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Harnessing Soil Diversity: Innovative Strategies for Potato Blight Management in Central-Eastern Poland

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Abstract: Faced with increasing climate challenges, this pioneering study introduces groundbreaking approaches to ensure the resilience of potato crops in east-central Poland. Our research was aimed at developing an innovative, cost-effective system tailored to the diverse local conditions of this region. Conducted between 2018 and 2020, the study analyzed integrated and organic production systems across different soil types and potato varieties. The experiment was conducted using a randomized block design with three replications in two locations. Integrated production systems involve the strategic use of mineral fertilization and chemical protection to optimize crop growth and health, whereas organic production systems rely solely on natural inputs and biological pest control methods. Integrated practices, enhanced by mineral fertilization and chemical protection, notably delayed the onset of late blight by 16 days and extended the critical infection period by 17% compared to their organic counterparts. Remarkably, the integrated systems resulted in a 49% increase in total production and a 52% increase in commercial yields, demonstrating their effectiveness in enhancing crop resilience. Different potato varieties exhibit varied responses to cultivation systems, influencing both yield and disease resistance. Further investigation into these varietal responses can help optimize cultivation practices, leading to improved efficiency and sustainability in potato farming. Location and soil conditions have a significant impact on potato yield and the spread of potato blight. Specific soil properties such as pH levels, organic matter content, soil texture (clay, silt, and sand composition), moisture retention capacity, and nutrient availability are crucial in determining potato productivity and disease dynamics. Further research into these soil properties and the adaptation of varieties to local conditions can contribute to increased productivity and stability in potato production. This study not only paves the way toward sustainable agriculture but also highlights the crucial role of soil diversity in shaping resilient farming practices. Potato producers in the eastern-central region of Poland should implement integrated production systems using mineral fertilization and chemical plant protection, adapted to local soil conditions and potato varieties. These practices can delay the appearance of late blight and increase the total and marketable potato yield. Further research on soil properties and variety adaptation may increase production stability and efficiency. Promoting soil diversity and modern technologies will ensure resilient and sustainable agricultural production in the face of climate change.

Keywords: late blight; integrated crop management; soil diversity; crop resilience; sustainable agriculture

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1. Introduction

Potatoes are a vital global food crop but their production faces threats from both abiotic and biotic factors. Late blight, caused by the oomycete *Phytophthora infestans*, is particularly devastating, capable of causing losses ranging from 20 to 80%. This pathogen's rapid evolution and adaptability make it highly destructive, capable of decimating entire potato plantations in just 10–15 days under favorable weather conditions. Late blight remains the most economically damaging potato disease worldwide, with annual losses exceeding USD 10 billion [1].

Current disease control relies heavily on fungicide use, which has negative environmental impacts. The excessive use of mineral fertilizers and chemical plant protection products exacerbates environmental degradation, highlighting the urgent need for sustainable agricultural practices. Harmonized world development, integrating economic growth with environmental preservation, is emerging as a solution to combat these threats [2]. The results of González-Jiménez et al. [3] also underscore the influence of disease development rate and infection timing on yield losses, with relatively low incidence and early onset of epidemics causing significant yield reductions. Additionally, simulations were conducted to assess the impact of temperature increase induced by climate change on both potato crops and *P. infestans* development, suggesting that higher temperatures may be more detrimental to the pathogen than to the crops.

Research emphasizes the importance of disease development rate and infection timing on yield losses, with low incidence and early epidemics causing significant reductions. Simulations suggest that climate change-induced temperature increases may be more detrimental to the pathogen than to potato crops [2].

The focus on sustainable agricultural practices covers the following aspects such as:

- Innovation: Technologies such as precision agriculture, smart sensors, and data analytics optimize the use of water, fertilizers, and pesticides [3,4].
- Education: Information campaigns, educational programs, and social activities that raise support for environmentally friendly agriculture.
- Policy: Implementation of subsidies, taxes, chemical limits, and support for organic farming promotes sustainable practices [5,6].
- International cooperation: That is, the exchange of knowledge through programs, conferences, and partnerships, which significantly accelerates progress in sustainable agriculture around the world [7].

Finally, there is a need for an integrated approach to agriculture that considers economic, social, and environmental aspects. Actions taken in each of these areas can contribute to achieving the goal of sustainable agricultural development [7,8].

In the agricultural domain, three primary farming systems have become prominent: conventional, integrated, and ecological. The integrated system harnesses advancements in both technology and biology to strike a balance between economic profitability and ecological sustainability. Conversely, the ecological system abstains from using chemically modified industrial production methods, instead relying on agrotechnical practices such as crop rotations, organic fertilization, and careful variety selection to bolster soil fertility and maintain a favorable sanitary environment [9]. The integrated system and the ecological system of potato cultivation have been designed based on different principles and goals that aim to ensure sustainable agricultural production, minimize environmental impact, and optimize yields. The purpose of the systems designed in the study was as follows:

In an integrated system:

- Optimizing productivity while minimizing costs and impact on the natural environment.
- Ensuring high-quality agricultural products through the sustainable use of chemicals.
- Risk reduction: Reducing losses caused by diseases and pests through the use of integrated plant protection methods.
- Enabling farmers to conduct sustainable agricultural activities [9–11].

In the Ecological System:

- Production of healthy, safe food without pesticide and artificial fertilizer residues.
- Protection of soil and water by improving the condition of the soil (natural fertilization and natural plant protection methods).
- Protection of water resources by reducing chemical pollution.
- Support for biodiversity by creating conditions favorable to biodiversity in agricultural ecosystems [9–11].

Central-eastern Poland's diverse soil conditions and temperate climate provide favorable conditions for potato cultivation. However, variations in soil types and microclimates across the region can significantly influence crop health and productivity. Understanding this interplay is crucial for developing effective strategies to manage potato blight and ensure sustainable crop production [3].

Recent research highlights the economic impact of potato blight, causing significant yield reductions and financial losses for farmers. Developing comprehensive disease management strategies, including research on resistant varieties and international cooperation, is crucial for protecting farmers and ensuring food security [8–12].

This work delves into the complex nature of *P. infestans*, reviews the effectiveness of current integrated pest management (IPM) strategies, and analyzes the potential of innovative, sustainable approaches for controlling this disease within both ecological and integrated potato cultivation systems [13].

While the macroeconomic implications of farming systems and soil conditions have been extensively explored, their influence on crop quality, especially potato health, remains relatively understudied. Therefore, this paper aims to fill this gap by evaluating the impact of cultivation systems on the health status and yielding of potatoes in central-eastern Poland.

2. Materials and Methods

The field experiment was carried out in central-eastern Poland at the experimental station in Parczew and ZDOO in Uhnin. The experiment was located on the Parczew Plain covering the north-eastern part of the Parczew district, which is part of the Western Polesie macroregion (Parczew—22°55′ E, 51°38′ N, H = 155) and Uhnin (51°34′ E, 23°02′ N, H = 157 m above sea level) (Figure 1) [14].

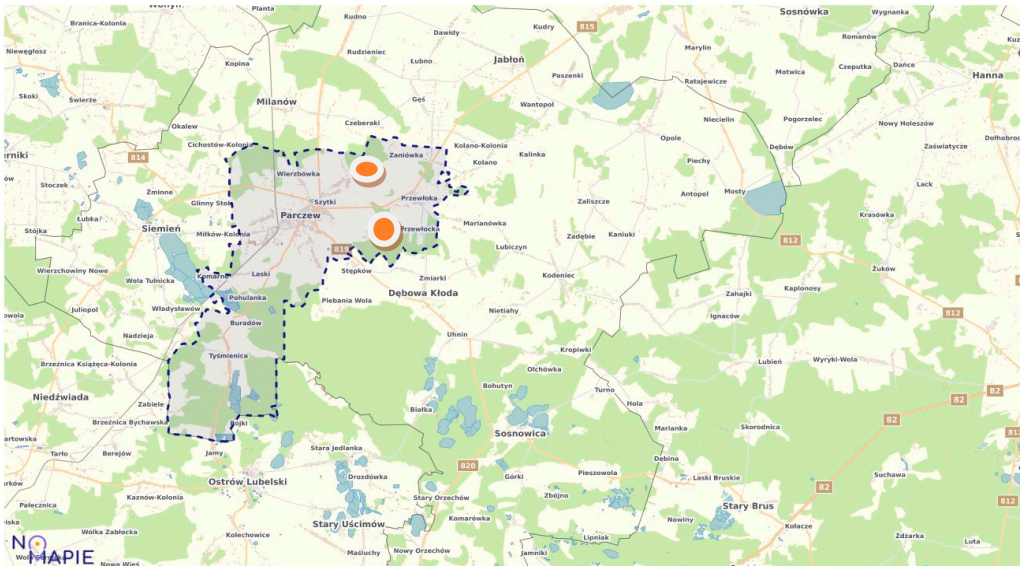


Figure 1. Physiographic map of the Parczew commune; http://parczew.geoportal2.pl/map/geoportal/wms.php (accessed on 2 May 2024). location of the field experiment.

