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The Role of Red Clover and Manure Fertilization in the Formation of Crop Yield of Selected Cereals

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Abstract: The use of legumes in rotation is beneficial and is of great importance in sustainable agricultural production in line with the assumptions of the European Green Deal. The aim of the presented research was to evaluate the cultivation of red clover as an undersown crop for spring barley and as a forecrop for winter wheat on the yield and quality of spring barley and winter wheat. To achieve this goal, two long-term static experiments set up in 1955 were used, in which diversified mineral and organic fertilization were used in two rotations: rotation without red clover (sugar beet–spring barley–winter rapeseed–winter wheat) and rotation with red clover (sugar beet–spring barley with undersown red clover–red clover–winter wheat). The obtained results indicate that the Norfolk rotation with red clover, as well as varied fertilization and years of research, influence the yield of plants. The highest grain yields of spring barley (5.7 t ha^{-1}) were ensured by mineral fertilization (NPK) and mineral fertilization in combination with manure (½NPK + ½FM). However, the highest yields of winter wheat grain (6.4 t ha^{-1}) were recorded in the treatments with exclusive mineral fertilization (NPK), significantly lower yields in the treatments where mineral fertilizers were used in combination with manure (5.7 t ha^{-1}) (½NPK + ½FM) and only manure (5.1 t ha^{-1}) (FM). The lowest yields of both cereals were found on soil that had not been fertilized since 1955 (0). The grain yield of spring barley was not significantly differentiated by the sowing method and was similar for spring barley grown with and without undersown red clover. Including legumes in the rotation had a positive effect on the yield of winter wheat. Fertilization had the greatest impact on the protein content in cereal grains. The use of mineral fertilization (NPK) and mineral fertilization in combination with manure (½NPK + ½FM) ensured the highest protein content in the grain of spring barley and winter wheat. Mineral fertilization (NPK) increased the protein content in spring barley grain by 2.9 percentage points compared to the unfertilized treatment (0) and by 2.1 percentage points compared to exclusive manure fertilization (FM), and in winter wheat grain by 2.3 and 1.4 percentage points, respectively. The cultivation of red clover in the rotation also had a positive effect on the protein content in spring barley and winter wheat grains.

Keywords: crop yield; farmyard manure FM; mineral fertilization NPK; crop rotation; red clover

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1. Introduction

Cereals like wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) are the major and most important crops in many countries. There are many attempts to increase wheat and barley productivity. It is widely known that a well-designed crop rotation improves soil structure, better utilization of nutrients by plants, reduces the occurrence of weeds, pests, and disease, and thus increases plant yields, including cereals [1–4]. For cereal plants such as winter wheat and spring barley, the forecrop is very important, the improper selection of which results in a significant reduction in yield [5,6]. Research by Suwara et al. [7] showed a beneficial effect of legumes on the yield of winter wheat. A significant share of cereal plants in the rotation leads to a reduction in the yield and deterioration of its quality, both in the case of spring barley and winter wheat [8–11]. The amount of yield obtained may be determined not only by rotation but also by fertilization. The yield of cereal plants largely depends on the amount of macro- and microelements accumulated in them [12] and the availability of nutrients such as nitrogen, potassium, and phosphorus [6,13,14].

The use of legumes and organic fertilization in rotation is beneficial and is of great importance in sustainable agricultural production in accordance with the assumptions of the European Green Deal [15,16]. Sustainable development is a way of meeting the needs of the current generation while not limiting the production potential of future generations [17]. According to Czyżewski et al. [18], the development of sustainable agriculture is one of the most important issues in modern agricultural economics. One of the main goals of sustainable agriculture is to reduce environmental pollution with chemical components from mineral fertilizers by adapting fertilization to the needs of plants and soil conditions. The essence of sustainable agriculture is not only the rational use of crop fertilization but concern for the protection of soil productivity [19,20]. Norfolk rotation and organic fertilization protect the soil against degradation because both fertilization and rotation have a positive effect on soil properties, which determine the course of a number of soil processes, including the supply of plants with water, air, and nutrients [21–24]. Using organic fertilizers instead of mineral fertilizers is an environmentally friendly practice that is very important in sustainable agricultural systems. The main advantage of organic fertilizers is that they are obtained from organic materials, i.e., plant remains, animal excrements, and food industry by-products. Organic fertilizers are cheap, improve soil structure and aeration, and increase porosity and the soil's ability to retain water. Additionally, manure is known to reduce the rate of evaporation, stimulate root development, and optimize plant growth. In summary, manure consistently provides nutrients to crops through a natural biological process [25–28]. Sustainable agriculture plays a decisive role in adapting to climate change as well as achieving sustainable development goals [29]. The availability of soil water for plants and the retention capacity of the soil in conditions of climate change, in addition to fertilization, are the basic elements determining plant yields.

