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Long-Term Analysis of Winter Wheat Yield and Climatic Influences in Ukraine

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ABSTRACT

This study examines how climate trends, soil moisture and phenological changes have influenced the magnitude and stability of *Triticum aestivum L*. production in the Kyiv region of Ukraine between 1968 and 2024. The purpose is to distinguish the impacts of warming, precipitation variability, soil moisture deficits and changes in growth stages (autumn cessation, spring regrowth, winter calm) on yield trends and interannual variability. Results show a statistically significant warming trend: annual temperatures rising ~0.050°C/year and during growing seasons ~0.046°C/year. Precipitation exhibits high interannual variability but no consistent long-term trend; however, wet/dry extremes and moisture deficits during spring regrowth and summer are increasingly frequent. Soil moisture droughts at 50–100 cm depth, below a productive baseline (~112 mm), have become notably more common since 2007, especially in seasons with elevated temperatures. The winter calm period has steadily shortened and phenological variability during both autumn and spring growth has increased. Winter wheat yields have increased from ~4.6 to ~7.1 t ha^{-1} between early (1968–85) and recent (2015–24) decades, with an average linear gain of ~0.038 t ha^{-1} per year. However, interannual yield variability remains large and phenological timing (late autumn cessation and early spring regrowth) is strongly associated with higher yield in many years. Yield gains are driven largely by nonclimatic factors and yield stability is increasingly constrained by compound climatic stresses and phenological shifts. To sustain productivity under ongoing climate change, adaptation should emphasise phenology-aware breeding, timing of sowing and spring renewal and soil moisture conservation during critical growth stages.

1 | Introduction

Wheat (*Triticum aestivum* L.) is one of the three most important cereal crops globally, serving as a staple food for a large portion of the world's population. With the global population projected to reach 9.7 billion by 2050, cereal production must increase by an estimated 2%–3% annually to meet future demand (Pye-Smith 2011; Yadav et al. 2020). However, in the past decade, the yield growth of the major cereals has slowed, with wheat showing the lowest rate of increase, at just 1.1% per year (Hawkesford et al. 2013; Wheat Initiative 2018). Its nutritional value, wide adaptability and polymorphism in growth type (winter, spring, facultative forms) and morphology have enabled wheat to spread across diverse agroecological zones (Shpaar 2012; Li and Yang 2017; Stewart and Lal 2018). Yet, these same features also make it highly exposed to transboundary pests, diseases and abiotic stresses, particularly heat and drought, which increasingly challenge yield stability (Erenstein et al. 2022).

Globally, Asia and Europe dominate wheat production, accounting for 44% and 34% of total output, respectively. North America contributes about 12%, while other regions produce less than 3% each. Average yields vary regionally, from approximately 2 t ha^{-1} in Oceania to over 4 t ha^{-1} in Europe (Le Gouis et al. 2020). Between 1999 and 2019, the global wheat area remained stable (~213–216 Mha), but production rose by 31%, from 585 Mt. to 766 Mt. Forecasts suggest that while the cultivated area will remain similar, global output could increase by nearly 19% in the coming decades (Neupane et al. 2022).

Ukraine's grain sector is strategic, generating over 25% of national crop output and growing global demand has supported exports (Gamayunova et al. 2021). Prior to Russia's invasion, Ukraine ranked 5th and 9th globally for maize production and wheat export, respectively (Arreyndip 2025). From 2011–2022, Ukraine was the 9th largest wheat producer, contributing up to 3.3% of global output; key trade partners include China, Egypt, Indonesia, the Netherlands and Turkey (Hamulczuk et al. 2023). Ukraine has been a leading exporter, with ~15% of global maize, 10% of wheat and 13% of barley and grain exports exceeding USD 12 billion in 2021–2022 (Lotish 2022). The ongoing war is projected to further disrupt food security in many developing countries (Mottaleb et al. 2022). Ukrainian wheat exports declined from 19.39 Mt. (2022/23) to 15.72 Mt. (2024/25), with further contraction anticipated in 2025/26 (Kalinichenko 2025). Although other major exporters (USA, China, India, Canada, Australia, France, Argentina, Germany) partially offset supply shocks (Lin et al. 2023), the FAO projects Ukrainian wheat output in 2025 to remain below the five-year average, due to both the war and adverse weather, including precipitation deficits (FAO 2025).

Climate change is intensifying these pressures. Recent decades brought more autumn–winter precipitation, warmer winters and more frequent, longer summer droughts (Aizebeokhai 2009; Gahlawat and Lakra 2020); anthropogenic climate change is expected to have strong, far-reaching effects on agriculture in the 21st century (Boychenko et al. 2016), with more frequent extremes that can markedly reduce yields (Tao et al. 2008; Deutschländer and Dalelane 2012). Impacts will be most pronounced where yields are sensitive to specific climate aspects (Pradhan et al. 2020). High temperatures accelerate phenology and notably shorten grain filling, reducing yield (Tashiro and Wardlaw 1989; Wang et al. 2018). Multiple studies estimate ~4%–10% global wheat yield loss per +1°C (Liu et al. 2016; Asseng et al. 2015; Guarino and Lobell 2011); regional projections include −1.9% in global production by mid-century overall, but much larger losses in tropical regions (−15% Africa, −16% South Asia) (Pequeno et al. 2021), −3.6 to −8.6% in Mexico by the 2050s (Hernandez-Ochoa et al. 2018), −1.2 to −10.2% in southern China (Tao et al. 2014) and −8% to −23% in Turkey by 2100 (Eruygur and Özokcu 2016). At the same time, some analyses report positive correlations between temperature change and cereal yields at broad scales, likely reflecting regional compensation (gains in some areas offsetting losses elsewhere) (FAO 2021). For winter wheat in temperate zones, several studies identify heat stress as the dominant constraint (Huzsvai et al. 2022).

In Ukraine, recent years show greater meteorological variability and more frequent extremes across agro-climatic zones (Lifenko et al. 2021; Yarosh and Ryabchun 2021). Ukraine has warmed faster than Europe, with the last two decades forming an almost continuous warming period (Lozinskiy et al. 2023). In the last 100 years, 43 drought years were recorded and climatic zone boundaries shifted 100–150 km northward (Tarariko et al. 2015). Observed and projected changes include warmer, less snowy winters and altered seasonal water balance. The projections indicate modest positive effects in the mixed-forest zone of the northern part due to more radiation and precipitation, small average effects in the forest-steppe, but risks with +2°C in its southern part and pronounced risks in the steppe, where hotter/dryer conditions and higher evapotranspiration may reduce yields by up to 5.5 t ha^{-1} by 2070; overall Ukrainian wheat production may decrease by ~6% (moderate scenario) to > 11% (high-emissions) (Müller et al. 2016).

Across Europe, projections show more hot summers and intense precipitation, with wetter winters and drier summers on average, though regional differences are large (Smith et al. 2014; Powell and Reinhard 2016; Semenov 2009). The likelihood of unfavourable weather for wheat is expected to increase, making yield losses more frequent in key producing regions (Trnka et al. 2014); growing-scale climate anomalies reduce the effectiveness of spatial compensation, heightening production risk (Zampieri et al. 2017; Pequeno et al. 2021). Observed extremes illustrate this vulnerability: France's wheat yield fell 27% in 2016 (the largest drop since 1960) with similar declines in Belgium (−23%) and Switzerland (−26%) (Ben-Ari et al. 2018; Le Gouis et al. 2020); in 2018, a warm/wet winter followed by an exceptionally hot, dry summer cut yields by 5.6%–10.2% across northern/central Europe, producing the lowest EU wheat output in recent history (−13 Mt. vs. 2017) (Beillouin et al. 2020; Moravec et al. 2021; Webber et al. 2020). Heat and drought indicators have become increasingly strong predictors of winter wheat yield anomalies in Germany over the past 30 years. In particular, the number of days with temperatures exceeding 25°C during flowering became a stronger predictor of yield variability during 2001–2010 (Lüttger and Feike 2018).