2.1. Field Experiment

The study conducted a field experiment from 2018 to 2020 at the experimental station in Parczew, focusing on a good rye complex soil. The experiment involved two main factors: crop production systems (integrated and ecological) and six potato cultivars ("Amarant", "Boryna", "Irga", "Jurek", "Jelly", and "Mila"). The experiments were conducted using the split-split-plot design in 3 replications, where the first-order factor was the cultivation systems: (a) organic system, without blight protection and mineral fertilization; (b) integrated system with organic and without mineral fertilization; and chemical protection against potato blight, with an appropriately early (prophylactic) protection scheme. The second-order factor was potato varieties with different levels of leaf blight resistance ("Irga", "Jurek", "Boryna", "Jelly", and "Amarant"). The selection of these six potato varieties ("Irga", "Jurek", "Boryna", "Mila", "Jelly", "Amarant") for the late potato blight experiment is justified by their diversity in terms of earliness, disease resistance, quality, and size. This diversity allows for a comprehensive examination of the effectiveness of different plant protection strategies under varying soil and climatic conditions, which could lead to more precise and sustainable agricultural practices in the region. Detailed characteristics of these varieties are provided in Section 2.2.

Potato tubers were planted with a spacing of 70 × 35 cm on 25–27 April. The propagation material used in the experiment was classified as Class A according to European Union standards. No proemergence process was conducted before planting the seed potatoes. The seed potatoes were stored under appropriate conditions for potato seed tubers.

The integrated system and the ecological system of potato cultivation have been designed based on different principles and goals that aim to ensure sustainable agricultural production, minimize environmental impact, and optimize yields. These are the basics of integrated and ecological system design:

Integrated system:

- Plant protection principles: Use scientific and technological advances to balance plant protection with minimal chemical use, following integrated pest management (IPM) guidelines for controlled fungicide, pesticide, and herbicide application.
- Fertilization principles: Combine mineral and organic fertilizers for optimal plant growth and soil health, based on soil analysis and plant needs.
- Monitoring and management: Regularly monitor crops for diseases, pests, and fertilization needs using precision agriculture technologies like drones, sensors, and GPS systems [9–11].

Organic system:

Ecological principles: Avoid synthetic chemicals and fertilizers, using natural pest control methods and organic fertilizers [9,10].

Different crop rotations and production technologies were implemented in both systems:

Integrated system: Crop rotation: potato → spring barley → red clover → winter wheat + after-crop (consisted of white mustard and spring vetch). Fertilization: Phosphorus-potassium fertilization was applied to compensate for the intake, with the following rates: 128 kg N, 60 kg P_2O_5, 60 kg K_2O. Compost application: Compost was applied at a rate of 35 t·ha^{-1} once during the rotation cycle, specifically under the potato. Chemical plant protection: Agrophage harm thresholds were used for chemical plant protection operations.

Ecological system: Crop rotation: potato → spring barley → red clover with grass performed for 2 years → winter wheat + after-crop (consisted of white mustard and spring vetch).

Fertilization: No mineral fertilizers were applied. Pesticide: Novodor was used against potato beetle. Compost application: only 2-year-old compost (stalks + red clover + hay) was introduced under the potato at the rate of 35 t·ha^{-1}.

Weed control: Weed control in this system involved harrowing using a harrow before shooting, triple hilling, and once manual hoeing just before the last hilling.

The experiment was conducted in one replication on fields where all plants were growing simultaneously, each covering about 1 hectare.

All plant care and protection treatments were applied in accordance with the IHAR methodology [15]. The first spraying took place as a preventive measure, performed before the plague occurred, based on the analysis of meteorological data; the second one was performed when the first plague spots appeared on the plants, and the next ones were carried out at regular intervals from 7 to n-days in the integrated cultivation system. Depending on the year and weather conditions, fungicides were applied from 3 to 9 times until the leaves were completely destroyed in the organic cultivation system. Fungicides containing the following active substances were used to protect against *P. infestans*: propamocarb hydrochloride + chlorothalonil; metalaxyl + mancozeb; dimethomorph + mancozeb (or cymoxanil + mancozeb); zoxamide + mancozeb; chlorothalonil + Zn; mancozeb; fluazinam; fentin hydroxide; in recommended doses. Fungicides used to protect against late blight are characterized by high selectivity as they usually act on one link in the life process of selected mushroom species. The development of resistance of fungi to a given chemical compound or group of compounds necessitates the use of multicomponent preparations containing fungicides with different mechanisms of action or the alternating use of single-component preparations [16,17]. This treatment was aimed at destroying the leaves and preventing the movement of *Phytophthora infestans* spores from the leaves to the tubers. The main criteria for assessing the effectiveness of the studied protection strategies were the rate of development of the blight and the percentage increase in the total and marketable yield of tubers [18].

Potato tubers were collected after achieving full maturity according to earliness groups from 13 September to 6 October using an elevator potato digger. Tuber yield and its structure were estimated in 3 repetitions. The assessment of tuber yield and its structure was made according to the COBORU methodology [19]. During harvest, the total and commercial yield of tubers (yield of tubers with a diameter > 3.5 cm (transverse diameter), excluding cracked and deformed tubers as well as initial symptoms of rot) was determined.

2.2. Characteristics of Potato Varieties

The characteristics of the examined varieties are presented in Table 1.

Table 1. Characteristics of the tested potato varieties.

Varieties	Resistance to Potato Leaf Blight (9-Degree Scale)	Skin Color	Flesh Color	Taste (Nine-Degree Scale)	Consumption Type **	Starch Content (%)
Edible, moderately early						
"Irga"	2	Pink	Creamy	6.5	B	13.9
"Jurek"	4.5	Yellow	Yellow	7	B-BC	13.7
"Mila"	5	Light beige	Yellow	7	BC	15.1
Starchy, moderately early						
"Boryna"	5.5	Red	White	5.8	C-CD	20.2
Edible, moderately late						
"Jelly"	5	Yellow	Yellow	7.5	B	14.4
Starchy, moderately late						
"Amarant"	6.5	Blue	White	nb *	nb	19.9

Source: own study based on Lenartowicz [19], * not tested, ** Consumption types of potatoes are designated by the letters A to D. Type A—Salad, with a firm texture, does not fall apart during cooking; Type B—All-purpose, with a medium-firm texture, slightly more mealy than type A; Type C—Mealy, with a soft texture, the flesh easily falls apart after cooking; Type D—Very mealy, with the softest and most disintegrating texture among all types. Types AB, BC, and CD are intermediate consumption types.

Among the varieties examined, four belonged to the moderately early group, with three varieties ("Irga", "Jurek", and "Mila") being edible and one ("Boryna") being a starch variety. Two varieties were classified as medium-late varieties: one edible variety

("Jelly") and one starch variety ("Amarant"). The resistance of the examined varieties to potato leaf blight varied: "Irga", with a resistance of 2°; "Jurek", with a resistance of 4.5°; "Mila", with a resistance of 5°; "Boryna" with a resistance of 5.5°; and two medium-late varieties: the edible "Jelly", with a resistance of 5°, and the high-starch variety "Amarant", with a resistance of 6.5° on a scale of 9° Nowacki [20]. Moreover, the examined varieties differed in starch content: "Irga" and "Jurek" were characterized by lower starch content (approximately 13.9%), while "Amarant" had a higher content at approximately 19.9%, and "Boryna" at approximately 20.2% [19,20].

2.3. Observations of Potato Blight

Observations of the plant's development stages and their health state were made throughout the vegetation period. Evaluation of plant infection by *P. infestans* was conducted every 10 days from the first disease symptoms observed until the end of the vegetation period using a 9-degree scale. This scale is based on observing disease symptoms in the plants and assigning a rating from 1 to 9, where 9° signifies no symptoms of the disease; 8° indicates slight symptoms on individual leaves or plant units, 7° signifies the spread of the disease to several leaves; 6° indicates moderate infection of the plant but without clear symptoms on the tubers; 5° signifies significant leaf infection and the appearance of initial symptoms on the tubers; 4° indicates moderately advanced infection, with visible symptoms on the tubers; 3° signifies significant infection of both potato leaves and tubers; 2° indicates severe infection of the potato plant with visible symptoms on most leaves and tubers; and 1° signifies total destruction of the potato plant [21]. This scale helps monitor and assess the level of potato plant infection by potato blight to take appropriate disease control actions, such as using plant protection products, changing cultivation practices, or selecting more resistant potato varieties [4,21].

2.4. Natural Conditions

Poland is located in the central part of Europe and is affected by the climatic conditions of both the Atlantic Ocean and the Eurasian continent. Therefore, the area is characterized by air crises with different characteristics of heat and humidity, which contribute to a high variability of the climate each year. Therefore, the area is distinguished by air advection with different thermal and moisture characteristics, which contribute to a high variability of weather types annually. Large-scale atmospheric circulation is an important factor, the occurrence of extreme rainfall in Poland [22,23]. Precipitation is of great importance for the functioning of the natural environment and in a number of areas for human activity. Heavy rains increase the risk of flooding, which often leads to significant deaths and financial losses [24]. It is assumed that an increase in global air temperature correlates with the intensity of precipitation events. This has also been observed recently in areas with decreasing annual rainfall [22].

