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How Weather and Fertilization Affected Grain Yield and Stability of Winter Wheat in a Long-Term Trial in the South Moravian Region, Czech Republic

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Abstract: We evaluated the impact of weather and fertilization treatments (Control, PK, NPK1, NPK2, and NPK3) on winter wheat grain yields in a long-term trial in Ivanovice, Czech Republic, established in 1956. A total of 15 seasons were evaluated. The mean, maximal, and minimal temperatures in Ivanovice have been significantly increasing since 1961, with annual increases of 0.04 °C, 0.03 °C, and 0.05 °C, respectively. Precipitation has been decreasing annually by −0.54 mm (trend is insignificant). Four significant correlations between weather and grain yield were recorded. There were positive correlations between mean (r = 0.7) and minimal (r = 0.5) temperatures in November and negative correlations between mean temperatures in May (r = −0.6) and June (r = −0.6). The combination of naturally fertile chernozem soil and a beneficial preceding crop (alfalfa) enables sustainable cultivation of wheat, even without mineral fertilizers. The application of mineral nitrogen (N) significantly increases wheat grain yield and yield stability. Without mineral N or with high doses of mineral N, yield stability decreases. According to two response models (quadratic and quadratic-plateau), a reasonable dose of fertilizer is 107 kg ha^{-1} N for modern wheat varieties, corresponding to a yield of 8.1 t ha^{-1}.

Keywords: *Triticum aestivum* L.; temperature; precipitation; mineral nitrogen; climate change; inter-annual variability; nonlinear response models; alfalfa; long-term field trial

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Citation: Hlisnikovský, L.; Menšík, L.; Barłóg, P.; Kunzová, E. How Weather and Fertilization Affected Grain Yield and Stability of Winter Wheat in a Long-Term Trial in the South Moravian Region, Czech Republic. *Agronomy* **2023**, *13*, 2293. https://doi.org/10.3390/agronomy13092293

Academic Editors: Arnd Jürgen Kuhn and Giuseppe Fenu

Received: 14 August 2023
Revised: 28 August 2023
Accepted: 29 August 2023
Published: 30 August 2023

1. Introduction

Wheat grain yield and its quality are influenced by a wide range of factors, such as the preceding crop [1–3] or tillage management [4,5]. However, two major factors that significantly impact wheat grain yield and quality are weather conditions (temperature and precipitation) and fertilizer application.

The relationship between weather patterns and agriculture has been observed since ancient times. Thanks to these long-term observations, we have acquired a wide range of weather folklore sayings. Scientific research into the relationship between weather and agriculture dates back to the late 19th and early 20th centuries. The first scientific papers analyzing the association between weather and crop yields were published in 1880 [6]. Subsequent papers were published in 1905 [7], 1907 [8], and 1910 [9]. In some of these papers, correlation was proposed and used as a suitable statistical tool for analysis. In 1925, a comprehensive analysis was published [10] comparing precipitation, the impact of fertilizer application, and grain yield of wheat cultivated at the Broadbalk Wheat Experiment, which was established in 1843. The study concluded that dry weather is generally advantageous for wheat cultivation under the UK's weather conditions. Long-term trials, such as those conducted in Broadbalk, represent an excellent source of data for evaluating the relationship between weather and crop productivity. According to a study conducted in Germany (Müncheberg, established in 1963) [11], the dominant factor affecting barley grain yields was weather, accounting for 55% of the variation. Fertilization, on the other hand, only accounted for 11% of the variation. Focusing on weather conditions, total precipitation during the growing season (April–July) was connected with higher yields, especially when high doses of mineral N were applied. On the other hand, March precipitation and April temperature were factors that negatively affected grain yields. In the UK (Broadbalk Wheat Experiment), total rainfall in October, February, and June and mean temperature in November, April, and May were evaluated as factors significantly influencing yields of winter wheat [12]. In the USA, specifically in Oklahoma, limited precipitation in April and May resulted in a reduction in wheat yield. May precipitation in Kansas and June-July precipitation in North Dakota represented dominant factors explaining wheat yield variation between 1950 and 2016 [13]. Studying the relationship between conditions in a specific month and crop yields is crucial due to the ongoing global warming phenomenon. Warming is being recorded worldwide, including in the Czech Republic [14–16], Poland [17], Germany [18], Austria [19], France [20], the United Kingdom [21], Europe [22], the USA [23], and Asia [24]. The consequence of global warming is a phenomenon called climate change, which can be difficult to define precisely [25,26] but can generally be described as increasing changes in the measures of climate over a long period of time, including precipitation, temperature, and wind patterns. The effect of climate change can also be seen in high inter-annual weather variability (weather instability). The occurrence of extreme weather conditions such as droughts and heat waves is increasing in the Mediterranean and Carpathian regions [27] and is expected to be more frequent than in the past [28,29]. Higher air temperature is associated with an increased capacity of the air to hold water vapor, resulting in more intense rainstorms, even in regions experiencing reduced precipitation [30]. It means that the distribution of precipitation throughout the year is influenced [31], even though the total amount of precipitation remains relatively constant (at least in the Czech Republic [32] and Poland [31]). This is affecting not only the biomass production, yield, and quality of arable crops but also soil degradation processes [33]. One negative effect thus reinforces the other. Detailed analyses of the weather and its impact on yields can provide us with insights into future trends and the potential benefits or drawbacks (risks) of global warming. This information allows us to make informed decisions and take necessary measures in advance.

One way to mitigate the impact of weather on year-to-year variations in crop yield is through fertilization. By applying mineral fertilizers to soil, we supply nutrients that can be utilized by the crops being grown. In the case of organic manures, we also incorporate organic matter. The rate of nutrient utilization depends on the type of fertilizer (mineral or manure) and the C:N ratio of manure fertilizers [34]. Nutrients from mineral fertilizers are available quickly, they are uniform, and their composition is well-defined, allowing for precise dosing. The effect of mineral fertilizers is also dependent on weather conditions. In the event of abnormal climatic conditions, such as drought, their application may be ineffective [35]. As droughts are occurring and will occur more frequently due to climate change [28,29], we can assume that cases of inefficient application of mineral fertilizers will also increase. Manures are heterogeneous, have a relatively low nutrient content, and must be applied in large quantities. The release of nutrients from manures is slower compared to mineral fertilizers, but they deliver them over a longer period of time. The composition of organic manures depends on their origin [36]. The application of manures is associated with many beneficial effects on crop yields and soil properties [37–41]. They are considered a key factor in our efforts to mitigate the negative effects of climate change [42] and promote sustainable agriculture [43]. Concerning climate change, the application of mineral nitrogen (N) and the combined application of mineral N with manures increase cereal yield stability [44,45].