Other regional evidence is consistent: Hungary recorded ~10% yield loss per +1°C since the 1980s (Pinke and Lovéi 2017); Kazakhstan showed positive correlations of warmer winters and spring precipitation with yield, but negative effects of warmer May temperatures (Morgounov et al. 2014); in Australia, rising maximum temperatures explained 30%–50% of yield increases (Nicholls 1997); in the United States, harvested area declined even as yields rose, partly reflecting warming-driven reductions in harvested area (Zhu and Burney 2021). Because average air temperature masks critical processes, studies emphasise maximum temperatures/minimum temperatures and diurnal temperature range (DTR) (Phillips et al. 2011; Lobell 2007) and call for direct stage-by-stage assessments (Peng et al. 2004; Lesk et al. 2022). Wheat responses are stage specific as excess water impairs emergence, excess rainfall reduces soil oxygen, non-extreme but unfavourable weather can still depress yields (Urruty et al. 2017). Wheat is particularly sensitive to heat at flowering and grain filling (Luo 2011; Bakker et al. 2005), while drought reduces density at establishment, tillers at tillering, height at elongation and grain set/filling (Sarto et al. 2017). Optimal temperatures are ~20°C–30°C, tolerated −40°C to 40°C (Brassard and Singh 2007). Winter-hardiness depends on multiple factors, including temperature, snow cover and cultivar genetics (Oberforster 2012); frost at flowering reduces grain set (Barlow et al. 2015). Heat/drought at flowering and grain filling shorten these phases (Lüttger and Feike 2018; Barnabás et al. 2008; Asseng et al. 2011); grain filling is optimal at ~14°C–15°C, with > 25°C lowering weight, ~35.4°C critical (Singh 1988; Porter and Gawith 1988) and > 32°C at flowering reducing kernel size (Martre et al. 2015). Heat stress also reduces above-ground biomass (Hütsch et al. 2019). Rainfall during grain filling shortens the phase and reduces kernel size (Wollmer et al. 2016). Combined stresses (CO_2, heat, drought, salinity) alter both yield and grain quality (Zahra et al. 2023); warming-adapted genotypes could raise yields by ~7% but reduce protein concentration (Asseng et al. 2019). Weather explains ~76.5% of annual variation in protein (Vollmer and Mußhoff 2018).

Phenological and genetic changes also mediate exposure to heat. In western Germany (1952–2013), modern cultivars required 14%–18% fewer degree-days from emergence to flowering compared with those grown in the 1950s–1960s. Phenological modelling indicated that both rising mean temperatures and cultivar properties contributed equally, with sowing-date changes playing only a minor role (Rezaei et al. 2018). Heading dates across Germany (1951–2009) were strongly linked to spring mean temperature (Rezaei et al. 2015). Changing crop phenology is therefore an important bio-indicator of climate change; in our context, this is reflected by observed shifts in the winter calm period (Rezaei et al. 2018). Soil quality and water availability at critical growth stages remain major determinants of yield variability (Wójcik-Gront 2018).

Despite abundant modelling studies, long-term empirical field data from Ukraine remain scarce. Given Ukraine's global role as a wheat producer and exporter, understanding how weather extremes and phenological shifts affect yield stability is essential. This study therefore provides a long-term analysis of winter wheat yield and climatic influences in central Ukraine, addressing a critical knowledge gap in regional crop–climate interactions.

2 | Data and Methods

2.1 | Site Description

The study was conducted at the Bila Tserkva Breeding and Research Station (BCBRS) of the Institute of Bioenergy Crops and Sugar Beet National Academy of Agrarian Sciences of Ukraine, located in Bila Tserkva district, Kyiv region, Ukraine. The experiment was conducted in a 10-field scientific crop rotation (pea, winter wheat, sugar beet, maize for grain, spring barley, green manure fallow, winter wheat, sugar beet, maize for grain, spring barley), representative of crop production systems in the Forest-Steppe zone of Ukraine. Winter wheat was included as a recurring crop in the rotation and yield observations were based on replicated experimental plots established each year according to the standard methodology of the station. Thus, the dataset represents repeated measurements under consistent soil conditions.

Meteorological data used in this study were obtained from the official records of the Bila Tserkva Meteorological Station of the Ukrainian Hydrometeorological Service. The station is part of the national meteorological monitoring network, where observations are conducted according to standardised operational procedures and quality-control protocols. Throughout the study period (1968–2024), meteorological observations followed the official observation program. The meteorological data used in this study represent the official operational climate records maintained by the Ukrainian Hydrometeorological Service. No additional processing or homogenisation of the climatic time series was performed and all analyses were based on the official archived observations.

2.2 | Soil Characteristics of the Study Site

The experimental fields are situated within the Kyiv region, in the central part of the Right-Bank Forest-Steppe of Ukraine. Soils are classified as deep, slightly humus-rich typical chernozems, formed on loess and loess-like loams. They are structurally stable, with favourable air–water properties resulting from a balanced ratio of capillary and non-capillary porosity. The pH is close to neutral, hydrolytic acidity is low and base saturation is high. Humus content in the plough layer (0–20 cm) ranges between 3.1%–3.6%. Nutrient availability is characterised by low to moderate mineral nitrogen (98–156 $mg\,kg^{-1}$), moderate to high phosphorus (106–123 $mg\,kg^{-1}$) and medium potassium availability (88–104 $mg\,kg^{-1}$). These soils are typical for the central Forest-Steppe zone, where water availability during critical growth stages is often the primary yield-limiting factor rather than soil fertility (Tsitsyura et al. 2020; Primak et al. 2017).

2.3 | Plant Material and Experimental Setup

The analysis used yield data of winter wheat (*Triticum aestivum* L.) varieties that served as national standards for the Forest-Steppe zone of Ukraine over different periods: Myronivska 808 (1968–1973), Illichivka (1974–1980), Poliska 70 (1974–1988), Kyyanka (1981–1986), Myronivska 61 (1987–2004), Donska Napivkarlykova (1984–1995), Poliska 87 (1988–1990), Bilotserkivska Napivkarlykova (2001–2018), Perlyna Lisostepu (2002–2024), Podolyanka (2005–2016), Lisova Pisnya (2015–2024).

All listed varieties belong to the winter wheat group adapted to the Forest-Steppe zone of Ukraine and represent predominantly medium-ripening types used as national standards during different periods of the study. Although cultivar replacement occurred over time, they were selected within the same agroecological adaptation group and maturity class.

Sowing was carried out at optimal dates for the crop using a grain seeder (SZ-3.6). The plot size was 75 m^2 (accounting area 50 m^2). A systematic layout with four replications was applied, with pea as the forecrop. Yield values used in the analysis represent annual means calculated from replicated experimental plots, reducing the influence of within-field variability on long-term trend evaluation.

Because the trials were conducted using uniform methodology throughout the study period, interannual yield variation mainly reflects climatic conditions and cultivar replacement rather than spatial differences among fields. The applied agrotechnology corresponded to common practices for winter wheat cultivation in the Forest-Steppe zone of Ukraine. Mineral fertilisers were applied at a rate of 60 kg ha^{-1} of active substance (superphosphate and potassium salt) during primary tillage. Ammonium nitrate (100 kg ha^{-1} physical weight) was applied twice: on thawed–frozen soil and at the stem elongation stage. Grain yield was determined by plot harvesting with a Sampo-130 combine harvester and adjusted to the standard moisture content of 14%.

The methods and plot sizes remained the same throughout the years of the experiment. The equipment used for sowing and crop maintenance (cultivators, sprayers) and the combine harvesters were updated during this period. Changes in the equipment did not affect the experimental data obtained. Wheat sowing took place at the optimal time between 15 and 25 September; the fertilisation regime was the same throughout the study period: PK_{60} during primary tillage, N_{60} on frozen–thawed soil and N_{30} during the wheat tillering phase. All the varieties studied during this period (11 varieties) belonged to the medium-maturing group, which rules out the influence of the 'Variety' factor on wheat yield in our studies.

Throughout the study period, yield assessment was conducted using consistent plot size, harvesting procedures and standard experimental methodology adopted at the research station, ensuring comparability of yield data across years.