2.5. Soil Conditions

The choice of soil for the experiment was justified by the need to ensure the representativeness of the results and to understand the impact of various soil conditions on the development of late potato blight and the effectiveness of the applied protection methods. Thanks to the diversity of the selected soils, the study could provide more comprehensive and useful information that can be used in agricultural practice in east-central Poland. Soils in different locations, even within the same region, may have different microclimates, which is important for (a) diversity of climatic conditions: research on the impact of local climatic conditions on the development of potato blight and the effectiveness of the applied protection methods; (b) variety adaptation: understanding how different potato varieties perform in different microclimates and soils.

The results of soil granulometric and an analysis of some physicochemical properties of soil are presented in Table 2. The experiment was carried out on a sandy loam soil type. According to the percentage content of sand, silt, and loam, this is a granulometric

subgroup—clay sand (light soil). Soil granulometric composition: the experience was determined by means of the aerometric method of Prószyński [25]. The fraction of sand was 66.97%, the dust fraction was 30.58%, and the loam was 2.45% (Table 2). This proportion of individual fractions corresponds to the composition of clayey dust. In terms of agricultural suitability, these soils belong to the good rye complex, the slightly acidic class. This soil is classified in the agronomic category, light mineral [26].

Table 2. The granulometric composition of soil.

Year	Composition Content of the Granulometric Fractions [%]									Soil Classification
	Sand					Silt			Loam	
	2.0–1.0 mm	1.0–0.5 mm	0.5–0.25 mm	0.25–0.10 mm	0.10–0.05 mm	0.05–0.02 mm	0.02–0.005 mm	0.005–0.002 mm	<0.002 mm	
Parczew										
2018	0.87	11.89	28.11	11.10	12.75	18.28	7.20	6.86	2.94	Sandy loam
2019	0.09	2.66	11.64	7.76	17.38	32.25	17.10	6.26	4.86	Sand dust
2020	1.00	19.92	32.08	14.00	8.00	15.00	6.04	2.96	1.00	Sandy loam
Mean	0.65	11.49	23.94	10.95	12.71	21.84	10.11	5.36	2.93	Sandy loam
Uhnin										
2018	0.10	16.58	29.56	12.05	8.61	16.02	11.17	3.30	2.61	Sandy loam
2019	0.98	17.86	28.27	11.75	8.33	15.40	11.16	3.56	2.69	Sandy loam
2020	0.71	15.09	25.39	13.59	21.05	18.48	10.27	2.37	2.05	Sandy loam
Mean	0.60	16.51	27.74	12.50	12.66	16.63	10.87	3.08	2.45	

Source: my own experiment results, which were made in the chemical and agricultural station in Lublin.

In Table 3 the granulometric composition of soils for the years 2018–2020 in two locations, Parczew and Uhnin, is presented. The table illustrates the percentage composition of various granulometric fractions in the soil, ranging from sand through silt to clay, across different size categories. Soil classification: Each entry in the table corresponds to a specific soil classification based on the dominant granulometric fraction. Classifications include "sandy clay" and "sandy dust". Comparison between Parczew and Uhnin: For each year in the table, data are provided for both Parczew and Uhnin, allowing for a comparison of the granulometric composition between the two locations. Generally, in both locations, the classification of soils as sandy clay predominates, with varying percentage compositions of different granulometric fractions.

Table 3. Physical and chemical properties of soil in Uhnin (2018–2020).

Year	Content of Assimilable Macronutrients [mg·100 g^{-1} soil]			Humus Content [%]	pH [KCL]	Micronutrients Content [mg·100 kg^{-1} soil]				
	P_2O_5	K_2O	Mg			Cu	Mn	Zn	Fe	B
Parczew										
2018	10.5	11.0	10.4	1.28	5.95	1.10	103.23	2.41	410.04	0.45
2019	19.4	20.8	10.6	1.61	6.32	1.11	140.80	7.66	392.01	0.49
2020	22.00	9.0	11.3	1.63	6.77	3.14	114.0	5.77	846.12	0.47
Mean	17.15	13.60	10.77	1.51	6.35	1.78	119.34	5.28	549.99	0.47
Uhnin										
2015	20.1	13.1	7.8	0.94	5.92	7.51	318	40.1	3760	7.24
2016	18.9	10.9	7.0	1.06	5.77	4.92	337	56.7	3925	5.28
2017	24.0	11.8	6.3	1.03	6.6	8.99	166	41.1	3600	6.04
Mean	21.0	11.9	7.03	1.02	6.09	7.02	273.8	45.96	3761.7	6.17

Source: my own experiment results, which were made in the Laboratory Central of Agro-Ecological (CLA), the University of Life Science in Lublin.

Table 3 presents the mean values of individual granulometric fractions over the years for both Parczew and Uhnin, providing an overview of the average soil composition in each location from 2018 to 2020.

The soil content in assimilable components was as follows: in phosphorus and magnesium very high (21.0 mg P_2O_5·100 g^{-1} soil, 7.03 mg Mg·100 g^{-1} soil), medium in potassium (11.9 mg K_2O·100 g^{-1} soil), in the medium copper (7.02 mg Cu·kg^{-1} soil), in manganese, iron and zinc also medium and was respectively 273.8 mg Mn·kg^{-1} of soil, 3761.7 mg Fe·kg^{-1} of soil, and zinc the average was 45.96 mg Zn·kg^{-1} of soil. In the case of boron, the average was high at about 6.17 B·kg^{-1} of soil (Table 3).

The average acidity of the soil, in a slurry of KCL, in 2015 and 2016 was 5.92–5.77 pH; these values allowed the classification of the experimental soil as slightly acidic soil. While this was natural acid soil in 2017 (6.6 pH). The humus content in the arable layer was low and formed at 0.94–1.06% (Table 3) [26,27]. Micronutrients such as copper (Cu), manganese (Mn), zinc (Zn), iron (Fe), and boron (B) are necessary for plant growth in small amounts. The content of these micronutrients differs between the two locations, with the average values generally being lower in Parczew compared to Uhnin (Table 3).

In general, the comparison of these micronutrients in the soil content reveals that although Parczew tends to have lower levels of available macro- and micronutrients compared to Uhnin, it boasts a higher humus content. Additionally, pH levels are similar in both locations. These disparities in soil characteristics can significantly impact agricultural productivity and necessitate different soil management practices in each location.

2.6. Meteorological Conditions

Table 4 presents the distribution of rainfall, air temperature, and the Sielianinov hydrothermal coefficient during the potato growing season in the years 2018–2020, according to meteorological data from the station in Uhnin.

Table 4. Rainfall, air temperature, and the hydrothermal coefficient of Sielianinov during the growing season of potatoes, according to the meteorological station in Uhnin 2018–2020.

Year	Month	Sum of Rainfall (mm)	Average Temperature (°C)	Hydrothermal Coefficient of Sielianinov *	Classification of the Month According to Sielianinov with Modification by Skowera [28]	Classification of the Month According to Radomski [29] **
2018	April	61.8	8.8	2.3	Wet	Dry
	May	120.3	12.8	3.0	Very humid	Normal
	June	46.7	16.7	0.9	Dry	Very dry
	July	45.2	19.4	0.8	Dry	Very dry
	August	6.1	21.4	0.1	Extremely dry	Extremely dry
	September	130.2	15.5	2.8	Very humid	Wet
	Mean 1.7					
2017	April	47.1	10.0	1.6	Optimum	Very dry
	May	46.3	15.3	1.0	Dry	Very dry
	June	87.3	19.1	1.5	Optimum	Normal
	July	114.1	20.5	1.8	Fairly humid	Normal
	August	41.0	19.5	0.7	Very dry	Very dry
	September	11.8	15.5	0.3	Extremely dry	Extremely dry
	Mean 1.2					

Table 4. *Cont.*

Year	Month	Sum of Rainfall (mm)	Average Temperature (°C)	Hydrothermal Coefficient of Sielianinov *	Classification of the Month According to Sielianinov with Modification by Skowera [28]	Classification of the Month According to Radomski [29] **
2020	April	51.8	8.1	2.1	Wet	Dry
	May	65.5	13.7	1.5	Optimum	Dry
	June	23.1	18.3	0.4	Extremely dry	Extremely dry
	July	132.0	19.4	2.2	Wet	Wet
	August	27.0	20.3	0.4	Extremely dry	Very dry
	September	83.3	14.8	1.9	Fairly humid	Normal
	Mean 1.4					

Source: The meteorological station in Uhnin; * Ranges of values of this index were classified according to Selianinov * as extremely dry—$k \leq 0.4$; very dry—$0.4 < k \leq 0.7$; dry—$0.7 < k \leq 1.0$; fairly dry—$1.0 < k \leq 1.3$; optimum—$1.3 < k \leq 1.6$; fairly humid—$1.6 < k \leq 2.0$; wet—$2.0 < k \leq 2.5$; very humid—$2.5 < k \leq 3.0$; extremely humid—k >3.0. Ranges of values of this index were classified according to Kubiak-Wójcicka et al. [30] ** as: wet—126 to 150 of the standard; normal—75 to 125%; dry—50 to 74%; very dry—25 to 45%; extremely dry precipitation below 25%.

The hydrothermal coefficient was calculated according to the formula Skowera [28]:

$$K = \frac{P * 10}{\Sigma t} \quad (1)$$

where: P—the sum of the monthl Σt y precipitation in mm, Σt—monthly total of air temperature > 0 °C.