The positive effect of mineral N on yield, quality [46,47], and production stability is only valid to a certain extent. As mentioned by [48], "Wheat production has been criticized because of a Janus-faced nature for the use of nitrogen (N) fertilizer...". The high productivity and quality of conventionally grown wheat are offset by the energy intensity of production and application [49]. Moreover, there is a potential negative impact on the environment [50], reduction in soil pH [51–54], and availability of risk elements in the soil [55]. Excessive fertilization is also unprofitable from an economic standpoint [56]. Particularly for cereals, their response to increasing rates of mineral N usually follows a concave down function. This means that as the mineral N rate increases, yields initially increase but eventually start to decline after reaching the critical rate. This decline is mainly attributed to lodging [57]. However, it is important to note that this may not always be the case and can vary depending on soil and climate conditions. For these reasons, optimization of N fertilization is necessary [58].

In this paper, we evaluated a long-term experiment in Ivanovice na Hané, established in 1956. Specifically, we examined the influence of fertilization and weather on wheat grain yields and yield stability when alfalfa (11 seasons) and *Lolium multiflorum* Lamk. (four seasons) were used as the preceding crop (15 years altogether). We also analyzed the weather patterns at the site and determined the optimal doses of mineral N. The main questions we aimed to address were as follows: (1) What is the trend in weather at a specific location (H_0: Weather parameters (temperature and precipitation) remain constant over time; H_A: Weather parameters significantly change over time)? (2) Do the climatic conditions of each month correlate with wheat grain yields (H_0: Relationships are not significant; H_A: Significant relationships exist)? (3) Is wheat grain yield affected by fertilization (H_0: Different fertilization treatments result in comparable yields; H_A: There are significant differences between treatments)? (4) Does fertilization affect yield stability (H_0: All treatments provide the same inter-annual yield variability; H_A: Yield stability varies between fertilizer treatments)? (5) What is the optimal rate of mineral N?

2. Materials and Methods

2.1. Description of the Field Trial Site

The long-term field trial analyzed in this paper is located in Ivanovice na Hané village, South Moravian Region, Czech Republic (49°19′ NL, 17°05′ EL). The elevation is 225 m above sea level. According to the Köppen–Geiger climate classification [59], the site is located in a warm summer continental climate area (Dfb). The soil is a fertile, degraded chernozem based on loess, which serves as the soil-forming substrate. The topsoil is dark brown and approximately 0.40 m deep. The humus content is approximately 4.4%. The long-term mean, maximal, and minimal temperatures are 9.0 °C, 15.5 °C, and 2.6 °C, respectively (1961–2022). The mean annual precipitation is 555 mm (1961–2022, the Ivanovice na Hané meteorological station).

2.2. Description of Field Trial

The long-term field trial was established in 1956 to analyze the long-term effects of farmyard manure and different combinations of mineral fertilizers on grain yield, quality of arable crops, and soil chemistry. Five fertilizer treatments are analyzed in this paper: (1) Control (unfertilized since trial establishment in 1956); (2) mineral phosphorus (P) and potassium (K), without mineral nitrogen (N)—PK; (3) combination of mineral NPK (40 kg ha^{-1} N)—NPK1; (4) NPK2 (80 kg ha^{-1} N); and (5) NPK3 (120 kg ha^{-1} N). Mineral N was applied in the form of lime ammonium nitrate, mineral P as granulated superphosphate, and mineral K as potassium chloride. While the doses of mineral N remained consistent throughout the trial, the doses of mineral P and K were not the same. The doses of these two nutrients have been adjusted over time, based on soil analyses. These adjustments are commonly used in conventional agriculture. However, in a long-term experiment, this can be seen as a possible complication that we want to highlight. However, in any given year, all the mentioned fertilizer treatments (PK, NPK1, NPK2, and NPK3) always received the same doses of mineral P and K, if applied. From this perspective, the results are therefore comparable and analyzable. The specific doses of mineral P and K were 200 kg ha^{-1} (1979–1982), 0 kg ha^{-1} (1995–1998), and 60 kg ha^{-1} (2004–2006; 2011–2014).

Both nutrients were applied in the same amount and are expressed in the form of P_2O_5 and K_2O.

The trial consisted of four fields, where fertilizer treatments were applied in randomized complete block design, with each treatment replicated four times. The size of one experimental plot, where one treatment–replication was applied, was 64 m^2 (8 × 8 m). All fertilizers were typically spread by hand. Mineral P and K fertilizers were applied in autumn. Mineral nitrogen (N) was applied during different stages of wheat cultivation. In autumn, before sowing the wheat, 40 kg ha^{-1} of N was applied as part of the NPK1, NPK2, and NPK3 treatments. In the beginning of spring, for regeneration purposes (BBCH 21–29), an additional 40 kg ha^{-1} of N was applied as part of the NPK2 and NPK3 treatments. Finally, in May, 40 kg ha^{-1} of N was applied as support for grain production, specifically as part of the NPK3 treatment (BBCH 49–51). Cattle farmyard manure was applied to maize (40 t ha^{-1}) three years before wheat was sown.

Over a span of 15 years (seasons), winter wheat was grown following *Medicago sativa* L. (alfalfa) in three different periods: 1979–1982, 2004–2006, and 2011–2014. Additionally, wheat following *Lolium multiflorum* Lamk. was also grown between 1995 and 1998. The years of harvest analyzed in this paper are 1979, 1980, 1981, 1982, 1995, 1996, 1997, 1998, 2004, 2005, 2006, 2011, 2012, 2013, and 2014. In 2003, a spring wheat variety was sown, so that year was excluded from the current analysis. Four wheat varieties were sown during different time periods: Slavia (1979–1982), Vega (1995–1998), Contra (2004–2006), and Mulan (2011–2014). Wheat was typically sown in October. The depth of sowing ranged from three to four cm, with a row spacing of 12.5 cm. The sowing rate was typically 400 seeds per square meter. Pesticides were used during the trial if necessary, and growth regulators were never applied.

2.3. Data Analysis

The grain yield results were checked for data normality using the Shapiro–Wilk test [60] and Anderson–Darling test. The effect of fertilizer treatments on grain yield was analyzed using the Kruskal–Wallis one-way ANOVA, followed by the Conover–Iman test [61]. Alternatively, ANOVA was used, followed by Tukey's HSD post hoc test (variances were identical, tested by Levene's test) and the Games–Howell test (homogeneity of variance was violated). Grain yield development as well as weather development were analyzed using the Mann–Kendall trend test [62,63] in conjunction with Sen's slope estimation [64]. The homogeneity test was used to select two time periods with different mean temperatures. Yield stability was analyzed using Kang's rank-sum statistic [65] with the software StabilitySoft [66]. To analyze the response of winter wheat to different N rates and establish optimal fertilization, two nonlinear models were calculated: quadratic and quadratic-plateau. All analyses and graphical outputs were performed using the Statistica 14.0 (Tibco Software, Palo Alto, CA, USA), SigmaPlot 14.5 (Systat Software Inc., San Jose, CA, USA), and XLStat software (Lumivero, Burlington, MA, USA).

