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The Future Probability of Winter Wheat and Maize Yield Failure in Hungary Based on Long-Term Temporal Patterns

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Abstract: The level of yield variation of primary crops has a considerable effect on the vulnerability of agriculture. The main factor that makes the agriculture of Hungary so vulnerable is climate change, and technological development cannot compensate for its unfavourable effects. We examined the yield failures of the two major field crops grown in Hungary that occurred during the last 100 years. The goals of our study were to determine how often yield losses at 15% and 30% occur, what their probability is and whether the probability has changed in recent decades. The Wald–Wolfowitz runs test was used to determine the randomness of yield failures. A series of yield failures for maize and winter wheat were found to be random. Based on the data for 1985–2023, failure by 15% and 30% can be expected approximately every 8th and 19th year for winter wheat and 3rd and 5th year for maize. Winter wheat yield failure at 15% shows a decreasing trend in occurrence, while at 30% it increases. On the other hand, the frequency of maize yield failure increased at both levels. The consideration of historical yield data can help to determine the extent of crop loss to be expected in the long term to maintain sustainable winter wheat and maize production in our changing climate.

Keywords: yield depression; maize; winter wheat; sustainable crop production; Wald–Wolfowitz runs test

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1. Introduction

Yield depression or failure can be caused by many factors. Among them, we can distinguish natural and human-induced factors; the former are basically related to climate change and soil degradation, while the latter mainly have agrotechnical or contamination origins, while some involve both with a close correlation between them. In our study, we examined the yield losses of the two major field crops grown in Hungary that occurred during the last 100 years. To judge or prove the main reasons of the yield losses was not our goal, only to quantify their frequency and probability. As a result of our former study, we figured out that the main factor that makes the agriculture of Hungary so vulnerable is climate change, and technological development cannot compensate for its unfavourable effects [1]. Nevertheless, in this study, we provide a brief overview of some other factors beyond climate change in terms of some general and the most characteristic ones relevant to winter wheat and maize production that can be also considered in some cases.

Climate change leads to unpredictable weather, like changes in rainfall patterns, which can harm crops and cause more frequent and severe climate-related stresses, such as droughts or floods. Changes in temperature and weather can lead to an increase in pests and diseases that harm plants as warmer temperatures can increase their number, while changes in weather patterns can create conditions that help them to spread [2]. Singhal and Jha [3] analysed the factors contributing to the vulnerability of agriculture and found climate change to be the major stressor in this respect, but non-climatic stressors like socio-environmental conditions also impact vulnerability. Mukesh et al. [4] classified G-20 countries into four classes of agri-environmental vulnerability using a composite index method, and they highlighted the higher risk of environmental degradation in developing countries compared to developed ones: population and economic growth are primary reasons for this vulnerability.

1.1. Yield Failure in Winter Wheat Production

Variability in weather due to climate change and preceding crop harvests can lead to a wide range of sowing dates of winter wheat. Copeland et al. [5] concluded in their study that timely the planting of wheat is crucial for maximizing yield, with significant reductions if planting is delayed, and even increasing seeding rates cannot compensate for the yield potential lost due to delayed planting.

Groom and Baker [6] studied the changes in the efficiency of light in wheat crops induced by climatic changes. They established that fluctuating winter temperatures and light levels correlate with changes in photosynthetic performance. Light-induced reductions in photosynthesis due to environmental conditions that decrease carbon assimilation potential, commonly termed photoinhibition. Low temperatures and high photosynthetic photon flux density are leading to the downregulation of photosynthesis.

Vigil and Nielsen [7] established that legume green fallow cropping systems can reduce winter wheat yields compared to traditional summer fallowing, as the termination of legume crops at suboptimal times can lead to insufficient soil water storage, affecting the yield potential of the subsequent winter wheat crop, though the competitiveness of legume green fallowing with winter wheat fallowing is highly weather-dependent and inconsistent.

Kolesnikov et al. [8] studied how soil contamination through lead and oil affects the yield of winter wheat. They found that heavy metal pollution leads to metabolic disorders due to the deterioration of cell membrane permeability, while disorders in the penetration of water and nutrients, alongside oxygen starvation, can occur due to contamination with oil. Lead content exceeding 25 mg/kg and oil content of 0.25% in soil significantly impair the growth and development of winter wheat significantly affecting both the generative and vegetative parts.

1.2. Yield Failure in Maize Production

For maize, seed yield fluctuation refers to short-term changes in crop yield that happen because of unusual weather patterns, e.g., extremely high temperatures during the growing season are a risk factor. Fluctuations are different from long-term trends, which are usually a result of to improvements in farming technology and stable climate conditions. According to Ji et al. [9], climate risks like night-time rain and very hot temperatures during the growing season are major factors causing these fluctuations. They used a novel method to separate long-term trends from short-term fluctuations to better understand the impact of climate on maize yield. This separation allows for a more accurate identification of the real relationship between maize yield and climate factors.

Water supply is a crucial factor of yield generation for all crops. Under water deficit conditions, plants generally produce lower yields compared to normal water supply conditions. Nevertheless, some crops, even with high water demand, can be grown under low water conditions with no considerable yield decrease compared to their optimal water supply level. Plants have different responses to water supply, with some tolerating water deficit better than others. Huang et al. [10] discuss the impact of water deficit on waxy maize, particularly regarding how it leads to a reduction in growth and ear quality. They found that water deficits at the V6-VT (from six-leaf stage to tasselling stage) and VT-R2 (from tasselling stage to blister stage) stages significantly decreased plant growth rate and leaf–gas exchange parameters and accelerated leaf senescence. This resulted in a notable decrease in grains per ear and 100-grain weight, leading to a reduction in fresh ear yield. The study indicates that the timing of the water deficit is crucial, as earlier deficits (V6-VT and VT-R2) have more severe impacts on maize growth and yield compared to later stages (R2–R3).

Improper crop rotation or the long-term use of monoculture production can also result in yield depression. Porter et al. [11] investigated the effectiveness of different crops in interrupting the yield depression in monoculture maize. The authors compared the yield of continuous maize with the yield of maize alternated with dicots, specifically alfalfa and sunflower. It was observed that maize yields increased when rotated with certain crops such as alfalfa and sunflower, while rotations with grasses or fallowing do not improve maize yields compared to monocultures. The authors concluded that leguminous alfalfa and non-leguminous sunflowers are equally effective in alleviating maize monoculture yield depression, while grasses are relatively ineffective rotation crops for maize. The results suggest that certain dicots are more effective at interrupting maize monoculture yield depression than monocots.

Inbreeding, or the breeding of individuals with similar genetic makeup, leads to a reduction in plant height and grain yield across successive generations due to reduced biological fitness in a given population. Ali et al. [12] tested inbred maize lines and experienced a reduction in yield from the S1 to S5 generations. Traits such as plant height and grain yield tended to decline over successive generations of inbreeding. Rashmi Jain and Bharadwaj [13] also stated that inbreeding depression is associated with negative outcomes such as reduced grain yield and other yield-contributing characteristics. The reduction in performance in the F2 generation can lead to a decrease in desirable traits such as grain yield and yield-contributing factors. Inbreeding also can result in yield depression in wheat production [14].

