effects of climate change and economic and political uncertainty. However, each research study, solution, or technological component can contribute to a faster and smoother transition to more sustainable farming.

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References

1. Nabavi-Pelesaraei, A.; Hosseinzadeh-Bandbafha, H.; Qasemi-Kordkheili, P.; Kouchaki-Penchah, H.; Riahi-Dorcheh, F. Applying optimization techniques to improve of energy efficiency and GHG (greenhouse gas) emissions of wheat production. *Energy* **2016**, *103*, 672–678. [CrossRef]
2. Pishgar-Komleh, S.H.; Zylowski, T.; Rozakis, S.; Kozyra, J. Efficiency under different methods for incorporating undesirable outputs in an LCA+ DEA framework: A case study of winter wheat production in Poland. *J. Environ. Manag.* **2020**, *260*, 110138. [CrossRef] [PubMed]
3. Saldukaitė-Sribikė, L.; Šarauskis, E.; Buragienė, S.; Adamavičienė, A.; Velička, R.; Kriaučiūnienė, Z.; Savickas, D. Effect of Tillage and sowing technologies nexus on winter wheat production in terms of yield, energy, and environment impact. *Agronomy* **2022**, *12*, 2713. [CrossRef]

4. Saleem, S.R.; Levison, J.; Haroon, Z. Environment: Role of precision agriculture technologies. In *Precision Agriculture: Evolution, Insights and Emerging Trends*; Zaman, Q., Ed.; Academic Press: Cambridge, MA, USA, 2023; pp. 211–229.
5. Fabiani, S.; Vanino, S.; Napoli, R.; Zajíček, A.; Duffková, R.; Evangelou, E.; Nino, P. Assessment of the economic and environmental sustainability of Variable Rate Technology (VRT) application in different wheat intensive European agricultural areas. A Water energy food nexus approach. *Environ. Sci. Policy* **2020**, *114*, 366–376. [CrossRef]
6. Munnaf, M.A.; Haesaert, G.; Van Meirvenne, M.; Mouazen, A.M. Site-specific seeding using multi-sensor and data fusion techniques: A review. *Adv. Agron.* **2020**, *161*, 241–323.
7. Šarauskis, E.; Kazlauskas, M.; Naujokienė, V.; Bručienė, I.; Steponavičius, D.; Romaneckas, K.; Jasinskas, A. Variable rate seeding in precision agriculture: Recent advances and future perspectives. *Agriculture* **2022**, *12*, 305. [CrossRef]
8. Nawar, S.; Corstanje, R.; Halcro, G.; Mulla, D.; Mouazen, A.M. Delineation of soil management zones for variable-rate fertilization: A review. *Adv. Agron.* **2017**, *143*, 175–245.
9. Medel-Jiménez, F.; Piringer, G.; Gronauer, A.; Barta, N.; Neugschwandtner, R.W.; Krexner, T.; Kral, I. Modelling soil emissions and precision agriculture in fertilization life cycle assessment-A case study of wheat production in Austria. *J. Clean. Prod.* **2022**, *380*, 134841. [CrossRef]
10. Zecevic, V.; Boskovic, J.; Knezevic, D.; Micanovic, D. Effect of seeding rate on grain quality of winter wheat. *Chil. J. Agric. Res.* **2014**, *74*, 23–28. [CrossRef]
11. Munnaf, M.A.; Haesaert, G.; Mouazen, A.M. Site-specific seeding for maize production using management zone maps delineated with multi-sensors data fusion scheme. *Soil Tillage Res.* **2022**, *220*, 105377. [CrossRef]
12. Munnaf, M.A.; Haesaert, G.; Mouazen, A.M. Map-based site-specific seeding of seed potato production by fusion of proximal and remote sensing data. *Soil Tillage Res.* **2021**, *206*, 104801. [CrossRef]
13. da Silva, E.E.; Baio, F.H.R.; Teodoro, L.P.R.; Campos, C.N.S.; Plaster, O.B.; Teodoro, P.E. Variable-rate seeding in soybean according to soil attributes related to grain yield. *Precis. Agric.* **2022**, *23*, 35–51. [CrossRef]
14. Roy, P.; Nei, D.; Orikasa, T.; Xu, Q.; Okadome, H.; Nakamura, N.; Shiina, T. A review of life cycle assessment (LCA) on some food products. *J. Food Eng.* **2009**, *90*, 1–10. [CrossRef]
15. Skowrońska, M.; Filipek, T. Life cycle assessment of fertilizers: A review. *Int. Agrophysics* **2014**, *28*, 101–110. [CrossRef]
16. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in life cycle assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef]
17. Arvanitoyannis, I.S. ISO 14040: Life cycle assessment (LCA)—Principles and guidelines. In *Waste Management for the Food Industries*; Academic Press: Cambridge, MA, USA, 2008; pp. 97–132.
18. Finkbeiner, M.; Inaba, A.; Tan, R.; Christiansen, K.; Klüppel, H.J. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *Int. J. Life Cycle Assess.* **2006**, *11*, 80–85. [CrossRef]
19. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The Ecoinvent Database Version 3 (Part I): Overview and Methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [CrossRef]
20. Costa, C., Jr.; Wironen, M.; Racette, K.; Wollenberg, E.K. Global Warming Potential (GWP): Understanding the Implications for Mitigating Methane Emissions in Agriculture. CCAFS Info Note. Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). 2021. Available online: https://hdl.handle.net/10568/114632 (accessed on 4 September 2023).
21. Griffin, S.; Hollis, J. Using profile soil electrical conductivity survey data to predict wheat establishment rates in the United Kingdom. In *Precision Agriculture'13*; Stafford, J., Ed.; Wageningen Academic Publishers: Wageningen, The Netherlands, 2013; pp. 491–497.
22. Bhatta, M.; Eskridge, K.M.; Rose, D.J.; Santra, D.K.; Baenziger, P.S.; Regassa, T. Seeding rate, genotype, and topdressed nitrogen effects on yield and agronomic characteristics of winter wheat. *Crop Sci.* **2017**, *57*, 951–963. [CrossRef]
23. Iqbal, J.; Hayat, K.; Hussain, S.; Ali, A.; Bakhsh, M.A.A.H.A. Effect of seeding rates and nitrogen levels on yield and yield components of wheat (*Triticum aestivum* L.). *Pak. J. Nutr.* **2012**, *11*, 531–536. [CrossRef]
24. Wang, Z.; Khan, S.; Sun, M.; Ren, A.; Lin, W.; Ding, P.; Noor, H.; Feng, Y.; Wang, Q.; Gao, Z. Optimizing the wheat seeding rate for wide-space sowing to improve yield and water and nitrogen utilization. *Int. J. Plant Prod.* **2021**, *15*, 553–562. [CrossRef]
25. Taki, M.; Soheili-Fard, F.; Rohani, A.; Chen, G.; Yildizhan, H. Life cycle assessment to compare the environmental impacts of different wheat production systems. *J. Clean. Prod.* **2018**, *197*, 195–207. [CrossRef]
26. Van Oers, L.; Guinée, J. The abiotic depletion potential: Background, updates, and future. *Resources* **2016**, *5*, 16. [CrossRef]
27. Li, X.; Mupondwa, E.; Panigrahi, S.; Tabil, L.; Adapa, P. Life cycle assessment of densified wheat straw pellets in the Canadian Prairies. *Int. J. Life Cycle Assess.* **2012**, *17*, 420–431. [CrossRef]
28. Charles, R.; Jolliet, O.; Gaillard, G.; Pellet, D. Environmental analysis of intensity level in wheat crop production using life cycle assessment. *Agric. Ecosyst. Environ.* **2006**, *113*, 216–225. [CrossRef]
29. Ghasemi-Mobtaker, H.; Kaab, A.; Rafiee, S. Application of life cycle analysis to assess environmental sustainability of wheat cultivation in the west of Iran. *Energy* **2020**, *193*, 116768. [CrossRef]
30. Holka, M.; Bieńkowski, J. Assessment of environmental burdens of winter wheat production in different agrotechnical systems. *Agronomy* **2020**, *10*, 1303. [CrossRef]

31. Naujokienė, V.; Šarauskis, E.; Bleizgys, R.; Sasnauskienė, J. Soil biotreatment effectiveness for reducing global warming potential from main polluting tillage operations in life cycle assessment phase. *Sci. Total Environ.* **2019**, *671*, 805–817. [CrossRef]
32. Houshyar, E.; Grundmann, P. Environmental impacts of energy use in wheat tillage systems: A comparative life cycle assessment (LCA) study in Iran. *Energy* **2017**, *122*, 11–24. [CrossRef]