3. Results

3.1. Weather Development

Since 1961, the mean, maximum, and minimum temperatures at the long-term trial site have been gradually increasing. All three trends are statistically significant ($p < 0.0001$). The mean, maximum, and minimum temperatures have been increasing annually by 0.04, 0.03, and 0.05 °C, respectively (Figure 1a,c,e). Significant changes in mean temperature date back to 1987. Before that year, the mean temperature was 8.4 °C, while after that year, the mean temperature rose to 9.6 °C (Figure 1b). A significant change in maximum temperature occurred in 1991. The period before 1991 was characterized by an average maximum temperature of 15.0 °C. After that year, the mean maximum temperature was one degree higher at 16.0 °C (Figure 1d). A significant increase in minimum temperature was recorded in 1998. The average minimum temperature was 1.9 °C before 1998, while it increased to 3.6 °C after 1998 (Figure 1f). In the case of precipitation, the trend has been a decrease by −0.54 mm annually, but this decrease is statistically insignificant (Figure 1g,h).

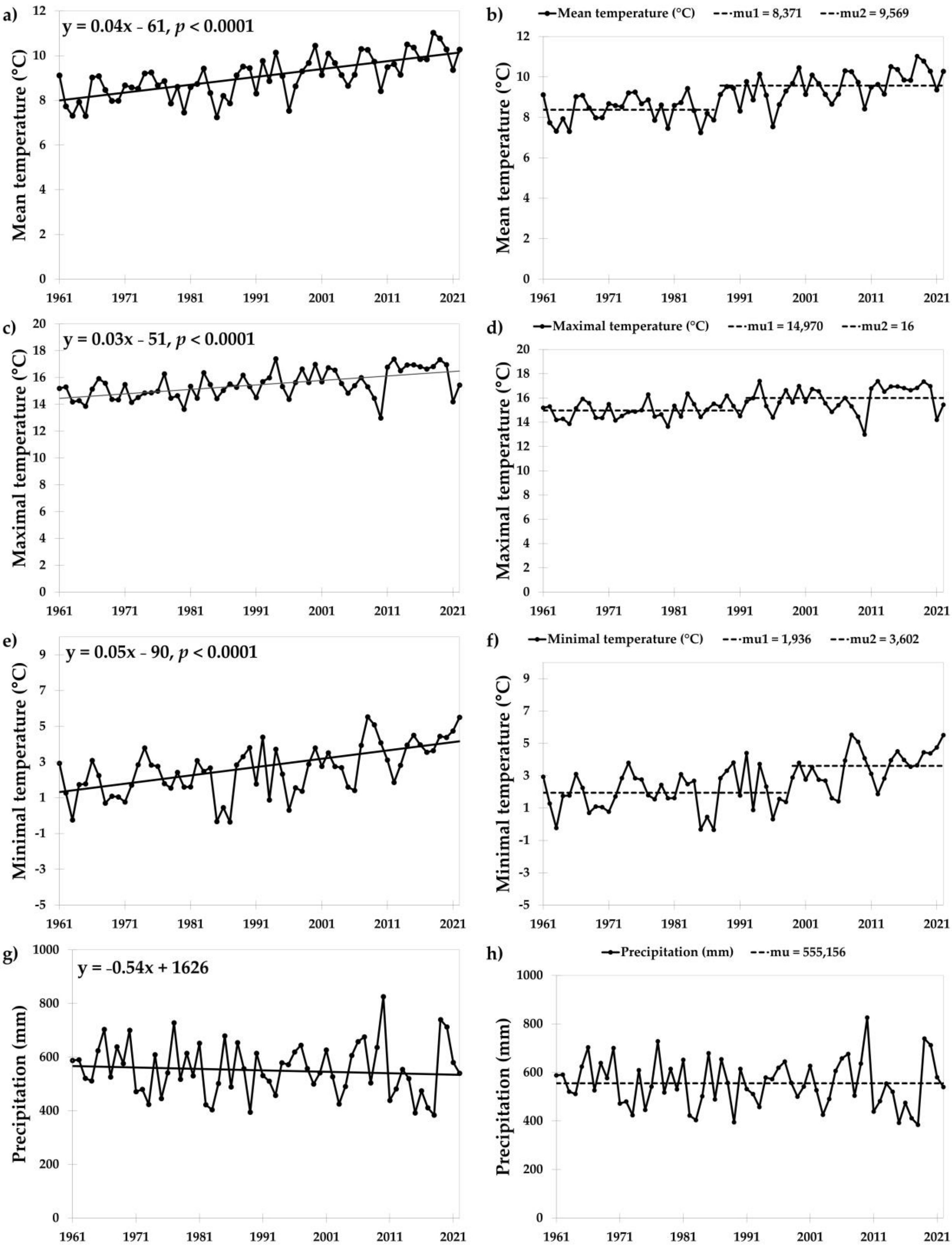

Figure 1. The development of (**a**) mean, (**c**) maximal, and (**e**) minimal temperatures (°C) and (**g**) precipitation (mm) between 1961 and 2022 (annual values). Separation of periods with different temperatures: (**b**) mean (1987), (**d**) maximal (1991), and (**f**) minimal temperatures (1998) and (**h**) precipitation.

Weather analysis shows that the crops grown in Ivanovice have to cope with gradually increasing temperatures, as the climate is warming significantly. However, the precipitation is decreasing at a statistically insignificant rate.

3.2. Grain Yield Development

All fertilization treatments exhibited a statistically significant increasing trend over time, as determined by the Mann–Kendall trend test ($p < 0.05$). Even the unfertilized Control confirmed that the growth of wheat in the South Moravian region is sustainable, even without fertilizer inputs (Figure 2), when wheat follows alfalfa in the crop rotation. The treatments with the lowest inter-seasonal increase in grain yields were PK (Sen's slope value of 34 kg ha^{-1} season^{-1}) and the Control (38 kg ha^{-1} season^{-1}). They were followed by NPK1 (60 kg ha^{-1} season^{-1}), NPK2 (87 kg ha^{-1} season^{-1}), and NPK3 (102 kg ha^{-1} season^{-1}) treatments.

