



Article

The Development of Winter Wheat Yield and Quality under Different Fertilizer Regimes and Soil-Climatic Conditions in the Czech Republic

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Abstract: Farmers must adapt to the changes brought about by the changing climate and market requirements. These adaptations are associated with fertilization—the availability of organic manures and mineral fertilizers and crop rotations. What is the effect of organic manures on wheat and soil? Is it necessary to apply mineral phosphorus P and potassium (K) fertilizers to the wheat? These questions are frequently asked in workshops in different growing areas. To provide a relevant answer on this issue, we evaluated how farmyard manure (FYM), mineral nitrogen (N) applied without phosphorus (P) and potassium (K) fertilizers, and application of NPK affected grain yield, grain quality, and soil properties under different soil-climate conditions (Ivanovice—Chernozem, Caslav—Phaeozem, Lukavec—Cambisol) between 2015 and 2018. The FYM significantly increased grain yield even after three years since being applied and incorporated into the soil in all localities, but its application did not affect grain quality. In the soil, the FYM significantly increased total nitrogen Nt, P, and K content in all localities and oxidable carbon Cox content in two localities. Mineral nitrogen significantly affected grain yield and quality and increased concentrations of soil N and C, but decreased pH in Caslav. Application of mineral P and K was not connected with a positive effect on grain yield and quality, but increased the concentration of these elements in the soil, preventing depletion of these elements from the soil. Maximal yields were recorded when 70–98 kg N ha^{−1} was applied in Ivanovice, 55–72 kg N ha^{−1} in Caslav, and 155 kg N ha^{−1} in Lukavec.

Keywords: *Triticum aestivum* L.; farmyard manure; mineral fertilizers; crude protein content; soil properties, site-specific requirements

1. Introduction

Farmers have recently been exposed to many pressures and challenges that affect their decisions and activities. These pressures and challenges arise from currently changing climatic conditions, increased public awareness of the environment, the development on the market with meat and dairy products, new technologies, and financial possibilities of farmers themselves. As a reaction, we can see a huge shift from the traditional approaches of farmers, who are responsible for food and feedingstuff production and maintaining the function of the landscape. Such examples in the Czech Republic are a two-thirds decline in numbers of animals over the last two decades and changes in crop rotations connected with increased biogas production [1], a decline in production of organic manures, decline in doses of applied mineral phosphorus and potassium (Figure 1), and worsening of the soil organic matter quality in Chernozems [2].

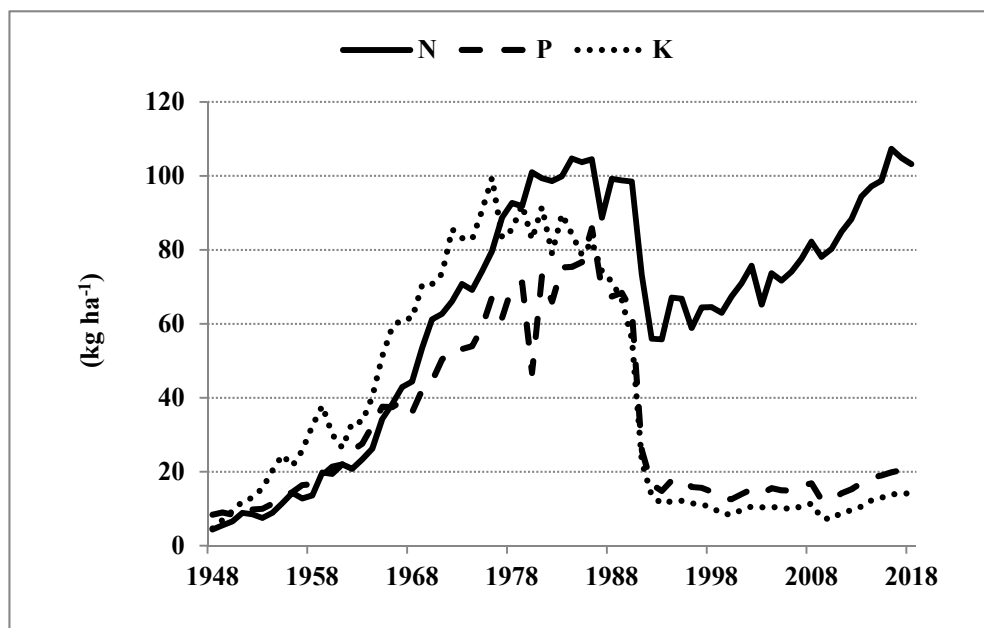


Figure 1. The mean doses of mineral N, P, and K applied on arable land in the Czech Republic.

The source of organic manures is significantly limited, because animal husbandry production decreased significantly since 1989 (the Velvet revolution, the transformation of the society from centrally planned economy into the market economy), and this trend continued when the Czech Republic joined the European Union (EU) [3]. Mineral P and K fertilizers are not applied in a sufficient amount owing to the high purchase prices, and crop rotations were adjusted to supply agricultural biogas stations. Moreover, with reduced animal husbandry, the need for clover and other grasses decreased, so their position in crop rotation was replaced.

Another challenge significantly affecting the behaviour and decision making of farmers represents upcoming weather change and weather instability. According to Olesen et al. [4], the farmers in Europe adapt to climate change by changing the timing of cultivation, and by selecting other crop species and cultivars.

In workshops with farmers, we often encounter questions about wheat fertilization and current weather changes. What are the benefits of organic manure? What will be the result of omitting P and K fertilizers? What dose of nitrogen should we choose? From the literature, we know that nitrogen is the most crucial element for wheat [5,6] and addition of mineral N was and is a standard way for securing high yields and grain quality of wheat. In the past, “the more fertilizer, the higher yield” strategy [7], which is characteristic by application of N doses greater than the crops need, led to the inefficiency and environmental problems and farmers and scientists focused on optimization of mineral fertilizer inputs. This optimization depends on many factors, mainly on soil-climate conditions, so such optimization differs site by site [7,8]. Another issue represents the application of P and K fertilizers. Is it necessary? According to Duncan et al. [6], the co-application of P, K, and sulfur fertilizers increases the N efficiency and helps to achieve higher yields with higher protein content via “protection against protein dilution as yields increase”. These questions are based on the above-mentioned issues. To answer some of these questions, we analysed suitable fertilizer treatments and the 4-year sequence (2015–2018) from the three long-term field experiments, established in the Czech Republic in 1955. In this paper, we evaluated the effect of seven different fertilizer treatments (control, farmyard manure—FYM, FYM+N1, FYM+N2, FYM+N1PK, FYM+N2PK, FYM+N3PK) and soil-climate conditions on the winter wheat grain yield and quality. The effect of different fertilization regimes on soil nutrient content and soil properties was also analysed in this study.

2. Materials and Methods

The long-term field fertilizer trials in Ivanovice, Caslav, and Lukavec were established in 1955. The trials aim to analyse the effect of different fertilizer treatments on yield and quality of arable crops and soil chemical properties under different soil-climate conditions.