The special role of legumes in the sustainable agriculture system results, among other things, from their ability to fix atmospheric nitrogen thanks to symbiosis with nodule bacteria. In practice, this could mean large savings resulting from limiting the use of nitrogen in mineral form [30–32]. Moreover, their cultivation has a positive effect on improving the soil structure and enriching it with large amounts of organic matter due to the huge amount of crop residue left behind [33,34]. Cereals are often grown with undersown cover crops, which are mainly small-seeded legumes, which are of great importance in achieving the goals of the Green Deal. The use of undersown cereal crops limits weed infestation, reduces the degree of disease infection, and eliminates the unfavorable effects resulting from the succession of cereal crops. Legumes are also an excellent forecrop for subsequent crops because they leave a large mass of post-harvest residues rich in nitrogen. Nitrogen stored in the roots of these plants accounts for over 25% of the total nitrogen taken up by legumes [35–37].

In order to obtain better yields and produce high-quality grains, it is recommended to use organic fertilizers in plant cultivation. Various organic fertilizers should be used combined with mineral fertilizers for the purpose of improving cereal productivity and achieving the optimal level of agricultural sustainability [38,39]. The effects of fertilization and crop rotation are best assessed based on long-term field experiments, which give a unique possibility to analyze changes in soils, plants, and ecosystems [40–43]. The aim of the presented research was to evaluate the cultivation of red clover as an undersowing for spring barley and a forecrop for winter wheat in two long-term static field experiments established in 1955 at the experimental field of the Warsaw University of Life Sciences in Chylice, central Poland, on the yield and quality of spring barley and winter wheat.

2. Materials and Methods

This paper presents a yield analysis based on the results obtained for spring barley from 2011, 2015, and 2019 and for winter wheat from 2009, 2013, and 2021. To achieve this goal, two long-term static experiments were used, in which diversified mineral and organic fertilization were used in two rotations: rotation without red clover (sugar beet–spring barley–winter rapeseed–winter wheat) and Norfolk rotation with red clover (sugar beet–spring barley with undersown red clover–red clover–winter wheat).

The basis of the research was two long-term static field experiments established in 1955 at the Agricultural Experimental Station of the SGGW Chylice in Jaktorów. They are located in Central Poland, in the Masovian Lowlands, approximately 40 km west of Warsaw, in a plain landscape, elevated approximately 105 m above sea level (52°06′ N, 20°33′ E). The experiments were carried out on leached black earth [44] (according to the World References Base for Soil Resources WRB–Endogleyic Phaeozems), which was formed from light boulder clay. The density of the solid phase of this soil is 2.62 $g \cdot cm^{-3}$, and the humus horizon has a thickness of 30–35 cm. This soil is characterized by medium humus content, slightly acidic reaction, and regulated water relations. Table 1 shows the characteristics of the topsoil properties after 40 years of experiments. Before the experiments were carried out, the arable layer was slightly acidic (pH 6.2–6.5) and contained 1.15% organic carbon, 44 mg kg^{-1} of available phosphorus (P), and 83 mg kg^{-1} of available potassium (K). In the two experiments, four fertilizer treatments were compared: mineral fertilization (NPK), farmyard manure (FM), mixed mineral and organic fertilization (½ NPK + ½FM), and control without any fertilization (0). These four treatments were investigated in a randomized block-design trial with four replicates. Fertilizers were applied in two crop rotations: Fertilization of particular crops is presented in Tables 2 and 3. The following mineral fertilizers were used for fertilization: ammonium nitrate (34% N), granulated superphosphate (18–19% P_2O_5), and potassium chloride (60% K_2O). Composted cattle manure is plowed into the soil in autumn. Mineral fertilizers (NPK) are used before sowing crops. In the case of winter wheat, the first dose of nitrogen (30% of the full dose) was applied before sowing together with P and K fertilizers, and the second dose (70% of the full dose) was applied in the tillering phase. In spring barley, the first dose of nitrogen (30% of the full dose) was applied before sowing together with P and K fertilizers, and the second dose (70% of the full dose) was applied after plant emergence. A plow tillage system was used in the experiments (plowing depth of 20 cm). Plant protection products (pesticides) were applied according to the needs of the plants. Both cereals were harvested after reaching full maturity with grain moisture below 18% and most often took place in the first half of August.

Table 1. Characteristics of the arable layer of the black earth in Chylice–pH, organic carbon content, and soil abundance in available forms of nutrients depending on the fertilization system and crop rotation.