2.4 | Statistical Analysis

2.4.1 | Description of Data

To assess the anomaly of weather conditions, we used the coefficient of significance of deviations (K_c), which expresses how unusual current values of temperature or precipitation are compared to long-term averages:

$$K_c = \frac{X - \overline{X}}{\sigma},$$

where X is the observed value of the meteorological variable in a given year (or period), $\overline{X}$ is the long-term mean value and σ is the standard deviation of the corresponding long-term series. This coefficient expresses the magnitude of deviation from the climatic norm in standardised units and allows comparison of anomalies across variables and periods.

Values close to zero indicate normal conditions, while higher values reflect increasingly rare or extreme deviations (Kalenska et al. 2020). No wheat data available for 2003 due to extreme weather conditions. The experiments were conducted in accordance with the State Variety Testing Procedures (1967) and the Procedures for the Qualification Assessment of Plant Varieties for Suitability for Distribution in Ukraine (1993, 2003 and 2016). The requirements of these methodologies comply with the requirements of the International Union for the Protection of New Varieties of Plants. The requirements for plot size in trials with cereal crops are internationally recognised (25–75 m^2).

Primary quality control and consistency checks of the meteorological observations were performed within the standard procedures of the station monitoring system and no discontinuities affecting the analysed variables were identified in the time series used in this study.

2.4.2 | Variable Description

Ten-day (decade) temperature averages and precipitation sums were available for Bila Tserkva research station. We used vegetation period weather metrics (September–July) for regression analyses. Additionally we calculated average temperature and precipitation sums for individual phenological periods (Autumn: Month of sowing—month before vegetation stoppage; Winter: Month of vegetation stoppage—month before vegetation restoration; Spring: Month of vegetation restoration—July; Summer: Month after harvest—Sowing month), as well as for critical phenological events (average temperature three decades after restoration, sum three decades after restoration precipitation, average temperature last three June & first July decades, average temperature of third May decade). These periods capture key stages of wheat growth: early spring regrowth (tillering and stem elongation), flowering in late May (sensitive to heat stress) and grain filling in late June-early July, when temperature and rainfall strongly determine yield.

Soil moisture metrics across four phenologically critical periods—July, May, restoration (spring regrowth) and sowing—measured at four depth intervals (0–10, 10–20, 20–50 and 50–100 cm) were available. Additionally, we averaged soil moisture across depths, periods and depths and periods to get a more general picture of soil moisture effects.

Further, yearly lengths of wheat phenological phases (autumn vegetation period, winter calm, spring vegetation period and full vegetation period) were calculated to include in the linear regression analyses. The annual duration of the autumn vegetation period was defined as the period between wheat germination and the onset of dormancy. Winter calm is defined as the time from the onset of dormancy in late autumn to the renewal of spring vegetation, which also defines the start of the spring vegetation period that lasts till the day of full ripeness. The duration of the full vegetation period was hence defined as the number of days between germination and full ripeness of winter wheat.

2.4.3 | Variable Selection

In the first step we used a correlation matrix to identify highly correlated variables that represent similar conceptual phenomena. Further, by detecting perfect multicollinearity using the alias function in R (R Core Team 2025), we excluded predictors that are exact linear combinations of others, ensuring estimability of all regression coefficients. In that process we selected *Average deep soil moisture* and *Average July soil moisture* as representative soil moisture measures and excluded highly correlated individual soil depth moisture measures from the initial model (Supporting Information S1). Further, the deepest soil layer (50–100 cm) showed the largest fluctuations and highest values, that is indicative for calculating soil drought. This layer is particularly relevant for winter wheat, which develops deep roots and relies on subsoil moisture reserves during periods of surface drying, especially in late spring and summer.

Likewise, spring vegetation period weather conditions were identified as aliased variables and removed from the initial parameter set.

2.4.4 | Model Selection

We used multiple linear regression to model wheat yield, duration of winter calm and duration of wheat spring regrowth period. Focusing on yield, modelling phenological variables helps to reveal indirect pathways through which climate conditions influence wheat productivity. Duration of phenological timing may influence plant stress, phenology or resource availability and ultimately indirectly affect yield. To select the most concise model, we applied a stepwise model selection procedure based on Akaikes's Information Criterion (AIC). Stepwise model selection was performed using the stepAIC-function from the MASS package (Venables and Ripley 2002). Starting from a full model including all candidate predictors, listed in Supporting Information S2, variables are added or removed iteratively using both forward and backward selection to minimise the AIC. The selection process is stopped when no addition or removal of variables improves the AIC. Finally, the model with the lowest AIC was selected. Diagnostic checks were conducted to validate model assumptions. In addition, we ran each model for a different subset of years to detect distinct effects under different conditions: (i) all available years, (ii) particularly warm years and (iii) drought years. Warm years were selected as years with above average vegetation period temperature means and drought years as years with above average vegetation period temperature means and below average vegetation period precipitation sums.

3 | Results

In recent decades, starting from the 1990s (Figure 1), the study site has experienced a pronounced warming trend in both the frequency and intensity of temperature anomalies during the calendar year and the full vegetative period of winter wheat, relative to the long-term average. These changes strongly influence crop development because temperature affects growth, yield stability and vegetation stages. The linear trend in temperature was evaluated using a linear regression model. The trend indicates a significant temperature increase over the study period of +0.050°C per year ($R^2 = 0.52$ and statistical significance $p < 0.05$) and +0.046°C per vegetation period ($R^2 = 0.42$, $p < 0.05$). The long-term mean air temperature was 8.2°C, with a maximum of 11.2°C recorded in 2024 and a minimum of 5.6°C in 1987. Years with notably higher values (9.2°C–10.3°C) included 1975, 1989, 1999, 2007–2009, 2015–2017, 2019 and 2022–2024, while markedly lower values (6.0°C–7.1°C) occurred in 1969, 1976, 1980, 1985, 1986, 1988, 1993, 1996 and 1997. Analysis further shows a consistent shift from predominantly negative anomalies in the 1970s–1980s, indicating cooler-than-average conditions, towards positive deviations beginning in the late 1980s, with especially sharp increases after 2000.

The yearly rainfall amount and intra-year distribution of precipitation varies strongly interannually. For example, 1996 and 2016 recorded particularly high annual precipitation totals, with 2016 accompanied by particularly high rainfall during the spring regrowth period (Figure 2). However, high annual precipitation totals do not always coincide with high rainfall during the spring regrowth period. In 1996 the spring regrowth precipitation sum reached average levels whereas annual precipitation was exceptionally high. In 2014, precipitation during the spring regrowth phase reached approximately 373 mm, which is significantly higher than the multi-year average with around average annual precipitation sum. In contrast, 2022 experienced one of the lowest recorded values, with only 135 mm during the winter wheat spring regrowth period, likely reflecting drought conditions that could have negatively impacted crop

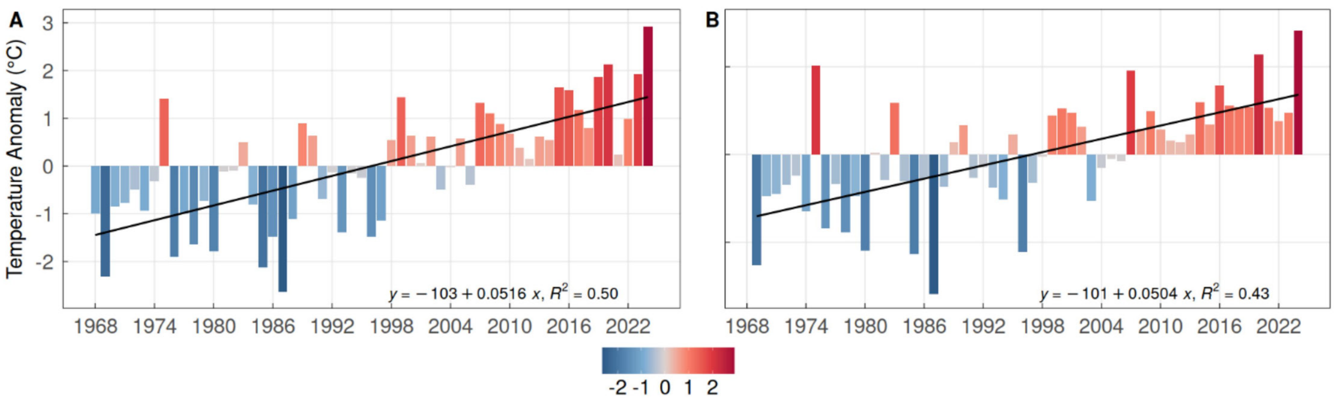

FIGURE 1 | Mean temperature deviation for the calendar year (A) and during vegetation period (B) from long term temperature average (1968–2024). [Colour figure can be viewed at wileyonlinelibrary.com]

development. The long-term mean annual precipitation was 567.9 mm (1968–2024), with a maximum of 931 mm in 1996 and a minimum of 350.4 mm in 1975. Years with markedly low totals (391–463 mm) included 1972, 1994, 2008, 2009, 2011, 2015, 2021 and 2022, while exceptionally wet years (678–838 mm) occurred in 1980, 1981, 2001, 2013 and 2016. Notably, more than half of these extremes were observed after 2008, reflecting an increase in variability. On average, precipitation during the spring regrowth phase accounted for 150–300 mm of annual totals.