2.1. Characteristics of Localities

2.1.1. Ivanovice

Ivanovice is located in the South Moravia Region (49°19' NL, 17°05' EL), the altitude is 225 m a.s.l. The soil is naturally fertile, the soil type is degraded Chernozem, and the soil-forming substrate is loess. The topsoil is dark brown, with an average depth of 40 cm. The content of humus is approximately 4.39%. The climate is warm and dry, with mild winters. The average temperature is 9.14 °C (1969–2019), and the average annual sum of precipitation is 542 mm (Ivanovice Meteorological Station, measurements 1969–2019).

2.1.2. Caslav

Caslav is located in the Central Bohemian Region (49°85' NL, 15°40' EL), the altitude is 263 m a.s.l. The soil type is greyic Phaeozem. The topsoil average depth is 40–50 cm, deeper layers (80 cm) are sandy. The content of humus is approximately 2.98%. The climate is moderately warm and dry, with mild winters. The average annual temperature is 9.3 °C, and the average sum of precipitation is 572 mm (Caslav Meteorological Station, measurements 1974–2019).

2.1.3. Lukavec

Lukavec is located in the Vysočina Region (49°34' NL, 14°59' EL), the altitude is 620 m a.s.l. The soil type is sandy-loamy Cambisol. The topsoil average depth is 20 cm, with approximately 52% of sand, 20% of clay, and 28% of silt. The climate is moderately warm and humid. The average annual temperature is 7.7 °C, and the average annual sum of precipitation is 688 mm (Lukavec Meteorological Station, measurements 1969–2019).

2.1.4. Weather Course

The average monthly temperatures and the sum of precipitation at the time of the experiment are shown in Tables 1 and 2. Values below 30% of the long-term normal (warmer, less precipitation) are marked in yellow, while values 30% above the long-term normal (colder, more precipitation) are marked in green. From this point of view, we recorded that January, February, November, and December were significantly warmer in all localities compared with the long-term average. For precipitation, we recorded a significant lack of precipitation throughout the year in Ivanovice. Precipitations in Lukavec and Čáslav were also below average, especially from February to April 2015 and 2018 (Lukavec), and in May (Caslav).

Table 1. The mean monthly temperatures (°C). Yellow marked values are more than 30% below the long-term normal in the area, while green marked values are more than 30% higher than long-term normal.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	
Ivanovice													
2015	1.1	0.9	4.8	9.5	13.8	17.7	21.6	22.7	15.4	8.7	5.7	2.4	10.4
2016	−1.6	4.5	4.7	8.9	14.7	19.0	20.3	18.9	17.1	8.5	3.9	−0.8	9.8
2017	−6.2	0.8	7.3	8.6	15.2	20.2	20.6	21.3	13.8	10.2	4.5	1.6	9.8
2018	2.0	−2.7	2.0	14.4	17.9	19.4	21.5	23.0	16.3	11.2	5.4	1.6	11.0
Caslav													
2015	2.5	1.5	5.5	9.4	13.8	17.2	21.8	23.2	14.7	9.0	7.3	5.7	11.0
2016	0.1	4.5	4.6	9.1	14.9	18.8	20.3	19.1	18.0	8.8	3.7	0.8	10.2
2017	−4.5	2.3	7.5	8.5	15.5	19.6	20.1	20.4	13.0	11.0	5.1	2.5	10.1
2018	3.3	−2.0	2.5	14.2	17.5	19.1	22.0	23.1	16.4	14.6	5.3	2.6	11.6
Lukavec													
2015	0.0	−1.2	3.2	6.9	11.5	15.3	19.7	20.5	12.2	6.9	5.2	3.8	8.7
2016	−1.5	2.1	2.3	6.9	12.2	16.3	17.9	16.6	15.3	6.2	1.8	−1.2	7.9
2017	−6.1	0.6	5.2	5.8	13.0	17.4	17.8	18.5	11.0	9.1	2.9	−0.2	7.9
2018	1.1	−4.9	−0.1	12.2	15.0	16.5	18.7	20.3	14.2	9.3	3.1	0.6	8.8

Table 2. The mean monthly precipitation (mm). Yellow marked values are more than 30% below the long-term normal in the area, while green marked values are more than 30% higher than long-term normal.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	
Ivanovice													
2015	21.8	5.4	39.2	17.9	34.8	77.1	28.0	83.7	23.9	27.7	22.1	5.4	387.0
2016	15.9	61.1	17.6	43.1	36.0	27.6	108.8	42.7	14.3	43.1	30.4	7.3	447.0
2017	15.6	8.3	20.0	38.9	25.6	41.6	71.8	35.2	67.7	23.5	29.9	12.8	390.9
2018	38.0	22.6	36.2	20.2	27.6	52.2	43.6	22.0	65.4	24.6	17.2	18.0	387.6
Caslav													
2015	38.5	6.3	35.0	17.2	62.3	59.6	23.3	51.4	18.6	42.5	68.7	19.0	442.4
2016	23.5	32.1	35.6	26.1	39.2	82.7	93.2	40.9	7.4	57.4	22.3	13.0	473.4
2017	28.1	15.2	33.6	95.9	40.6	84.0	93.2	65.9	59.7	80.0	58.3	40.2	694.7
2018	40.5	27.3	40.6	14.7	32.8	48.7	23.5	24.1	54.9	39.6	17.4	55.8	420.0
Lukavec													
2015	54.9	7.9	24.2	23.5	55.6	62.6	20.8	94.3	24.4	75.4	113.6	18.9	576.1
2016	30.8	48.2	41.0	32.0	89.3	58.4	110.5	22.8	16.4	79.7	32.1	39.3	600.5
2017	30.1	33.3	68.4	102.1	33.0	66.0	135.4	67.1	35.0	110.1	51.6	44.8	776.9
2018	34.1	16.1	30.1	7.2	51.5	65.7	43.6	38.9	78.3	42.8	22.9	78.1	509.3

2.2. Field Trial Description

The design and methodology of all three trials (in three localities) are equal. The trial consists of four fields, where twelve fertilizer treatments are applied and analysed (twelve treatments per one field) in randomized complete block design. Each fertilizer treatment is replicated four times ($12 \times 4 = 48$ experimental plots per one field). The size of one experimental plot is 64 m^2 ($8 \times 8 \text{ m}$).

Out of twelve fertilizer treatments, seven treatments are evaluated in this paper: (1) the unfertilized control (control); (2) farmyard manure (FYM); (3–4) farmyard manure applied with mineral nitrogen (FYM+N1; FYM+N2); and (5–7) farmyard manure applied with mineral nitrogen, phosphorus, and potassium (FYM+N1PK; FYM+N2PK; FYM+N3PK). The doses of applied farmyard manure and mineral fertilizers are shown in Table 3. Mineral nitrogen was applied as lime ammonium nitrate, the mineral phosphorus as granulated superphosphate, and potassium as potassium chloride.

The FYM and mineral fertilizers were spread by hand. Applied FYM (cattle farmyard manure from local farmers) was incorporated into the soil within 24 h after application. The FYM was in the crop rotation applied to the maize, three years before the wheat was sown (2012—maize, 2013—spring barley, 2014—winter rapeseed, 2015—winter wheat), so winter wheat was the fourth crop following the FYM application. If the FYM and mineral fertilizers were applied together, mineral fertilizers were applied first (the case of maize in the crop rotation, no FYM was applied to spring barley, winter rapeseed, and winter wheat). The dose of FYM, applied to the maize, was 40 t ha⁻¹ (approximately 200 kg N ha⁻¹, 56 kg P ha⁻¹, and 236 kg K ha⁻¹). Because winter wheat was sown three years after the FYM was applied, we estimate that the total amount of available nutrients from FYM to wheat was 5% (10 kg N ha⁻¹, 3 kg P ha⁻¹, and 12 kg K ha⁻¹) (for further information, see Section 4.4.).