Treatment	pH in KCL	P [$mg \cdot kg^{-1}$]	K [$mg \cdot kg^{-1}$]	C org. [$g \cdot kg^{-1}$]
		Fertilization		
NPK	6.1	79.4	68.9	10.05
FM	6.4	74.6	126.2	12.39
½ NPK + ½ FM	6.3	80.7	83.0	11.30
0	6.3	49.3	48.1	8.91
		Crop rotation		
Norfolk rotation	6.1	65.0	77.2	12.34
Rotation without legumes	6.4	77.2	86.3	8.75

Mineral fertilization (NPK), farmyard manure (FM), mixed mineral and organic fertilization (½ NPK + ½FM), control without any fertilization (0).

Table 2. Diagram of fertilizer experiments in Norfolk rotation.

Crop	Treatment								O
	NPK			FM		½ NPK + ½ FM			
	N	P	K	FM	FM	N	P	K	
	[kg·ha^{-1}]			[t·ha^{-1}]	[t·ha^{-1}]	[kg·ha^{-1}]			
Sugar beet	200	56.0	200.0	40	20	100	28.0	100.0	0
Spring barley with red clover	100	36.5	91.5	20	10	50	18.3	45.8	0
Red clover	0	36.5	91.5	0	0	0	18.3	45.8	0
Winter wheat	100	36.5	91.5	20	10	50	18.3	45.8	0

Mineral fertilization (NPK), farmyard manure (FM), mixed mineral and organic fertilization (½ NPK + ½FM), control without any fertilization (0).

Table 3. Diagram of fertilizer experiments in crop rotation without legumes.

Crop	Treatment								O
	NPK			FM		½ NPK + ½ FM			
	N	P	K	FM	FM	N	P	K	
	[kg·ha^{-1}]			[t·ha^{-1}]	[t·ha^{-1}]	[kg·ha^{-1}]			
Sugar beet	200	56.0	200.0	40	20	100	28.3	100.0	0
Spring barley	100	36.5	91.5	20	10	50	18.3	45.8	0
Winter rapeseed	100	36.5	91.5	20	10	50	18.3	45.8	0
Winter wheat	100	36.5	91.5	20	10	50	18.3	45.8	0

Mineral fertilization (NPK), farmyard manure (FM), mixed mineral and organic fertilization (½ NPK + ½FM), control without any fertilization (0).

Meteorological data on temperature and precipitation in Chylice in the years 2009, 2011, 2013, 2015, 2019, and 2021 are summarized in Tables 4 and 5. In 2011, 2015, and 2019, when spring barley was cultivated, the most favorable rainfall and thermal conditions were recorded in 2019. It was a warm year with good rainfall distribution during the spring barley growing season. In 2011, excessive rainfall in July had a negative impact on the ripening and harvesting of this cereal. However, 2015 was relatively dry, with a cold spring and very low rainfall recorded in June. In the years of winter wheat cultivation (2009, 2013, and 2021), the best moisture conditions for the growth and development of this plant occurred in 2021. In 2009 and 2013, unfavorable moisture conditions were found in the spring growing season of winter wheat due to excessive rainfall in May (2013) and June (2009 and 2013). Moreover, in April 2009, an extreme drought was recorded.

Table 4. Sum of precipitation in Chylice in 2009–2021 compared with the long-term average (1921–2020) data [mm].

Year	Sum	Month											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
2009	713.6	37.4	47.2	60.6	14.1	79.4	114.5	90.7	78.1	17.4	82.8	53.1	42.8
2011	693.5	37.0	27.1	15.1	78.2	48.1	57.4	251.4	118.7	6.9	14.2	1.6	37.8
2013	825.8	71.1	39.9	54.7	49.8	126.9	211.6	23.2	60.5	82.2	33.0	45.5	27.4
2015	421.3	43.5	12.1	26.0	45.8	51.2	16.1	64.0	6.4	37.2	44.5	56.2	18.5
2019	516.9	36.0	34.7	34.2	31.9	47.5	24.1	64.3	69.5	79.1	21.6	13.6	40.4
2021	685.4	88.9	88.4	17.6	59.5	58.2	46.4	135.1	179.2	29.6	8.9	47.2	33.4
Averaged monthly sums for 1955–2001		25.5	28.9	31.4	44.6	56.6	76.6	87.4	56.9	58.0	37.8	40.3	35.6

Table 5. Mean temperature in 2009–2021 compared with the long-term average (1921–2020) data [°C].