In the successive months of the potato growing season in the years 2018–2020, various levels of rainfall and their distribution over time, as well as diverse air temperatures, were observed. This had an impact on the overall classification of these months in terms of humidity according to the classification by Sielianinov modified by Skowera [28].

In 2018, April and May were characterized by moderate rainfall and relatively cool air temperatures, resulting in their classification as humid and optimal, respectively. In contrast, June and July were drier months, with low rainfall and higher air temperatures, classified as very dry and dry. August was exceptionally dry with very low rainfall. In 2019, April and June were classified as optimal, with moderate rainfall and air temperatures, while May and July were dry months with lower rainfall. August and September were very dry months with very low rainfall. In 2020, April and July were humid, while June and August were exceptionally dry. September was classified as moderately humid.

The rising air temperature may increase evaporation and intensify meteorological droughts even though annual rainfall trends do not fully explain yearly rainfall variability [29–31].

The Sielianinov hydrothermal coefficient, which considers the ratio of rainfall to average air temperatures, fluctuated between different humidity classes in individual months and years, which had significant implications for plant growth conditions and the rate of potato blight spread. Hydrothermal coefficients (k) indicate the balance between precipitation and temperature during specific months, specifically June, July, and August. The index values categorize the conditions into different moisture levels ranging from extremely dry to extremely humid (Table 4).

2.7. Statistical Calculations

The study results were statistically processed mainly using analysis of variance (ANOVA). The aim of the ANOVA was to assess whether the mean values of different groups (e.g., potato varieties, cultivation systems) differ significantly. ANOVA allowed for the simultaneous comparison of many varieties and cultivation systems and the identi-

fication of interactions between various factors, which is important when examining the impact of combinations of varieties, soil conditions, and meteorological conditions on late potato blight. After conducting the ANOVA, post-hoc tests, such as the Tukey test, were used to more closely compare pairs of groups to determine which specific groups differed from each other. These precise differences allowed us to identify exactly which potato varieties differ significantly in terms of yield, structure, and resistance to late blight. Regression: modules for linear, multiple, and logistic regression analysis were used. Regression analysis was used to model the relationship between variables such as the impact of soil conditions and cropping systems on yield and the occurrence of late blight. Regression analysis made it possible to predict results based on various independent variables and helped to understand which factors had the greatest impact on results, which is crucial for optimizing agricultural practices. R software (version 4.2.1), and SPSS software (version 28.0) were used to perform statistical analyses. R software is a powerful tool for statistical analysis and data visualization, while SPSS is a valued tool for its intuitive user interface and the wide range of statistical tests available [32,33].

The rate of potato blight spread depending on the observation date was calculated using regression calculus. For calculations, observation terms were encoded accepting the first date as "0", the second as "10", the third as "20", etc. Leaf infection was expressed in logarithmic values corresponding to 9° grade and using the formula [34]:

$$Y = \log \frac{x}{1 - x} \quad (2)$$

where x—values expressed in hundred parts. They make it possible to express the percentage of leaf surface damage in the form of a straight line. The rate of potato blight spread was regarded as a unitary increase in infection over time.

3. Results

3.1. The Rate of Spread of Potato Blight

The rate of spread of potato blight refers to the speed at which the fungal pathogen *Phytophthora infestans*, which causes late blight disease, spreads within a potato crop (Figure 2).

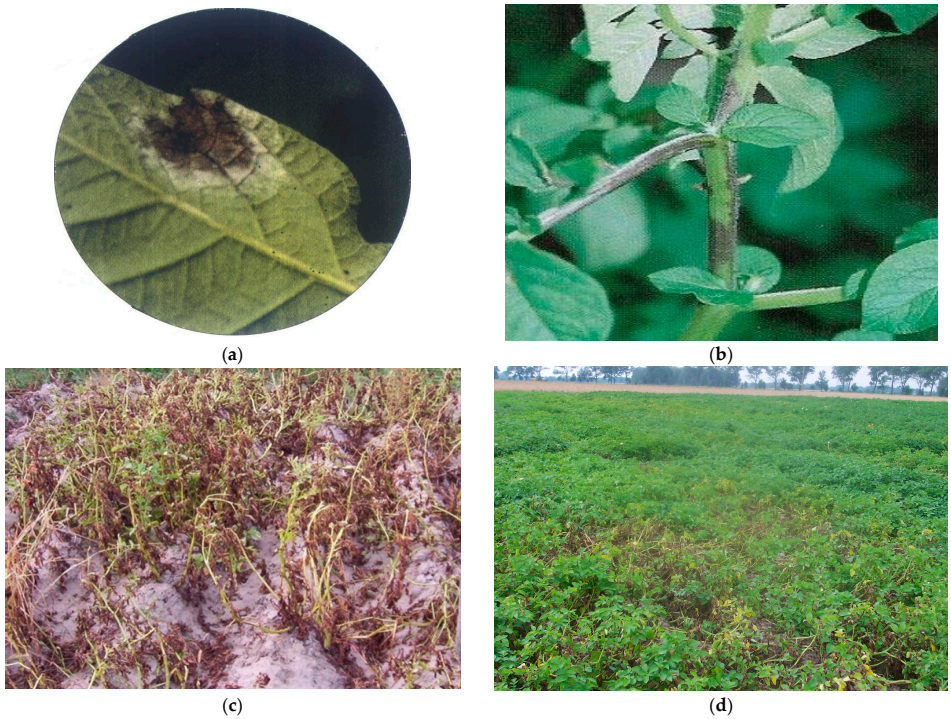


Figure 2. *Cont.*



(**e**) (**f**)

Figure 2. *Phytophthora infestans* [Mont] De Barry—late potato blight: (**a**) Late potato blight leaf inoculant; (**b**) Late potato blight—stem form; (**c**), Potato blight on an organic field in Parczew; (**d**) Potato blight on the integrated field in Uhnin; (**e**) Potato blight on leaves, stems, and tubers; (**f**) Late potato blight on tuber.

Several factors influence the rate of spread of potato blight, including environmental conditions such as temperature, humidity, and rainfall, as well as agronomic practices, host plant resistance, and the presence of the pathogen in the vicinity. Warm, humid conditions are particularly conducive to the rapid spread of the disease, as they promote the growth and dispersal of the pathogen's spores. Table 5 presents the coefficients of the rate of late blight spread for the years 2018–2020, dependent on location (Parczew and Uhnin) and cultivation systems (Ecological and Integrated).

Table 5. Coefficients of rate of late blight spread (2018–2020).

Specificalities		Years		
		2018	**2019**	**2020**
Locations	Parczew	0.192	0.201	0.138
	Uhnin	0.140	0.165	0.114
Cultivation systems	A *	0.200	0.224	0.132
	B **	0.132	0.142	0.120
Mean		0.166	0.183	0.126

* Ecological crop production system; ** Integrated crop production system.

In 2018, the rate of late blight spread in Parczew was 0.192 under the ecological system and 0.200 under the integrated system. In Uhnin, the rates were 0.140 and 0.132, respectively. In 2019, the rates in Parczew were 0.201 (ecological) and 0.224 (integrated), while in Uhnin, they were 0.165 (ecological) and 0.142 (integrated). In 2020, the rates in Parczew were 0.138 (ecological) and 0.132 (integrated), and in Uhnin, they were 0.114 (ecological) and 0.120 (integrated).

These coefficients serve as indicators of the rate at which late blight spreads under different conditions, providing valuable insights for disease management and agricultural practices.

Hydrothermal coefficients (k) indicate the balance between precipitation and temperature during specific months, specifically June, July, and August. The index values categorize the conditions into different moisture levels ranging from extremely dry to extremely humid.

Coefficients of the rate of potato blight spread were higher in Parczew than in Uhnin in all years of the study (Table 5). This could be attributed to different weather conditions favoring the faster emergence and spread of the pathogen (Table 4), as well as soil conditions, as the soils in Parczew exhibited significantly higher humus content and higher soil pH (Tables 2 and 3).

Table 5 provides insight into meteorological conditions and their impact on the development of *P. infestans* over a three-year period, which may be valuable for understanding disease dynamics and optimizing crop management strategies. The infection of 50% of the potato leaf blade surface is an indicator of the degree of plant infection by the pathogen known as *P. infestans*, which causes the disease commonly known as potato blight. This is a significant criterion because it indicates the point at which the infection reaches a level that has a significant impact on yield. When the infection covers 50% of the leaf blade surface, it negatively affects the plant's ability to photosynthesize and produce tubers, ultimately leading to a reduction in yield. Therefore, this moment is crucial for assessing the effectiveness of disease management strategies and making decisions regarding further disease control actions.

Plant production systems and the resistance of potato varieties had a significant impact on the rate of pathogen spread in plants (Figures 3 and 4. *P infestans* spread the fastest over time. Infestans on the medium-early potato variety "Irga", not resistant to late blight, with resistance 2 on a 9-point scale.