Table 3. Doses of N, P, and K (kg ha⁻¹) applied in selected fertilizer treatments. FYM, farmyard manure; N, mineral nitrogen; P, phosphorus; K, potassium.

	N	P	K
Control	0	0	0
FYM	10	3	12
FYM+N1	(10)+40	(3)+0	(12)+0
FYM+N2	(10)+80	(3)+0	(12)+0
FYM+N1PK	(10)+40	(3)+60	(12)+60
FYM+N2PK	(10)+80	(3)+60	(12)+60
FYM+N3PK	(10)+120	(3)+60	(12)+60

Note: values in parentheses represent the amount of nutrients mineralised from manure.

Mineral nitrogen was applied in the autumn before the wheat was sown (40 kg N ha⁻¹, N1, N2, and N3 treatments), during the beginning of the spring for regeneration (40 kg N ha⁻¹, N2 and N3 treatments, late February, beginning of March), and during the May to support the grain production (40 kg N ha⁻¹, N3 treatment). The P and K fertilizers were applied during the autumn, before the wheat was sown.

Winter wheat cultivar, sown between 2014/2015 and 2017/2018, was Julie (Selgen a.s., Sibirina, the Czech Republic). It is a short straw cultivar offering high yields in all cropping areas, high frost resistance, offering class “E” (elite) grain quality, and a high volume of bakery products. Wheat was sown in October (according to the climate conditions), the depth of sowing ranged from three to four cm, the row spacing was 12.5 cm, and the sowing rate was 400 seeds per m². Pesticides were used during the experiments if necessary, while growth regulators havenot been introduced and applied. The harvest was done during the right BBCH stage, and was performed by the HEGE 180 (Hege Maschinen GmbH, Lichtenstein, Germany) in Ivanovice, Sampo Rosenlew 2010 (Sampo Rosenlew Ltd., Pori, Finland) in Caslav, and by Seedmaster Universal, Wintersteiger (Ried im Innkreis, Austria) in Lukavec.

2.3. Grain Quality Analyses

The crude protein content (CPC) was analysed according to the Kjeldahl method [9] (ČSN EN ISO 20483). The Zeleny’s sedimentation test (ZST) was analysed according to the ČSN ISO 5529. Owing to the different issues, the quality parameters (CPC, ZST) from the Caslav were analysed only in grain from seasons 2015 and 2018.

2.4. Data Analyses

To compare the effect of fertilizer treatment and year on grain yield, grain quality, and soil chemical composition, we used analysis of variance (ANOVA) and multivariate analysis of variance MANOVA, followed by a post-hoc analysis performed by Tukey’s HSD test (Statistica 13.3, TIBCO Software, Palo Alto, CA, USA). To analyse and visualize the relationships between fertilizer treatments, years,

and soil chemical properties, we used principal component analysis (PCA), performed by Analyse-it software (Analyse-it 5.30, Analyse-it Software, Ltd., Leeds, UK).

2.5. Soil Analyses

The soil chemical properties were analyzed at the beginning (2015) and in the end (2018) of the analyzed period. The soil samples were taken from the upper Ap horizons (0–30 cm) using the soil probe. Four soil samples were taken from each fertilizer treatment. The soil reaction was analyzed potentiometrically in 50 mL of 0.2 mol KCl (inoLab pH 730, Xylem Analytics-WTW, Weilheim, Germany). The soil organic carbon (SOC) content was measured according to [10,11]. The soil nitrogen content was analyzed using the sulfuric acid in the heating block (Tecator Inc., Hoganas, Sweden), followed by the Kjeldahl method [9]. The soil phosphorus, potassium, calcium, and magnesium were extracted by Mehlich III solution [12], followed by ICP–OES analysis (Thermo Scientific iCAP 7400 Duo, Thermo Fisher Scientific, Cambridge, UK).

3. Results

3.1. Effect of the FYM

Application of the FYM to the maize three years before wheat was sown (see the crop rotation description in Section 2.2.) significantly affected average wheat yields in all experimental sites (Table 4).

Table 4. Comparison of average grain yields (t ha^{-1}) as affected by locality, year, and fertilizer treatment.

	2015	2016	2017	2018	
Ivanovice					
Control	3.79±0.20 Aa	4.48±0.10 Ab	5.14±0.19 Ac	4.37±0.07 Aab	4.44±0.14 A
FYM	4.32±0.14 Aa	5.00±0.10 Bb	5.74±0.19 Ac	4.93±0.12 Bb	5.00±0.14 B
Caslav					
Control	5.87±0.14 Ad	5.31±0.06 Ac	4.48±0.13 Ab	3.83±0.09 Aa	4.87±0.21 A
FYM	6.60±0.21 Bc	5.91±0.08 Bb	5.10±0.15 Ba	4.98±0.06 Ba	5.65±0.18 B
Lukavec					
Control	2.11±0.12 Aa	2.48±0.11 Aab	2.07±0.10 Aa	2.87±0.12 Ab	2.38±0.10 A
FYM	2.90±0.12 Bb	2.90±0.18 Ab	2.36±0.08 Aa	3.29±0.11 Bb	2.86±0.10 B

Mean values with the standard error of the mean SE, followed by the same letter (A vertically, a horizontally), are not significantly different ($\alpha < 0.05$).

The average grain yield increase between the control and FYM treatments ranged from 0.48 t ha^{-1} in Lukavec to 0.78 t ha^{-1} in Caslav. However, the highest percentage increase was recorded in Lukavec (20%), followed by Caslav (16%) and Ivanovice (13%). The differences in average grain yields were not achieved by the only application of the FYM, as the effect of the year also significantly affected the compared grain yields. While the overall effect of the fertilizer treatment and weather conditions on average yield was equal in Ivanovice (49% for fertilizer treatment; 51% for weather conditions) and Caslav (47% for fertilizer treatment; 52% for weather conditions), the higher effect of the fertilizer treatment was recorded in Lukavec (62% for fertilizer treatment; 35% for the weather conditions), showing a lower fluctuation of grain yields between the years.

3.2. Effect of the Mineral N Applied without P and K Mineral Fertilizers

In comparison with the control, application of mineral N fertilizers applied without mineral P and K fertilizers significantly increased the average grain yields in all experimental stations (Table 5).

Table 5. Comparison of average grain yields (t ha^{-1}) as affected by locality, year, and fertilizer treatment.