Shen et al. [15] studied how environmental stresses such as shading and drought during the flowering stage of maize can lead to a significant loss of seeds, specifically mentioning that 20–30% of fertilised kernels can be aborted at maturity due to these stresses as they cause a decrease in sugar levels and an increase in ethylene emission, which in turn leads to kernel abortion.

Soil erosion, which leads to land degradation, has a significant negative impact on yields. Munodawafa [16] assessed the relationship between land degradation, specifically soil erosion, and the decline in maize grain yield under semi-arid conditions and granitic sandy soils of Zimbabwe. Maize yields were found to decline significantly with an increase in erosion severity. The decline in yield was quantified as 131 kg/ha for every centimetre of soil depth lost under normal fertilisation and 158 kg/ha under double fertilisation. The study concluded that soil erosion, particularly when more than 10 cm of topsoil has been lost, leads to a decline in soil productivity. Fertilisers were found to be ineffective in masking the effects of erosion. Therefore, soil conservation is crucial to preventing the costly and ineffective redressing of erosion effects using fertilisers.

1.3. Goals of the Study

Parallel to the occurrence of extreme weather events, the demand to project the risk of yield failure has increased all over the world [17]. It is challenging to extrapolate historical data with statistical models due to the complex interactions between the changing environmental conditions and crop demands [18]. For the consideration of such interactions, crop models are needed that dynamically simulate crop resources and yield formation in response to environmental and management factors in future climate scenarios [19]. Our study is the first to analyse the yield losses of the two major field crops grown in Hungary that occurred during the last hundred years. The goals of our study were to determine how often yield losses of winter wheat and maize at 15% and 30% occur, what the probability is, whether the probability has changed in recent decades and whether the probability depends on the plant species involved. The yield loss data do not include economic analysis, as in the case of a long time series of more than 100 years, the economic conditions change continuously, so the common denominator that can be evaluated in the years is the yields of the crops. We were wondering whether it is possible to predict yield failure or if it is a completely random process. We sought the answer to this question using the method of Wald and Wolfowitz. The basic assumption of the model is that the elements of the time series follow each other completely randomly. If this could be disproved, there is a chance of forecasting the future based on the data of the past.

2. Materials and Methods

2.1. Materials and Time Frame of the Study

We examined the yield losses of two field crops with different life cycles, the autumn-sown wheat and the spring-sown maize produced in Hungary from the 1920s to the present day. In Hungary, the vegetation period of wheat takes an average of 280 days, while for maize it lasts 150 days. These two crops generate their yields under different meteorological conditions. Winter wheat avoids the summer drought, while maize is fertile and produces its crop in that season. For both crops, we examined two periods in terms of the level of development of agrotechnics. Within each period, we considered the agrotechnical level to be nearly homogeneous. Rudimentary agrotechnics, the cultivation of varieties in the case of maize and low levels of nutrient supply characterise the first period (1926–1960). The second period (1985–2023) is the era of the application of modern technology, hybrids instead of varieties and high-quality plant nutrition.

2.2. Data Source and Processing

The national yield data originate from the Hungarian Central Statistical Office and cover the period 1921–2023. According to the European guidelines [20], a production (yield) loss is identified when the loss is more than 30% of the average production. Several studies proved that crop failure set at a lower threshold may be more appropriate for risk analysis at aggregate scales [21–24]. Therefore, in our study, the degree of yield loss was fixed at 15% and 30%; we considered yield loss in a year in which the yield was at least 15% or 30% lower than the average yield of the previous 5 years. During the five-year moving average, the smallest and largest values of the period were not taken into account when determining the average. For each year, we subtracted the previous five-year moving average from the given yield average and divided the difference by the five-year moving average. The result was expressed as a percentage. The same approach and yield loss levels were used by Webber et al. [25]; they counted a yield failure when the simulated yield was lower than a threshold relative to the Olympic average yield (used by the insurance industry and governments to define yield failures) of the previous five years.

The time series was divided into two parts as the development of the socialistic, large-scale industrial technology involving intensive fertilisation began in the 1960s and resulted in an exponential increase in yields. Therefore, the period between 1960 and 1980 was omitted from the analyses, because the increasing trend does not allow a correct estimation of yield losses. Hence, we analysed two periods, the years 1921–1960 and 1980–2023. Since we lost the data of the first five years for both periods due to the five-year moving average, we were able to examine the yield loss starting from 1926 and 1985. The number of years included in the analysis was thus 35 and 39 years, respectively. The annual probability (p), which means the relative frequency of yield failures, was calculated by dividing the number of years with yield losses of 15% and 30% by the number of years of the relevant investigated period (35 and 39).

2.3. Statistical Method

The Wald–Wolfowitz runs test [26] was used to determine the randomness of yield failures. The following values were determined: number of runs (runs); number of years with yield losses (n1); number of years without yield losses = ‘normal’ years (n2); number of years of the investigated period (n); and probability of the null hypotheses (p-value) demonstrating that each element in the sequence is independently drawn from the same distribution. The data were transformed into a dichotomous vector accordingly as each value was above or below a given threshold. Values equal to the level were removed from the sample. The default threshold value used in applications is the sample median which gives us the special case of this test where n1 = n2, i.e., the runs test above and below the median. The possible alternative values were "two-sided", "left-sided" and "right-sided", which define the alternative hypotheses. By using the alternative "left-sided" value, the null of randomness was tested against the trend. By using the alternative "right-sided" value, the null hypothesis of randomness was tested against a first-order negative serial correlation. Since the number of yield failures is much smaller than the number of normal years, the median cannot be used in our case. For reliable analysis, the threshold value was fixed at 0.5. The years with yield failure were marked as 1 and the normal years as 0. The setting modified in this way gives reliable results.

3. Results

3.1. Yield Failures of Winter Wheat

Winter wheat is produced in the largest area in Hungary, and this crop has covered 0.7–1.7 million hectares of land in the last hundred years. Figure 1 shows the national average winter wheat yields in Hungary for the period of 1921–2023.

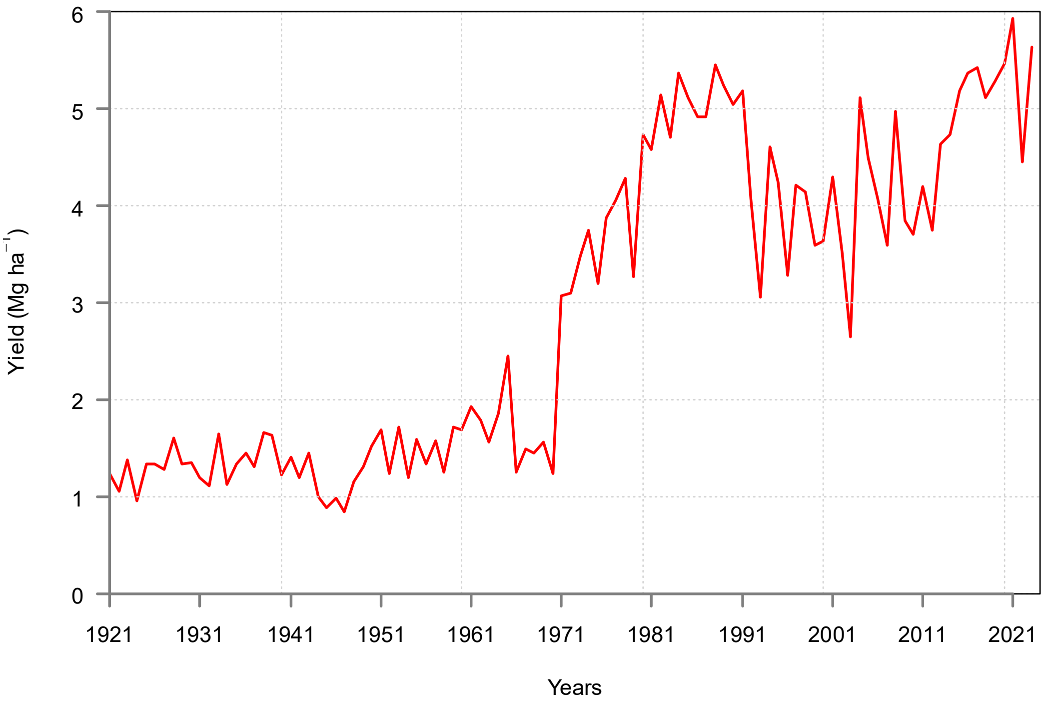

Figure 1. Average winter wheat yields in Hungary in the period of 1921–2023.