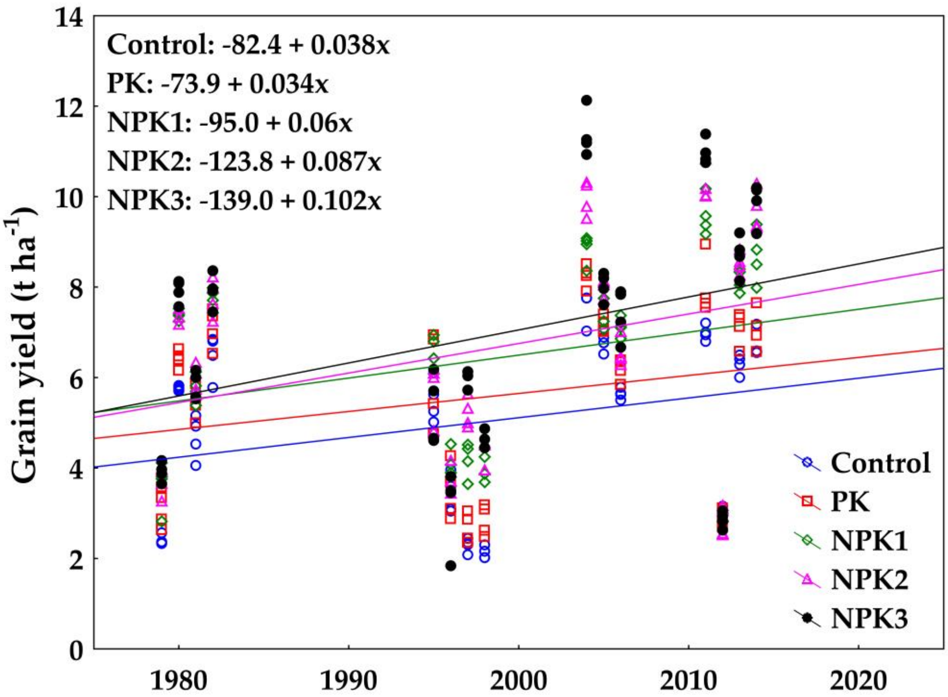

Figure 2. The development of grain yields (t ha^{-1}) as affected by fertilizer treatment (15 seasons).

3.3. Effect of Fertilization on Grain Yield

The lowest grain yield was recorded in the unfertilized Control treatment, followed by the PK, NPK1, NPK2, and NPK3 treatments (Table 1). The Control mean grain yield was statistically comparable to the PK treatment. The PK treatment represents a dividing line between the unfertilized Control and the mineral fertilizer treatments. The application of PK resulted in statistically comparable yields to NPK1 and NPK2. However, there was a difference in mean yield of 800 kg ha^{-1} compared to NPK1 and 1000 kg ha^{-1} compared to NPK2 (Table 1). The reason why PK treatment resulted in yields comparable to those following NPK1 and NPK2 treatments can be found in the preceding crop, alfalfa, which can fix N from the air and provide this important nutrient to the following crops. The highest yields were recorded in NPK3. However, this yield was statistically comparable to the yields of the NPK1 and NPK2 treatments. The average yields from each year are shown in Table S1.

Table 1. The mean grain yield (t ha^{-1}) as affected by fertilizer treatment (average of 15 seasons).

Fertilizer Treatment	Grain Yield (t ha^{-1})
Control	5.0 ± 0.2 ^{A}
PK	5.6 ± 0.3 ^{AB}
NPK1	6.4 ± 0.3 ^{BC}
NPK2	6.6 ± 0.3 ^{BC}
NPK3	6.9 ± 0.3 ^{C}

Note: Mean grain yield values (t ha^{-1}) ± standard error followed by the same letter are not statistically different (α = 0.05, Kruskal–Wallis ANOVA followed by Conover–Iman test).

3.4. Effect of Wheat Variety

Four wheat varieties (Slavia, Vega, Contra, and Mulan) were used in the experiment during the evaluation period from 1979 to 2014. The mean grain yields, categorized by wheat variety, are shown in Table 2.

Table 2. Grain yield (t ha^{-1}) as affected by wheat variety.

Wheat Variety	Grain Yield (t ha^{-1})
Slavia (1979–1982)	5.8 ± 0.2 ^{B}
Vega (1995–1998)	4.3 ± 0.2 ^{A}
Contra (2004–2006)	7.8 ± 0.2 ^{C}
Mulan (2001–2014)	7.1 ± 0.3 ^{C}

Note: Mean grain yields (t ha^{-1}) ± standard error followed by the same letter are not statistically different (α = 0.05, Kruskal–Wallis ANOVA followed by Conover–Iman test).

Slavia provided relatively high yields as the average wheat grain yield was 4.1 t ha^{-1} in the entire country from 1979 to 1982. Yields of the Vega variety were comparable to the average yield in the Czech Republic (4.5 t ha^{-1}). We assume that the lower yields of the Vega variety were due to the preceding crop, which was an annual form of *Lolium multiflorum* Lamk. (Poaceae family), so this variety could not benefit from the positive effects of alfalfa. The Contra and Mulan varieties recorded exceptionally high yields, with the mean grain yield in the Czech Republic reaching 5.1 t ha^{-1} and 5.5 t ha^{-1} in the selected years (Table 2).

3.5. Fertilization Optimization

For the optimization of fertilization, two nonlinear models were used: quadratic and quadratic-plateau. The results of these two models for each wheat variety are shown in Table 3 and Figure 3.

Table 3. Results of quadratic and quadratic-plateau response models. The model results represent the mineral N dose (kg ha^{-1} N) and the corresponding grain yield (t ha^{-1}).

	Quadratic Model	Quadratic-Plateau Model
Slavia	99 kg ha^{-1} N–6.4 t ha^{-1}	64 kg ha^{-1} N–6.3 t ha^{-1}
Vega	86 kg ha^{-1} N–4.9 t ha^{-1}	50 kg ha^{-1} N–4.8 t ha^{-1}
Contra	Not applicable	Not applicable
Mulan	111 kg ha^{-1} N–8.1 t ha^{-1}	107 kg ha^{-1} N–8.1 t ha^{-1}

The growth patterns of the Slavia (Figure 3a), Vega (Figure 3b), and Mulan (Figure 3d) wheat varieties were typical for both models. As mentioned in the Introduction, the pattern of wheat response to increasing mineral N application is typically concave downward (quadratic model). After reaching the maximum of the function, grain yields usually decrease with increasing N dose. However, such a course was not recorded for Contra (Figure 3c), where yields increased almost linearly as the N rate increased. The explanation can be found in the particularly high yields in 2004 (Table S1). We assume that the weather conditions for above-average production were excellent that year. In the years following (2005 and 2006), Contra yields were already comparable to or lower than those of the Mulan variety. Compared to the modern wheat varieties (Contra and Mulan), Slavia and Vega provided lower yields but also had lower nutrient requirements (Figure 3). This reflects the progress in breeding, where newer varieties produce higher yields. However, this increased yield potential is balanced with higher mineral N requirements. Since Mulan was the last modern type of wheat growing in Ivanovice, the recommendation of 107 kg ha^{-1} of N, which corresponds to a yield of 8.1 t ha^{-1}, could be considered an appropriate amount of mineral N for wheat cultivation in these specific soil and climate conditions.