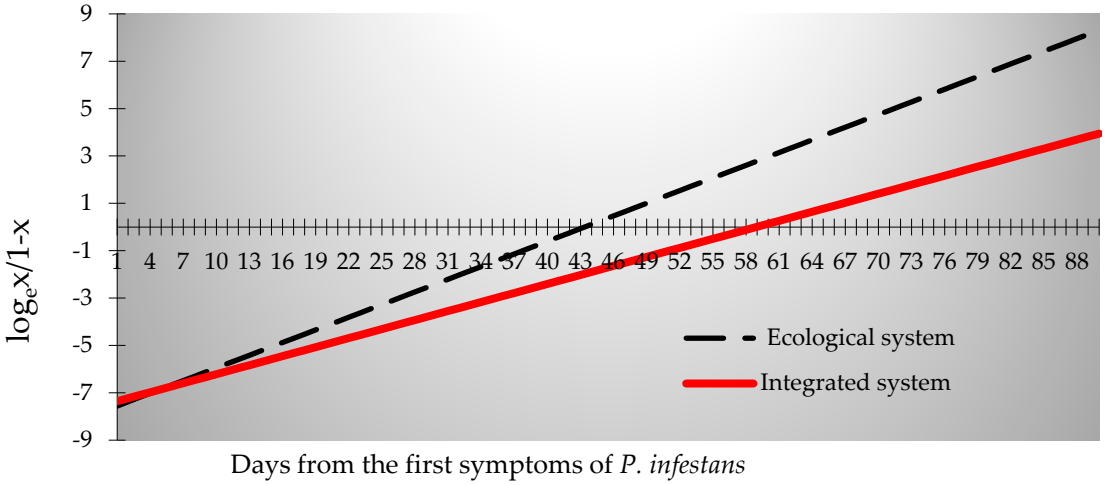
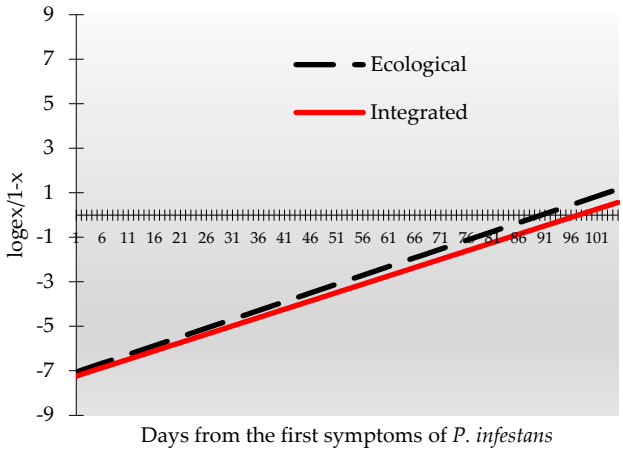
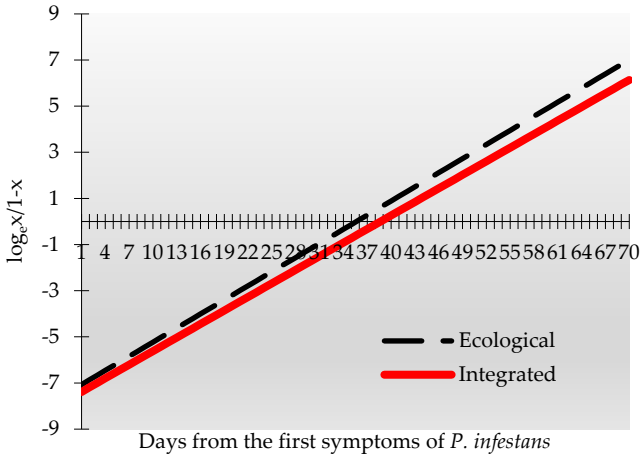


Figure 3. Late potato blight in the ecological and integrated crop system (mean for the years 2018–2020).

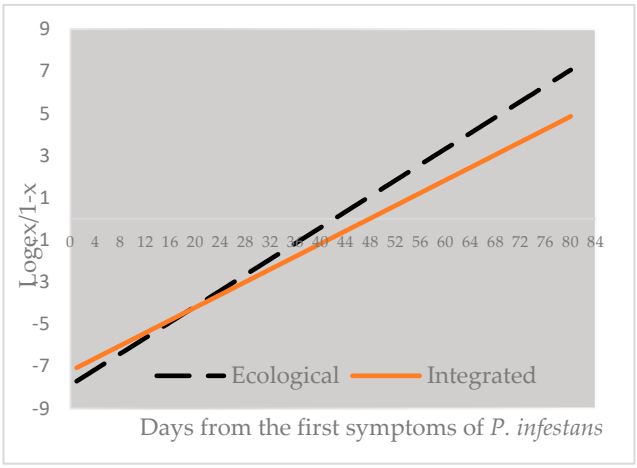


(**a**)

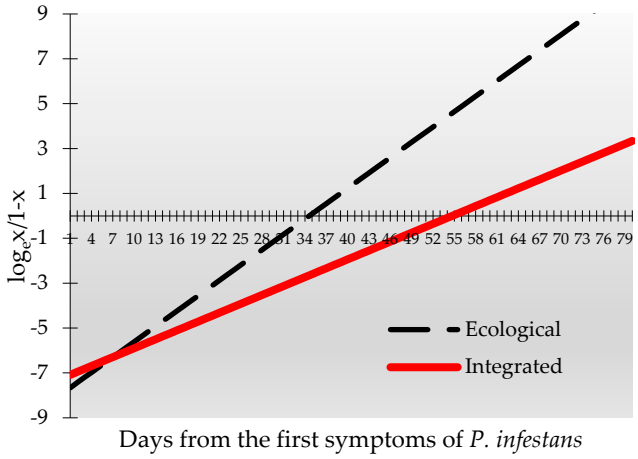


(**b**)

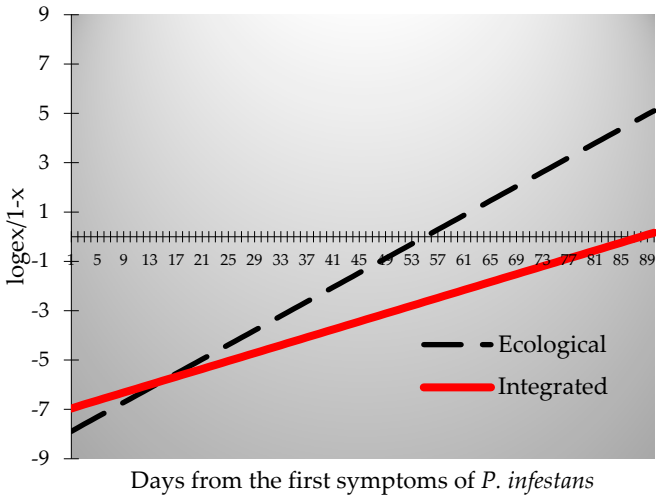
Figure 4. *Cont.*



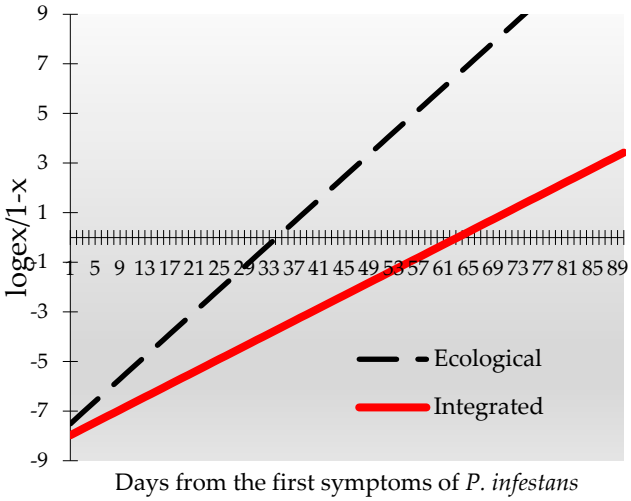
(**c**)



(**d**)



(**e**)



(**f**)

Figure 4. Late blight rate of infection on varieties in the ecological and integrated system; (**a**) "Boryna", (**b**) "Irga", (**c**) "Jurek", (**d**) "Mila", (**e**) "Amarant", (**f**) "Jelly".

In the ecological system, 50% of potato leaf blade infection occurred on average 43 days after the appearance of the first late blight spots, which determine the accumulation of tuber yield, while in the integrated system, this moment occurred 15 days later (Figure 3).

Potatoes were infected sooner in the ecological system. The average infection of 50% of the leaf blade surface, determining yield accumulation, occurred 44 days after the first infection symptoms (spots) were observed. In the integrated cultivation system, where protective measures against potato blight were applied, plant infection by *P. infestans* occurred, on average, 16 days later than in the ecological system. The effectiveness of plant protection against the blight depended on the plant's resistance to the pathogen and their reaction to fungicide application (Figure 3).

Leaf blight developed the slowest in the medium-early variety "Boryna", with a resistance of 5.5° on a scale of 9°. Infection of 50% of the leaf blades of medium-early, quite resistant to *P. infestans* of the "Boryna" variety (5.5° on a scale of 9°) occurred 90 days after the first plague spots appeared in the organic system, and 6 days later in the integrated system (Figure 4a).

Figure 4b depicts the rate of potato blight spread on plants of the moderately early, edible variety "Irga" in both ecological and integrated cultivation systems. Critical in-

fection, affecting 50% of leaf blades for this variety, occurred after 36 days from the first observation of late blight spots in the ecological system and 3 days later in the integrated cultivation system.

