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Adaptive Agronomic Strategies for Enhancing Cereal Yield Resilience Under Changing Climate in Poland

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Abstract: Climate-driven changes have raised concerns about their long-term impacts on the yield resilience of cereal crops. This issue is critical in Poland as it affects major cereal crops like winter triticale, spring wheat, winter wheat, spring barley, and winter barley. This study investigates how soil nutrient profiles, fertilization practices, and crop management conditions influence the yield resilience of key cereal crops over a thirteen-year period (2009–2022) in the context of changing climate expressed as varying Climatic Water Balance. Data from 47 locations provided by the Research Centre for Cultivar Testing were analyzed to assess the combined effects of agronomic practices and climate-related water availability on crop performance. Yield outcomes under moderate and enhanced management practices were contrasted using Classification and Regression Trees to evaluate the relationships between yield variations and agronomic factors, including soil pH, nitrogen, phosphorus, potassium fertilization, and levels of phosphorus, potassium, and magnesium in the soil. The study found a downward trend in Climatic Water Balance, highlighting the increasing influence of climate change on regional water resources. Crop yields responded positively to increased agricultural inputs, especially nitrogen. Optimal soil pH and medium phosphorus levels were identified as crucial for maximizing yield. The findings underscore the importance of tailored nutrient management and adaptive strategies to mitigate the adverse effects of climate variability on cereal production. The results provide insights for field crop research and practical approaches to sustain cereal production in changing climatic conditions.

Keywords: yield resilience; climatic water balance; agronomic practices; classification and regression trees (CARTs)

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1. Introduction

Recent decades have witnessed significant shifts in climate patterns, influencing agricultural productivity worldwide. These changes are particularly impactful for cereal crops, which are fundamental to global food security [1]. Rising temperatures negatively impact the growth and yield of cereals. Higher temperatures accelerate crop maturation, reduce grain filling periods, and increase water stress. For example, in Afghanistan, a 1 °C increase in temperature is projected to decrease wheat yields by 0.3 t ha^{-1} and barley yields by 0.2 t ha^{-1} [2]. The resilience of cereal yields to climatic variability has thus become a pressing concern in agricultural research and policy [3]. Climate change is characterized by increasing temperatures, altered precipitation patterns, and more frequent extreme weather events. Shenoy et al. [4] discuss how extreme temperature events in the US are becoming more frequent, though rainfall changes are seasonal and varied. Garderen et al. [5] highlight using dynamic and event storylines to quantify climate change's impact on extreme weather, demonstrating its application to southern hemisphere precipitation and the Russian heatwave in 2010. Significant warming and reduced precipitation under future climate scenarios are predicted in the Kashmir Himalaya, leading to more frequent warm temperature extremes [6]. These changes significantly affect agriculture, affecting crop growth, development, and yields [7]. Cereal crops, which include staple foods such as wheat, barley, and triticale, are particularly vulnerable to these climatic shifts. Understanding how changing climatic conditions influence agricultural productivity is key to developing strategies to adapt to adverse effects and ensure food security [8,9].

The Climatic Water Balance (CWB) is vital in agricultural planning and crop management [10]. It quantifies the difference between the water supplied to an area through precipitation and the water lost through processes like evapotranspiration. Positive CWB values indicated periods of sufficient moisture, associated with higher yields in regions with optimal rainfall. Negative CWB values highlighted deficit conditions, indicating periods where evapotranspiration exceeded precipitation, leading to soil moisture depletion and reduced yields. While CWB does not directly measure crops' water consumption, it indicates how much water is available in the soil for plant uptake. CWB is critical for assessing water availability to crops over time, influencing decisions related to irrigation, planting schedules, and crop selection [11]. As climate change progresses, the reliability of CWB as an indicator of water availability becomes increasingly important for sustainable farming practices.

Soil health, defined by the availability and balance of essential nutrients, is important in agricultural productivity. Key nutrients such as nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg) are fundamental for optimal crop development and yield. N is crucial for vegetative growth, P for energy transfer and root development, K for overall plant health and stress resistance, and Mg is a central component of the chlorophyll molecule. It can mitigate stress caused by high temperatures and other environmental factors [1,12–14].

Poland provides a significant context for this research due to its diverse agricultural zones and substantial cereal production [15]. The country's varied soil types, climatic conditions, and agricultural practices offer a comprehensive landscape for studying the interactions between climatic factors, soil nutrients, and crop yields [16–18]. Cereal crops are economically significant in Poland, contributing to domestic food and export markets. In 2023, Poland's cereal production reached approximately 35 million metric tons. This production level underscores Poland's significant role in the European Union's agricultural landscape, contributing about 13% of the EU's total cereal production [19,20]. In 2023, land under cereal production for Poland was 7.1 million hectares, of which wheat was over 2.4 million hectares, rye was about 0.7 million hectares, barley was over 0.6 million hectares, and triticale was about 1.2 million hectares. Winter triticale occupies a significant portion of Poland's agricultural land due to its adaptability and high yield potential. Spring wheat is extensively cultivated across Poland, given its importance for food production. Winter wheat is one of the most important cereal crops in Poland. Despite cold and dry spring conditions, spring barley maintains considerable production levels. Winter barley is critical for early harvests and supports double cropping systems in some regions. Wheat is one of the major cereal crops grown in Poland, and it is essential for the domestic food supply. It is used for bread, pasta, and other food products. Poland is among the top wheat producers in the European Union. Barley is primarily used for animal feed and brewing. It is also an important crop for the food industry, contributing to the production of various foodstuffs. Triticale, a hybrid of wheat and rye, is valued for its high yield and disease resistance. It is used for both human consumption and animal feed.

This research aimed to analyze the effects of CWB, fertilizers, and soil nutrients on the yields of five different cereal crops under varying management practices over 13 years. The study employs Classification and Regression Tree (CART) [21] analysis to evaluate the relationships between yield variations and agronomic factors such as soil pH, NPK fertilization, and P, K, and Mg levels in soil. By contrasting yield outcomes under moderate and enhanced management practices, the study aims to identify strategies that enhance crop resilience to climatic variability. Several studies have been conducted in Poland and similar regions that address the impact of climate, soil nutrients, and agronomic practices on cereal crop yields. Cereal crops in the UK are increasingly vulnerable to compound climate events, which pose a greater risk to yield stability than individual climate stressors [3]. The research highlights that the resilience of crop yields varies significantly depending on crop type, location, and the management practices employed. In the Mediterranean climate, crop yields are particularly sensitive to water stress during critical growth stages [22]. Adaptation strategies, like adjusting sowing dates and using more drought-tolerant cultivars, are shown to improve resilience. The study by Hlavinka et al. [23] on winter wheat and barley yields in the Czech Republic focuses on crop rotation, optimized fertilization, and adjusted irrigation practices as potential adaptation strategies to climate change. Northern and Central Europe may optimize nutrient management and reduce soil compaction to cope with seasonally increased waterlogging [24].