	2015	2016	2017	2018	
Ivanovice					
Control	3.79±0.20 Aa	4.48±0.10 Ab	5.14±0.19 Ac	4.37±0.07 Aab	4.44±0.14 A
FYM+N1	7.30±0.10 Bb	7.79±0.17 Bc	7.53±0.09 Bbc	6.31±0.05 Ba	7.23±0.15 B
FYM+N2	8.87±0.29 Cc	9.08±0.12 Cc	7.28±0.14 Bb	6.00±0.14 Ba	7.81±0.33 C
Caslav					
Control	5.87±0.14 Ad	5.31±0.06 Ac	4.48±0.13 Ab	3.83±0.09 Aa	4.87±0.21 A
FYM+N1	9.11±0.11 Cc	8.24±0.05 Bb	7.98±0.13 Bb	5.24±0.10 Ba	7.64±0.38 C
FYM+N2	7.88±0.23 Bb	8.50±0.06 Cc	7.75±0.11 Bb	4.87±0.11 Ba	7.25±0.37 B
Lukavec					
Control	2.11±0.12 Aa	2.48±0.11 Aab	2.07±0.10 Aa	2.87±0.12 Ab	2.38±0.10 A
FYM+N1	4.76±0.12 Bbc	3.56±0.08 Ba	4.41±0.10 Bb	5.17±0.09 Bc	4.48±0.16 B
FYM+N2	6.94±0.26 Cb	5.20±0.11 Ca	5.38±0.36 Ca	5.63±0.20 Ba	5.79±0.21 C

Mean values with SE, followed by the same letter (A vertically, a horizontally), are not significantly different ($\alpha < 0.05$).

The average grain yield increase was 2.79 t ha^{-1} (+63%) for FYM+N1 treatment and 3.37 t ha^{-1} (+76%) for FYM+N2 treatment in Ivanovice. The effect of the fertilizer treatment on overall grain yields was dominant (86%) when compared with the effect of the season (9%). The difference between FYM+N1 and FYM+N2 treatments was significant. According to the quadratic model, the maximum grain yield was reached at FYM+70 kg N ha^{-1} (Figure 2a).

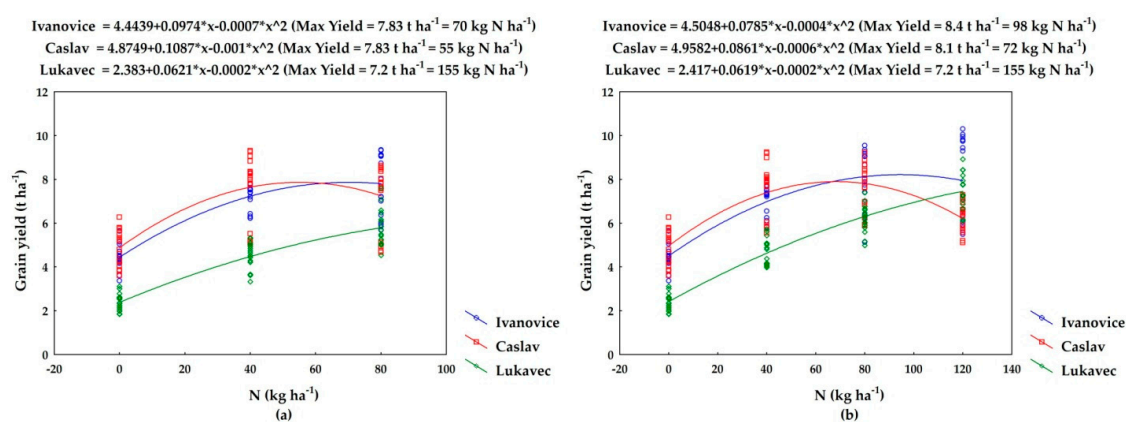


Figure 2. The average wheat grain yield as affected by fertilizer treatment ((a)—control, FYM+N1, FYM+N2; (b)—control, FYM+N1PK, FYM+N2PK, FYM+N3PK), and locality over the period 2015–2018.

3.3. Grain Quality

In Caslav, the average grain yield increase, following the application of mineral N, was lower than in Ivanovice. The average grain yield increase was 2.77 t ha^{-1} (+57%) for FYM+N1 treatment and 2.38 t ha^{-1} (+49%) for FYM+N2 treatment. The overall grain yields were affected by fertilizer treatment by 61%, while the effect of the season represents 37%. The difference between FYM+N1 and FYM+N2 treatments was significant. According to the quadratic model, the maximum grain yield was reached at FYM+55 kg N ha^{-1} (Figure 2a).

In Lukavec, the average grain yield increase, following the application of mineral N, was the highest out of all experimental stations. The average difference between the control and FYM+N1 was only 2.10 t ha^{-1} , but expressed as a percentage, it represents an 88% increase. Comparing the control and FYM+N2 treatments, the average grain yield increase was 3.41 t ha^{-1} , representing a 143% increase. The effect of the fertilizer treatment was, as in the case of Ivanovice, dominant (93%), while the effect

of the season was marginal (4%). The difference between FYM+N1 and FYM+N2 treatments was significant. According to the quadratic model, the maximum grain yield was reached at FYM+155 kg N ha⁻¹ (Figure 2a).

3.4. Effect of the Mineral N Applied with P and K Mineral Fertilizers

In comparison with the control, application of mineral NPK significantly increased average grain yields in all experimental stations (Table 6).

Table 6. Comparison of average grain yields (t ha⁻¹) as affected by locality, year, and fertilizer treatment.

	2015	2016	2017	2018	
Ivanovice					
Control	3.79±0.20 Aa	4.48±0.10 Ab	5.14±0.19 Ac	4.37±0.07 Aab	4.44±0.14 A
FYM+N1PK	7.38±0.05 Bb	7.53±0.16 Bb	7.56±0.09 Bb	6.19±0.15 Ba	7.16±0.16 B
FYM+N2PK	9.26±0.11 Cc	9.03±0.14 Cc	7.50±0.21 Cb	5.99±0.29 Ba	7.95±0.35 C
FYM+N3PK	9.98±0.12 Dc	9.61±0.15 Cc	6.68±0.15 Cb	5.76±0.14 Ba	8.01±0.47 C
Caslav					
Control	5.87±0.14 Ad	5.31±0.06 Ac	4.48±0.13 Ab	3.83±0.09 Aa	4.87±0.21 A
FYM+N1PK	8.79±0.36 Bb	8.00±0.04 Cb	7.96±0.12Cb	5.83±0.10 BCa	7.64±0.30 C
FYM+N2PK	8.71±0.25 Bc	8.27±0.11 Cc	7.28±0.21BCb	5.99±0.08 Ca	7.56±0.28 C
FYM+N3PK	6.21±0.46 Aab	6.72±0.16 Bb	6.70±0.19 Bb	5.56±0.13 Ba	6.29±0.17 B
Lukavec					
Control	2.11±0.12 Aa	2.48±0.11 Aab	2.07±0.10 Aa	2.87±0.12 Ab	2.38±0.10 A
FYM+N1PK	4.76±0.33 Bab	4.06±0.04 Ba	4.79±0.21 Bab	5.31±0.17 Bb	4.73±0.15 B
FYM+N2PK	6.68±0.31 Ca	5.82±0.31 Ca	6.39±0.30 Ca	5.94±0.27 Ba	6.21±0.16 C
FYM+N3PK	8.33±0.25 Db	7.45±0.49 Dab	7.37±0.26 Dab	6.83±0.25 Ca	7.49±0.20 D

Mean values with SE, followed by the same letter (A vertically, a horizontally), are not significantly different ($\alpha < 0.05$).