Figure 4c depicts the rate of potato blight spread on plants of the moderately early, edible variety "Jurek" in both ecological and integrated cultivation systems. Critical infection, affecting 50% of leaf blades for this variety, occurred after 41 days from the first observation of late blight spots in the ecological system and 7 days later in the integrated cultivation system.

Figure 4d illustrates the impact of resistance characteristics of the moderately early, edible variety "Mila" and cultivation systems on the timing of infection of 50% of the potato leaf blade surface. For this variety, with a resistance rating of 5 on a 9-degree scale, critical leaf blade surface infection occurred as early as 34 days after the first observation of late blight spots in the ecological system, and due to full protection against potato blight in the integrated system, it occurred 21 days later (Figure 4d).

The effect of resistance characteristics of the moderately late, starch variety "Amarant" and potato cultivation systems is presented in Figure 4e. Critical infection, affecting 50% of the leaf blade surface of this variety, occurred 54 days after the appearance of the first late blight spots in the ecological system. However, the integrated system, utilizing organic and mineral fertilization along with full protection against potato blight, contributed to extending this period by 45 days (Figure 4e).

The response of the moderately late, edible variety "Jelly" to the applied cultivation systems is presented in Figure 4f. In the ecological cultivation system, infection of 50% of the leaf blade surface of the "Jelly" variety was observed after just 34 days from the appearance of the first late blight spots, while the integrated cultivation system extended this period by 30 days (Figure 4f).

Table 6 presents the results regarding the regression coefficient of the spread rate of *P. infestans* for the examined potato varieties and two production systems. For each variety, resistance to late blight is provided on a 9-degree scale, where a higher number indicates greater resistance to late blight. The regression coefficients determine how quickly the pathogen spreads for each variety and production system. Lower coefficient values suggest slower pathogen spread, indicating greater resistance to the variety or more effective disease control strategies in the specific production system. Variability in the regression coefficient values across varieties and production systems suggests that the effectiveness of variety resistance or disease prevention strategies may depend on specific growing conditions.

Table 6. Infection coefficients of *P. infestans* over time (mean for years and localities).

Varieties	Resistance of Potato Varieties to Late Blight on a 9-Degree Scale *	Crop Production Systems		Mean
		Ecological	Integrated	
"Amarant"	6.5	0.146	0.080	0.113
"Boryna"	5.5	0.079	0.075	0.077
"Irga"	2.0	0.204	0.196	0.200
"Jelly"	5.0	0.226	0.128	0.177
"Jurek"	4.5	0.187	0.151	0.169
"Mila"	5.0	0.228	0.132	0.180

* 9—Signifies no symptoms of the disease; 8—Indicates slight symptoms on individual leaves or plant units; 7—Signifies the spread of the disease to several leaves; 6—Indicates moderate plant infection but without apparent symptoms on the tubers; 5—Signifies significant leaf infection and the appearance of initial symptoms on the tubers; 4—Indicates moderately advanced infection, with visible symptoms on the tubers; 3—Signifies significant infection of both potato leaves and tubers; 2—Indicates severe infection of the potato plant with visible symptoms on most leaves and tubers, 1—means the highest susceptibility to potato blight, damaged and dried leaves and stems [22].

Resistance levels: Varieties with higher resistance levels, such as "Amarant" (6.5) and "Boryna" (5.5), generally exhibit lower infection coefficients compared to those with lower resistance levels, like "Irga" (2.0). Crop production systems: Across all varieties, the

ecological crop production system tends to result in slightly lower infection coefficients compared to the integrated crop production system. Varietal performance: "Jelly" and "Mila", both with a resistance level of 5.0, show relatively high infection coefficients compared to varieties with similar resistance levels. This suggests that factors beyond resistance level, such as environmental conditions or cultivation practices, may influence varietal performance in terms of late blight resistance (Table 6).

Overall, the table underscores the importance of both varietal resistance and crop production practices in managing late blight infection. Additionally, it highlights the need for further investigation into factors influencing varietal performance under different production systems to optimize disease management strategies.

Overall, these results underscore the importance of both variety resistance and the implementation of effective crop management strategies, including plant protection, fertilization, and pest control, in minimizing the risk of potato blight occurrence and spread, as well as ensuring high-yield productivity. This indicates that the integrated production system contributed to delaying the onset of infection on the leaf blade surface for all varieties compared to other cultivation methods. The longer delay observed for certain varieties, such as "Jelly" and "Amarant", suggests that these varieties may possess inherent traits or characteristics that make them more resilient to infection under integrated production conditions. Conversely, varieties with shorter delays, like "Irga" and "Jurek", may require additional management practices or interventions to mitigate the risk of early infection. These findings emphasize the importance of considering both the cultivation system and varietal characteristics when implementing strategies to manage late potato blight effectively.

3.2. Total and Commercial Yield of Tubers

Total and marketable yields of potatoes differed significantly depending on the potato varieties and production systems (Table 7). In the ecological system, the total yield of tubers was lower by 49.1% and the marketable yield by 52.3% compared to the integrated system. Moreover, it was calculated that extending the potato vegetation period by 1 day in the integrated cultivation system, due to the combined application of fertilization and plant protection measures, contributed to an increase in tuber yield by 795.9 kg per hectare (Table 7).

Table 7. The influence of crop production systems and varieties on total and trade yield ($t \cdot ha^{-1}$) (2018–2020).

Varieties	Total Yield			Trade Yield		
	Crop Production Systems					
	Ecological	Integrated	Mean	Ecological	Integrated	Mean
"Amarant"	29.1 b *	41.1 b	35.1 b	27.3 b	38.1 b	32.7 b
"Boryna"	41.8 a	52.3 a	47.0 a	40.8 a	50.6 a	45.7 a
"Irga"	21.4 bc	29.0 c	25.2 cd	18.6 bc	26.8 c	22.7 cd
"Jelly"	23.1 bc	42.6 b	32.9 bc	20.1 bc	38.6 b	29.4 bc
"Jurek"	17.4 c	32.7 c	25.1 cd	16.5 d	31.8 bc	24.1 c
"Mila"	22.9 bc	34.0 bc	28.4 c	19.1 bc	30.5 c	24.8 c
LSD $p_{0.05}$	8.4		4.8	7.7		4.5
Mean	25.9 b	38.6 a	32.3	23.7 b	36.1 a	29.9
LSD $p_{0.05}$	1.6			1.5		

* Equal letter notations indicate that the mean values for different groups do not differ significantly from each other. This means that there is no significant statistical difference between the groups, indicating that we cannot reject the null hypothesis, which assumes no differences between the groups.

The medium-early variety "Jurek" had the lowest yields. The "Amarant" variety followed closely behind "Jurek". In terms of total yield, the "Irga" and "Jurek" varieties

were homogeneous, whereas for marketable yield, the "Jurek" and "Mila" varieties were homogeneous in this trait (Table 7).

The integrated cultivation system generally resulted in higher total and marketable yields compared to the ecological system for most varieties, indicating the effectiveness of the integrated approach in increasing potato productivity. In this system, the "Boryna" variety exhibited the highest yield, while the "Jurek" and "Irga" varieties had the lowest total yields and the "Irga" and "Mila" varieties had the lowest marketable yields. Additionally, the "Amarant" and "Jelly" varieties were homogeneous in terms of these traits (Table 7).

In the ecological system, the "Boryna" variety also produced the highest total yield, while the "Jurek" variety had the lowest yield. The "Irga", "Jelly", and "Mila" varieties were homogeneous in terms of this trait. For marketable yield, the response of the varieties to the cultivation systems was also varied. The "Boryna" variety responded best to the ecological system, followed by the "Amarant" variety, while the remaining varieties were in the same homogeneous group (Table 7). Significant differences in yields between varieties and between the ecological and integrated systems highlight the importance of variety selection and production system management in optimizing potato yields.

Table 8 presents the impact of the experiment locations (Parczew and Uhnin) and potato varieties on total and marketable yields from 2018 to 2020. In both Parczew and Uhnin, the "Boryna" variety achieved the highest total and marketable yields, followed by the "Amarant" and "Jelly" varieties. The variety with the lowest marketable yield was "Jurek", with homogeneous traits observed in several varieties.

Table 8. The influence of locations and varieties on total and trade yield (t·ha^{-1}) (2018–2020).

Varieties	Total Yield			Trade Yield		
	Localizations					
	Parczew	Uhnin	Mean	Parczew	Uhnin	Mean
Amarant	32.9 b *	37.2 b	35.1 b	30.7 b	34.6 ab	32.7 b
Boryna	43.9 a	50.1 a	47.0 a	42.1 a	49.3 a	45.7 a
Irga	26.9 c	23.0 d	25.0 d	24.9 c	20.5 c	22.7 d
Jelly	28.1 bc	37.6 b	32.9 bc	24.6 c	34.1 ab	29.4 bc
Jurek	19.9 c	30.3 c	25.1 d	18.0 d	30.1 b	24.1 c
Mila	25.7 c	31.1 c	28.4 c	22.6 dc	27.0 bc	24.8 c
LSD $p_{0.05}$	8.4			7.7		
Mean	25.9 b	38.6 a	32.3	23.7 b	36.1 a	29.9
LSD $p_{0.05}$	1.6		4.8	1.5		4.5

* Equal letter notations indicate that the mean values for different groups do not differ significantly from each other. This means that there is no significant statistical difference between the groups, indicating that we cannot reject the null hypothesis, which assumes no differences between the groups.