The focus of this study lies in its comprehensive, integrative approach to understanding how CWB, soil nutrients, and agronomic management practices collectively influence the yield resilience of key cereal crops in Poland over a 13-year period. Using data from 47 locations across Poland, this study provides a long-term perspective on the impacts of climate variability on cereal yields. A single representative cultivar was chosen for each of the five cereal species studied—winter triticale, spring wheat, spring wheat, spring barley, and winter barley. This approach ensures that the observed yield responses are due to variations in climate, soil, and management practices rather than genetic differences between cultivars. This research integrates both aspects, unlike many previous studies focusing solely on climatic factors or agronomic practices. The application of CARTs to analyze the interactions between climate, soil nutrients, and management practices is relatively novel in the context of cereal yield studies. The method's ability to identify non-linear relationships and critical thresholds is crucial for developing practical, adaptive strategies to optimize cereal production under changing climatic conditions. CARTs have been used to identify the key agronomic factors influencing Poland's winter wheat and triticale yields [16,18,25,26] or to predict the yield of spring wheat in Western Siberia [26]. These studies demonstrate the applicability of CARTs in agricultural research, particularly in understanding how various factors influence cereal yields.

2. Materials and Methods

2.1. Experimental Locations, Species, and Genotypes

Experiments were conducted in 47 locations across Poland between 2009 and 2022 (Figure 1). The following species were studied: winter and spring wheat, winter and spring barley, and winter triticale. Each species was represented by one cultivar: spring barley—Radek, spring wheat—Mandaryna, winter barley—Zenek, winter triticale—Rotondo, and winter wheat—Linus. Those cultivars were selected because they were studied for the longest period. Yield data were collected from the Research Centre for Cultivar Testing (COBORU, Słupia Wielka, Poland) [27], which assesses yield and other traits of newly released cultivars through multi-environment trials. This study utilized data from trials conducted under two different levels of input intensity, a_1 and a_2. The moderate input level (a_1) included moderate mineral fertilization with nitrogen, phosphorus, and potassium tailored to each location, herbicides and insecticides, and seed treatment. The high input level (a_2) included additionally 40 kg ha^{-1} year^{-1} of nitrogen, foliar fertilization, fungicides, and growth regulators, which were not used under moderate input conditions. Each experiment's crop planting dates, plant density, and NPK fertilizer rates followed common regional practices. Tillage operations and weed and insect management were decided independently in each location. Based on data provided by COBORU, the sowing and harvesting dates for the studied cereals vary across different regions in Poland due to differences in climatic conditions and local agricultural practices. The approximate dates for sowing of winter triticale were from late September to early October and harvesting from late July to early August. Winter wheat was typically sown between mid-September and early October and harvested from late July to mid-August. Winter barley was usually sown in early to mid-September and harvested in early to mid-July, making it one of the earliest cereal crops to be harvested. In northern Poland, the sowing may be slightly delayed due to cooler autumn temperatures and the higher risk of early frost, while in southern regions, it can occur earlier, where autumn conditions are milder. Spring wheat was generally sown from the end of March to early April, depending on soil temperature and weather conditions, and harvest took place from late July to early August. Spring barley was sown from late March to early April once the soil had sufficiently warmed and typically harvested from late July to early August. In western Poland, where spring arrives earlier, sowing can start in late March, while in cooler eastern regions, it may be delayed into early April. The experimental design in each location was a randomized complete block design with three replications. The plot size was 15 m^2.

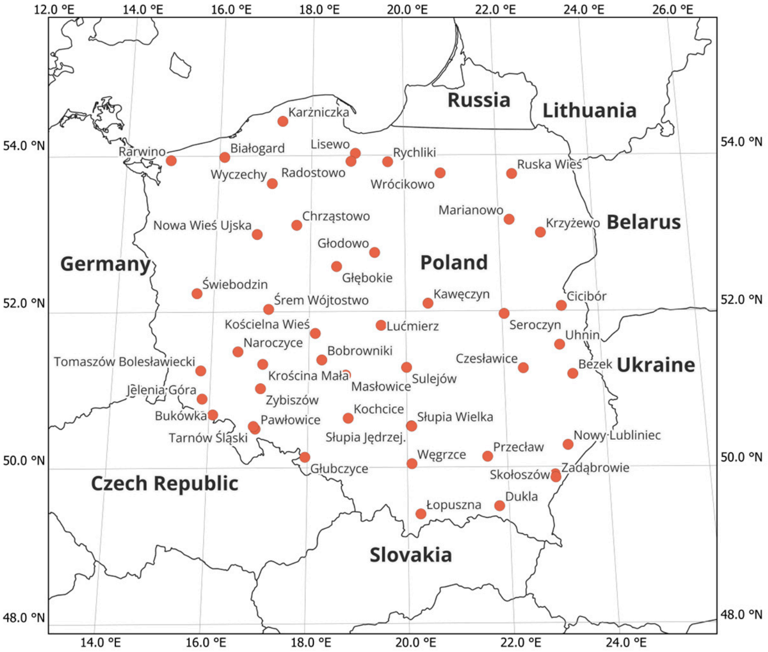

Figure 1. Locations of the cereal experiments that took place between 2009 and 2022 in Poland.

Spring barley data begin in 2013 and show the number of locations ranging from 10 to 37, with a noticeable decrease in recent years (2020–2022) (Table 1). In the case of spring wheat, the experiments were recorded starting in 2011, with a peak of 32 locations in 2014 and 2015 and a gradual decline to 18 locations by 2022. Winter barley experiments started in 2011, with the number of locations fluctuating between 6 and 24, showing a more consistent decline after 2015. For winter triticale, starting in 2012, the number of locations ranges from 8 to 30, with a sharp decrease to 8 by 2022. Winter wheat was recorded for the longest, from the beginning in 2009, starting at 15 and peaking at 36 in 2013, with a decrease to 23 by 2022.

Table 1. Number of locations where the experiments took place divided by species and years (higher numbers are indicated by greener cells).