Year	Average	Month											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
2009	7.4	−3.9	−1.6	1.7	9.6	11.9	15.4	17.6	16.9	13.3	5.3	4.5	−2.3
2011	8.6	−1.0	−5.5	2.3	9.0	14.9	18.5	17.7	19.2	14.6	8.8	2.2	2.2
2013	8.1	−3.9	−1.2	−2.6	7.2	17.7	17.4	17.9	18.1	10.8	9.2	4.8	1.7
2015	9.3	0.5	0.5	4.4	7.5	13.0	16.3	18.8	21.1	14.1	6.4	4.6	4.1
2019	10.5	−1.6	3.2	6.2	9.8	13.2	22.0	19.0	20.1	14.0	10.4	6.0	3.1
2021	8.3	−1.5	−2.5	3.0	6.4	12.1	19.4	20.9	16.6	13.1	8.7	4.7	−1.3
Averaged monthly means 1955–2001		−1.8	−0.4	2.3	8.5	14.1	17.3	18.7	18.3	13.2	9.2	3.0	−1.1

The yield of cereal plants was determined by collecting winter wheat and spring barley plants after full grain maturity (BBCH 89) from each experimental plot with an area of 50 m^2 and converting them into grain yield per 1 ha at 14% humidity. Then, the quality parameters of winter wheat and spring barley grain were assessed in the laboratory using the Infratec 1241 grain analyzer from FOSS Analytics (Hilleroed, Denmark). It is a whole-grain analyzer that uses the absorption of near-infrared radiation to simultaneously determine various grain quality parameters at the same time. Measurements are performed in the wavelength range 570–1055 nm. Grain parameters were determined using this analyzer: protein content [%], wet gluten efficiency [%], starch content [%], and Zeleny sedimentation index [cm^3] [https://www.fossanalytics.com/en/products/infratec (accessed on 15 October 2024)].

In this study, the results of yield and quality characteristics are given as averages over the years for spring barley from 2011, 2015, and 2019 and for winter wheat from 2009, 2013, and 2021. For the tested parameters, averages over the years of research were calculated to compare the impact of the studied factors, i.e., fertilization and rotation. For three years, a three-way analysis of variance (ANOVA) was performed where the factors were crop rotation, fertilization, and year. Comparisons of means were performed using the Tukey procedure, and NIR values were calculated at a significance level of 0.05. On the basis of these analyses, homogeneous groups of means were distinguished, i.e., groups of means that did not differ significantly statistically were marked with the same letter of the alphabet. *p*-values were presented for selected traits for evaluation of the main effects of the studied factors as well their interactions, including interaction with years. In all analyses, the significance level was set at 0.05. Analyses were performed in Statistica 13 (TIBCO Software Inc., Palo Alto, CA, USA) [45,46].

3. Results and Discussion

The obtained results indicate that the Norfolk rotation with red clover, as well as varied fertilization and years of research, influence the yield of plants. It was found that the yield of spring barley is mainly determined by the fertilization system (Figure 1). The use of NPK and ½NPK + ½FM clearly stimulated the productive tillering of spring barley in both experiments. The number of spring barley ears per square meter was on average 556 in the soil fertilized only with mineral fertilizers (NPK), 587 with mineral fertilizers including manure (½NPK + ½FM), and 528 in the plots fertilized only with manure (FM). The lowest number of ears was found in the unfertilized plot (336). In all fertilized treatments (NPK, FM, and ½NPK + ½FM), the highest thousand-grain weight (49.6–51.1 g) was recorded compared to the treatment that had not been fertilized since 1955 (45.9 g). As a result, the highest yields of spring barley grain were ensured by mineral fertilization (NPK) and mineral fertilization combined with manure (½NPK + ½FM), which is in agreement with reports in the literature [47–50].

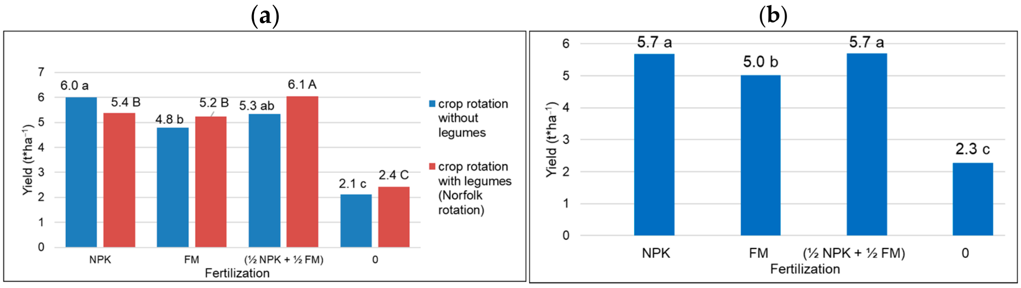

Figure 1. Spring barley grain yield depending on fertilization in two rotations (**a**) and only fertilization (**b**), means of years 2011, 2015, and 2019. Individual letters indicate homogeneous groups of means, mean values marked with the same letters do not differ significantly at α = 0.05, different letters indicate significant differences at α = 0.05. In subfigure (**a**), lowercase letters refer to crop rotation without legumes; capital letters refer to crop rotation with legumes (Norfolk rotation) Table.