Generally, most varieties yielded higher in Uhnin compared to Parczew, suggesting potential differences in soil and climate conditions between the two locations. Significant differences in yields between varieties and locations were also observed, as indicated by LSD values. For total yield, the "Boryna" variety achieved the highest yield regardless of location, while the "Jurek" variety had the lowest yield in Parczew, and the "Irga" variety had the lowest yield in Uhnin. A similar varietal response to location conditions was observed for marketable yield. The interaction effect between location and variety underscores that the impact of a variety on yield can vary significantly depending on the location (Table 8).

The analysis of total and marketable tuber yields of the studied potato varieties, depending on the years of research and varieties, showed significant differences in productivity both between years and between varieties (Table 9). The highest yields, both total and marketable, were obtained in 2020, which had favorable weather conditions for potatoes, while the lowest total and marketable tuber yields were obtained in 2019, which

experienced a shortage of rainfall and unfavorable distribution during the potato growing season. The "Boryna" variety consistently showed the highest total and marketable yields across all three years, with an average total yield of 47.0 t ha^{-1} and an average marketable yield of 45.7 t ha^{-1}. Conversely, the medium-early variety "Irga" had the lowest yields compared to other varieties, with an average total yield of 25.0 t ha^{-1} and an average marketable yield of 22.8 t ha^{-1}. Varieties with LSD values at $p < 0.05$ that did not differ significantly from each other are considered to produce homogeneous yields. For total yield, the "Boryna" and "Amarant" varieties produced homogeneous yields in 2018 and 2019, indicating no significant differences between these varieties. Homogeneous total tuber yields were also observed for the "Irga", "Jelly", "Jurek", and "Mila" varieties in the dry year of 2018, and for the "Irga", "Jurek", and "Mila" varieties in 2019 (Table 9).

Table 9. The influence of years and varieties on total and trade yield (t·ha^{-1}) (2018–2020).

Varieties	Total Yield				Trade Yield			
	Years							
	2018	**2019**	**2020**	**Mean**	**2018**	**2019**	**2020**	**Mean**
"Amarant"	34.0 a *	31.1 a	40.1 b	35.1 b	31.5 a	29.4 a	37.1 b	32.7 b
"Boryna"	45.7 a	40.0 a	55.2 a	47.0 a	44.3 a	38.8 a	54.0 a	45.7 a
"Irga"	30.4 b	21.7 b	23.4 c	25.2 d	27.1 b	19.8 bc	21.3 c	22.7 d
"Jelly"	29.4 b	26.0 ab	43.2 ab	32.9 bc	26.8 b	23.3 b	38.2 b	29.4 bc
"Jurek"	29.0 b	19.4 b	26.8 c	25.1 c	28.0 b	18.3 bc	26.2 c	24.2 cd
"Mila"	25.4 b	24.6 b	35.1 bc	28.4 c	22.1 bc	21.0 b	31.4 bc	24.8 c
LSD $p_{0.05}$		14.4				13.5		
Mean	32.3 b	27.1 c	37.3 a	32.2	30.0 b	25.1 c	34.7 a	29.9
LSD $p_{0.05}$		2.5		4.8		2.3		4.5

* Equal letter notations indicate that the mean values for different groups do not differ significantly from each other. This means that there is no significant statistical difference between the groups, indicating that we cannot reject the null hypothesis, which assumes no differences between the groups.

For marketable yield, the "Boryna" and "Amarant" varieties also showed homogeneous yields in 2018 and 2019. Additionally, the "Irga" and "Jurek" varieties achieved homogeneous marketable yields in 2018 and 2020 (Table 9).

Additionally, an interaction between years and varieties was observed for both total and marketable yields. This interaction is evident in the yield fluctuations. Some varieties consistently produced stable yields throughout the years of the study, while others showed variability in this trait. For example, while the "Boryna" variety consistently maintained a high yield level, the "Irga" and "Jelly" varieties exhibited different yield levels over the years 2018–2020.

4. Discussion

4.1. The Impact of Cultivation Systems on the Spread Rate of Potato Blight and Yield

An analysis of the results regarding the rate of spread of *P. infestans* on potato plants presented in this study confirms the significant impact of plant production systems and the resistance of potato varieties on the spread of this pathogen. The results demonstrate that differences in variety resistance and applied protective measures can significantly influence disease development and crop yield.

Potatoes were infected significantly earlier by *P. infestans* in the ecological system compared to the integrated system. Infection of 50% of the leaf blade area, which determines the ability to accumulate yield, occurred on average 43 days after the first symptoms of infection by this pathogen were observed. In the integrated cultivation system, where chemical protection against late potato blight was applied, the infection of plants occurred on average 15 days later than in the ecological system (Figure 3).

Recent studies confirm that integrated pest management (IPM) practices, including the use of resistant varieties, optimized planting times, and targeted fungicide applications, can effectively delay the onset of late blight and reduce its impact on yield. IPM strategies are crucial for sustainable agriculture, balancing the need for crop protection with environmental and economic considerations. These practices are continually evolving with advances in plant breeding, precision agriculture, and fungicide development, offering new tools and techniques to manage late blight more effectively [2,8,18,35]. Mujica and Mujica et al. [36] and Kroschel et al. [37] evaluated integrated pest management (IPM) versus farmer practices for controlling pests and diseases in potatoes (*Solanum tuberosum* L.) on the central coast of Peru. IPM technologies included seed treatment, pest and disease detection using action thresholds for pesticide application, and the use of trapping devices and selective insecticides compared to farmers' chemical controls. An ecological, environmental, and economic analysis was conducted using biodiversity indices, environmental impact indicators, and partial budget analysis. Farmers applied nearly twice as many pesticide treatments (16.7 applications) compared to IPM plots (9.7 applications). Total pesticide use was higher in farms (4614.3 g a.i. ha^{-1}) versus IPM plots (2042.6 g a.i. per ha), with insecticides accounting for most of this difference. Metamidophos and chlorpyrifos made up 65% of the environmental impact (EI) value of 137 per ha on farmer fields, while IPM reduced EI to 42.4 per ha (a 69.2% reduction). Additionally, IPM resulted in a 35% higher marketable potato yield than farmer practices. Partial budget analysis showed higher net profits on all IPM plots, with an average increase of USD 1410 per ha. Field trials demonstrated the environmental and economic viability of IPM for potatoes on the central coast of Peru. However, there is a need to develop and integrate more sustainable and ecological strategies for managing other significant pests.

In the ecological system, the total yield of tubers was 49.1% lower and the commercial yield was 52.3% lower compared to the integrated system. Additionally, it was determined that for each day of extended potato vegetation in the integrated cultivation system, resulting from the combined application of fertilization and plant protection measures, there was an increase in tuber yield of around 796 kg per hectare.

4.2. Influence of Varieties on Potato Blight Infection and Yield

The conducted studies revealed that varieties with higher resistance levels to potato blight generally exhibited lower infection rates. However, it was also found that some varieties with similar resistance levels differed in their response to plant protection measures. This suggests that resistance level is not the only factor affecting the effectiveness of plant protection, warranting further investigation.

The integrated cultivation systems had an impact on delaying the development of infections across all potato varieties. Some varieties exhibited longer delays in the outbreak of potato blight, indicating that they might possess traits that make them more resistant to infections under integrated cultivation conditions. This finding is supported by research from other authors [7,12,38,39]. This aspect warrants deeper analysis to better understand how different cultivation systems affect varietal resistance.

The effectiveness of plant protection against potato blight depended on the varieties' resistance to the pathogen and their response to fungicide use. The extension of the infection period for 50% of the leaf blade surface, caused by the implementation of the integrated production system, averaged 3 days for the "Irga" variety, 6 days for "Boryna", 7 days for "Jurek", 21 days for "Mila", 30 days for "Jelly", and 45 days for "Amarant" (Figures 3 and 4). The "Irga" variety exhibited the biggest spread rate of *P. infestans* over time, correlated with the lowest resistance to *P. infestans*, while the moderately early "Boryna" variety had the slowest spread rate with a resistance of 5.5° on a 9° scale. However, the "Amarant" variety showed the most positive response to plant protection in the integrated cultivation system combined with full fertilization, while the "Boryna" variety had the least response. Similar varietal responses to potato blight were observed by Sawicka et al. [9], Blossei et al. [39], and Amin et al. [40].

The diverse response of potato varieties to cultivation systems can be attributed to differences in their genetic resistance to pathogens and their reaction to plant protection measures, including fungicides. Several factors may influence this varied response. Additionally, each potato variety has different genetic resistance to pathogens, including *P. infestans*. Varieties that are more resistant may exhibit lower susceptibility to infection even without fungicide application. Hence, varieties like "Irga" may display a faster spread rate of *P. infestans* over time with lower resistance. Sawicka et al. [9] and Kołodziejczyk [41,42] demonstrated that within integrated production systems, where fungicides are used, different varieties may vary in their response to these protection measures. Some varieties may be more effective in utilizing fungicides to combat infections, leading to delayed or limited disease development. In this context, the "Jelly" variety may have shown a positive response to plant protection in the integrated system, resulting in lower infection rates.