In comparison with the control, the average grain yield increase varied from 2.72 t ha⁻¹ (+61%, FYM+N1PK) to 3.57 t ha⁻¹ (+80%, FYM+N3PK) in Ivanovice. The effect of fertilizer treatment on average grain yield was marginal (69%), while the season conditions affected average grain yields by 23%. No significant differences were recorded between FYM+N2PK and FYM+N3PK treatments. According to the quadratic model, the highest grain yield was achieved at FYM+98 kg N ha⁻¹ (Figure 2b).

The lowest average grain yield increase, when compared with the control, was recorded in Caslav, ranging from 1.42 t ha⁻¹ (+29%, FYM+N3PK) to 2.77 t ha⁻¹ (+57%, FYM+N2PK). The effect of the fertilizer treatment on average grain yield was 62%, while the effect of the season was 36%. The highest grain yields were recorded in FYM+N1PK (7.64 t ha⁻¹) and FYM+N2PK (7.56 t ha⁻¹) treatments (without significant differences between these two treatments). According to the quadratic model, the highest grain yield was achieved at FYM+72 kg N ha⁻¹ (Figure 2b).

The average grain yield increase in Lukavec ranged from 2.35 t ha⁻¹ (+99%, FYM+N1PK) to 5.11 t ha⁻¹ (+215%, FYM+N3PK). The factor “fertilizer treatment” dominantly affected the average grain yield (98%). According to the quadratic model, the highest grain yield ought to be achieved at FYM+155 kg N ha⁻¹ (Figure 2b).

3.4.1. Ivanovice

The CPC was significantly affected by year ($p < 0.001$), fertilizer treatment ($p < 0.001$), and their interaction ($p < 0.001$). The most dominant factor influencing the CPC was fertilizer treatment (97%). The average CPC ranged from 8.1% (control) to 14.5% (FYM+N3PK) (Table 7). No differences between the control and FYM treatments were recorded. The year to year differences were significant in the FYM and FYM+N3PK treatments, especially in the FYM+N3PK treatment, showing a fluctuation

based on the weather conditions of the season. However, the contribution of this factor was small when compared with the effect of fertilizer treatment (Table 7).

Table 7. The average crude protein content (CPC) (%) and the value of Zeleny's sedimentation test (ZST) (mL) of wheat grain as affected by locality, fertilizer treatment, and the year.

	2015	2016	2017	2018	
Ivanovice					
CPC (%)					
Control	7.9±0.1 Aa	8.3±0.1 Aa	8.1±0.1 Aa	8.1±0.2 Aa	8.1±0.1 A
FYM	8.1±0.1 Aa	8.7±0.1 Ab	8.0±0.2 Aa	8.3±0.2 Aab	8.3±0.1 A
FYM+N3PK	13.1±0.3 Ba	13.3±0.3 Ba	15.3±0.4 Bb	16.4±0.2 Bb	14.5±0.4 B
ZST (mL)					
Control	15.5±0.6 Aa	20.0±0.7 Ac	16.8±0.6 Aab	18.3±0.5 Abc	17.6±0.5 A
FYM	15.8±0.6 Aa	20.0±0.4 Ab	16.5±0.3 Aa	19.3±0.5 Ab	17.9±0.5 A
FYM+N3PK	44.3±2.5 Ba	55.0±1.1 Bb	59.5±1.2 Bbc	67.0±2.0 Bc	56.4±2.3 B
Caslav					
CPC (%)					
Control	8.2±0.1 A	n.a.	n.a.	10.3±0.1 A	9.3±0.4 A
FYM	8.3±0.3 A	n.a.	n.a.	10.3±0.4 A	9.3±0.4 A
FYM+N3PK	14.0±0.2 B	n.a.	n.a.	12.9±0.8 B	13.4±0.4 B
ZST (mL)					
Control	16.8±0.6 A	n.a.	n.a.	30.5±1.2 A	23.6±2.7 A
FYM	18.0±0.6 A	n.a.	n.a.	30.8±2.1 A	24.4±2.6 A
FYM+N3PK	48.5±1.2 B	n.a.	n.a.	52.3±8.0 B	50.4±3.8 B
Lukavec					
CPC (%)					
Control	9.4±0.2 Ab	8.6±0.2 Aa	8.1±0.1 Aa	8.6±0.2 Aa	8.7±0.1 A
FYM	8.9±0.1 Ab	8.9±0.1 Ab	8.1±0.1 Aa	9.2±0.2 Bb	8.8±0.1 A
FYM+N3PK	11.2±0.4 Bab	10.2±0.2 Ba	12.2±0.2 Bbc	13.0±0.1 Cc	11.6±0.3 B
ZST (mL)					
Control	19.0±0.8 Ab	18.3±0.9 Ab	14.8±0.3 Aa	17.0 Aab	17.3±0.5 A
FYM	18.8±0.5 Ab	19.0±0.6 Ab	15.0±0.4 Aa	18.3±0.5 Ab	17.8±0.5 A
FYM+N3PK	34.3±2.5 Aab	30.3±1.5 Ba	37.0±3.1 Bab	43.0±1.2 Bb	36.1±1.6 B

Mean values with SE, followed by the same letter (A vertically, a horizontally), are not significantly different ($\alpha < 0.05$). n.a.—results not available.

The value of ZST developed similarly as the CPC. The average values ranged from 17.6 mL (control) to 56.4 mL (FYM+N3PK) (Table 7). The major factor affecting the ZST was fertilizer treatment (97%). No differences between the control and FYM treatments were recorded. The value of ZST fluctuated from year to year in the same treatment, but the general effect of this factor was negligible in comparison with the fertilizer treatment.

3.4.2. Caslav

The CPC was significantly affected by year ($p < 0.01$), fertilizer treatment ($p < 0.001$), and their interaction ($p < 0.01$). The major factor influencing the CPC was fertilizer treatment (80%), followed by the year (10%) and their interaction (10%). The average CPC ranged from 9.3% (control, FYM) to 13.4% (FYM+N3PK) (Table 7).

The value of ZST was significantly affected by year ($p < 0.01$), fertilizer treatment ($p < 0.001$), and their interaction ($p < 0.01$). The major factor influencing the ZST value was fertilizer treatment

(73%), followed by the year (24%) and their interaction (3%). The average ZST values ranged from 24 mL (control, FYM) to 50 mL (FYM+N3PK) (Table 7).

3.4.3. Lukavec

The CPC was significantly affected by the year, fertilizer treatment, and their interaction ($p < 0.001$). The dominant factor influencing the CPC in Lukavec was fertilizer treatment (93%). The average CPC ranged from 8.7% (control) to 11.6% (FYM+N3PK) (Table 7).

The ZST value was significantly affected by year, fertilizer treatment, and their interaction ($p < 0.001$), mainly by the fertilizer treatment (95%). The mean values ranged from 17.3 mL (control) to 36.1 mL (FYM+N3PK) (Table 7).