Significantly lower yields were found in the area fertilized only with manure (FM), and the smallest were found in soil unfertilized since 1955 (0) (Figure 1).

The grain yield of spring barley was not significantly altered by the sowing method and was similar for spring barley grown with and without undersown red clover. Spring barley yielded at a similar level, regardless of the use of undersowing or not (Figure 1). Also, Alaru et al. [16] found that red clover as an undersow in spring barley had no significantly positive effect on the grain yield and protein content of barley. In turn, Wanic et al. [51] noted that the number of barley ears at the end of the vegetation period in pure sowing was significantly higher than with underseeds, and, as a result, spring barley grown with underseeds yielded worse than in pure sowing. In the study by Andruszczak et al. [52], when growing spring barley in monoculture, undersowing of red clover promoted spring barley yield by 24.0% compared to barley in pure sowing.

The yield of winter wheat depended on both fertilization and rotation. The use of NPK clearly stimulated the productive tillering of winter wheat in both experiments, and in this treatment, the highest grain yields of winter wheat were recorded (Figure 2). In the plots fertilized with mineral fertilizers together with manure (½NPK + ½FM), winter wheat yielded on average about 10% lower, and in the plots fertilized only with manure (FM), the yield was over 20% lower.

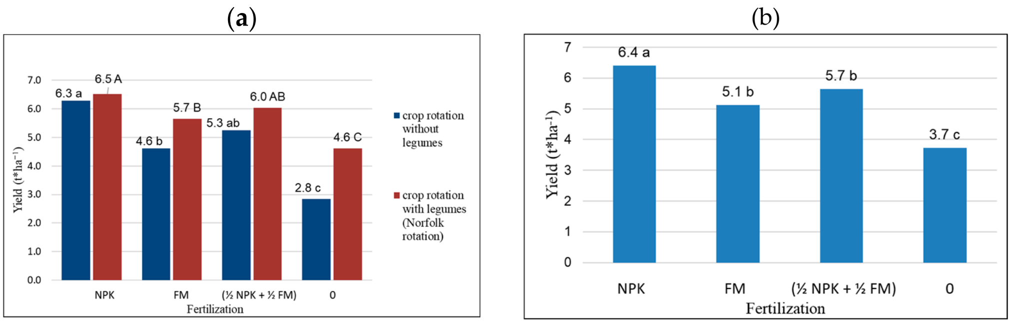

Figure 2. Winter wheat grain yield depending on fertilization in two rotations (**a**) and only fertilization (**b**), means of years 2011, 2015, and 2019. Individual letters indicate homogeneous groups of means, mean values marked with the same letters do not differ significantly at α = 0.05, different letters indicate significant differences at α = 0.05. In subfigure (**a**), lowercase letters refer to crop rotation without legumes; capital letters refer to crop rotation with legumes (Norfolk rotation).

Some researchers received different results [53,54]. Jiang et al. [53] found the highest yields of wheat with organic fertilizers combined with NPK and almost 1 t ha^{-1} higher yields when compared to NPK without organic compounds. Also Blecharczyk et al. [55], Ailincăi et al. [56] and Barzegar et al. [57] obtained higher grain yields with NPK incorporated with farmyard manure in comparison with NPK alone.

Yields were the lowest in unfertilized soil (0), significantly so in relation to fertilized treatments. It should be emphasized that winter wheat in the Norfolk rotation yielded relatively well on plots that had not been fertilized since 1955. Yields of winter wheat on unfertilized plots with red clover as a forecrop were, on average, about 50–60% higher compared to wheat grown after winter rapeseed (Figure 2a). The grain yield of winter wheat was significantly differentiated by forecrop. Including legumes in the rotation had a positive effect on the yield of winter wheat. Winter wheat yields in the rotation with red clover were 20% higher than in the rotation without legume (on average 5.7 t ha^{-1} vs. 4.8 t ha^{-1}, respectively) (Figure 3). Winter wheat grown after red clover produced a greater number of ears per square meter (504) than wheat after winter rapeseed (456) Including legumes in the rotation had a positive effect on the yield of winter wheat. This is evidenced by significantly higher grain yields of winter wheat grown after red clover (Figure 3). The beneficial effect of legumes on wheat grain yields was also noted by Berzsenyi et al. [58], Norwood [59], Blecharczyk et al. [60], Buczek et al. [61], Smagacz and Kuś [62], Amato et al. [63], and Małecka-Jankowiak et al. [64].