The data in Figure 3 reveal a modest but consistent downward trend in the duration of winter calm over the past 56 years. In

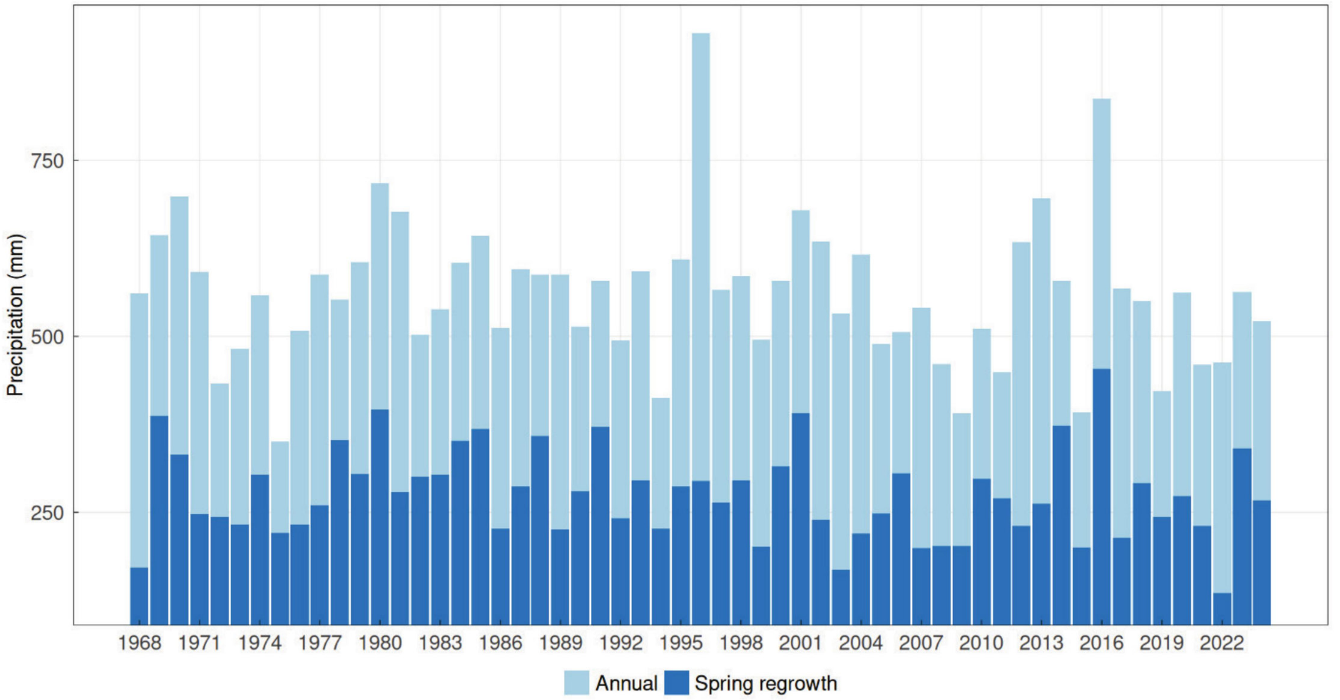

FIGURE 2 | Annual and spring regrowth precipitation sums at Research Station (1968–2024). [Colour figure can be viewed at wileyonlinelibrary.com]

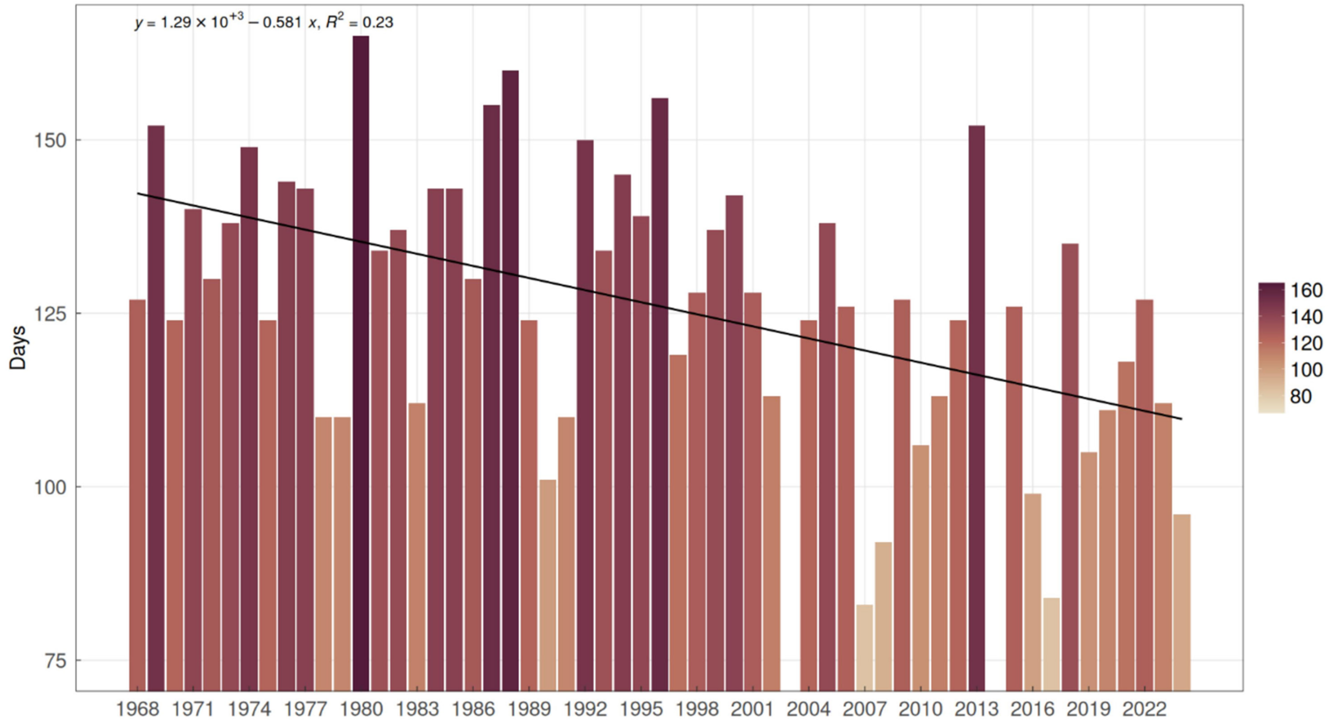

FIGURE 3 | Duration of winter calm. [Colour figure can be viewed at wileyonlinelibrary.com]