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
spring barley					10	9	37	37	37	35	30	27	21	22
spring wheat			13	14	14	32	32	28	24	21	19	20	20	18
winter barley			6		7	24	23	11	20	17	13	12	10	9
winter triticale				14	14	13	27	30	30	27	27	23	23	8
winter wheat	15	13	13	24	36	30	31	32	32	30	31	30	29	23

Note: The background color can stay as its intensity indicates the number of locations with experiments.

2.2. Weather Conditions, Soil, and Management

The experimental locations captured major cereal production regions in Poland and included various soil and weather conditions. Weather conditions were analyzed from 1 April (average emergence date) to 30 July (average end of grain filling date) using CWB values individually for each of the 47 locations and studied years. The exemplary map for CWB1 (21.03–20.05) for 2020 is shown in Figure 2. In the study, three CWBs for each year were used: CWB1 (21.03–20.05), CWB4 (21.04–20.06), and CWB7 (21.05–20.07) [28,29].

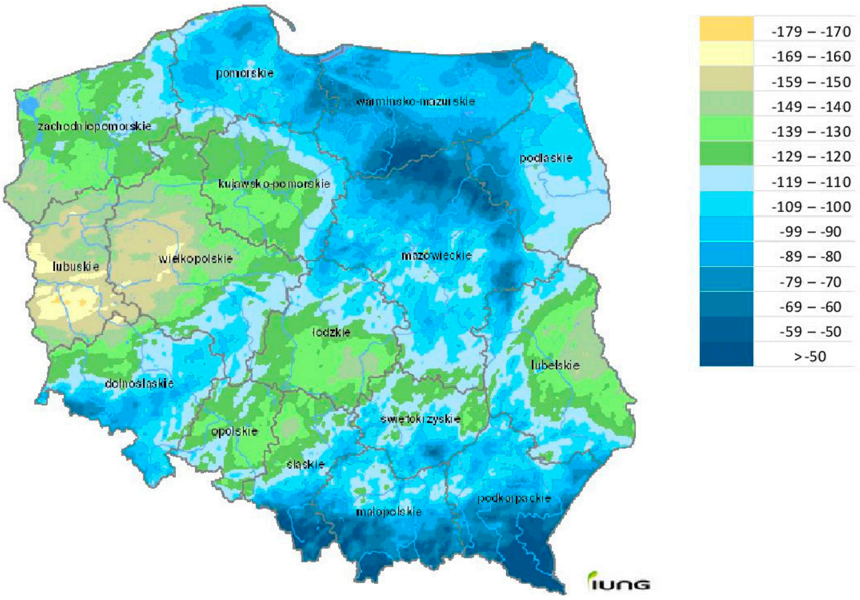

Figure 2. CWB (Climatic Water Balance in mm)—CWB1 (21.03–20.05) for 2020.

The soil from the top layer was analyzed in each location. The data were collected by COBORU. The pH variable was recorded. Magnesium (Mg), phosphorus (P), and potassium (K), the essential nutrients that play crucial roles in plant growth and soil fertility, were measured in each location and classified as very high, high, medium, low, or very low depending on the soil type. The soil's Mg, P, and K content can significantly depend on the soil type, particularly whether the soil is heavy or light. Soil type affects the retention, availability, and mobility of these nutrients in various ways [30].

The P content ranges are as follows:

- Very low (0–5 mg P_2O_5/100 g): soils in this range have critically low levels of phosphorus;
- Low (5–10 mg P_2O_5/100 g): soils have slightly better phosphorus content but are still insufficient for optimal plant growth;
- Medium (10–15 mg P_2O_5/100 g): soils with an adequate phosphorus level for many crops;
- High (15–20 mg P_2O_5/100 g): soils indicate a good potential for supporting robust plant growth;
- Very high (20 mg P_2O_5/100 g and above): the soil has an abundance of phosphorus.

The K content ranges are as follows:

- Very low K (very light soils: 0–2.5, light soils: 0–5, medium soils: 0–7.5, and heavy soils: 0–10 mg K_2O/100 g);
- Low K (very light soils: 2.6–7.5, light soils: 5.1–10, medium soils: 7.6–12.5, and heavy soils: 10.1–15 mg K_2O/100 g);
- Medium K (very light soils: 7.6–12.5, light soils: 10.1–15, medium soils: 12.6–20, and heavy soils: 15.1–25 mg K_2O/100 g);
- High K (very light soils: 12.6–17.5, light soils: 15.1–20, medium soils: 20.1–25, and heavy soils: 25.1–30 mg K_2O/100 g);

- Very high K (very Light Soils: 17.6+, light soils: 20.1+, medium soils: 25.1+, and heavy soils: 30.1+ mg K_2O/100 g).

The Mg content ranges are as follows:

- Very low Mg (very light soils: 0–1, light soils: 0–2, medium soils: 0–3, and heavy soils: 0–4 mg Mg/100 g);
- Low Mg (very light soils: 1.1–2, light soils: 2.1–3, medium soils: 3.1–5, and heavy soils: 4.1–6 mg Mg/100 g);
- Medium K (very light soils: 2.1–4, light soils: 3.1–5, medium soils: 5.1–7, and heavy soils: 6.1–10 Mg/100 g);
- High K (very light soils: 4.1–6, light soils: 5.1–7, medium soils: 7.1–9, and heavy soils: 10.1–14 Mg/100 g);
- Very high K (very Light Soils: 6.1+, light soils: 7.1+, medium soils: 9.1+, and heavy soils: 14.1+ Mg/100 g).

Each location recorded N, P_2O_5, and K_2O fertilizers rates and preceding crops (cereal, legume, rapeseed, root crop). All locations were rainfed.

2.3. Statistical Analysis

CARTs, Spearman correlation, and linear regression models were used to analyze whether the yield differed across environments and management practices. CARTs, which stands for Classification and Regression Trees, are a popular decision tree learning technique for constructing data prediction models. CARTs involve creating binary decision trees from a dataset by repeatedly splitting the data into smaller subsets [16,25]. This process continues until the subsets at a node have a specified minimum size or until no further gains can be made. Each decision in the tree represents a binary logical condition that separates the data based on different features. For regression tasks, the reduction in variance was a criterion for making splits. This means choosing the split that results in subsets with the lowest variance in their outcomes. The dataset is split into two child nodes starting at the root node. This process is recursively repeated on each derived subset. Trees can handle non-linear relationships between features. CARTs can handle missing values and outliers during model construction. All calculations were performed in the Statistica software v. 13 [31].