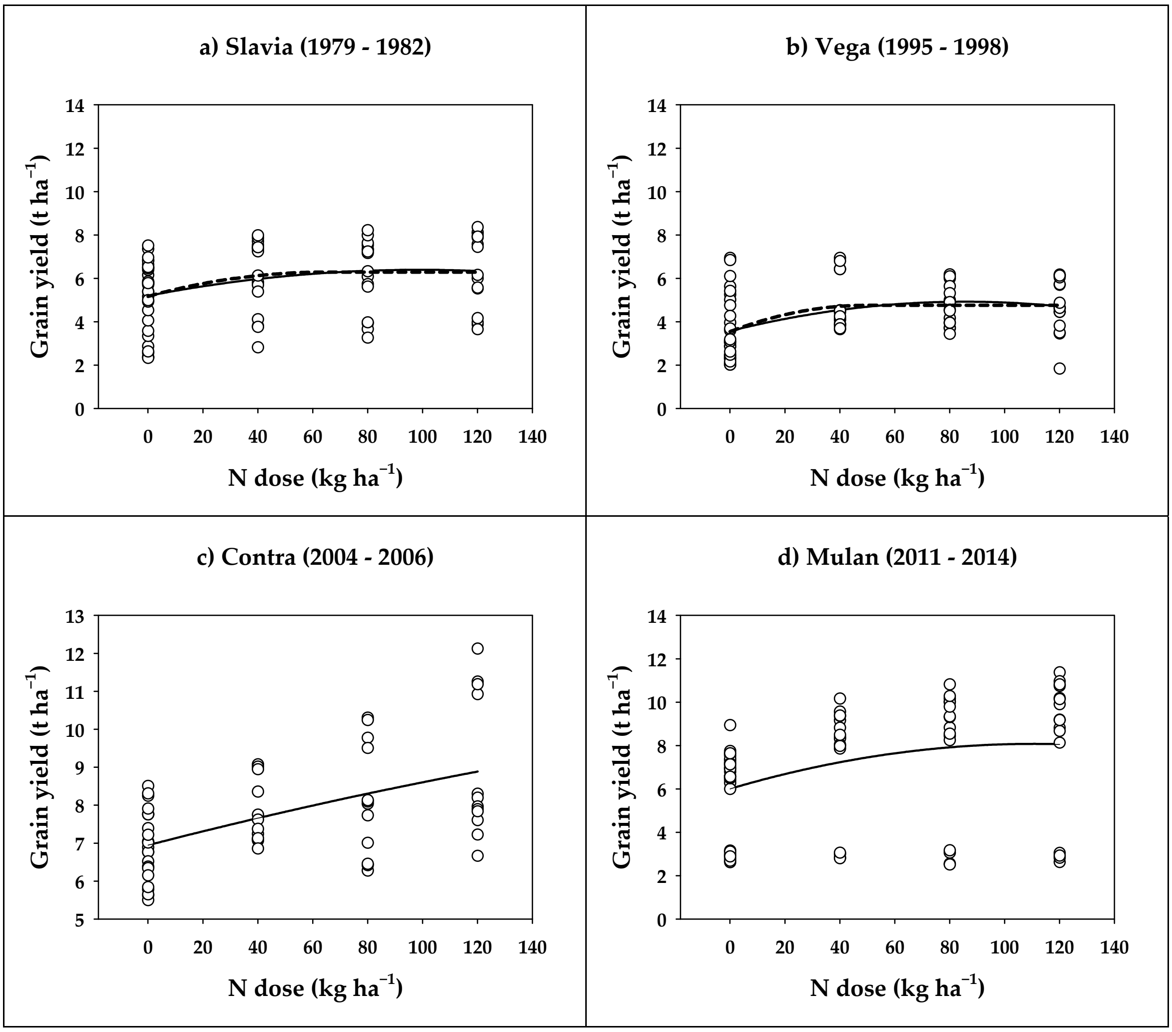

Figure 3. The response of (**a**) Slavia, (**b**) Vega, (**c**) Contra, and (**d**) Mulan wheat varieties to N dose (kg ha^{-1}). Data are interleaved with quadratic (black line) and quadratic-plateau (short dash line) functions.

3.6. Relationship between Weather, Grain Yield, and Fertilization

A correlation analysis was conducted to evaluate the relationship between weather conditions in specific months and yield. Four relationships were found to be statistically significant: (1) mean temperature in November (r = 0.7, Figure 4a), (2) mean temperature in May (r = −0.6, Figure 4b), (3) mean temperature in June (r = −0.6, Figure 4c), and (4) minimal temperature in November (r = 0.5, Figure 4d).