Environmental conditions, such as temperature, humidity, rainfall, and even wind, can also affect the effectiveness of plant protection against diseases [31]. Some varieties may be better suited to specific environmental conditions, influencing their response to cultivation systems. In addition to pathogen resistance, potato varieties may differ in other genetic traits that affect their growth, development, and response to protection measures. These additional genetic factors can also contribute to the varied response of varieties to potato cultivation systems [39,43,44]. The greatest positive response to the application of plant protection measures against *P. infestans* in the integrated system combined with fertilization was observed in the "Jelly" variety, while the "Boryna" variety showed the least response.

In summary, the varied response of potato varieties to cultivation systems can result from differences in their genetic resistance to pathogens, response to plant protection measures, environmental conditions, and other genetic traits. Therefore, it is important to conduct further research on the differences between varieties and their response to different potato cultivation systems to better understand and utilize these differences in agricultural practice.

4.3. Environmental Factors and the Rate of Potato Blight Spread and Potato Yield

The conducted studies observed significant differences in both the spread rate of *P. infestans* and the total and marketable yields of tubers. This is partly related to the type of reproduction of the potato blight. Sexual reproduction in *P. infestans* occurs under specific conditions when both mating types, A1 and A2, are present. This process begins with meiosis in the gametangia, followed by the fusion of the male antheridium nucleus with the female oogonium nucleus (karyogamy). This fusion results in the formation of a thick-walled, diploid oospore capable of long-term dormancy [8,45]. The coexistence of both mating types increased the potential for sexual reproduction and oospore formation in *P. infestans*, posing a serious threat to potato and tomato production worldwide [35].

The environmental factors that influence *P. infestans* development underscore the need for targeted strategies in disease management. For instance, cool and wet conditions favor the rapid spread and infection of crops by zoospores, while dry and sunny conditions can limit the spread of sporangia [8,12,39,41,45,46]. Therefore, understanding and monitoring these environmental conditions are essential for effective disease control measures. Implementing practices such as crop rotation, resistant varieties, and timely application of fungicides can help mitigate the impact of *P. infestans* on potato crops.

Environmental factors influencing the development of *P. infestans* highlight the need to develop targeted disease management strategies. Temperature, humidity, and rainfall are key to determining the severity and spread of late blight. High humidity and moderate temperatures create ideal conditions for spore germination and infection, and wet leaves facilitate the spread of the pathogen [12,42,47–49].

Based on the research of Kubiak-Wójcicka et al. [30], it can be suggested that the variability of precipitation and the increase in air temperature observed in 2018–2020 are consistent with long-term trends in climate variability in northern Poland, especially in the region we study. In their opinion, an increase in air temperature may lead to increased

evaporation, which in turn may intensify the occurrence of meteorological droughts, even though annual rainfall trends alone do not fully explain the variability of rainfall throughout the year. These observations confirm the need for further research on climate change and its impact on water resources in the region [28,29].

Inherent and accompanying meteorological factors: By leveraging inherent factors, such as local microclimate conditions, and conducting annual assessments of potato varieties, cultivation strategies can be better adapted to changing conditions beyond our control. Meteorological factors, while often unpredictable, are crucial—especially in the context of ongoing climate changes. These changes can influence the development of *P. infestans* and contribute to the emergence of new fungicide-resistant strains of this pathogen [28]. Climate change is leading to higher temperatures, which may change the life cycle of *P. infestans*. Warmer and wetter conditions may increase the frequency and severity of late blight outbreaks. Longer growing seasons due to climate change may lead to more generations of the pathogen in one season, increasing disease pressure on potato crops [50,51]. Advanced monitoring and predictive models such as:

- Remote sensing and GIS: The use of remote sensing and geographic information systems (GIS) enables real-time monitoring of environmental conditions favorable to the development of *P. infestans*. These technologies allow us to predict epidemics and take appropriate interventions [48,49,52,53].
- Predictive modeling: Advanced models that take into account weather data, crop growth stages, and pathogen biology can predict late blight risk, helping farmers apply fungicides more effectively and efficiently. Ibrahim et al. [54] reported that potato blight forecast models predicted 72–96% field infection rates. The MCC model identified June's spatiotemporal frequency of *P. infestans* susceptibility as a key infestation indicator. A five-day exposure period, considering temperature, precipitation, and humidity, was most effective for developing a spray system. This led to an early warning system for potato diseases in Africa's tropical highlands, incorporating spatial hazards for a balanced approach [37].
- Integrated disease management (IDM) [13,47].
- Resistant varieties: A key strategy is to grow and plant potato varieties that are resistant to *P. infestans*. Advances in genetic engineering and traditional breeding have led to the creation of new varieties with increased resistance [53].
- Biological control: The use of natural enemies of *P. infestans*, such as certain species of bacteria and fungi, can reduce the pathogen load in the field [39,42].
- Sustainable practices: Reduced chemical dependency: Integrated pest and disease management (IPM) emphasizes reduced use of chemical fungicides, relying more on biological control and resistant varieties for sustainable control of late blight [47].
- Soil health: Maintaining healthy soil through organic amendments and proper nutrient management can improve plant resistance to *P. infestans* [37].

Thus, the growing understanding of environmental factors influencing the development of *P. infestans* requires a multifaceted approach to disease management. Implementing the latest technologies and sustainable practices will be essential to mitigate the effects of late blight and ensure stable potato production in the face of changing climatic conditions.

4.4. Interaction of Varieties and Growing Years

Overall, the interaction between varieties and growing years highlights the complexity of agricultural systems, where multiple factors influence yields. Understanding these interactions is crucial for developing effective management strategies to optimize yield stability and productivity over time (Table 9).

Uniform tuber yields across different varieties typically indicate that these varieties achieve consistent yields under various conditions or years. Sawicka et al. [48] suggest that varieties with uniform yields tend to produce similar quantities of tubers regardless of external factors such as weather conditions or farming practices. Such consistency is desirable for farmers as it provides yield predictability. Uniform yields also indicate that

the varieties are stable in production. This stability is crucial for ensuring food security and maintaining farmers' profitability, as they can rely on consistent yields for planning and management purposes.

In summary, uniform tuber yields of selected varieties indicate consistency, stability, and reduced risk in potato production, benefiting both farmers and consumers. These findings underscore the importance of variety selection in maximizing the yield potential of potatoes. Growers can benefit from prioritizing the cultivation of varieties like "Boryna" or "Amarant" due to their consistently high yields, considering factors such as market demand and specific growing conditions [45]. Further research could investigate the underlying factors contributing to yield differences among potato varieties and develop strategies to enhance the overall productivity and profitability of crops.

4.5. Influence of Location on the Spread of Late Blight and Potato Yields

In the years 2018–2020, the spread rate of late potato blight was studied in Parczew and Uhnin under both ecological and integrated farming systems. In Parczew, potato blight spread rate coefficients under the ecological system were 0.192, 0.201, and 0.138, respectively, while under the integrated system, they were 0.200, 0.224, and 0.132. In Uhnin, the rates for the ecological system were 0.140, 0.165, and 0.114, and for the integrated system, they were 0.132, 0.142, and 0.120. These coefficients indicate the rate at which late blight spreads under different conditions, providing valuable insights for disease management and agricultural practices. The data also highlight the impact of location on the spread of the disease.

The location of the research also had a significant impact on potato yields. Generally, higher yields were obtained in Uhnin than in Parczew, suggesting more favorable soil and climatic conditions in Uhnin. The "Boryna" cultivar consistently performed best at both locations, while the "Jurek" and "Irga" cultivars had the lowest yields, showing a location-specific response. The significant interaction effect between location and variety highlights the importance of matching potato varieties to specific environmental conditions for optimal performance.

Recent research [12,40] continues to emphasize the importance of environmental factors such as soil type, moisture level, and temperature on potato yield. Advances in precision agriculture enable more detailed monitoring of soil and climate, which can help tailor growing practices to specific locations. Techniques such as remote sensing and soil mapping are increasingly being used to optimize input use and improve crop performance.

Additionally, climate change necessitates a better understanding of local environmental conditions. Varieties that are resistant to temperature fluctuations, drought, and other stressors are being developed to ensure consistent yields under a variety of conditions [9,39]. Integrated pest management (IPM) and sustainable agricultural practices are also being more broadly integrated to increase crop yields while maintaining environmental health.

In summary, the interaction between location and farming system plays a critical role in the management of late blight and the optimization of potato yields. Continuous research and the adoption of advanced agricultural technologies are essential to address the challenges posed by varying environmental conditions and climate change.

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5. Conclusions

The rate of spread of potato blight varies with the growing season, making early detection and timely intervention crucial. Effective disease management involves fungicide applications, cultural practices, crop rotation, resistant varieties, and integrated pest management. Integrated cropping practices significantly improve yields by combining fertilization and plant protection, highlighting the contrast between organic and integrated systems.

Potato variety resistance impacts pathogen spread; varieties like "Irga" are more susceptible, while "Boryna" shows natural resistance and is suitable for organic farming. In integrated systems, there is generally a yield higher than in organic systems due to the effective use of plant protection and fertilization.

Location influences yield, with Uhnin outperforming Parczew, possibly due to better soil, climate, or management practices. "Boryna" yields the most, while "Irga" and "Jurek" yield less. Farmers should tailor practices to local conditions and select appropriate varieties for optimal potato cultivation.

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