To identify the primary drivers of yield variation for studied cereal species in Poland, the following variables were included in the analysis (with their respective types in the CART model):

- ○ CWB (quantitative);
- ○ Soil nutrients: P, K, and Mg levels, from very low, low, medium, and high to very high (quantitative, from 0 to 4, respectively);
- ○ Nitrogen application at moderate (a_1) and high (a_2) input levels, and application of P_2O_5, and K_2O (quantitative);
- ○ Soil pH (quantitative);
- ○ Previous crop type: cereal, legume, rapeseed, or root crop (qualitative).

The CART analysis was conducted separately for each cereal species (winter and spring triticale, winter and spring wheat, and winter and spring barley) and for each agrotechnical input level (a_1 and a_2). This approach offered a more detailed understanding of how the selected variables influenced yield variation under different management intensities.

3. Results

Table 2 provides an overview of agronomic parameters across five cereal crops: winter triticale, spring wheat, winter wheat, winter barley, and spring barley. The parameters measured and compared across these crops include soil pH, nitrogen (N) application at two levels of agricultural management (a_1 and a_2), phosphorus (P_2O_5), potassium (K_2O), and crop yields at two management levels. All crops were grown at similar pH values, averaging from around 6.1 to 6.2, suggesting relatively neutral soil conditions generally favorable for cereal crops. Winter wheat receives the highest N application under both management levels, which might correlate with its higher yield performance. P_2O_5 application rates are relatively consistent across the cereals, with minor variations. Spring wheat and winter wheat have slightly higher averages, suggesting a potentially greater focus on phosphorus fertilization in these crops. Similar to phosphorus, potassium application is relatively uniform across the crops. Winter wheat and winter barley show slightly higher potassium application rates, which could be linked to specific soil or crop requirements. The yields represent the productivity of each cereal crop under moderate (a_1) and high (a_2) input levels. Winter wheat consistently shows the highest yields among the cereals at both management levels, suggesting it benefits most from the conditions and management practices. Notably, all crops exhibit an increase in yield from a_1 to a_2, indicating a positive response to increased input intensity, particularly nitrogen. The standard deviations indicate variability in each parameter, with nitrogen application and yield showing significant variability. This could be due to different environmental conditions, soil types, or specific site management practices.

Table 2. Mean and SD of the quantitative variables used in the study for the total period (2009–2022).

	Winter Triticale	**Spring Wheat**	**Winter Wheat**	**Winter Barley**	**Spring Barley**
pH	6.10 ± 0.62	6.18 ± 0.53	6.20 ± 0.51	6.13 ± 0.50	6.18 ± 0.57
N at a_1 [kg ha^{-1}]	96.91 ± 18.00	92.37 ± 18.76	112.33 ± 18.03	91.65 ± 18.98	82.63 ± 22.73
N at a_2 [kg ha^{-1}]	136.76 ± 17.87	134.30 ± 19.20	152.16 ± 18.66	131.68 ± 20.17	120.92 ± 23.54
P_2O_5[kg ha^{-1}]	50.73 ± 16.36	51.64 ± 20.20	52.28 ± 16.40	49.50 ± 16.57	49.00 ± 17.81
K_2O[kg ha^{-1}]	82.62 ± 22.01	84.85 ± 23.45	88.30 ± 23.58	88.23 ± 23.43	81.12 ± 23.83
yield at a_1 [t ha^{-1}]	7.46 ± 1.91	6.61 ± 1.58	8.48 ± 1.71	8.39 ± 2.02	6.44 ± 1.78
yield at a_2 [t ha^{-1}]	8.96 ± 2.08	7.44 ± 1.79	9.59 ± 1.94	9.42 ± 2.20	7.14 ± 1.92

3.1. CWB Trends Influenced by Climate Change

The changes in CWB from 2009 to 2022, across three periods within the agricultural growing season, reflect trends potentially influenced by climate change. Figure 3 shows a decreasing moisture availability trend, emphasizing the urgency of adaptive water management strategies in response to evolving climatic conditions.

Figure 3 depicts a scatter plot tracking changes in CWB, which measures moisture availability, with values ranging from about −200 to 50, across three distinct periods (CWB4 and CWB7) over several years, from 2009 to 2022. The CWB mean values for each period are plotted against the years, and the linear regression lines illustrate the trends for each period. CWB1 had a very slight negative trend with no statistical significance, indicating almost no change in CWB1 over the years. CWB4 (orange line) shows a more pronounced negative trend and is statistically significant, suggesting a decrease in CWB4 values over time, with the model explaining a substantial amount of the variation ($R^2 = 0.44$). Similarly to CWB4, CWB7 (blue line) exhibits a significant negative trend, indicating a reduction in CWB7 values over the years. The decline in CWB during these later periods of the growing season could imply less rainfall or increased evapotranspiration rates, which could have implications for agricultural practices, particularly regarding irrigation needs and water resource management.

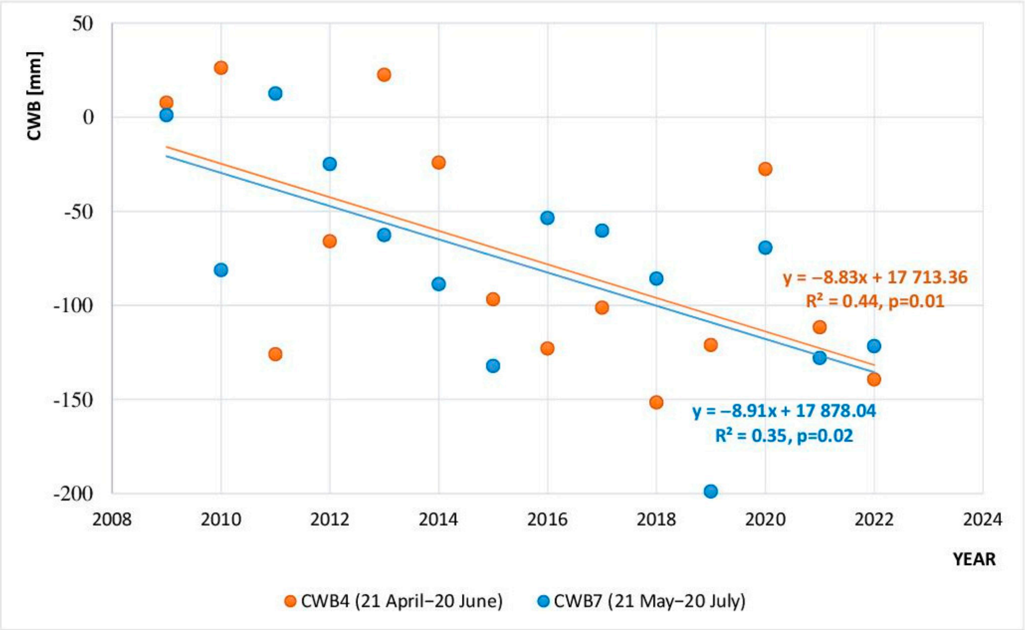

Figure 3. Regression analysis for mean CWB (Climatic Water Balance in mm) across all locations presenting changes over the study period (2009–2022). The orange line represents the trend for CWB4 and the blue one for CWB7; R^2 is the coefficient of determination, and both p-values suggest a statistically significant downward trend (at a significance level of 0.05).