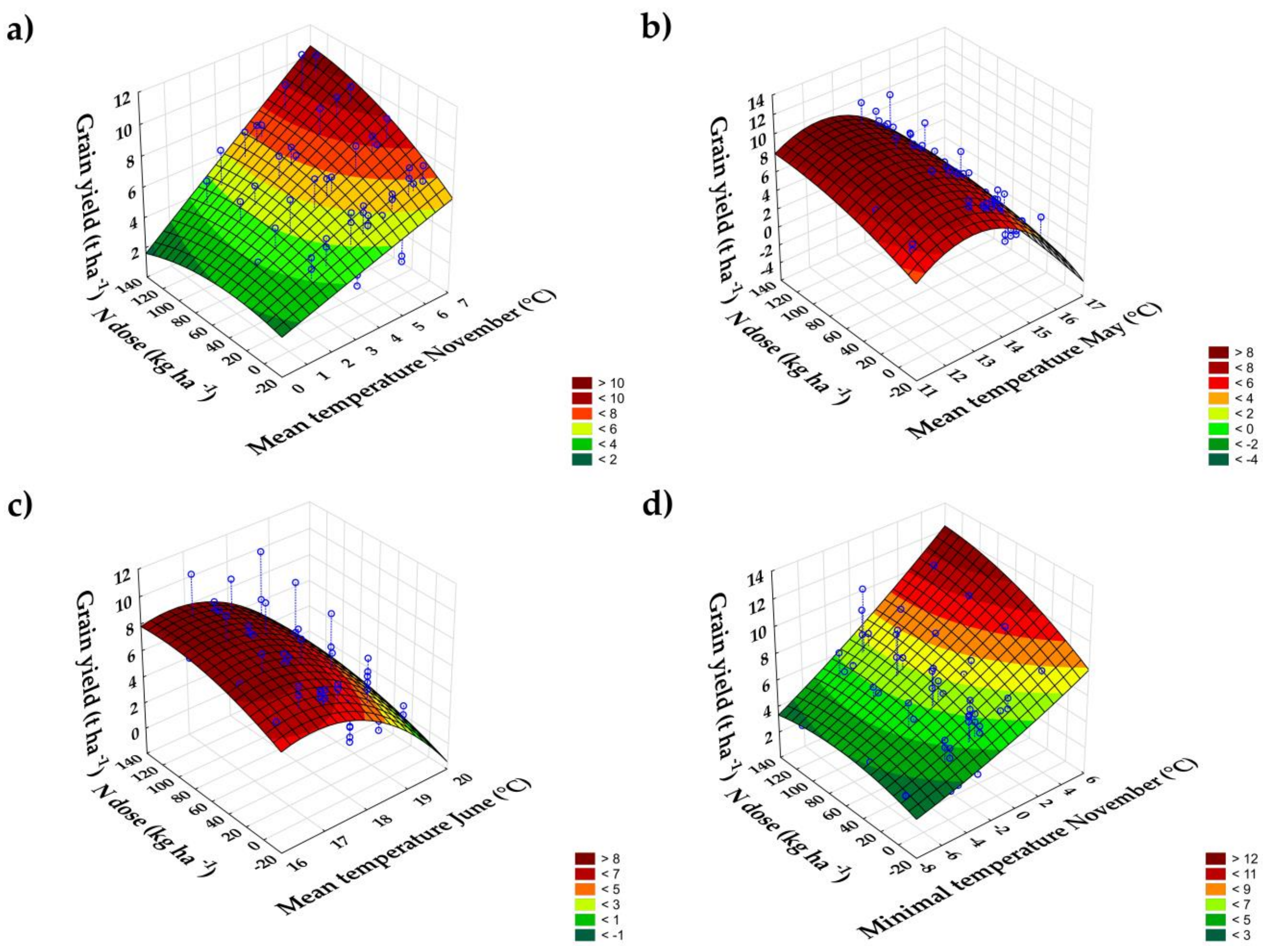

Figure 4. The relationship between grain yield (t ha^{-1}); N dose (kg ha^{-1}); and (**a**) mean temperature in November (°C), (**b**) mean temperature in May (°C), (**c**) mean temperature in June (°C), and (**d**) minimal temperature in November (°C). The color legend at the bottom right represents the grain yield rate (t ha^{-1}).

According to Figure 4a,d, warmer Novembers were associated with higher yields, and this effect became stronger with higher mineral N rates. According to the Mann–Kendall test, the mean temperature in November increased significantly by 0.03 °C annually ($p < 0.05$, Figure 5a). The minimal temperature also shows an increasing trend, although it is not statistically significant ($p = 0.06$, on the edge of significance, Figure 5d), with an annual increase of 0.04 °C. From this perspective, warmer Novembers should serve as a beneficial factor that positively influences growing conditions for wheat both currently and in the future.

The relationship between yield and mean temperature in May is negative. Lower temperatures in May were associated with higher yields. Highest yields could be expected when May temperatures varied between 12 and 13 °C. However, yields decreased with higher temperatures (Figure 4b). The long-term mean temperature is 14.3 °C, and there is a significant upward trend of 0.03 °C annually ($p < 0.05$, Figure 5b). A similar situation was recorded in June, where the optimal temperatures ranged between 16 and 17 °C. However, the long-term average temperature is 17.8 °C, and there is a significant upward trend of 0.04 °C per year ($p < 0.05$, Figure 5c). In this case, warming and climate change are counterproductive for both the present and the future, and they will have a negative impact on wheat yields due to these significant trends.

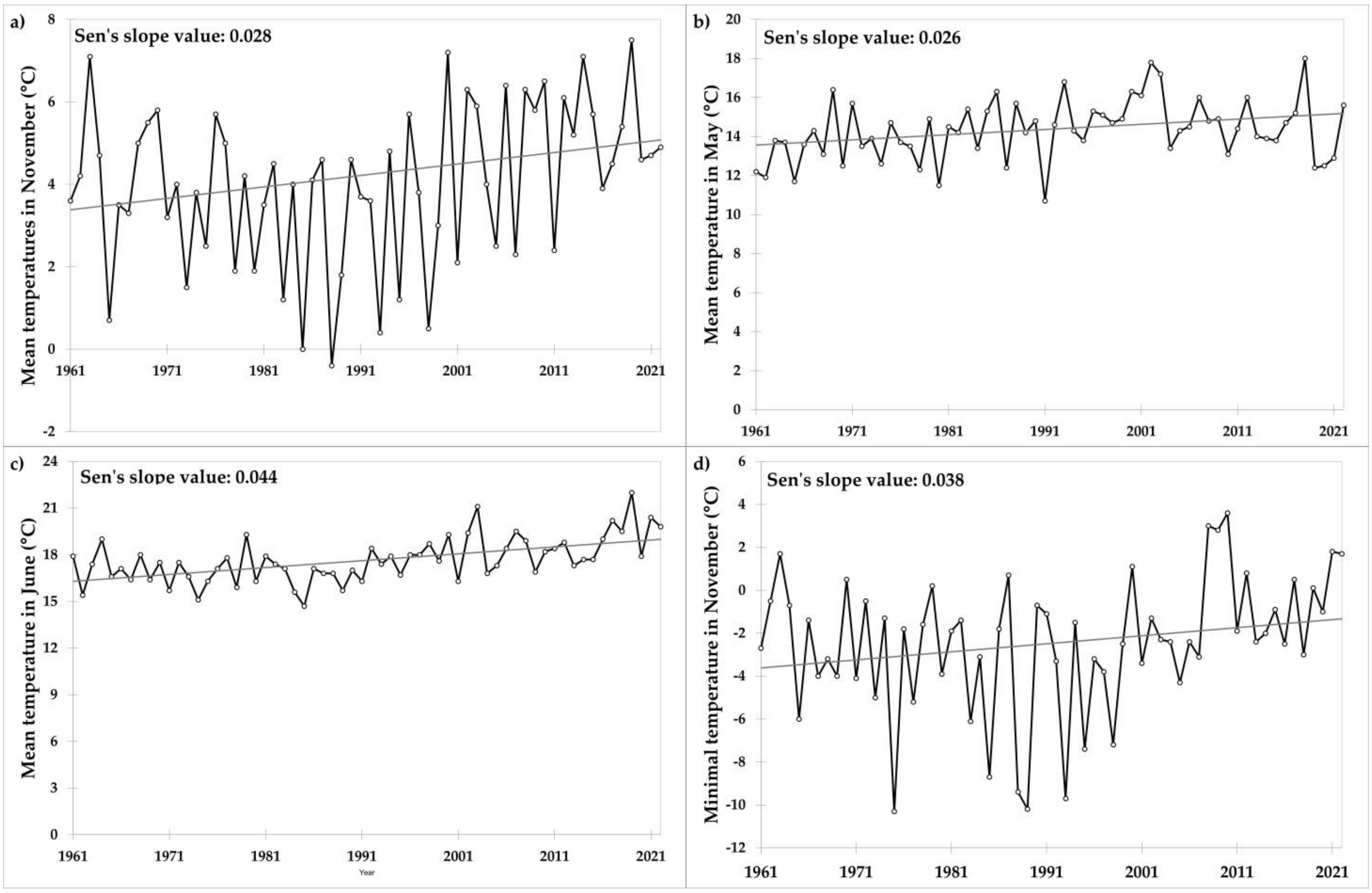

Figure 5. The development of (**a**) mean temperatures in November (°C), (**b**) mean temperatures in May (°C), (**c**) mean temperatures in June (°C), and (**d**) minimal temperatures in November (°C).