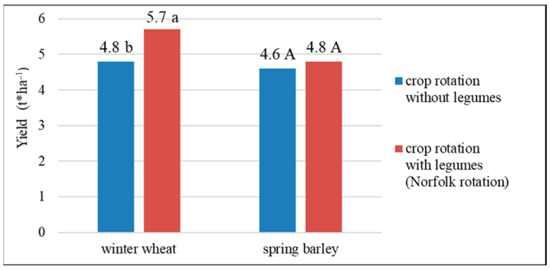

Figure 3. Winter wheat grain yield (means of years 2009, 2013, and 2021) and spring barley (means of years 2011, 2015, and 2019) depending on the crop rotation. Individual letters indicate homogeneous groups of means, mean values marked with the same letters do not differ significantly at α = 0.05, different letters indicate significant differences at α = 0.05; lowercase letters refer to winter wheat; capital letters refer to spring barley.

In order to determine the quality of wheat grain, the content of protein, gluten, starch, and the Zeleny index were investigated. The quality characteristics of wheat are important to consumers, growers, millers, and bakers. The quality of wheat is determined by its protein and gluten content. The quality of flour and dough is influenced by starch content, gluten, falling number, and dough rheology. A high protein content in wheat grain improves the structure and volume of the bread, while gluten has an impact on the stability of the dough during baking [65]. For spring barley grain, the main uses are in the brewing and feed industries. Because barley does not contain gluten, it is used to a lesser extent in food production, e.g., as an admixture in bread making. Due to its high starch and fiber content and moderate protein content, it is popular for feeding ruminant animals. For the brewing industry, one of the most relevant factors is protein content in grain [66,67].

The results presented in Figures 4–9 indicate that fertilization significantly affects the technological parameters of spring barley grain and winter wheat grain. The quality of spring barley grain depended mainly on fertilization and the presence of underseed red clover. Fertilization had the greatest impact on the protein content in grain (Figure 4). The use of mineral fertilization and mineral fertilization in combination with manure ensured the highest protein content in spring barley grain. The lowest protein level was recorded in grain from unfertilized treatments and those fertilized only with manure. In turn, originating grain contained the most starch from unfertilized treatments and fertilized only with manure, and the least in grain from mineral fertilized treatments (Figure 5).

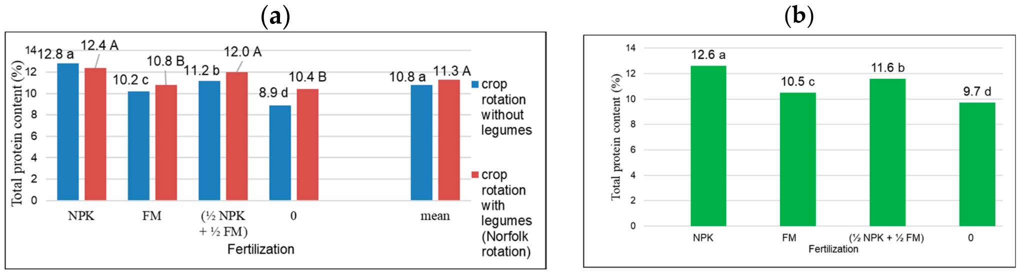

Figure 4. Protein content in spring barley grain depending on fertilization in two rotations (**a**) and only fertilization (**b**), means of years 2011, 2015, and 2019. Individual letters indicate homogeneous groups of means, mean values marked with the same letters do not differ significantly at α = 0.05, different letters indicate significant differences at α = 0.05. In subfigure (**a**), lowercase letters refer to crop rotation without legumes; capital letters refer to crop rotation with legumes (Norfolk rotation).

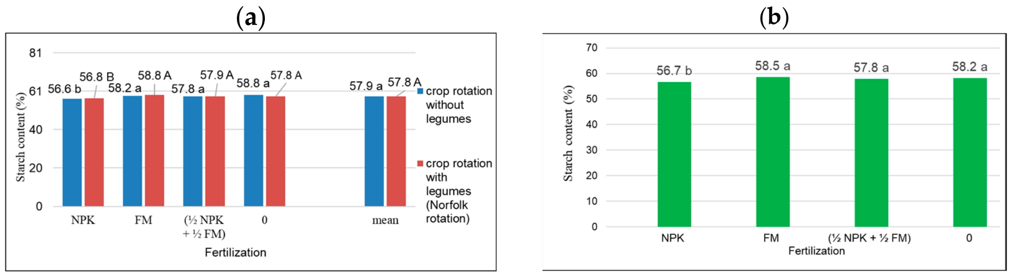

Figure 5. Starch content in spring barley grain depending on fertilization in two rotations (**a**) and only fertilization (**b**), means of years 2011, 2015, and 2019. Individual letters indicate homogeneous groups of means, mean values marked with the same letters do not differ significantly at α = 0.05, different letters indicate significant differences at α = 0.05. In subfigure (**a**), lowercase letters refer to crop rotation without legumes; capital letters refer to crop rotation with legumes (Norfolk rotation).