3.2. Correlation Analysis

The majority of the species exhibit a declining trend in yield over time (Table 3). However, the correlations are statistically insignificant in most cases. In the case of winter wheat and winter barley, the correlations are positive and mostly statistically significant. The pH levels show a statistically significant positive correlation with the yield of spring barley and winter triticale at a_1 and a_2 levels. This suggests that soil pH has a noticeable impact on the yield of spring barley, potentially influencing nutrient availability and root growth. No statistically significant correlations between the pH and yield were observed in the rest of the species. In winter barley, P_2O_5 displays a stronger positive correlation with yield at the a_1 level (0.19) and a_2 level (0.24). High correlations suggest that phosphorus availability is important for the yield in winter barley, affecting root development and energy transfer within the plant. However, there is a negative correlation between winter barley yield at the a_1 level (–0.22) and a_2 level (–0.20) with the P_2O_5 content in the soil, suggesting the complexities of soil nutrient dynamics and the potential for nutrient imbalances. No statistically significant correlations were found between N and K_2O, indicating that the impact of nitrogen and potassium fertilization on yields might not be as pronounced or consistent across the crops under the conditions studied. In the case of spring wheat and spring barley, there are strong positive correlations at both management levels (a_1 and a_2) between yield and both CWB1 (21.03–20.05) and CWB4 (21.04–20.06), with coefficients ranging from 0.20 to 0.36. This indicates that water availability during the growth season highly influences yields. Adequate moisture during critical growth phases is key to maximizing yield. CWB7 (21.05–20.07) is statistically significantly negatively correlated with winter wheat yield at the a_1 level (-0.19) and a_2 level (-0.13). These correlations suggest that late-season moisture conditions significantly affect plant health and soil nutrient dynamics after the main growth period. Excessive moisture in this period can lead to detrimental effects, including yield reductions.

Table 3. Spearman correlation coefficients between yield and input variables at both intensity levels for the total period of the study (2009–2022). In red font are indicated significant correlations. CWB1 (21.03–20.05), CWB4 (21.04–20.06), and CWB7 (21.05–20.07).

	Yield a_1	**Yield a_2**	**Yield a_1**	**Yield a_2**	**Yield a_1**	**Yield a_2**	**Yield a_1**	**Yield a_2**	**Yield a_1**	**Yield a_2**
	Winter Triticale		**Spring Wheat**		**Winter Wheat**		**Spring Barley**		**Winter Barley**	
year	−0.11	−0.08	−0.03	−0.07	0.14	0.06	−0.11	−0.13	0.24	0.17
pH	0.14	0.13	0.08	0.08	0.05	0.05	0.19	0.17	0.06	0.07
N at a_1	0.02		−0.01		−0.06		−0.07		−0.12	
N at a_2		0.01		−0.02		−0.05		−0.09		−0.08
P_2O_5	0.06	0.00	0.02	0.07	0.09	0.08	0.10	0.11	0.19	0.24
K_2O	0.08	0.02	0.01	0.07	0.04	0.05	0.04	0.05	−0.06	−0.05
P_2O_5 in soil *	−0.01	−0.03	0.02	0.02	−0.07	−0.08	−0.02	−0.03	−0.22	−0.20
K_2O in soil *	0.02	0.07	0.03	−0.01	0.06	0.06	0.19	0.18	−0.03	−0.02
Mg in soil *	0.01	0.00	0.08	0.09	−0.03	0.00	0.00	−0.01	0.01	0.02
CWB1	−0.04	0.13	0.22	0.26	0.07	0.14	0.20	0.26	0.02	0.10
CWB4	0.06	0.14	0.26	0.36	−0.06	0.03	0.20	0.27	−0.01	0.05
CWB7	−0.05	0.02	0.05	0.11	−0.19	−0.13	0.06	0.12	−0.13	−0.09

* soil nutrient content from very low (0), low, medium, and high to very high (4).

3.3. CART Results

The CART analysis focused on the yield of studied species. Figure 4 presents the results for yield at two levels of management. A mean yield for winter triticale at the a_1 level was 7.46 t. Different soil conditions, specifically the pH and phosphorus content, affect the yield the most. Soils with a pH lower or equal to 5.79 provide a mean yield of 6.60 t, which is 1.09 t lower than higher pH values. This node indicates lower yields with a lower pH, suggesting that more acidic soil conditions may be associated with reduced triticale yields. The second split, for higher pH values, was then divided according to the available phosphorus. The P_2O_5 in medium contents yielded a higher yield of 0.85 t than other phosphorus contents (both low and high). This may indicate that medium levels of phosphorus in the soil are optimal, resulting in the highest mean yields (by 0.85 t) observed in the tree. In spring wheat, the influence of CWB was notable, with thresholds marking significant changes in yield (by 2.35 t when CWB4 was higher than −159.5 mm). Soil conditions played a secondary role. CWB and the subsequent soil nutrient availability played crucial roles in the yield formation of winter wheat. A phosphorus fertilization higher than 24.95 kg ha^{-1} resulted in a higher yield of 2.64 t. Phosphorus levels in the soil considerably impacted winter barley yield, with medium levels proving most beneficial, reflecting the importance of balanced nutrient management. The yield of spring barley was influenced by CWB, with significantly different yields based on thresholds in CWB values (by 1.12 t when CWB4 was higher than −139 mm) and soil potassium levels (by 1.05 t when K_2O level was very high). Enhanced management (a_2) helped achieve higher yields, especially in environments with favorable CWB values and nutrient levels, emphasizing the benefit of comprehensive crop management strategies. Additional inputs might stabilize or enhance yield under certain climatic conditions. The impact of CWB is a recurrent theme across all species, indicating its fundamental role in crop development and yield outcomes. Soil nutrients, particularly phosphorus and potassium, and their optimal levels are crucial in determining yield, which can be further enhanced or stabilized through tailored agricultural management practices. Enhanced management tends to buffer the negative impacts of less-than-ideal soil and climatic conditions, suggesting its effectiveness in yield improvement. This analysis underscores the importance of climatic factors and soil conditions in crop yield outcomes. It illustrates how enhanced agricultural management practices can increase yield stability and productivity across cereal species.