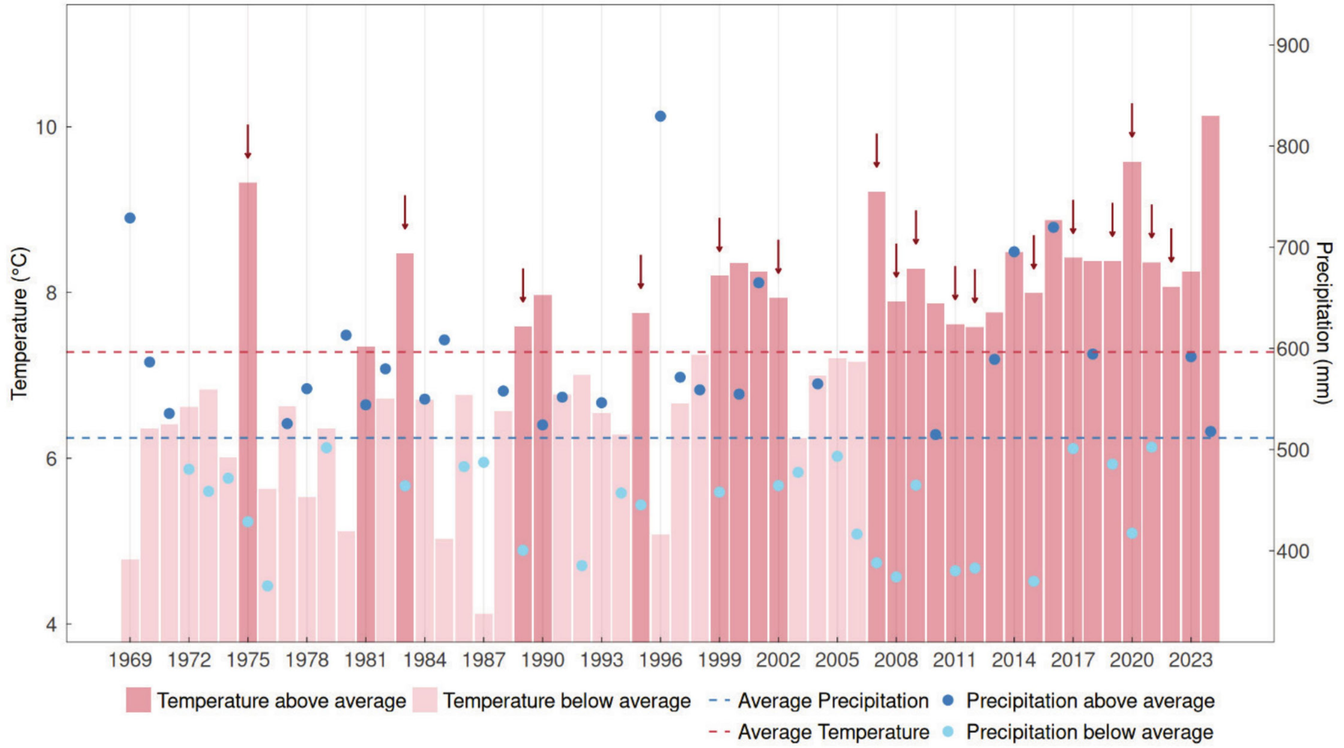

FIGURE 4 | Atmospheric drought in full vegetation periods of winter wheat. [Colour figure can be viewed at wileyonlinelibrary.com]

the early decades, particularly 1980–1989, the calm period often exceeded 150 days, with maxima approaching 165 days. In contrast, after 1996 values generally fell below 130 days and in several years (most notably 2007, 2008, 2014, 2017) dropped under 95 days. On average, the calm period has shortened by approximately 24 days after 2007 compared with 1968–2006, indicating a gradual reduction that may alter winter soil moisture recharge, soil thermal regimes and subsequent crop emergence. Analysis of autumn vegetation stoppage dates shows a marked shift towards later timings: the mean date moved from 8 November in 1967–1976 to 23 November in 2008–2017, with a long-term average of 13 November and a wide range between 22 October and 18 December. Across the study period, autumn vegetation lasted on average 50 days, ranging from 26 days in 2023 to 84 days in 2006. Based on this, autumn stoppage was classified as very early (before 28 October), early (28 October–7 November), optimal (8–18 November), late (19–29 November) and very late (after 29 November). Consistent with these shifts, the mean winter calm period declined from 139 days in 1967/68–1976/77 (amplitude 28 days) to 115 days in 2008/09–2023/24, with variability widening from 28 to as much as 85 days (67–152). These findings demonstrate both the shortening and increasing variability of winter calm, reflecting broader climatic changes affecting the seasonal development of winter wheat.

Figure 4 highlights years of combined heat and drought stress during the winter wheat vegetation period, characterised by above-average temperatures and below-average precipitation (arrows). The most recent period (2007–2024) shows a clear clustering of such events, with growing-season temperatures consistently exceeding the long-term mean (~7.3°C) by 0.3°C–2.8°C, averaging about +1°C in drought years. Over the full study period, mean precipitation was ~512 mm, with roughly half of the years before 2007 exceeding this value. After 2007, however, most seasons fell below the average, with deficits of ~100 mm on average, underscoring an increasing tendency towards warm and dry conditions. This warming trend since the early 21st century has been accompanied by a greater frequency of years with above-average temperatures, while precipitation remained highly variable. The combination of elevated temperatures and insufficient rainfall intensifies water stress, particularly in years such as 1975, 1992 and 2019, when extreme anomalies occurred. Importantly, even near-average or above-average rainfall can fail to offset higher evaporative demand under elevated temperatures, meaning that the interaction of heat and drought exerts a stronger negative effect on crop development than either factor alone.

The productive soil moisture baseline was approximately 112 mm (Figure 5). When moisture levels dropped below this threshold under growing-season temperatures equal to or exceeding the long-term average of 7.3°C, a clear pattern of compound stress emerged. In the past 17 years, eight hot-dry seasons were recorded (2007, 2008, 2010–2012, 2016, 2018, 2020), with extreme deficits in 2010 (55 mm) and 2020 (57 mm). By contrast, only five such events occurred in the preceding 38 years, meaning that soil moisture droughts (defined by the co-occurrence of high temperature and markedly reduced subsoil water) now occur in roughly half of the years after 2007, compared to approximately 13% earlier. This marks a pronounced shift towards more frequent and persistent soil drought during the winter wheat vegetation period. Notably, in most years since 2000, mean temperatures have exceeded the long-term average, while deep soil moisture more often remained below it. This interaction indicates that even when rainfall is present, elevated temperatures accelerate soil drying and reduce water availability, amplifying drought stress. Such combined effects of heat and low soil moisture are more detrimental to yield than either factor in isolation.

The annual average winter wheat yield showed a consistent increase over the study period (Figure 6). Yields rose from approximately 3.2–6.3 t ha^{-1} (mean 4.6 t ha^{-1}) in the early decades (1968–1985) to 5–9.6 t ha^{-1} (mean 7.1 t ha^{-1}) in recent years (2015–2024), with peak values above 8 t ha^{-1} in 1994, 2015 and 2018. A linear regression ($y = -70.1 + 0.0379x$, $R^2 = 0.17$) indicated an average annual increase of approximately 0.038 t ha^{-1}/year. Yield