A significant positive break can be seen in the time series data (Figure 1), which was caused by the development of agricultural technology, not including irrigation as winter wheat is grown under rain-fed conditions in Hungary.

Figure 2 shows the percentage yield fluctuations of the first investigated period.

Between 1926 and 1960, yield fluctuations in the positive range (above 0) were greater than in the negative range characterizing yield losses of winter wheat.

Based on the results of the Wald–Wolfowitz runs test for at least a 15% yield loss, the series of losses can be considered random (Figure 3).

Yield losses include neither trends nor negative autocorrelation. Over the course of 35 years, yield losses of more than 15% occurred a total of nine times. On average, we can expect yield losses of this magnitude once every 3.9 years, so roughly every 4 years.

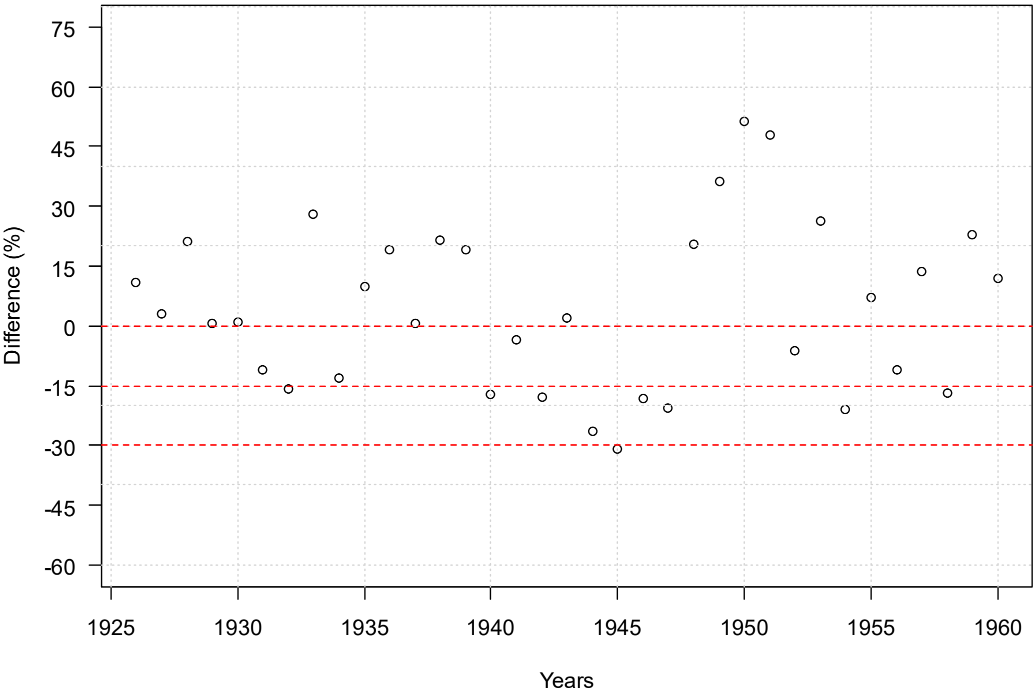

Figure 2. Yield fluctuations of winter wheat in Hungary in the period of 1926–1960. Red dashed lines indicate the values of no yield loss (0), at least a 15% yield loss (−15) and at least a 30% yield loss (−30).

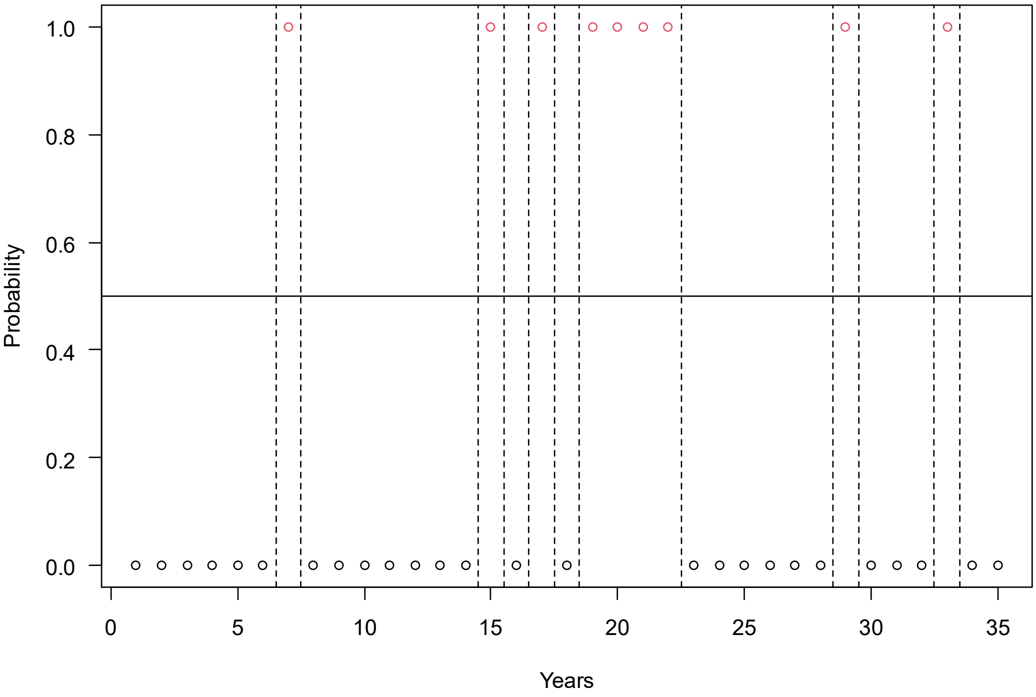

Figure 3. The number of years with yield losses of winter wheat below and above 15% in Hungary in the period of 1926–1960. Years with yield failure are marked with a probability of 1 (red circles) and the normal years with a probability of 0 (black circles). Legends: runs = 13; n1 = 9, n2 = 26, n = 35; *p*-value = 0.5341.

The results of the Wald–Wolfowitz runs test carried out for at least a 30% yield loss of winter wheat are shown in Figure 4.