In CARTs, the importance score for each variable is calculated based on how effectively the variable helps to split the data, thereby reducing the overall variance at each node of the tree. CARTs use the Mean Squared Error (MSE) to assess how well a variable reduces the variance within the groups formed by the split. At each split in the tree, CARTs calculate the amount of variance that is reduced due to that split. The importance of a variable is determined by aggregating the reductions in variance it provides every time it is used to make a split in the tree. Variables used in more splits and/or that provide larger reductions in variance are considered more important. To make the importance scores more interpretable, they are normalized so that the sum of all importance scores across all variables equals 100%.

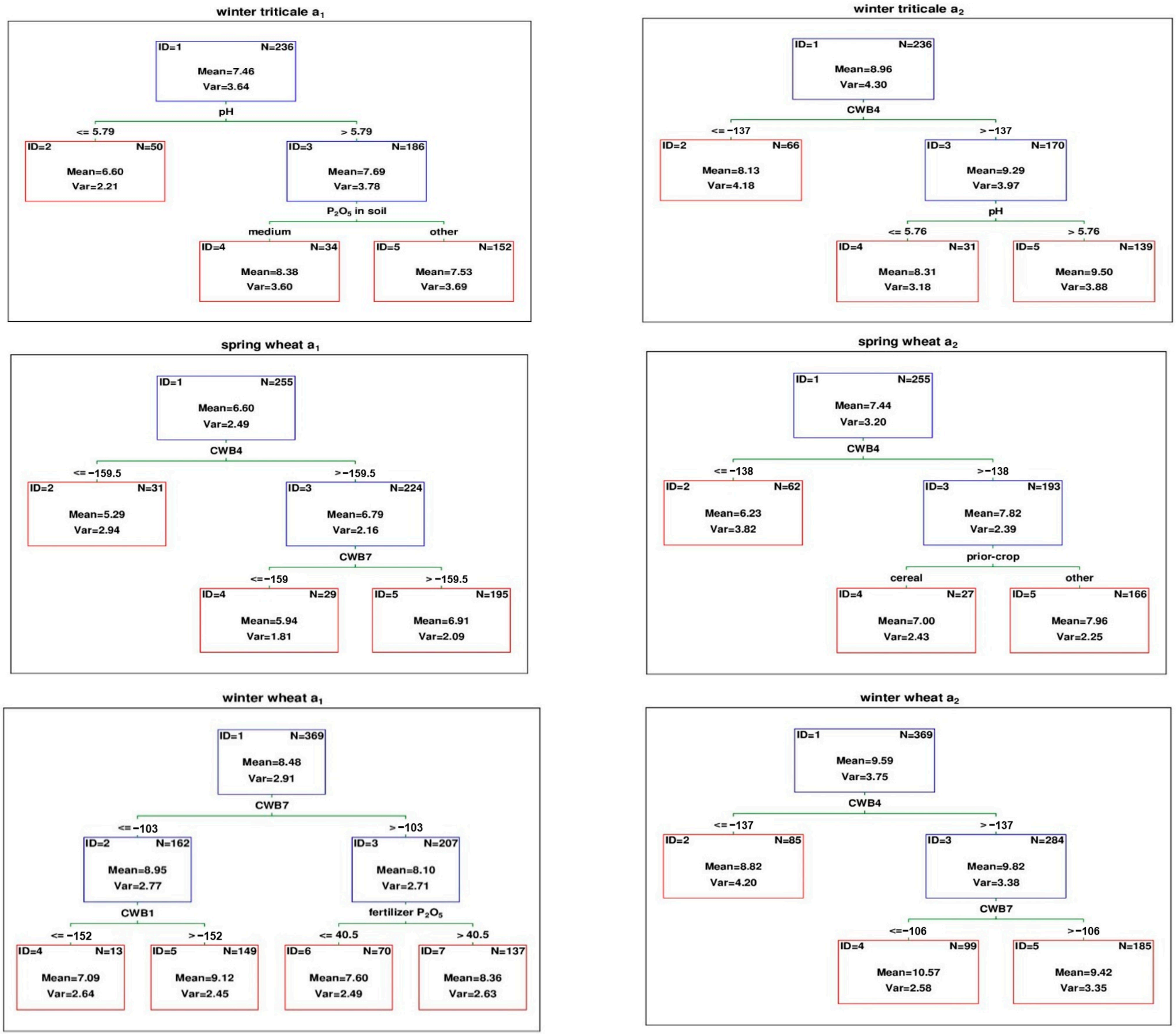

Figure 4. *Cont.*

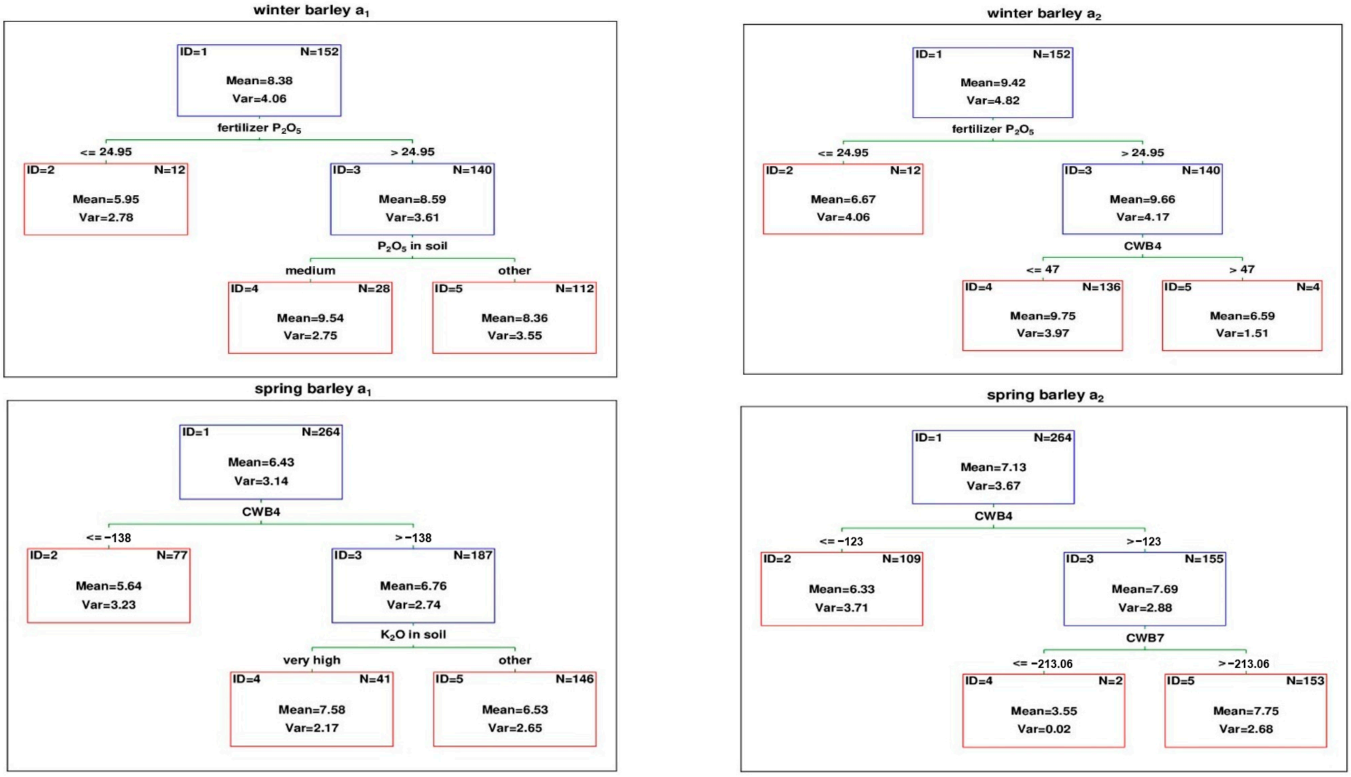

Figure 4. CART analysis based on the data for 2009–2022 for the grain yield prediction of the studied cereals.

Table 4 outlines the relative importance (ranging from 0 to 100) of various independent variables in creating CARTs for different cereal crops under the two levels of agricultural management (a_1 and a_2). Nitrogen fertilizer varies significantly across crops and management levels but is particularly crucial for winter barley (100 in both a_1 and a_2), indicating its critical role in optimizing yield for this crop. Spring wheat also highly depends on nitrogen, especially under a1 management (86). P_2O_5 fertilizer is highly important for winter triticale in both management practices (importance score of 100), suggesting that phosphorus availability is vital for this crop. It remains important for winter barley, especially under a_2 management (96). K_2O nutrient