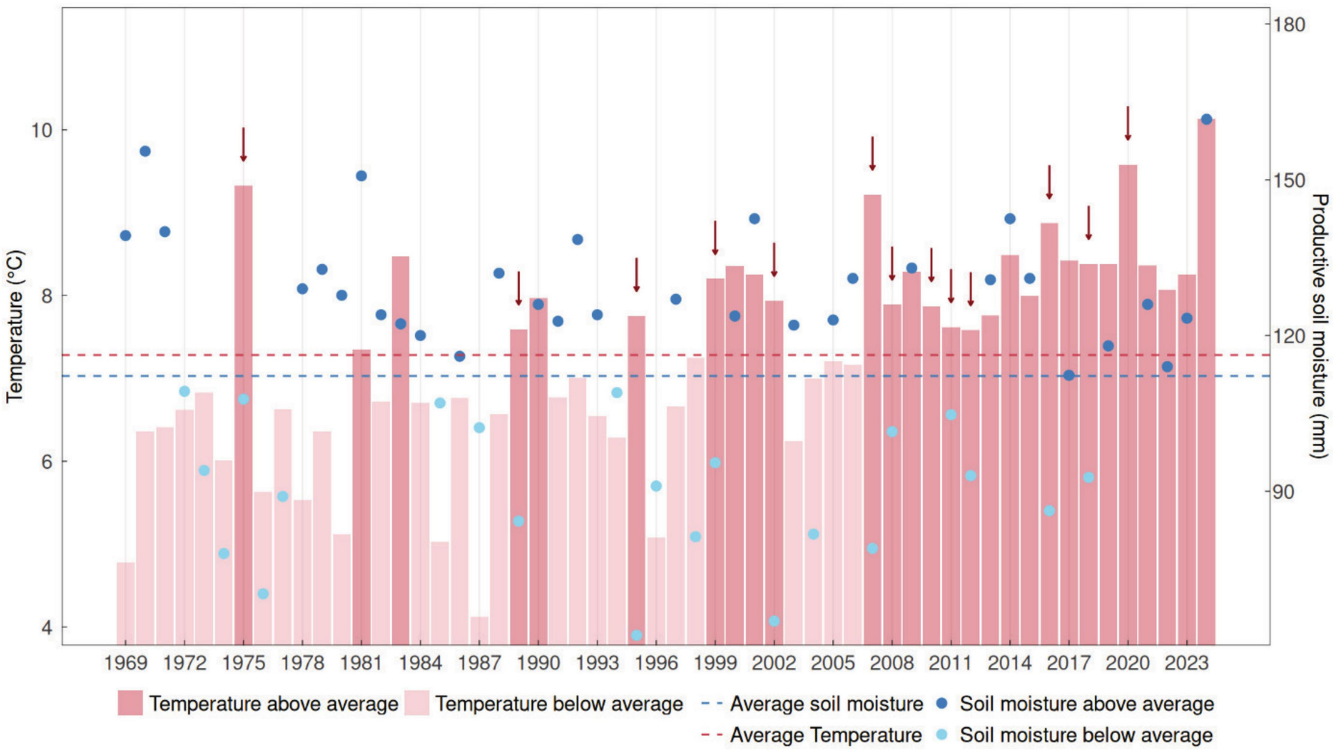

FIGURE 5 | Soil drought at 50–100 cm depth in vegetation periods of winter wheat. [Colour figure can be viewed at wileyonlinelibrary.com]

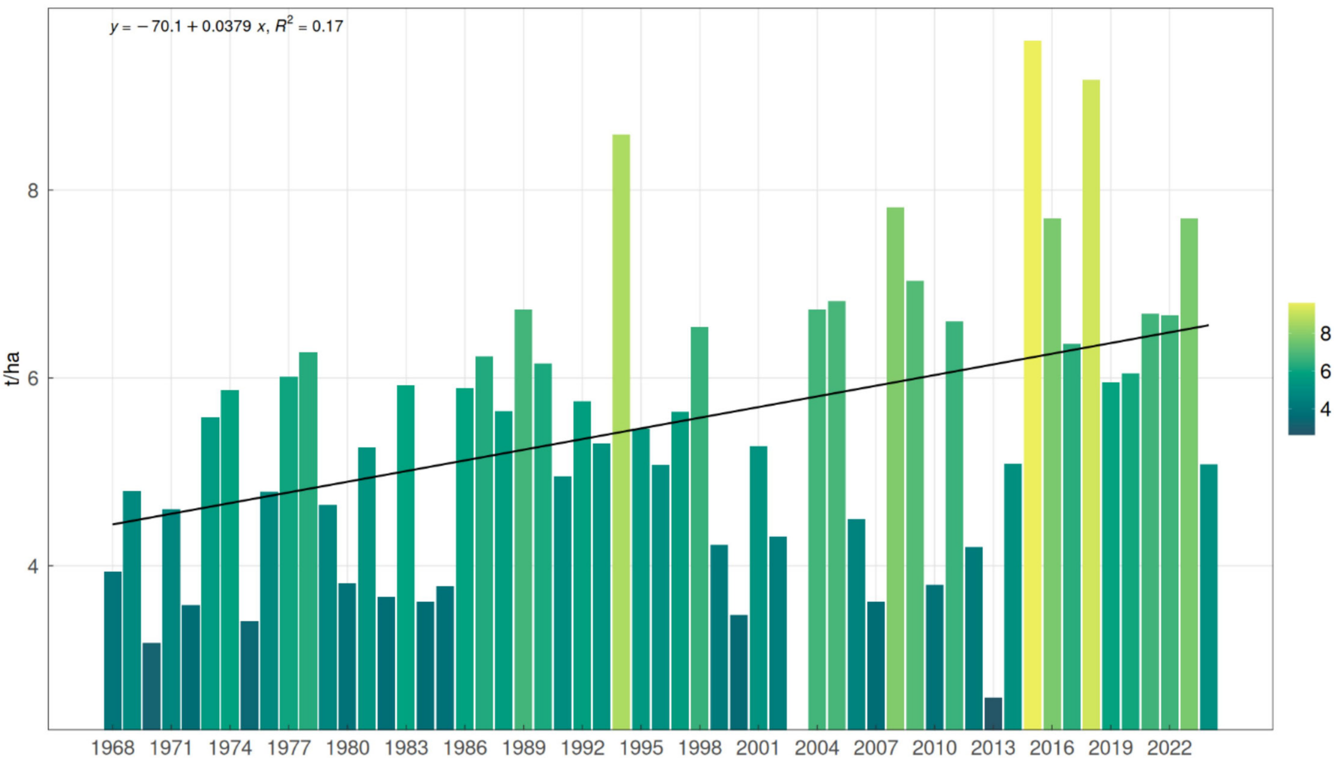

FIGURE 6 | Annual average yield of winter wheat. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 | Linear model results for yield as dependent variable after variable selection process for three different subsets of years, whereas *n* indicates the number of years for each subset.

	All years (R^2 0.61; $n=53$)			Hot years (R^2 0.66; $n=28$)			Drought years (R^2 0.84; $n=17$)		
Characteristic	**Beta**	**95% CI**	***p***	**Beta**	**95% CI**	***p***	**Beta**	**95% CI**	***p***
Duration of winter calm (day)	−0.03	−0.05, −0.01	**0.002**	−0.04	−0.07, −0.01	**0.018**	−0.04	−0.08, 0.00	**0.040**
Duration of autumn vegetation period (day)	−0.03	−0.06, 0.00	0.061				−0.05	−0.11, 0.00	0.055
Average July soil moisture (mm)	−0.03	−0.05, −0.01	**0.003**	−0.05	−0.08, −0.02	**0.007**	−0.06	−0.09, −0.03	**<0.001**
Average autumn temperature (mm)	−0.32	−0.49, −0.14	**<0.001**	−0.74	−1.1, −0.40	**<0.001**	−0.18	−0.42, 0.07	0.14
Temperature (°C)				−1.1	−2.5, 0.22	0.10	−0.57	−1.5, 0.38	0.2
Precipitation (mm)				0.00	0.00, 0.01	0.2			
Average summer temperature (°C)				0.54	−0.16, 1.2	0.12			
Sum summer precipitation (mm)				−0.02	−0.04, −0.01	**0.008**			
Average winter temperature (°C)				0.36	−0.22, 0.95	0.2			
Average deep soil moisture (mm)				0.04	0.01, 0.07	**0.007**	0.03	0.01, 0.05	**0.015**
Sum autumn precipitation (mm)							−0.01	−0.03, 0.00	**0.015**

Note: Applies to this and the following tables. Beta: shows the direction and strength of the relationship between the respective predictors and dependent variable. Bold values indicate statistically significant beta coefficients ($p < 0.05$).
Abbreviation: CI, confidence interval.

variability remained substantial, with only ~17% of the interannual variation explained by the temporal trend.

Across 56 years of observations, the timing of autumn vegetation cessation influenced yield outcomes. The highest mean yields (6.13 t ha^{-1}) were obtained under late cessation, while early and very early cessations resulted in slightly lower averages (5.77 and 5.45 t ha^{-1}, respectively). Optimal cessation dates yielded 5.21 t ha^{-1}, while extremely late cessation beyond 29 November produced yields close to the long-term mean (5.75 t ha^{-1}). Individual years showed deviations, such as 1967/68 and 1969/70, when late cessation corresponded to relatively low yields (3.94 and 3.18 t ha^{-1}). Early cessation in 1979/80 likewise produced a reduced yield (3.81 t ha^{-1}). In contrast, several years with optimal timing, such as 1972/73, 1985/86, 2003/04 and 2019/20, achieved yields of 5.6–7.7 t ha^{-1}.