3.7. Yield Stability

The highest stability was recorded in the NPK1 and NPK2 fertilizer treatments (rank 1), followed by NPK3 (rank 2), PK (rank 4), and the Control (rank 5). It shows that the unfertilized Control and PK treatments were the most vulnerable to inter-annual weather variability, resulting in the least stable yields with high inter-annual fluctuation. The NPK1 and NPK2 treatments provided the most stable yields, indicating that regular application of lower doses of mineral N acted as a stabilizer, helping plants adapt to weather variability. Application of higher N doses (NPK3) sometimes resulted in higher yields, but these yields exhibited greater fluctuation compared to the NPK1 and NPK2 treatments. This fluctuation is associated with increased uncertainty in the long term. The NPK1 and NPK2 treatments provided more stable yields, which are statistically comparable to those from the NPK3 treatment.

4. Discussion

4.1. Weather Development

Based on weather data records and analyses, we can conclude that the air in Ivanovice has been warming since the second half of the 20th century. The trends for minimum, mean, and maximum temperatures are statistically significant and increasing (see Figure 1, panels a, c, and e, respectively). This result confirms findings from other parts of the world, indicating that atmospheric warming is occurring globally [14–23,67–69]. However, the average amount of precipitation remains the same (insignificant linear trend, Figure 1g), which is consistent with findings from other studies conducted in the Czech Republic [32], Serbia [69], and Slovakia [70]. In Slovakia, only 25% of weather stations recorded a significant increasing trend in precipitation, while no trends were observed in the remaining stations. Although the trend in precipitation is insignificant and slightly decreasing in Ivanovice, the results of other researchers emphasize the varying distribution of precipitation throughout the year in the context of climate change [30–32]. This means that the distribution of rainfall throughout the year has changed compared to the past. Long periods of drought and high temperatures are followed by cooler weather and heavy rainfall, particularly during the summer months. Crops are unable to utilize this water, and after a period that promotes wind erosion, a period that promotes water erosion follows. This is just one example of many describing a negative effect of global warming and climate change on soil erosion. This effect is expected to increase towards the end of the 21st century [71]. The example mentioned above is, of course, not a description of the standard weather nowadays, but rather extreme situations that are becoming increasingly frequent in the Czech Republic and Europe [28,29]. Such an extreme situation occurred in Ivanovice in 2012 when a severe drought caused unprecedentedly low yields in the South Moravian Region and also in our long-term trial (Figure 2, Table S1) [35,72].

Crops in Ivanovice have to endure increasing temperatures that are not offset by an increase in rainfall. Will it be good for growing wheat? Some publications predict that the current weather trend in the Czech Republic will have a positive impact on wheat [14,16], especially at higher altitudes, as a higher occurrence of droughts ought to be expected in lowlands [73,74]. According to Figure 4 (panels a and d), warmer conditions in November are associated with higher yields, and there is a significant trend of increasing November temperatures year by year. From this point of view, such weather conditions seem beneficial for wheat. A warmer November provides suitable conditions for seedling emergence, density, and the development of a stronger root system. This has a positive effect on the development of above-ground parts and tillering before the upcoming winter, increasing the chances of successful overwintering and high production. A consistent relationship between November temperatures and winter wheat grain yield was also observed in long-term trials in Prague [75] and Rothamsted [12]. High temperatures in May and June have a negative impact on wheat yields. The optimal average temperature for achieving the highest yields is between 12 and 13 °C in May and 16 to 17 °C in June. However, we know from the long-term series that the average temperature in both months is higher, and the long-term temperature trends are increasing at the site. The same results were recorded in Rothamsted, leading to the conclusion that "high temperatures around anthesis are known to reduce grain yield in wheat due to poorer seed set, and warmer temperatures and drought after anthesis reduce grain filling" [12]. However, a different reaction was recorded in another long-term trial, where higher May temperatures were positively correlated with higher yields [75]. These different responses are related to the different altitudes of the two trials. Prague is at an altitude of 370 m above sea level, while Ivanovice is 225 m above sea level; thus, while warmer springs in Prague provide better conditions for crop growth and development after winter, the weather in Ivanovice, which is located at a lower elevation and in a naturally warmer area, is already counterproductive in terms of spring temperatures.

4.2. Yield Stability

Grain yield stability represents an important factor for sustainable wheat production. The major challenge for wheat breeders is to develop high-yielding varieties without sacrificing yield stability [76]. In Germany, yield stability is a factor that is more important for farmers and advisors in the field of wheat than the grain yield itself, especially in relation to climate change. There are several ways to influence yield stability, such as selecting appropriate wheat varieties, implementing a beneficial crop rotation, using plant protection fertilization and tillage practices, and adjusting sowing date and density [77]. In our case, we employed various fertilization treatments to evaluate the stability of crop yield.

The lowest yield stability was recorded for the PK and Control treatments in Ivanovice. A similar result was recorded in other long-term trials [11,44,45,75,78,79], where the unfertilized control ranked last in the stability assessment. Crops without any fertilizer application and without mineral N are much more vulnerable to weather conditions and are highly susceptible to climate change [79]. Furthermore, only a well-balanced supply of all important nutrients ensures the most stable yields [78]. Application of mineral N acts as a significant factor in increasing yield stability [11,44,80]. However, this effect is only observed up to a certain dosage, as treatments with high N rates typically rank lower in stability assessments [44,75]. There are several reasons why mineral N plays such an important role in stable production, and they are interrelated. Sufficient N ensures the growth of a strong root system [81], which in turn leads to stronger plants with a higher chlorophyll content [82]. These plants thrive better even under less favorable climatic conditions. A well-developed root system contributes to the soil's organic matter content after harvest, thereby benefiting the soil's microbial components and nutrient cycle. Thus, organic matter is a key factor for yield stability [83], not only for wheat. This is why the combination of mineral fertilizers and organic manure provides the best stability and lowest agronomic risk for yield failure [44,79].

4.3. Grain Yield Development and Fertilization Optimization

Technological and socio-political developments after the Second World War led to a rapid increase in wheat yields, not only in Europe [84] but also worldwide [85]. The main reasons for such a significant increase in wheat yields were the development and implementation of genetic knowledge [86] and the increased availability and consumption of N mineral fertilizers [87–90]. In the field of genetics, we must especially mention the discovery of the dwarfing genes Rht1, Rht2, and Rht3 (reduced height genes). These genes were discovered in Japanese wheat lines, particularly in the Norin 10 variety. Crossbreeding with American wheat lines has resulted in the development of new varieties of wheat that are resistant to lodging. The reduction in stem height made it possible to apply higher doses of N fertilizer, which until then had been counterproductive or pointless due to the high percentage of lodging [91].