3.5. Soil Chemical Properties

The effects of fertilizer treatments on soil chemical properties are shown in Tables 8–10 and the relationship between the parameters, localities, and fertilizer treatments are shown in Figure 3. The value of pH was not affected by any treatment in Ivanovice (Chernozem) and Lukavec (Cambisol). On the other hand, the application of mineral fertilizers significantly decreased the soil pH value in Caslav (Phaeozem). Application of all fertilizers significantly increased the Nt (%) and Cox(%) in all localities. The same pattern can be seen in the case of P (mg kg⁻¹) and K (mg kg⁻¹). Only in Lukavec, we did not record any differences in P and K concentrations between the control, FYM+N1, and FYM+N2 treatments. The concentration of Ca (mg kg⁻¹) was not affected by any treatment, except for low, but significant differences in Caslav (Control and FYM+NPK treatments). On the other hand, the Mg (mg kg⁻¹) content varied significantly in Ivanovice and Caslav, while no fluctuation was recorded in any fertilizer treatment in Lukavec.

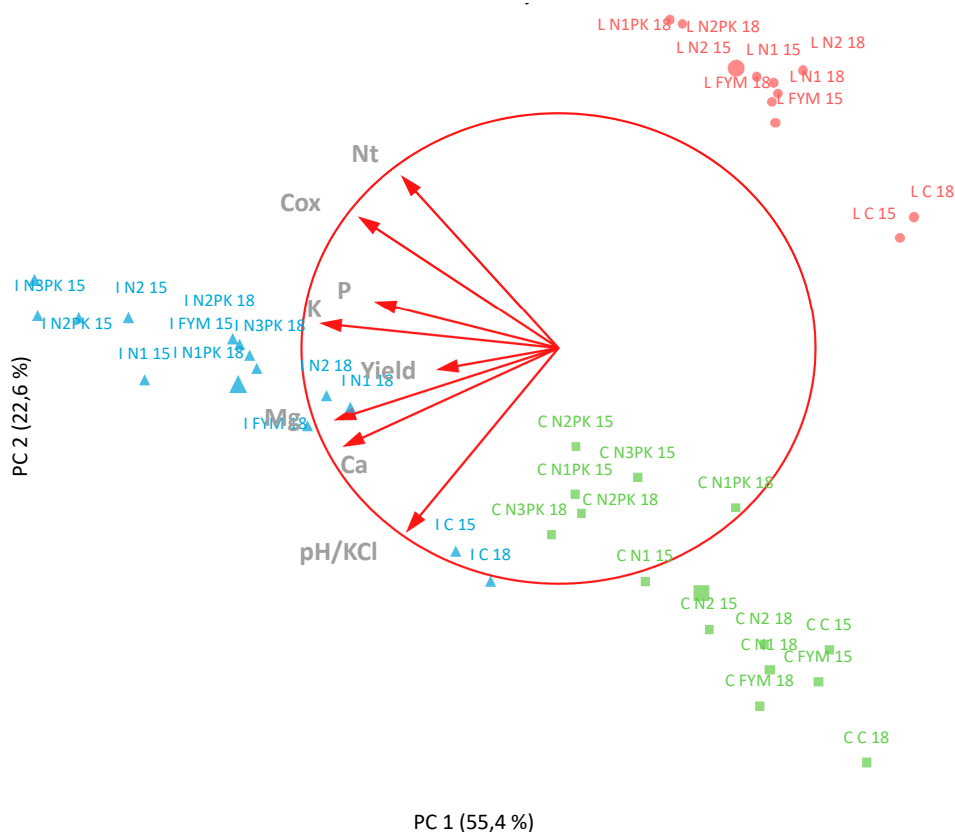


Figure 3. The relationships between soil chemical properties as affected by locality (I—Ivanovice, C—Caslav, L—Lukavec), fertilizer treatment, and year (15—2015, 18—2018).

Table 8. The pH; Nt; Cox; and content of P, K, Ca, and Mg, as affected by fertilizer treatment in Ivanovice.

Ivanovice							
	pH/KCl	Nt (%)	Cox (%)	P (mg kg ⁻¹)	K (mg kg ⁻¹)	Ca (mg kg ⁻¹)	Mg (mg kg ⁻¹)
Control	6.87±0.03A	0.19±0.01A	1.70±0.02A	97±6A	203±10A	4437±121A	198±3A
FYM	6.90±0.03A	0.23±0.01B	1.96±0.03B	159±12B	306±19B	4334±74A	217±6B
Control	6.87±0.03A	0.19±0.01A	1.70±0.02A	97±6A	203±10A	4437±121A	198±3A
FYM+N1	6.78±0.04A	0.22±0.01B	1.97±0.03B	153±17B	282±26B	4358±142A	235±9B
FYM+N2	6.83±0.03A	0.24±0.01C	2.03±0.04B	136±10AB	275±20B	4376±100A	232±7B
Control	6.87±0.03A	0.19±0.01A	1.70±0.02A	97±6A	203±10A	4437±121A	198±3A
FYM+N1PK	6.82±0.03A	0.23±0.01B	2.00±0.04B	205±13B	410±36B	4193±85A	226±5B
FYM+N2PK	6.78±0.02A	0.23±0.01B	1.99±0.03B	204±12B	379±30B	4201±97A	225±4B
FYM+N3PK	6.80±0.02A	0.24±0.01B	2.02±0.03B	187±12B	362±31B	4334±68A	242±8B

Mean values with SE, followed by the same letter (A vertically, a horizontally), are not significantly different ($\alpha < 0.05$). n.a.—results not available.

Table 9. The pH; Nt; Cox; and content of P, K, Ca, and Mg, as affected by fertilizer treatment in Caslav.

Caslav							
	pH/KCl	Nt (%)	Cox (%)	P (mg kg ⁻¹)	K (mg kg ⁻¹)	Ca (mg kg ⁻¹)	Mg (mg kg ⁻¹)
Control	6.72±0.02A	0.13±0.01A	1.16±0.04A	47±4A	107±3A	2876±23A	118±7A
FYM	6.69±0.05A	0.14±0.01B	1.19±0.02A	73±5B	129±5B	2917±30A	135±6A
Control	6.72±0.02B	0.13±0.01A	1.16±0.04A	47±4A	107±3A	2876±23A	118±7A
FYM+N1	6.65±0.01AB	0.16±0.01B	1.34±0.04B	73±10B	122±4B	2912±35A	161±3B
FYM+N2	6.68±0.03A	0.15±0.01B	1.29±0.01B	67±3AB	122±1B	2895±24A	154±6B
Control	6.72±0.02C	0.13±0.01A	1.16±0.04A	47±4A	107±3A	2876±23B	118±7A
FYM+N1PK	6.54±0.02A	0.16±0.00B	1.34±0.02B	171±5B	210±16B	2824±17AB	131±4AB
FYM+N2PK	6.51±0.01A	0.17±0.01B	1.38±0.02B	184±2B	237±5B	2746±39A	151±11AB
FYM+N3PK	6.61±0.01B	0.17±0.01B	1.42±0.03B	172±4B	213±14B	2810±18AB	163±11B

Mean values with SE, followed by the same letter (A vertically, a horizontally), are not significantly different ($\alpha < 0.05$). n.a.—results not available.

Table 10. The pH; Nt; Cox; and content of P, K, Ca, and Mg, as affected by fertilizer treatment in Lukavec.