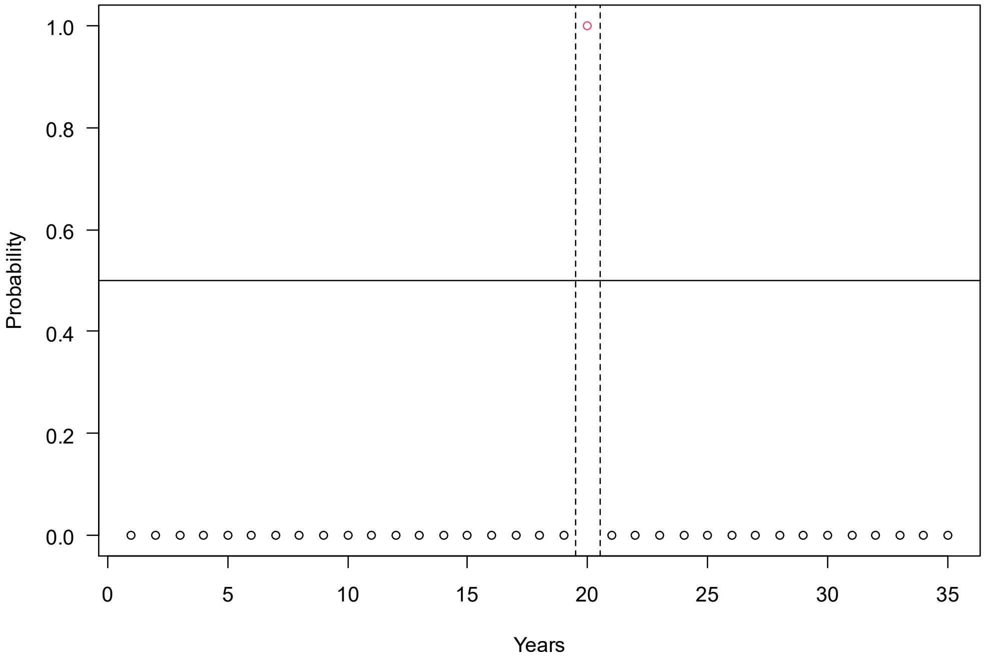

Figure 4. The number of years with yield losses of winter wheat below and above 30% in Hungary in the period of 1926–1960. Years with yield failure are marked with a probability of 1 (red circles) and the normal years with a probability of 0 (black circles). Legends: runs = 3; n1 = 1, n2 = 34, n = 35; *p*-value = 0.8055.

The 30% yield loss results were similar to the 15% ones; the series of yield losses can be considered random, and they show neither trends nor negative autocorrelation. During the 35 years, there was a total of one yield loss of more than 30%.

We also examined the yield fluctuations of winter wheat for the second period (between 1985 and 2023), and the data are shown in Figure 5.

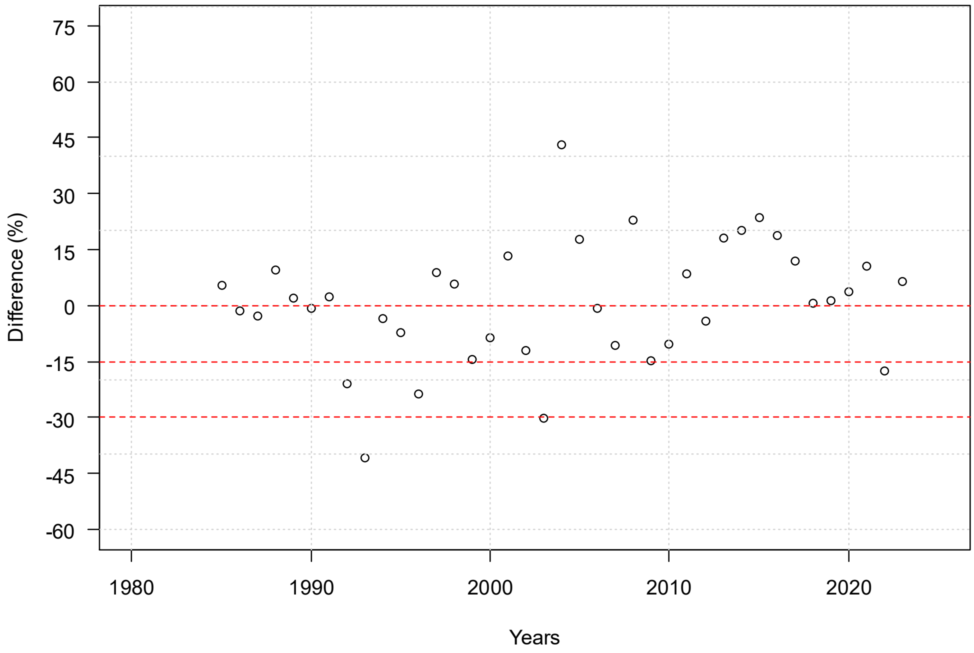

Figure 5. Yield fluctuations of winter wheat in Hungary in the period of 1985–2023. Red dashed lines indicate the values of no yield loss (0), at least a 15% yield loss (−15) and at least a 30% yield loss (−30).

Between 1985 and 2023, yield fluctuations of winter wheat showed a similar rate between yields above and below the median.

Similarly to the results of the Wald–Wolfowitz runs test determined for the first period, the series of losses of at least 15% in the second period can be considered random, and they do not include either trends or negative autocorrelation (Figure 6). During the investigated 39 years, a 15% yield loss occurred a total of five times. On average, we can expect yield losses of this magnitude once every 7.8 years, so roughly every 8 years. In this period, the frequency of yield failure was halved compared to the period of 1926–1960.

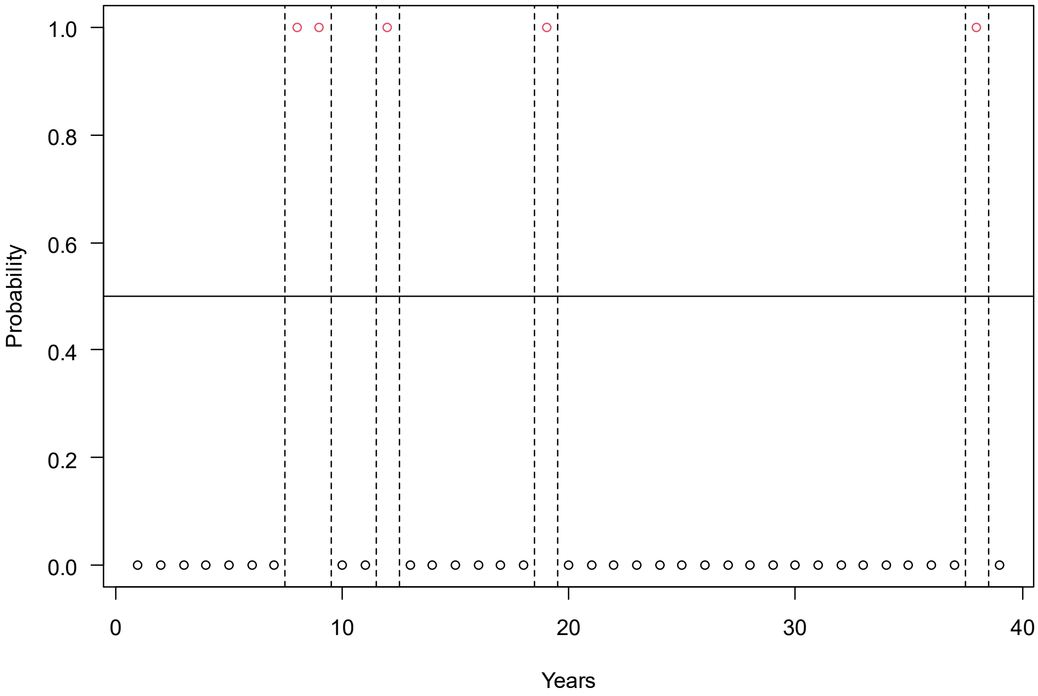

Figure 6. The number of years with yield losses of winter wheat below and above 15% in Hungary in the period of 1985–2023. Years with yield failure are marked with a probability of 1 (red circles) and the normal years with a probability of 0 (black circles). Legends: runs = 9; n1 = 5, n2 = 34, n = 39; *p*-value = 0.5895.