During the 18th century, the scientific community began to understand the importance of N for living organisms [92]. N is one of the most important nutrients for arable crops, significantly affecting their yield and quality [93]. However, N fertilization was considered a secondary issue in the past. The natural supply of N to crops through crop rotations, which included forage crops, and through the incorporation of post-harvest residues, was sufficient for a long time. Where appropriate, small amounts of mineral N fertilizers were applied in the past [94]. However, the discovery of the Haber–Bosch ammonia process changed everything. Originally, the process was designed for the military industry, but after the end of the Second World War, it found a use in agriculture [92,95]. The increased availability of fertilizers and the introduction of new wheat varieties led to the so-called Green Revolution [91].

The impact of the new wheat varieties is clearly evident in our long-term experiment in Ivanovice. Grain yields have gradually increased (Figure 2), and this trend is still evident today in Czech long-term trials [96–98]. The response of wheat to fertilization was also significant (Tables 1 and S1). However, the difference between the unfertilized Control (average yield 5.0 t ha^{-1}) and NPK3 was only 1.9 t ha^{-1}. The high yields of the unfertilized Control were attributed to the favorable soil and climate conditions (chernozem, warm area) as well as the preceding crop (alfalfa), which resulted in relatively small yield differences between the Control and the N-fertilized treatments. It is believed that the preceding crop effect also influenced the yields of the Vega variety (1995–1998), which were lower compared to other varieties. In this period, the preceding crop was *Lolium multiflorum*, an annual grass species from the Poaceae family. Other factors such as the weather during the period or the suitability of the variety for the soil–climate conditions could have also played a role. However, accurately assessing these factors is beyond our ability. Alfalfa, on the other hand, is a superior preceding crop, and not only for wheat. Legumes are able to form a symbiotic relationship with nitrogen-fixing bacteria known as rhizobia, which can convert atmospheric N into ammonia. This ammonia is then made available to plants, helping to improve soil properties [99–102]. This allows for a reduction in N fertilizers for crops that follow alfalfa in the crop rotation. According to several studies, the reduction can range from 40 kg ha^{-1} to almost 80 kg ha^{-1} [103–105]. In certain cases, N fertilization can even be completely skipped [106]. The use of alfalfa as a preceding crop also explains why the grain yields from the PK, NPK1, and NPK2 treatments were statistically comparable (Table 1). As alfalfa is capable of fixing aerial N, we assume that it provided a sufficient amount of N to the wheat. Therefore, the PK treatment (without mineral N) resulted in quite high yields. The regular inclusion of forage crops in the crop rotation, along with consistent manure application and favorable soil and climatic conditions, also contributes to sustainable wheat production, even in the absence of mineral fertilizers.

Fertilizing with N fertilizers also has a negative side. The application of N fertilizers can be described as Janus-faced because while it can lead to high yields and quality of arable crops, it also brings about environmental, sociological, financial, and health problems [86,107–111]. In the European Union (EU), environmental protection in terms of agriculture and fertilizers is addressed by the Nitrates Directive (Council Directive 91/676/EEC), the implementation of which has significantly reduced the impact of agriculture on soil and water quality [112] since the beginning of the 21st century, but this trend has stagnated in the last decade. For these reasons, optimizing fertilizer inputs is necessary to protect the environment, save farmers' finances, and achieve optimal grain yields. The most modern wheat variety used in the trial was Mulan. It is a variety with high grain density, no development delay in the generative phase, and stable yields. According to our calculations, approximately 107 kg ha^{-1} N should provide yields of around 8.0 t ha^{-1} under the given soil–climate conditions. Such recommendations must always be tied to a specific location. Other site-specific recommendations can be found for different localities [113,114].

5. Conclusions

(1) The weather is and has been changing significantly at the Ivanovice long-term experiment site. Since 1961, we have observed a statistically significant increasing trend in mean, maximum, and minimum temperatures, with annual increases of 0.04 °C, 0.03 °C, and 0.05 °C, respectively. On the other hand, the amount of precipitation has been relatively stable, with a slight annual decrease of −0.5 mm (although this trend was statistically insignificant). This means that crops have to cope with higher temperatures than in the past, but the amount of precipitation is slightly lower than before.

(2) Four significant relationships between weather conditions and wheat grain yields were recorded. Two of them were positive, namely mean ($r = 0.7$) and minimal ($r = 0.5$) temperatures in November, and two of them were negative, namely mean temperature in May ($r = -0.6$) and in June ($r = -0.6$). While a warmer November is beneficial for winter wheat, warmer spring and summer temperatures have a negative impact. Based on the results, we know that all of these months will continue to become progressively warmer.

(3) The unfertilized Control and the treatments without mineral N (PK) resulted in the lowest yield stability, characterized by high inter-annual variability of yields. Mineral N application represents a long-term stabilizing factor. However, high doses of N (120 kg ha^{-1}) reduced stability, while lower doses ranging from 40 to 80 kg ha^{-1} showed lower inter-annual variability in yield.

(4) Excessive doses of mineral N (120 kg ha^{-1} in our case) not only decrease yield stability but are also unjustifiable economically and yield-wise (price/performance ratio). The optimal N rate for the most modern wheat variety (Mulan), grown under site-specific conditions and following alfalfa in the crop rotation, was calculated to be 107 kg ha^{-1} N, resulting in a yield of 8.1 t ha^{-1}. However, the cultivation of wheat under the conditions of the South Moravian Region is sustainable even without the use of mineral fertilizers when wheat is grown after alfalfa in the crop rotation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13092293/s1, Table S1. Winter wheat grain yields as affected by year (n = 15) and fertilization treatment.

Author Contributions: Conceptualization, L.H., E.K. and L.M.; methodology, E.K.; software, L.H. and L.M.; validation, E.K., L.M. and P.B.; formal analysis, L.H.; investigation, L.H. and L.M.; resources, E.K. and L.M.; data curation, E.K.; writing—original draft preparation, L.H.; writing—review and editing, L.H.; visualization, L.H. and L.M.; supervision, E.K.; project administration, E.K. and L.M.; funding acquisition, E.K. and L.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the research plan of the Ministry of Agriculture of the Czech Republic (No. RO0423) and the projects of the Ministry of Agriculture of the Czech Republic (project Nos. QK21010124, QK21020155, QK22010251, and QK23020056).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We thank our predecessors who founded the long-term experiment in Ivanovice na Hané and participated in its operation and also the staff maintaining the trial presently. We also thank Dana Večeřová for her work in the laboratory.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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