Although average lengths of active growth in autumn and spring–summer changed little across decades (170 days in 1967/68–1976/78 vs. 166 days in 2008/09–2023/24), variability more than doubled, from 32 to 68 days. The total vegetation period shortened from 309 days to 282 days on average, indicating climate-driven shifts in crop development. The timing of spring regrowth was especially critical: very early renewal produced the highest mean yields (6.43 t ha^{-1}), while late and very late renewals led to marked reductions (5.12 and 4.50 t ha^{-1}, respectively). These findings suggest that earlier resumption of growth allows plants to exploit favourable conditions before the onset of late spring and summer heat stress.

Across all years, longer winter calm periods and reduced July soil moisture were both significantly associated with lower yields ($\beta = -0.03$ t ha^{-1} day^{-1}, CI [−0.05, −0.01 t ha^{-1} day^{-1}], $p = 0.002$; $\beta = -0.03$ t ha^{-1} mm^{-1}, CI [−0.05, −0.01 t ha^{-1} mm^{-1}, $p = 0.003$], respectively) (Table 1). Regression coefficients (β) and respective confidence intervals (CI) are expressed in units of yield (t ha^{-1}) per unit increase or decrease in the respective predictor. With probability values (p) expressing the statistical evidence against the null hypothesis (see also Table 1). Higher average autumn temperatures also negatively impacted yields ($\beta = -0.32$ t ha^{-1}°C^{-1}, CI [−0.49, −0.14 t ha^{-1}°C^{-1}], $p < 0.001$). Similar, though somewhat stronger, effects were observed in the hot-years subset: winter calm ($\beta = -0.04$ t ha^{-1} day^{-1}, CI [−0.07, −0.01 t ha^{-1} day^{-1}], $p = 0.018$), July soil moisture ($\beta = -0.05$ t ha^{-1} mm^{-1}, CI [−0.08, −0.02 t ha^{-1} mm^{-1}], $p = 0.007$) and autumn temperature ($\beta = -0.74$ t ha^{-1}°C^{-1}, CI [−1.10, −0.40 t ha^{-1}°C^{-1}], $p < 0.001$) were all significant predictors. In drought years, extended winter calm again reduced yields

($\beta = -0.04$ t ha^{-1} day^{-1}, CI [−0.08, −0.00 t ha^{-1} day^{-1}], $p = 0.040$) and July soil moisture had an even stronger negative coefficient ($\beta = -0.06$ t ha^{-1} mm^{-1}, CI [−0.09, −0.03 t ha^{-1} mm^{-1}], $p < 0.001$), while increased deep-soil moisture during winter showed a positive association with yield ($\beta = 0.03$ t ha^{-1} mm^{-1}, CI [0.01, 0.05 t ha^{-1} mm^{-1}], $p = 0.015$). Additionally, autumn precipitation modestly reduced yield in drought years ($\beta = -0.01$ t ha^{-1} mm^{-1}, CI [−0.03, −0.00 t ha^{-1} mm^{-1}], $p = 0.015$). Overall, models explain more variance under stress conditions ($R^2 = 0.61$, 0.66 and 0.84 for all, hot and drought years respectively), highlighting the increasing relevance of seasonal water and temperature dynamics under elevated heat and moisture stress.

Models for hot years largely mirror the full dataset, with temperature K_c ($\beta = -10.0$, $p = 0.012$), spring ($\beta = -0.75$ day day^{-1}, $p < 0.001$) and autumn vegetation durations ($\beta = -0.87$ day day^{-1}, $p < 0.001$) significantly associated with reduced calm period (Table 2). Additionally, the sum of summer precipitation ($\beta = -0.15$ day mm^{-1}, $p = 0.003$) and the average July soil moisture ($\beta = -0.28$ day mm^{-1}, $p = 0.022$) showed significant negative effects and average summer temperature also negatively impacted calm duration ($\beta = -5.4$ day °C^{-1}, $p = 0.022$).

In drought years, models explain even more variability ($R^2 = 0.94$). Spring ($\beta = -1.1$ day day^{-1}, $p < 0.001$) and autumn vegetation durations ($\beta = -0.92$ day day^{-1}, $p < 0.001$) remain strong negative predictors. Precipitation K_c showed a significant positive relationship ($\beta = 1.6$, $p = 0.017$) and the cumulated winter precipitation had a modest negative effect ($\beta = -0.15$ day mm^{-1}, $p = 0.024$). Other variables (e.g., temperature K_c, winter temperature, autumn temperature or precipitation) were not consistently significant.

Overall, the duration of the winter calm period is most strongly constrained by phenological timing (spring/autumn vegetation phases) and crop water/energy demand parameters, notably temperature K_c and summer moisture, in both average and stress-year contexts, with model explanatory power increasing under drought conditions.

Table 3 summarises the linear regression models predicting the duration of the spring vegetation period across three scenarios (all years, hot years and drought years). In the full dataset ($n = 53$, $R^2 = 0.60$), longer autumn vegetation duration ($\beta = -0.42$ day day^{-1}, $p < 0.001$), extended winter calm ($\beta = -0.42$ day day^{-1}, $p < 0.001$) and greater winter precipitation ($\beta = -0.10$ day mm^{-1}, $p < 0.001$) were all significantly associated with shorter spring growth duration. Increased autumn precipitation showed a weaker negative effect ($\beta = -0.06$ day mm^{-1}, $p = 0.041$). Under hot-year conditions ($n = 28$, $R^2 = 0.63$),

TABLE 2 | Linear model results with the duration of winter calm as dependent variable after variable selection process for three different subsets of years.

	All years (R^2 0.78; $n = 53$)			Hot years (R^2 0.78; $n = 28$)			Drought years (R^2 0.94; $n = 17$)		
Characteristic	**Beta**	**95% CI**	***p***	**Beta**	**95% CI**	***p***	**Beta**	**95% CI**	***p***
Temperature K_c	−9.1	−12, −6.6	**< 0.001**	−10	−18, −2.5	**0.012**	−6.1	−19, 6.7	0.3
Precipitation K_c	−0.32	−0.67, 0.03	0.074				1.6	0.38, 2.8	**0.017**
Sum summer precipitation (mm)	−0.05	−0.10, 0.00	0.067	−0.15	−0.25, −0.06	**0.003**	−0.09	−0.26, 0.07	0.2
Duration of spring vegetation period (day)	−0.74	−0.98, −0.50	**< 0.001**	−0.75	−1.1, −0.42	**< 0.001**	−1.1	−1.5, −0.73	**< 0.001**
Duration of autumn vegetation period (day)	−0.75	−0.98, −0.51	**< 0.001**	−0.87	−1.3, −0.49	**< 0.001**	−0.92	−1.3, −0.52	**< 0.001**
Average July soil moisture (mm)	−0.13	−0.28, 0.02	0.091	−0.28	−0.52, −0.04	**0.022**			
Average summer temperature (°C)				−5.4	−10, −0.86	**0.022**			
Average winter temperature (°C)							5.4	−0.47, 11	0.066
Sum winter precipitation (mm)							−0.15	−0.27, −0.03	**0.024**
Average autumn temperature (°C)							−1.6	−4.5, 1.3	0.2
Sum autumn precipitation (mm)							−0.07	−0.19, 0.05	0.2

Note: Bold values indicate statistically significant beta coefficients ($p < 0.05$).

TABLE 3 | Linear model results with the duration of spring regrowth period as dependent variable after variable selection process for three different subsets of years.