Figure 6 shows the results of the Wald–Wolfowitz runs test determined for the winter wheat yield losses of at least 15% in the second period.

Similarly to the results of the Wald–Wolfowitz runs test determined for the first period, the series of losses of at least 15% in the second period can be considered random, and they do not include either trends or negative autocorrelation. During the investigated 39 years, a 15% yield loss occurred a total of five times. On average, we can expect yield losses of this magnitude once every 7.8 years, so roughly every 8 years. In this period, the frequency of yield failure was halved compared to the period of 1926–1960.

The results of the Wald–Wolfowitz runs test carried out for at least a 30% yield loss were similar to the 30% yield loss results (Figure 7).

This series of yield losses can be considered random, and they show neither trends nor negative autocorrelation. During the 39 years, yield losses of at least 30% occurred a total of two times, on average once every 19.5 years. In this period, the frequency of yield failure almost doubled compared to the 1926–1960 period, which suggests that technological development could not fully compensate for the negative effects of extreme weather.

We can conclude that modern cultivation technology was able to reduce only the frequency of the slight (15%) yield losses caused by unfavourable weather. However, the frequency of the large yield losses (30%) caused by climate change increased.

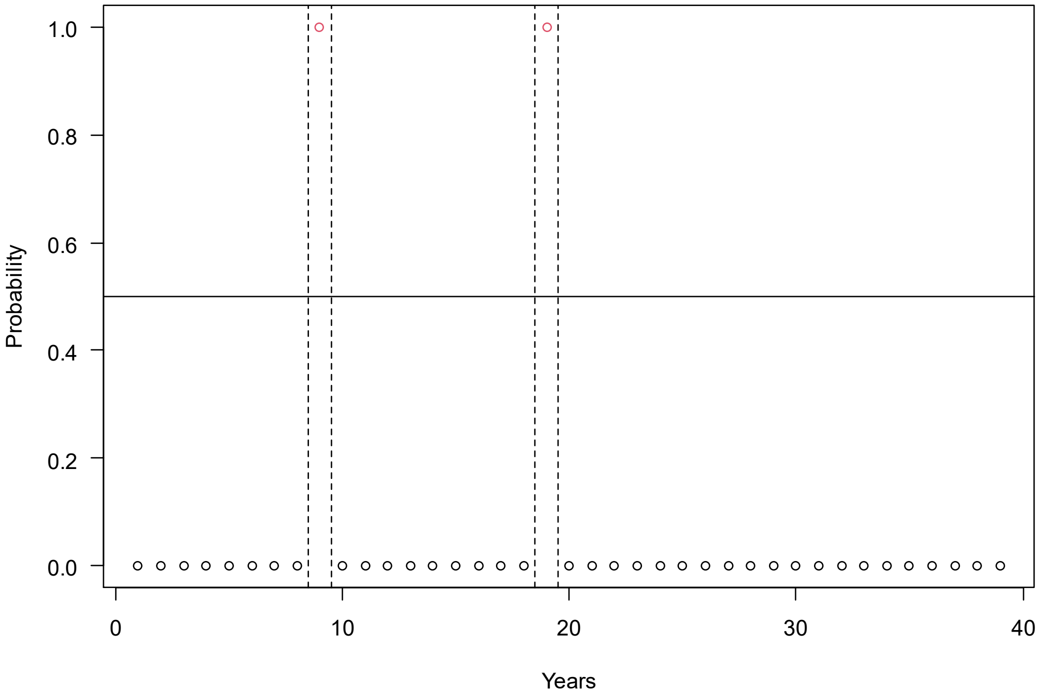

Figure 7. The number of years with yield losses of winter wheat below and above 30% in Hungary in the period of 1985–2023. Years with yield failure are marked with a probability of 1 (red circles) and the normal years with a probability of 0 (black circles). Legends: runs = 5; n1 = 2, n2 = 37, n = 39; *p*-value = 0.6978.

3.2. Yield Failures of Maize

We also performed the analyses on maize plants. The area in Hungary planted with maize has not changed drastically in the past hundred years, averaging around 1.1 million hectares. Figure 8 shows the yield averages of maize in Hungary.

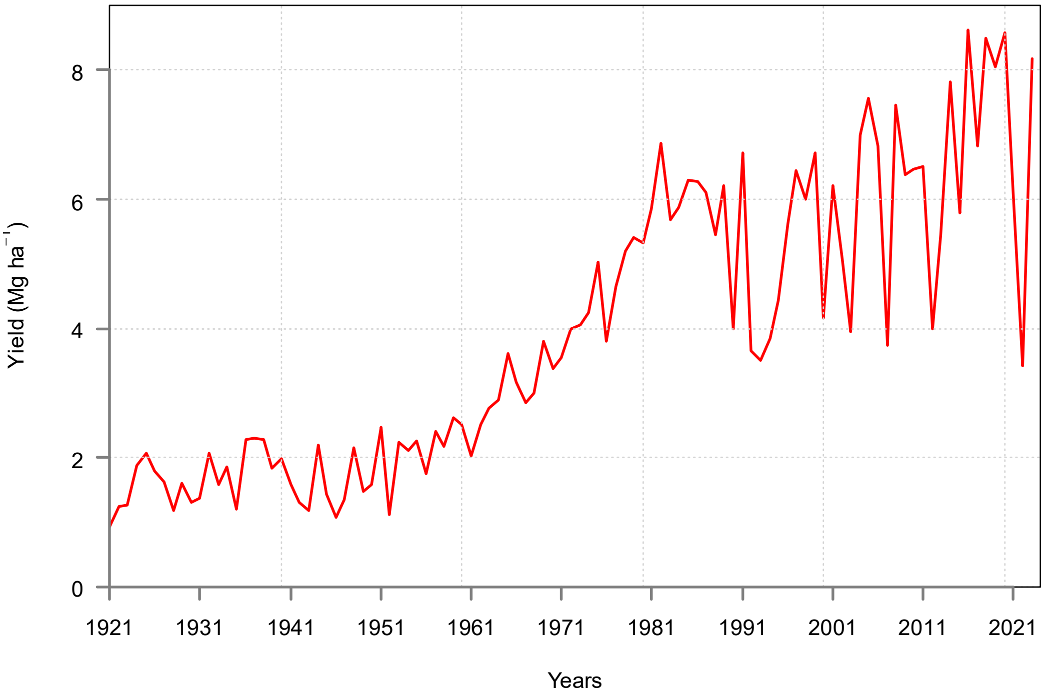

Figure 8. Average maize yields in Hungary in the period of 1921–2023.