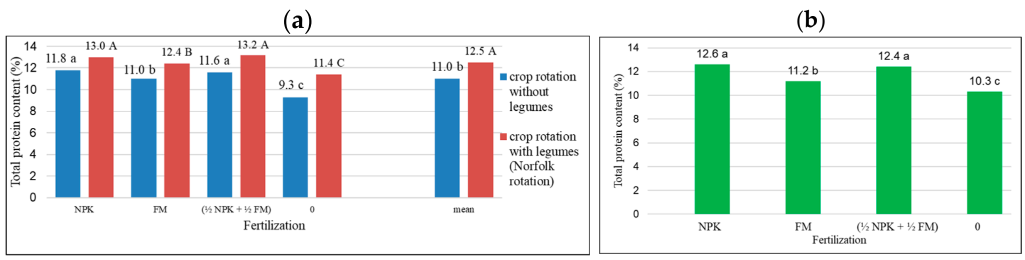

Figure 6. Protein content in winter wheat grain depending on fertilization in two rotations (**a**) and only fertilization (**b**), means of years 2011, 2015, and 2019. Individual letters indicate homogeneous groups of means, mean values marked with the same letters do not differ significantly at α = 0.05, different letters indicate significant differences at α = 0.05. In subfigure (**a**), lowercase letters refer to crop rotation without legumes; capital letters refer to crop rotation with legumes (Norfolk rotation).

The results in Figures 6–8 indicate that fertilization significantly affects the technological parameters of winter wheat grain, primarily the content of total protein and wet gluten. The highest protein and wet gluten content, as well as the highest Zeleny sedimentation index, were found in winter wheat grain fertilized with minerals (NPK and ½NPK + ½FM) and then fertilized only with manure. Significantly, the lowest values of these parameters were recorded on the unfertilized treatment (0). These findings are consistent with those from Barneix [68] and Hlisnikovský and Kunzová [54].

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

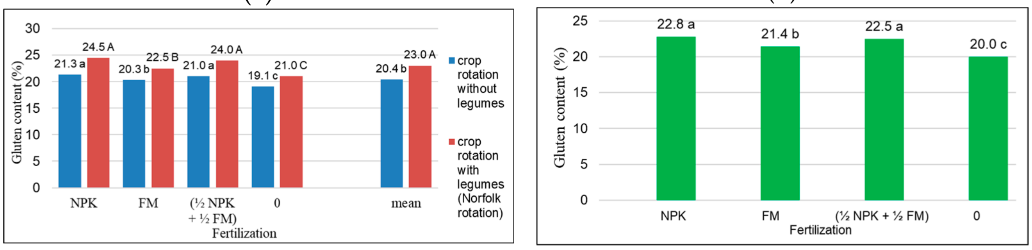

Figure 7. Gluten content in winter wheat grain depending on fertilization in two rotations (**a**) and only fertilization (**b**), means of years 2011, 2015, and 2019. Individual letters indicate homogeneous groups of means, mean values marked with the same letters do not differ significantly at α = 0.05, different letters indicate significant differences at α = 0.05. In subfigure (**a**), lowercase letters refer to crop rotation without legumes; capital letters refer to crop rotation with legumes (Norfolk rotation).

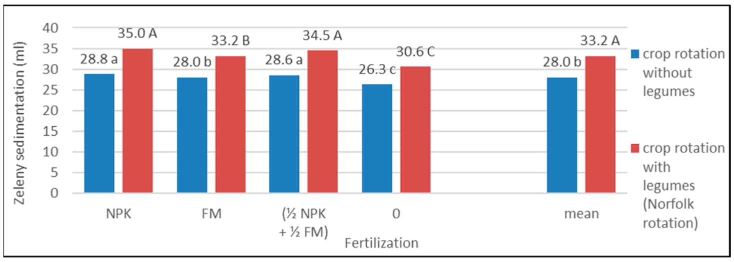

Figure 8. Zeleny sedimentation in winter wheat grain depending on rotation and fertilization (means of years 2009, 2013, and 2021). Individual letters indicate homogeneous groups of means, mean values marked with the same letters do not differ significantly at α = 0.05, different letters indicate significant differences at α = 0.05; lowercase letters refer to crop rotation without legumes; capital letters refer to crop rotation with legumes (Norfolk rotation).