Lukavec							
	pH/KCl	Nt (%)	Cox (%)	P (mg kg ⁻¹)	K (mg kg ⁻¹)	Ca (mg kg ⁻¹)	Mg (mg kg ⁻¹)
Control	5.77±0.04A	0.19±0.01A	1.44±0.05A	42±3A	125±9A	2055±31A	117±6A
FYM	5.86±0.06A	0.21±0.01B	1.67±0.05B	79±12B	169±5B	2079±42A	123±4A
Control	5.77±0.04A	0.19±0.01A	1.44±0.05A	42±3A	125±9A	2055±31A	117±6A
FYM+N1	5.79±0.05A	0.22±0.01B	1.70±0.04B	45±6A	147±7A	2098±50A	115±4A
FYM+N2	5.71±0.05A	0.22±0.01B	1.70±0.04B	37±2A	145±6A	2020±48A	108±5A
Control	5.77±0.04A	0.19±0.01A	1.44±0.05A	42±3A	125±9A	2055±31A	117±6A
FYM+N1PK	5.78±0.07A	0.22±0.01B	1.80±0.06B	193±16B	207±11B	2030±42A	111±4A
FYM+N2PK	5.79±0.05A	0.22±0.01B	1.79±0.06B	167±12B	183±10B	2056±37A	105±3A
FYM+N3PK	5.68±0.06A	0.22±0.01B	1.78±0.05B	173±9B	180±4B	2001±30A	114±5A

Mean values with SE, followed by the same letter (A vertically, a horizontally), are not significantly different ($\alpha < 0.05$). n.a.—results not available.

4. Discussion

4.1. Effect of the FYM

The effect of manure application on grain yield was significantly visible in all three localities with different soil-climatic conditions even three years after its incorporation into the soil. The differences in grain yield between the control and FYM treatments have not always been significant in particular

years (Table 4). However, the average grain yields in the FYM treatment have always been higher in comparison with the control, when the whole time period was evaluated (2015–2018). By comparing all three localities, we find that the greatest benefit of manure manifested itself in Lukavec (+20% mean grain yield increase in comparison with the control), followed by Caslav (+15%) and Ivanovice (+12%). In general, farmyard manure efficiency was slightly higher in the locality with poorer soil type and more humid climatic conditions and decreased on higher quality soils. The positive effect of the farmyard manure on the yield of arable crops three years after the manure application was also recorded by [13], who analyzed the effect of mineral fertilizers and organic manures in the long-term fertilizer experiment in Switzerland. Application of the FYM affected not only yields (Table 4), but also the soil chemical properties (Tables 8–10), so the effect of the FYM was two-sided and both aspects synergized, resulting in higher yields than in the control even three years after FYM application. The same conclusions and explanations published [13] who recorded a higher SOC content in the soil treated with manure. A 6.40% higher SOC content in the soil treated with manure, together with higher microbial biomass, was also recorded by [14]. Positive influences on yields and soil properties of manure application have also been published in the meta-analysis from China, provided by [15], who analyzed more than 140 studies and more than 770 treatment comparisons. In our case, the soil fertilized with FYM showed a significantly higher content of Nt and Cox (significantly higher in Ivanovice and Lukavec), and a higher content of soil P and K (Tables 8–10). As the estimated amount of nutrients available directly from the FYM to the wheat was relatively low in our case (5%), we incline to the fact that the positive effect of manure consisted in the direct effect of released nutrients, which were mostly utilized by pre-crops and partially by wheat, and also in influencing the microbial part, nutrients turnover, and organic matter pool in soil. As we did not perform the PLFA or other methods for evaluation of soil microbial activity, we cannot confirm these suggestions directly, but are in an agreement with the results of other researchers [16,17].

As mentioned above, the positive effect of the FYM on the wheat yield was significant in all localities. The opposite was true for qualitative parameters. On the basis of our results, we know that manure was able to provide nutrients and adjust soil conditions for higher yields of wheat grain (Table 4), but this was not enough to affect the CPC and ZST (Table 7). Except for the climate conditions, nitrogen is the most limiting factor for high CPC in the wheat grain [18,19]. From this point of view, the application of manure cannot replace mineral fertilizers for the production of bread-making quality grain, at least if wheat is not fertilized with manure directly (which is not a common practice in the Czech Republic). On the other hand, the effect of the FYM can be taken as an advantage if wheat is produced for minor supply-chains (biscuit production) [19], or as the feedstuff.

4.2. The Effect of Mineral N

No wonder, application of mineral N directly to wheat significantly increased grain yield in all localities. Nitrogen is considered as the wheat's most important nutrient, and its addition positively influences the root length and density, water uptake, above-ground biomass production [20], phenology and leaf traits [21], and grain yield [22,23]. Focused on the site-specific nutrient management, Ivanovice and Lukavec provided the highest yields in the FYM+N2 treatment, with the maximum yield at 70 kg N ha⁻¹ in Ivanovice and 155 kg N ha⁻¹ in Lukavec. On the other hand, Caslav provided maximum yield in FYM+N1 treatment, and according to the quadratic model, the optimum dose represents 55 kg N ha⁻¹. This means that similar wheat yields can be harvested in all localities, but with extremely different nitrogen rates. It also means that nitrogen fertilization ought to be adjusted to the soil-climate conditions of the specific site—a single recommendation about the dose of mineral nitrogen cannot be applied nationwide. This knowledge can thus save the farmer's financial resources, the number of field operations, and the environment, as the excess of mineral nitrogen fertilizers applied to agricultural land is associated with negative impacts on soil nitrogen pool [24], leaching, and groundwater nitrate contamination [25,26]. Focused on the soil properties, application of mineral nitrogen significantly decreased the pH in Caslav, while no changes were recorded in Ivanovice and

Lukavec (Tables 8–10). The soil nitrogen concentration was higher in all localities, as well as the Cox content when compared with the control. Concentrations of P, K, and Mg were significantly higher in Ivanovice and Caslav, while no differences were recorded in Lukavec. From this point of view, the soil answer to N addition was similar in Ivanovice (Chernozem) and Caslav (Phaeozem)—these soils were more sensitive to the addition of mineral N. Both soil types are almost comparable, both represent the most fertile types in the Czech Republic, but Phaeozems are more prone to leaching during the wet seasons and do not contain so many carbonates in the topsoil layer [27], as can be seen in Tables 8 and 9. Another aspect is the soil buffering capacity against acidification, which is high in the case of Chernozems and lower in Phaeozems [28]. Lukavec (Cambisol) offers similar values of Nt and Cox (even slightly higher) to Caslav, but the natural properties of the soil type in Lukavec are low pH value, the soil is lighter, and with lower sorption capacity [28]. Together with colder weather, the soil type creates a natural barrier that significantly affects wheat prosperity.