In more than a hundred years, values have quadrupled. Dynamic growth can be seen starting from the 1960s, which can be attributed to the development of agricultural technology, although this does not include irrigation, as approximately 1% of the total maize-producing area is irrigated in Hungary, and this rate did not change significantly over the last century. We also omitted the period between 1960 and 1980 from further analyses.

Figure 9 shows the percentage yield fluctuations of maize for the first investigated period.

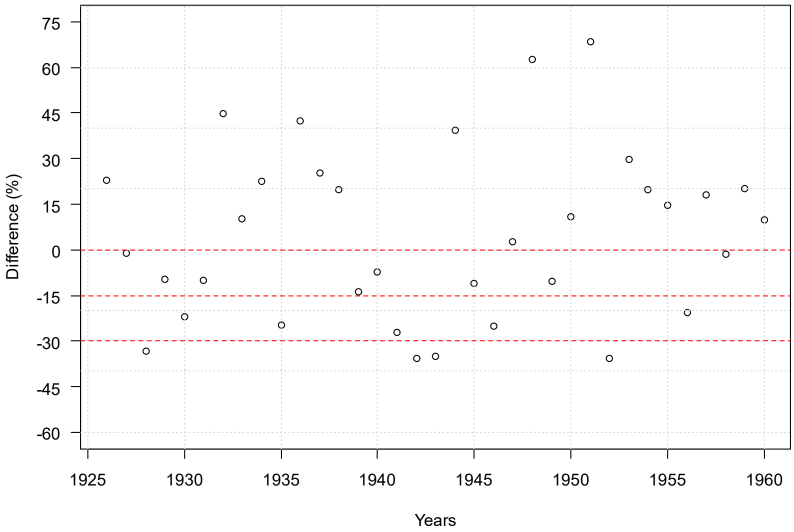

Figure 9. Yield fluctuations of maize in Hungary in the period of 1926–1960. Red dashed lines indicate the values of no yield loss (0), at least a 15% yield loss (−15) and at least a 30% yield loss (−30).

Between 1926 and 1960, yield fluctuations in the positive range (above 0) were greater than in the negative range, characterizing the yield losses of maize, which is similar to that of winter wheat.

The results of the Wald–Wolfowitz runs test carried out for at least a 15% yield loss of maize were similar to the yield loss results of winter wheat (Figure 10).

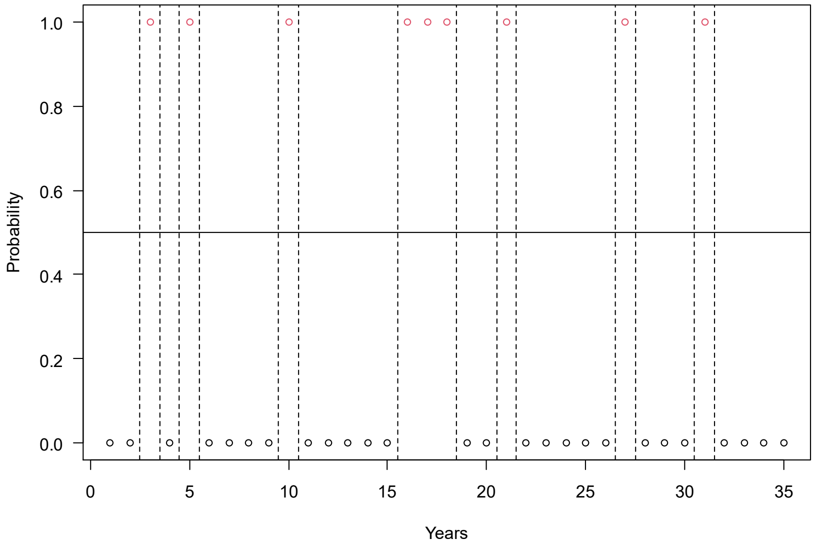

Figure 10. The number of years with yield losses of maize below and above 15% in Hungary in the period of 1926–1960. Years with yield failure are marked with a probability of 1 (red circles) and the normal years with a probability of 0 (black circles). Legends: runs = 15; n1 = 9, n2 = 26, n = 35; *p*-value = 0.7757.

The series of yield losses of maize in the second investigated period can be considered random and they show neither trends nor negative autocorrelation. During the 35 years, there were a total of nine yield losses of more than 15%. On average, we can expect yield losses of this magnitude once every 3.9 years, so roughly every 4 years.

Based on the results of the Wald–Wolfowitz runs test for at least 30% yield loss of maize, the series of losses can be considered random (Figure 11).

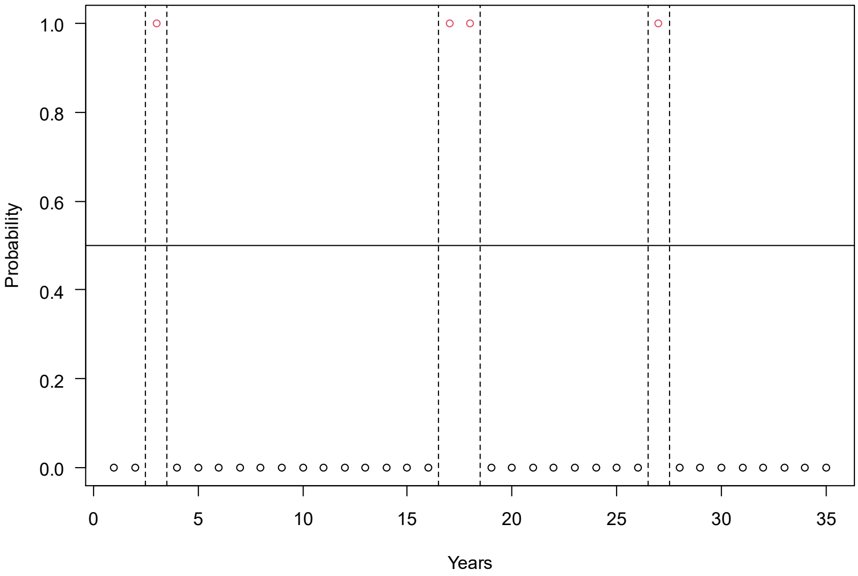

Figure 11. The number of years with yield losses of maize below and above 30% in Hungary in the period of 1926–1960. Years with yield failure are marked with a probability of 1 (red circles) and the normal years with a probability of 0 (black circles). Legends: runs = 7; n1 = 4, n2 = 31, n = 35; *p*-value = 0.335.

This series of yield losses includes neither trends nor negative autocorrelation. Over the course of 35 years, yield losses of more than 30% occurred a total of four times. On average, we can expect yield losses of this magnitude once every nine years.

The percentage yield fluctuations of maize in the second period are shown in Figure 12.