in the soil also varies in importance but is notably high for winter triticale and barley under a1 management (62). The consistent importance across management types for barley indicates that potassium is a key factor for barley yield. Mg and P_2O_5 in the soil show varied importance across crops, with relatively lower scores than fertilizer variables, indicating that, while soil nutrient content is crucial, the direct application of fertilizers may have a more immediate and measurable impact on yield. CWB1, CWB4, and CWB7 show very high importance across most crops and management levels, often reaching the maximum score (100). This underscores the significant impact of water availability and timing on crop yields and highlights the critical nature of water balance during the growing season. Soil pH holds substantial importance for crops, suggesting that soil acidity or alkalinity is crucial in nutrient availability and overall plant health. The type of preceding crop holds moderate importance with variations across crops and management levels.

Table 4. Importance scores of the variables used in the CART model (higher numbers are indicated by greener cells).

	Winter Triticale		Spring Wheat		Winter Wheat		Winter Barley		Spring Barley	
	a_1	a_2	a_1	a_2	a_1	a_2	a_1	a_2	a_1	a_2
pH	78	72	59	62	43	63	74	80	94	72
N fertilizer (a_1 or a_2)	75	75	86	79	49	61	100	100	68	67
P_2O_5 fertilizer	100	100	42	41	55	64	85	96	62	57
K_2O fertilizer	62	62	45	40	42	60	62	45	57	42
P_2O_5 in soil	19	27	25	30	48	52	69	67	33	29
K_2O in soil	41	60	38	37	32	39	35	34	58	65
Mg in soil	59	41	54	54	50	50	62	46	38	36
CWB1 (21.03–20.05)	62	92	89	100	88	93	81	76	100	100
CWB4 (21.04–20.06)	88	100	92	95	100	99	93	100	82	93
CWB7 (21.05–20.07)	82	82	100	97	82	100	97	73	78	90
prior crop	45	38	52	38	41	75	63	43	35	33