4.3. The Effect of Mineral N, P, and K

As with the effect of FYM+N, the application of mineral NPK fertilizers significantly increased wheat yields. In Ivanovice and Lukavec, the grain yield increased with increasing N dose (Control < FYM+N1PK < FYM+N2PK < FYM+N3PK). The difference between FYM+N2PK and FYM+N3PK was not significant in Ivanovice, and maximal yield was reached with 98 kg N ha^{−1}. This suggests that we have reached the maximum potential yield here, and increasing the nitrogen doses will not be connected with higher grain yield. From this point of view, we cannot influence the natural barriers of the locality and only new breakthroughs, such as the transformation of wheat from C3 to C4 pathway [29], could bring the new “green revolution”, connected with significantly higher yields. Different behaviour was recorded in Caslav, where a significant decline in grain yields was connected with increasing doses of mineral N, and maximal yield was reached with 72 kg N ha^{−1}. Finally, the light soil in Lukavec responded to increasing nitrogen doses with significantly higher yields. According to the quadratic model, the maximum yield was reached with 155 kg N ha^{−1}. These results of the quadratic model specify the previous values obtained for the variants FYM+N1 and FYM+N2 (the variant FYM+N3 would be great for the comparison. However, it was not established when setting up the experiment). Another thing we can compare is the effect of added P and K fertilizers. As mentioned above, the average amount of applied P and K mineral fertilizers is very low in the Czech Republic. This creates a contrast between what is taught in schools and common agricultural practice. According to the results, no significant differences were recorded between FYM+N and FYM+NPK treatments in Ivanovice, where naturally fertile soil occurs and the pool of nutrients is high even in unfertilized Control treatment. Thus, the addition of 60 kg P and K ha^{−1} was not connected with any benefits if we speak about grain yields. In Čáslav, the high dose of nitrogen was counterproductive and the application of P and K again did not bring significant differences in yields, although the concentration of P and K were significantly lower in FYM+N treatments in comparison with FYM+NPK treatments. The high N dose counter-productivity theoretically stems from the fact that high doses of nitrogen supplied to the soil increase nitrogen losses from the soil, thereby reducing its usability by wheat [26], or from an increased risk of lodging and disease incidence and severity [30]. Finally, the third kind of reaction was recorded in Lukavec, where an increasing dose of mineral N increased grain yield, and yield reduction is expected at doses above 155 kg N ha^{−1}. Comparing the effect of P and K fertilizers in Lukavec, no differences between grain yields provided by FYM+N and FYM+NPK treatments were recorded, although the differences between the P and K concentrations in the soil were significant. According to the results, the application of P and K fertilizers significantly boosted the soil concentrations of P and K (Tables 8–10). This is a very important result showing that dependency on N, which is a current situation in the Czech Republic, is not long-term sustainable management and will slowly lead to soil depletion. Excellent review represents this paper [6]. According to [6], it was not clearly proven that application of P and K increases grain yield (some evaluated experiments proved that hypothesis, some did not), but it was stated that “improved soil P, K, or S availabilities has

potential to increase grain yield and improve the efficiency of N fertiliser use". It is suggested that application of P and K fertilizers increases the efficiency of N, but we cannot confirm this conclusion, at least from the point of view of grain yields.

4.4. Grain Quality

Owing to the limited budget, we were able to analyze only three fertilization treatments in terms of quality (control, FYM, and FYM+N3PK). Our results are of limited value, yet they can provide important information. The first important finding is that, as the FYM significantly affected grain yield (in comparison with the control), it was not able to provide a sufficient amount of nutrients, or beneficially affect the soil environment to produce quality grain. At least in the Czech Republic, where the minimum CPC content for bread-making "elite class" quality is 12.6%. The lower threshold is, for example, in France, where the CPC limit required for organic breadmaking wheat increased during the time from 9 to 10.5% [31]. However, even this value was not reached in our experiment. Manure is a valuable source of organic matter and nutrients that are released over time from the organic form to the inorganic form via the mineralization process. The released nutrients thus become accessible to plants. Most of the nutrients are released into the soil environment in the first year after application and, in subsequent years, this amount gradually decreases. The yearly rates of mineralization, expressed as decay series, vary significantly between the authors [32–34], but generally range (for nitrogen) from 40 to 60% in the first year, 10 to 25% in the second year, and 5 to 10% in the third year. The expected very low amount of available nutrients released from the manure during the third year after application could not meet the needs of wheat to produce higher amounts of protein. On the other hand, application of NPK significantly increased the CPC and ZST in all localities. Application of mineral N represents an effective way to increase grain's CPC [6,35,36]. Suitable soil-climate conditions in Ivanovice provided the highest CPC and ZST, followed by Caslav, which offers similar soil-climate conditions. Both sites provided grain meeting the requirements for category "E" (min. CPC 12.6%, min. ZST value 49 mL). On the other hand, even high doses of mineral fertilizers cannot break naturally created soil-climate barriers, such as in Lukavec (Table 7), where these requirements were not met in the currently evaluated period, as well as in the previous years (2011–2013) [37]. The CPC in the wheat grain is significantly affected mainly by two factors: (1) N supply and (2) weather conditions. In Lukavec, N supply was at the same level as in Ivanovice and Caslav, but the results were not satisfying. According to Barneix [35], the CPC cannot be increased, despite the ample N supply, because two main regulatory points are active at the same time during the grain-filling period. This means that wheat (*Triticum aestivum*) has a ceiling in terms of protein content that cannot be exceeded. This can be seen in Ivanovice and Caslav. Ancient wheat species, such as *Triticum monococcum*, *Triticum dicoccum*, and *Triticum spelt*, have the ability to produce higher CPC in comparison with *T. aestivum* [38], so the CPC is influenced by wheat species, too. The weather conditions are the second factor affecting the grain's CPC. Both yield creation (accumulation of starch) and grain's CPC (accumulation of proteins) are independent processes. Dry and hot conditions usually lead to high CPC, while wet and colder conditions lead to lower CPC [39], because dry conditions decrease starch synthesis and deposition, while proteosynthesis is not inhibited as much as starch synthesis by these environmental factors [40]. From this point of view, it is unlikely that, in Lukavec and other localities with comparable soil-climatic conditions, we will achieve a harvest of high-quality grain, at least via the fertilization. However, this could change with upcoming weather changes, as is expected for example in the UK [41], or generally in Europe [42]. The direction of such changes can be seen in the results from Lukavec from 2018. This season was dry in Ivanovice and Caslav, with relatively low yields and high quality. However, in Lukavec, the year 2018 was characterized by relatively good yields and, at the same time, high quality. This means that the drought has acted here as a positive factor, smoothing the negative effect of the local soil-climate barriers.

5. Conclusions

Application of farmyard manure three years before wheat was sown significantly affected wheat grain yields in all localities and positively influenced soil chemical properties, but has no further beneficial effect on grain quality.

Application of mineral nitrogen significantly increased grain yield and grain quality in all localities, and also positively affected Cox and Nt concentration. No effect on the pH value was recorded in Chernozem and Cambisol soil types, but Phaeozem reacted on N fertilizers with a decrease of the pH value.

Application of mineral nitrogen, phosphorus, and potassium was not connected with any significant increase in grain yields when compared with application of only mineral nitrogen. On the other hand, soil P and K concentrations were statistically significantly higher in treatments with P and K, and their application prevents depletion of these elements in the soil.

The highest yields were recorded between 70 and 98 kg N ha^{−1} in Ivanovice, 55 and 72 kg N ha^{−1} in Caslav, and with 155 kg N ha^{−1} in Lukavec.

Grain quality is mainly affected by nitrogen supply and limited by natural soil–climate barriers of the locality.

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