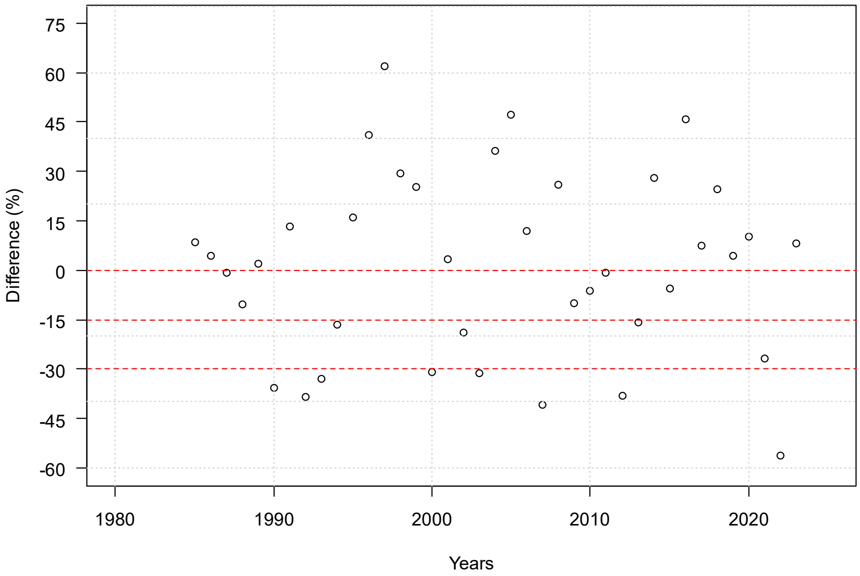

Figure 12. Yield fluctuations of maize in Hungary in the period of 1985–2023. Red dashed lines indicate the values of no yield loss (0), at least a 15% yield loss (−15) and at least a 30% yield loss (−30).

Between 1985 and 2023, the positive and negative deviations in the yield of maize were similar to the ones in the first investigated period.

The results of the Wald–Wolfowitz runs test carried out for at least a 15% yield loss of maize in the second period can be considered random, and they show neither trends nor negative autocorrelation (Figure 13).

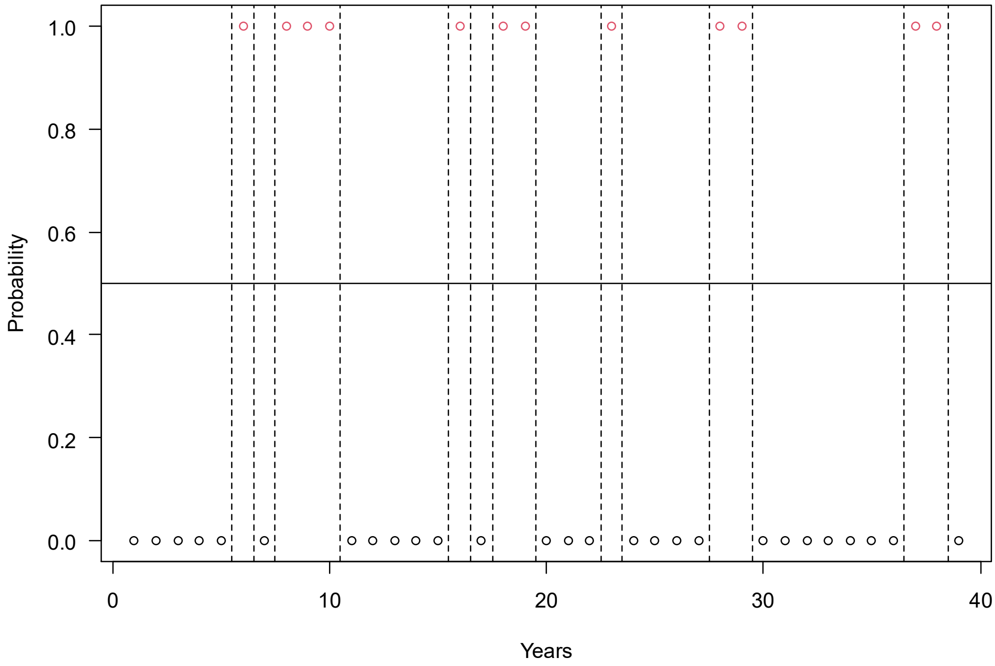

Figure 13. The number of years with yield losses of maize below and above 15% in Hungary in the period of 1985–2023. Years with yield failure are marked with a probability of 1 (red circles) and the normal years with a probability of 0 (black circles). Legends: runs = 15; n1 = 12, n2 = 27, n = 39; *p*-value = 0.3169.

During the 35 years, there were a total of 12 yield losses of more than 15%, on average once every 3.25 years, so roughly every 3 years. In the second investigated period, the frequency of yield failure increased compared to the period of 1926–1960.

The results of the Wald–Wolfowitz runs test carried out for at least a 30% yield loss of maize in the second period can be considered random, and they show neither trends nor negative autocorrelation (Figure 14).

During the second period, there were a total of eight yield losses of more than 30%, on average once every 4.9 years, so roughly every 5 years. In this period, the frequency of yield failure almost doubled compared to the 1926–1960 period, which suggests that technological development could not compensate for the negative effects of extreme weather conditions associated with climate change. This statement strengthens the findings published in our previous study regarding the unfavourable effects of climate change on maize production [1].

Table 1 shows the quantified conclusions drawn from our investigations. There is a significant difference in yield loss between the autumn- and spring-sown crops. Yield loss occurs less frequently in winter wheat than in maize.

For winter wheat, the probability of a moderate yield loss (15%) decreased (from 0.26 to 0.13), while in the case of maize, this value increased (from 0.26 to 0.31). Larger fluctuations (30%) almost doubled for both crops (from 0.03 to 0.05 and from 0.11 to 0.21, respectively).

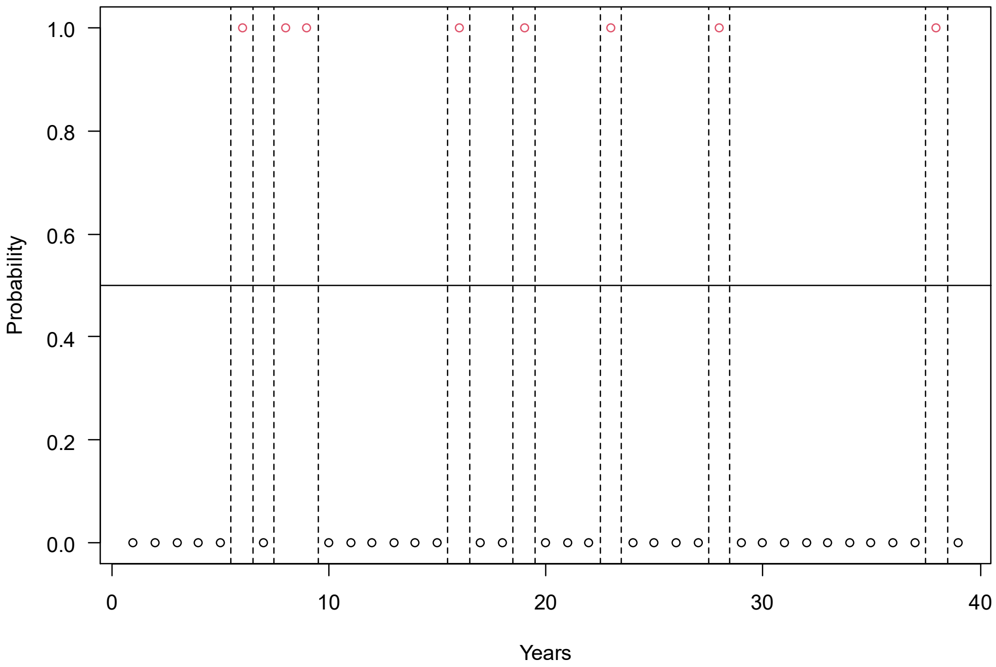

Figure 14. The number of years with yield losses of maize below and above 30% in Hungary in the period of 1985–2023. Years with yield failure are marked with a probability of 1 (red circles) and the normal years with a probability of 0 (black circles). Legends: runs = 15; n1 = 8, n2 = 31, n = 39; *p*-value = 0.5174.