4. Discussion

The study of CWB, soil nutrient levels, and their impact on the yields of five major cereal crops across Poland from 2009 to 2022 has yielded insights into the interaction between environmental factors (water available to plants) and agricultural management. The findings underscore the influence of CWB and soil nutrients on crop yield outcomes, explaining the varied responses across different cereal species and management practices. The analysis revealed a downward trend in CWB values across the study period, reflecting a decrease in available water due to factors likely linked to climate change, such as reduced precipitation and increased evapotranspiration rates caused by higher air temperature. This decline in CWB was strongly correlated with yield variations in all studied cereal crops, highlighting the crucial role of water availability in crop productivity. The impact of CWB was particularly pronounced during critical growth periods of April to June and May to July, with significant yield reductions observed in years of lower CWB values. These findings illustrate the sensitivity of crops, including cereal crops, to water stress and underscore the need for effective water management strategies to mitigate the impact of reduced water availability [32]. The study further established that soil nutrient levels influence cereal yields, specifically N, P_2O_5, and K_2O. Higher yields were consistently associated with optimal levels of these nutrients, particularly under enhanced management practices that included increased fertilization [13]. For example, winter barley at the a_2 management level had yields almost 3 t ha^{-1} higher when P_2O_5 fertilizer was more than 25 kg ha^{-1}. Notably, the interaction between soil nutrients and CWB highlighted a complex dynamic where optimal nutrient levels could partially offset the negative impacts of low CWB. For instance, in plots where nitrogen and phosphorus were applied at higher rates under enhanced management practices (a_2), crops demonstrated improved resilience to the adverse effects of reduced water availability. Comparing moderate (a_1) and enhanced (a_2) management practices, the results indicate a general trend of increased yields under a_2, which involved higher N fertilizers, fungicides, and growth regulator inputs. In the case of all species, the yield at the a_2 management level was higher, from 0.7 t ha^{-1} for spring barley to 1.5 t ha^{-1} for winter triticale, also due to a higher N fertilization rate. This suggests that intensive management practices can effectively enhance the yield potential, especially under challenging environmental conditions. However, the benefits of intensified management were not uniform across all crops or environmental settings, suggesting that the effectiveness of such practices may be contingent on specific crop requirements and local climatic and soil conditions [33–35]. In India, an increase in temperature and potential evapotranspiration coupled with a decrease in precipitation has reduced wheat yields, highlighting a significant decrease in wheat production by up to 11% from 1986 to 2015 [36]. Similarly, in Mediterranean regions like Southern Spain, increasing aridity and reduced precipitation during the growing season correlate strongly with diminished crop yields, particularly in rainfed agriculture [22]. Furthermore, long-term assessments from 1970 to 2019 indicate increasing irrigation requirements due to climate variability, significantly affecting water-stressed crops across various global regions [37]. In the Czech Republic, projections up to 2080 suggest that drier conditions will severely impact the yields of certain crops under future climatic scenarios, underscoring the necessity for adaptive strategies to manage water resources more efficiently [23]. Climate change is significantly impacting agricultural management practices and crop yields worldwide. Rising temperatures, changing precipitation patterns, and increased frequency of extreme weather events necessitate adaptive strategies to mitigate these effects. A study by Abramoff et al. [38] utilizes a meta-model based on 8703 site-level process-model simulations for crops like maize, rice, wheat, and soybean. It predicts global crop yields will decline by 6–21% without adaptation. However, adaptive practices, such as improved irrigation methods and selecting resilient cultivars, significantly mitigate these losses. Similarly, Mwangi (2023) highlights the adverse effects of climate change on crop yields, emphasizing the importance of building adaptive capacity and resilience through climate-smart agricultural practices like agroforestry, conservation agriculture, and sustainable water management [39]. These practices are crucial for maintaining productivity and ensuring food security in changing climatic conditions. By adopting climate-smart sustainable agriculture, farmers can improve soil health, optimize water use, and reduce the carbon footprint of agricultural activities. A combination of advanced genomic technologies, smart agricultural practices, and integrated management strategies is crucial to enhance cereal yield resilience. Genomic tools like genome editing and genome-wide association studies are essential for developing stress-resilient cereal cultivars in the face of climate change and various stresses [40]. Additionally, adopting smart technologies such as climate-based cropping systems, balanced fertilization, and site-specific nutrient management can significantly improve crop production while reducing fertilizer usage and enhancing climate resilience [41]. Furthermore, the integration of optimized agronomic practices, diversification of farming systems, and reduced post-harvest losses are vital components in achieving sustainable stress management and boosting cereal yield in resource-constrained agricultural settings [42].

The analysis of correlation coefficients between yield and CWB variables for winter wheat highlights the critical role of late-season moisture conditions. These conditions significantly influence plant health and the dynamics of soil nutrients well beyond the primary growth period. Excessive moisture can lead to detrimental effects, including yield reductions. Over-saturation can cause root rot, nutrient leaching, and poor soil aeration, negatively impacting crop productivity [25].

The balance of nitrogen, phosphorus, and potassium levels also significantly influences cereal yields, with enhanced management practices showing varied effectiveness across different studies. In wheat, increased nitrogen and phosphorus application significantly improved biological yield, grain weight, and chlorophyll content, with the highest yield achieved at 160 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1} [12]. Similarly, in wheat grown in Nepal, optimal yields were obtained with N at 125 kg ha^{-1} and K_2O at 50 kg ha^{-1}, indicating significant yield enhancement with proper nutrient management [13]. The efficiency of nutrient use in wheat is critical, with studies showing higher yields and nutrient efficiency at moderate levels of N, P, and K. For instance, N at 125 kg ha^{-1}, P_2O_5 at 25 kg ha^{-1}, and K_2O at 50 kg ha^{-1} provided optimal nutrient use efficiency [13]. In barley, moderate phosphorus fertilization and adequate nitrogen and potassium levels yielded the highest grain and protein yields [43]. Balanced nutrient management, particularly with moderate N and K levels, tends to maximize yields across cereals. While specific optimal levels vary by region and crop type, the principle of balanced fertilization remains consistent. The observed positive correlation between P_2O_5 fertilization and winter barley yield, contrasted with a negative correlation between soil P_2O_5 content and yield, can be attributed to several factors. In many soils, especially those with a high clay content or high levels of calcium or iron, phosphorus can become fixed in forms that are not readily available to plants. This means that, despite the high total phosphorus content, the phosphorus is not in a form that plants can use, leading to a negative correlation with yield [44].

While the findings of this study highlight the critical role of optimized nutrient management and the need for adaptive water resource strategies in the face of climate change, there are several weak points and areas for future exploration. The study's reliance on data from a single country may limit the generalizability of the findings to other regions with different climatic and soil conditions. Focusing on only a few cereal species and specific cultivars may not capture the full variability of responses to climatic and management factors across other crops. The study considers only three nutrients: Mg, P, and K. This limited scope overlooks other essential nutrients that may be crucial for comprehensive soil health and crop productivity. Research could also focus on developing integrated models that combine climatic, soil, and genetic information to predict crop outcomes more accurately, aiding in designing more effective climate-adaptive agricultural strategies.

Climate change will likely make crops like maize, soybeans, and sunflowers more common in central–eastern Europe due to warmer temperatures and longer growing seasons. Conversely, traditional crops like rye, wheat, and barley end triticale may decrease as they are more sensitive to higher temperatures, drought, and shifting rainfall patterns [45–47].

5. Conclusions

This analysis reveals a significant decreasing trend in CWB values from April to July, with a decline of approximately 10% per year over the 13-year period, emphasizing the increasing challenges in agricultural water resource management. As these periods become progressively drier, crop yields will likely be affected, necessitating adaptive changes in farming practices. The study demonstrates that targeted agronomic practices, particularly increased nitrogen application (additional 40 kg ha^{-1} leading to an average yield increase of around 10%) and optimized soil pH, significantly buffer cereal crops against the adverse effects of climatic variability. Specific interventions can sustain productivity even as mid-season water availability declines. These findings provide actionable insights for long-term agricultural planning, particularly in high-risk areas, highlighting that integrating soil and fertilizer management improves crop resilience. While our study confirms that tailored agronomic management can mitigate some adverse impacts of climatic stresses, the potential for these practices to sustain yields under extreme climatic events (e.g., multi-year droughts or heatwaves) remains uncertain. Further research is needed to assess the scalability and adaptability of these strategies across diverse geographic and climatic regions and evaluate their effects on soil health and crop productivity over successive growing seasons. Expanding future studies to include a wider range of environments and crop types would enhance the applicability and robustness of these findings, helping ensure the long-term sustainability of cereal production in increasingly variable climatic conditions.

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