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

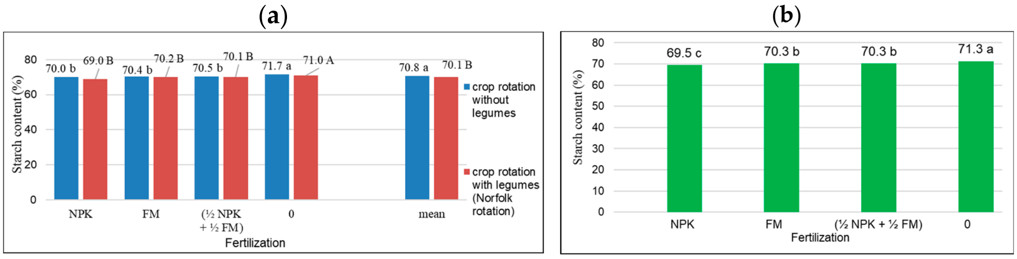

Figure 9. Starch content in winter wheat grain depending on fertilization in two rotations (**a**) and only fertilization (**b**), means of years 2011, 2015, and 2019. Individual letters indicate homogeneous groups of means, mean values marked with the same letters do not differ significantly at α = 0.05, different letters indicate significant differences at α = 0.05. In subfigure (**a**), lowercase letters refer to crop rotation without legumes; capital letters refer to crop rotation with legumes (Norfolk rotation).

The cultivation of red clover in the rotation also had a positive effect on the protein content, gluten content, and Zeleny sedimentation index in winter wheat grains.

The results in Figure 9 show that the lowest starch content was found in wheat grains fertilized only with minerals, and the highest in unfertilized wheat grains. Red clover as a pre-crop for winter wheat also resulted in a significant reduction in the starch content in the grain. Hlisnikovský and Kunzová [54] reported similar results and found a significantly lower starch content in wheat grain fertilized with mineral and organic fertilizers compared to the control.

The evaluation of the general effect of the experimental factors and years, as well as their interaction results of the ANOVA (*p*-values) for grain yield, which is the most important variable, are presented in Table 6. In the case of interaction with year, the only significant interaction was year x fertilization for grain yield of spring barley. It proves that the effect of fertilization on the grain yield of barley was modified by weather conditions in various years. It is probably because of the higher sensitivity of spring crops on water stress in drought seasons and the effect of fertilization, which modifies the effect of water stress [69].

Table 6. Results of ANOVA (*p*-values), which present the main effects and interactions for the grain yield of spring barley and winter wheat.

Effect	Spring Barley	Winter Wheat
Year	<0.001	0.008
Crop rotation	0.229	0.007
Fertilization	<0.001	0.001
Year × crop rotation	0.232	0.680
Year × fertilization	0.014	0.079
Crop rotation × fertilization	0.100	0.144

4. Conclusions

Our research, based on many years of static experiments on black soil, has shown that the Norfolk rotation with red clover as well as varied fertilization and weather conditions in the years of research affect the yield of cereal plants.

1. The highest grain yields of spring barley (5.7 t ha^{-1}) were ensured by mineral fertilization (NPK) and mineral fertilization in combination with manure (½NPK + ½FM). Significantly lower yields were found in the area fertilized only with manure (FM) (5.0 t ha^{-1}), and the lowest were found (2.3 t ha^{-1}) in the absence of fertilization since 1955. However, the highest yields of winter wheat grain were recorded in the treatments with exclusive mineral fertilization (NPK) (6.4 t ha^{-1}). Significantly lower yields were found in the treatments where mineral fertilizers were used in combination with manure (½NPK + ½FM) (5.7 t ha^{-1}) and only manure (FM) (5.1 t ha^{-1}), and the lowest yields were found in the absence of fertilization since 1955.
2. The use of undersown red clover in cultivation did not significantly affect the yield of spring barley grain, while clover as a forecrop for winter wheat created favorable conditions for plant growth. This is evidenced by significantly higher grain yields of winter wheat grown after red clover compared to the yields of this plant obtained after winter rapeseed (on average 5.7 t ha^{-1} vs. 4.8 t ha^{-1}, respectively).
3. Mineral (NPK) and mineral fertilization with manure (½NPK + ½FM) and the cultivation of red clover in the rotation had a beneficial effect on the quality of spring barley and winter wheat grain. Mineral fertilization and mineral fertilization with manure resulted in an increase in the content of protein, wet gluten, and the Zeleny sedimentation index in winter wheat grain.

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