Table 1. Yield losses of winter wheat and maize in Hungary for the two investigated periods.

Crop	Period	Loss at Least	Annual Probability (p)
Winter wheat	1926–1960	15%	0.26
		30%	0.03
	1985–2023	15%	0.13
		30%	0.05
Maize	1926–1960	15%	0.26
		30%	0.11
	1985–2023	15%	0.31
		30%	0.21

4. Discussion

Assessing vulnerability is challenging due to data scarcity, but expert opinions and official documents helped complete the assessment [27]. In their study, Kalogiannidis et al. [28] highlighted that vulnerabilities in agriculture, such as climate change, negatively affect the sustainability of the rural economy and act as an obstacle to rural economic development. Vulnerability in agriculture is further exacerbated by a lack of knowledge about weather patterns and financial options for purchasing new equipment. Some farmers cannot adapt to the various effects of climate change, which affects agricultural yields and the level of rural economic transformation. The lack of improved seeds and limited access to water for irrigation also contribute to the vulnerability of rural farmers.

Crop failure can be caused by a combination of climate variability and land–atmosphere feedback. Extreme weather conditions, particularly dry and hot years, are often associated with the largest agricultural failures [29]. Goulart et al. [30] studied both individual weather features and compound events, where multiple weather variables interact and lead to crop failures. The multiple and combined meteorological drivers of crop failure include a range of weather conditions that can adversely affect crop yields. These conditions can be complex and non-linear, often involving the interaction of various weather elements, but the most common ones are temperature extremes, precipitation deficits and high evapotranspiration rates. In addition to climate modes, crop yields are also affected by other factors such as weather events, pests, diseases and management decisions [31]. Li et al. [32] also highlighted the importance of considering both local and upwind land-atmosphere feedback in the context of crop failure and agricultural productivity.

In Hungary, according to our results, the frequency of major crop losses increased even more strongly, practically doubling the probability of extreme crop losses. We established that in Hungary, the risk, and therefore the vulnerability, of growing winter wheat and maize has become higher compared to the first half of the last century. According to our findings, for winter wheat, this risk is much lower than for maize. Stella et al. [33] also presented a methodology using relative distribution to assess the changing risk of yield failure in rain-fed wheat and grain maize across Europe in various climate change scenarios, revealing shorter return periods for maize yield failures and less frequent wheat yield failures due to shifts in yield distributions influenced by heat and drought stress. The results indicate that in various climate change scenarios, maize generally exhibited shorter return periods of yield failures. This was associated with a shift in the yield distribution towards lower values and changes in the shape of the distribution that further reduced the frequency of high yields, particularly in areas with high baseline yields and long return periods of failure. Conversely, wheat yield failures were projected to become less frequent in future scenarios, which was linked to a shift in the distribution towards higher values and a change in shape, increasing the frequency of extreme yields at both ends of the distribution. The ensemble estimates of return periods for yield failures showed consistent responses across individual climate models, although individual crop models exhibited more uncertainty and less agreement on the direction of change in return periods among group members.

According to our results, the probability and frequency of moderate yield loss (15%) of winter wheat decreased. We assume that up-to-date winter wheat cultivation technology can reduce such small fluctuations; thus, the effect of climate change is not dominant. In many winter wheat-growing areas, weather extremes like hot, dry and windy conditions have become more common. Zhao et al. [34] assessed how bad weather with heat, dryness and wind is causing less winter wheat to grow. They found that tough weather conditions are occurring more often and are a significant reason why wheat crops are not coping well. When these bad weather conditions occur frequently during the time when wheat is filling out with grain, for every 10 h of these bad weather conditions, wheat yields can drop by 4%, resulting in a decrease in wheat yields of up to 0.09 tons per hectare each decade. Iwańska and Stępień [35] determined the factors causing depression in winter wheat crops. Climatic water balance, precipitation, temperature and hydrothermal coefficients were all related to wheat yield. The interaction of rising air temperature and precipitation, leading to increased evapotranspiration, negatively affects yields. Drought significantly reduces winter wheat yields, with the strongest effects observed during the heading and grain-filling stages. Nevertheless, it was established that in Poland, soil properties had a greater impact on winter wheat yield than weather conditions. Lower yields are more associated with soils of lower suitability and in conditions of longer or more frequent drought periods, especially near the heading stage.

In Hungary, the frequency and probability of moderate and extreme yield losses of maize increased. We believe that even today's technology cannot reduce low volatility that and climate change is the determining factor in this respect. In their study, Huzsvai et al. [1] concluded that mean annual temperatures increased by 2 °C in Hungary in the last 50 years. At the same time, the amount of annual precipitation did not change, leading to increasing potential evapotranspiration and resulting in a gradually increasing deficit in the climatic water balance. They established that 60–80% of the fluctuations in maize yield can be explained by these climatic trends. Ribeiro et al. [29] demonstrated that the effects of compound dry and hot extremes on crop failure are significant, as these conditions tend to exacerbate the risk of crop loss. When drought and heat stress occur together, they can lead to a higher likelihood of crop damage compared to when these stressors occur individually. Jin et al. [36] established that heat and drought stresses are expected to increasingly reduce crop yields. Their study suggests that current maize models may not adequately capture the impact of climate extremes, specifically heat and drought, on maize photosynthesis and yield. In their survey, Obour et al. [37] studied the primary causes of maize production failure in Ghana. They revealed that factors such as poor soil quality, inadequate farm inputs and under-resourced mechanisation had a lesser impact on maize production failure than drought conditions that are unfavourable for maize growth.

5. Conclusions

Based on the analysis of the data by the Wald–Wolfowitz test for the period 1985–2023, the yield failures of both maize and winter wheat occurred completely by chance, and only their probability can be given. In Hungary, the risk of extreme winter wheat yield failure is expected to be lower compared to that of maize in the future: failure by 15% and 30% can be expected approximately every 8th and 19th year for winter wheat and 3rd and 5th year for maize, respectively. During the examined century, the weather underwent significant changes, not only in Hungary. Especially after the turn of the millennium, the impact of climate change intensified, which has been manifested mainly in the rise in temperature and the increase in the frequency of extreme weather situations, which we consider the main reason for significant fluctuations in crop yield. Safe, sustainable production in agriculture can be characterised by yield fluctuations. The smaller the yield fluctuation, the lower the production risk and the more a sustainable food supply can be ensured. The examination of historical yield data can help to determine the extent of crop loss to be expected in the long term, how to prepare for uninterrupted demand satisfaction and what amount of safety reserves should be built up to maintain sustainable winter wheat and maize production. Knowing the chance of crop failure, farmers can reconsider whether they should follow current crop rotations or involve plant species that represent a lower risk of failure and increase biodiversity at the same time. Another option—if farmers stick to the production of winter wheat and maize—is the selection and growing of up-to-date, region-specific varieties/hybrids (landraces) that were bred to tolerate weather extremes, thus providing higher levels of safety in terms of yield and the sustainability of agriculture in the mid-term in our changing climate.

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