	All years (R^2 0.60; $n=53$)			Hot years (R^2 0.63; $n=28$)			Drought years (R^2 0.90; $n=17$)		
Characteristic	**Beta**	**95% CI**	***p***	**Beta**	**95% CI**	***p***	**Beta**	**95% CI**	***p***
Temperature K_c	−2.6	−5.4, 0.15	0.063				−4.3	−15, 6.6	0.4
Precipitation K_c	0.34	−0.16, 0.84	0.2				1.3	0.31, 2.3	**0.018**
Duration of autumn vegetation period (day)	−0.42	−0.66, −0.18	**<0.001**	−0.50	−0.84, −0.16	**0.005**	−0.74	−1.1, −0.38	**0.002**
Duration of winter calm (day)	−0.42	−0.62, −0.22	**<0.001**	−0.45	−0.66, −0.24	**<0.001**	−0.77	−1.0, −0.50	**<0.001**
Sum winter precipitation (mm)	−0.10	−0.15, −0.04	**<0.001**	−0.07	−0.12, −0.02	**0.010**	−0.12	−0.23, −0.02	**0.027**
Sum autumn precipitation (mm)	−0.06	−0.13, 0.00	**0.041**				−0.07	−0.16, 0.03	0.2
Sum summer precipitation (mm)							−0.06	−0.20, 0.08	0.3
Average winter temperature (°C)							4.6	−0.23, 9.3	0.059
Average autumn temperature (°C)							−1.3	−3.7, 1.1	0.3

Note: Bold values indicate statistically significant beta coefficients ($p<0.05$).

these relationships remained significant: autumn vegetation ($\beta=-0.50$ day day^{-1}, $p=0.005$), winter calm ($\beta=-0.45$ day day^{-1}, $p<0.001$) and winter precipitation ($\beta=-0.07$ day mm^{-1}, $p=0.010$). During drought years ($n=17$, $R^2=0.90$), the model explained more variance, with more substantial negative effects of autumn vegetation duration ($\beta=-0.74$ day day^{-1}, $p=0.002$), winter calm ($\beta=-0.77$ day day^{-1}, $p<0.001$) and winter precipitation ($\beta=-0.12$ day mm^{-1}, $p=0.027$), alongside a positive influence of rainfall responsiveness coefficient, precipitation K_c ($\beta=1.3$, $p=0.018$). These results indicate that both phenological timing (autumn and winter durations) and winter moisture availability consistently and strongly constrain the length of the spring vegetation period, with the most pronounced effects observed under drought conditions.

4 | Discussion

Our results indicate a steady long-term increase in winter-wheat yield, but the low R^2 of the regression trend underscores that interannual variability is driven largely by weather conditions and phenology rather than time alone. This upward shift likely reflects the cumulative effects of agronomic improvements (cultivars, fertilisers, crop protection and management practices) and only to a limited degree of weather. Because the dataset is based on long-term observations from a single experimental site using successive standard cultivars, part of the observed yield dynamics may reflect cultivar replacement and gradual improvements in agronomic practices. However, the use of a stationary experimental design with consistent methodology allows separation of interannual climatic variability from long-term technological trends and climate effects were evaluated primarily through regression models including temperature, precipitation, soil moisture and phenological indicators rather than through yield trends alone. Sowing dates followed the recommended regional time window throughout the study period and fertilisation schemes remained within standard production practices for the Forest-Steppe zone, which limits their influence on interannual variability compared with weather-related and phenological controls. Years of drought in the atmosphere and soil did not consistently reduce yield, supporting the idea that the timing of stress relative to the phenological stages is decisive. For example, yields were often higher under late autumn vegetation cessation, with occasional high yields also under very early/early cessation, while optimal cessations did not always correspond to highest yields. Similarly, earlier spring regrowth in our data set was associated with higher mean yields, suggesting that faster vegetative cover development allows crops to capture resources before late-spring/early-summer heat and evaporative demand intensify (Figure 6 and Table 1).

These patterns align with experimental and modelling studies showing that heat stress during flowering and grain filling, combined with water deficits, disproportionately reduce kernel number and weight (Urruty et al. 2017; Luo 2011; Bakker et al. 2005; Sarto et al. 2017; Lüttger and Feike 2018; Barnabás et al. 2008; Asseng et al. 2011; Martre et al. 2015; Hütsch et al. 2019; Wollmer et al. 2016). Literature also emphasises that precipitation during vegetative stages enhances yield, whereas high maximum temperature is detrimental (Barnabás et al. 2008). This is consistent with our observation that delayed renewal of spring vegetation lowered yields (Mostipan et al. 2021) and with other studies that found yield to correlate positively with precipitation and relative humidity and negatively with air temperature and sunshine, with spring and May conditions being most influential (Faghih et al. 2021). Grain filling remains particularly vulnerable: high temperatures and water shortage shorten the phase and reduce grain weight by limiting starch accumulation (Barnabás et al. 2008).

Broader regional analyses support this view. In Germany, recurrent dry and warm springs/summers (2003, 2018) caused substantial yield losses, with below-trend years often well explained by extreme weather (Heil et al. 2023). For wheat in 1976–2005, negative yield trends were found in 51 of 244 regions, while others (UK, Germany, Belgium, Netherlands) reported small positive trends (Supit et al. 2010). Global modelling indicates ~5.7% yield loss per +1°C (Liu et al. 2016). Studies in western Germany (1952–2013) found that modern winter wheat cultivars required 14%–18% fewer degree-days from emergence to flowering compared with cultivars grown in the 1950s–1960s. Phenological modelling based on field observations indicated that both rising mean temperatures and cultivar properties contributed equally to these flowering-date trends, whereas sowing-date changes had only a minor effect (Rezaei et al. 2018). Heading dates were further shown to be strongly linked to spring mean temperature (Rezaei et al. 2015). Changing crop phenology is thus an important bio-indicator of climate change (Rezaei et al. 2018).

Our findings that longer winter calm and lower soil moisture in July are significantly associated with reduced yields (Table 2) are consistent with other studies showing that yield correlates with winter duration (Holmer 2008). Shorter winters generally favour higher yields, as seen in our models. Soil quality and water availability during crucial stages are among the most important determinants of yield variability (Wójcik-Gront 2018), reinforcing the significance of July soil moisture as a predictor. At the same time, phenology itself mediates exposure: earlier maturity can reduce flowering heat stress (Rezaei et al. 2015) but shortened grain filling curtails biomass deposition even without extremes (Martre et al. 2015).

These results also fit European observations where yield anomalies have increasingly correlated with heat/drought indicators in recent decades (Trnka et al. 2014; Zampieri et al. 2017; Beillouin et al. 2020; Moravec et al. 2021; Webber et al. 2020; Lüttger and Feike 2018). Yet regional exceptions show that warmer winters with more spring precipitation can enhance yield in some continental climates (Morgounov et al. 2014) and rising T_{min} contributed to yield gains in Australia (Nicholls 1997). Such contrasts help explain reports of positive temperature–yield correlations at broader scales due to spatial compensation (FAO 2021). More broadly, stress factors such as heat and drought interact with cultivar change (Rezaei et al. 2018) and compound extremes (hot–dry or hot–humid) are becoming more frequent and severe (Liu et al. 2025), further complicating projections.

Looking ahead, climate projections suggest little increase in heat stress in the near term (2020–2049), but a substantially higher risk of grain fill heat stress by 2070–2099 (Gouache et al. 2012). Adaptation via earlier sowing appears least effective, while earlier-heading cultivars may help in the short term. However, breeding for heat-stress tolerance is the most promising long-term strategy. Together with our findings on phenological durations and July soil moisture, this underlines the importance of phenology-aware adaptation: breeding for stress resilience, adjusting sowing dates and conserving soil water during critical stages (Müller et al. 2016; Yashavanthakumar et al. 2021; Rezaei et al. 2023; Ulukan 2024; Neupane et al. 2022; Tao et al. 2017). Finally, given large model uncertainty in mid- to high latitudes (Xiong et al. 2020) and the scarcity of long, stage-resolved datasets (Bönecke et al. 2020), future work should combine multifactor trials and process-plus-data models to better disentangle genotype × environment × management effects.

Beyond the statistical relationships identified in our models, several broader aspects deserve consideration. First, part of the observed upward yield trend likely reflects cultivar turnover and advances in breeding. Newer winter wheat cultivars have shorter thermal requirements for development, improved resistance to pests and diseases and greater tolerance to abiotic stress compared to older varieties (Rezaei et al. 2018). This genetic progress, together with enhanced input use and management, has contributed substantially to productivity gains, complementing rather than replacing the role of climate.

Second, our regression results emphasise seasonal averages; extreme events remain decisive for yield stability. Isolated years such as 2003 and 2018 demonstrate how single seasons with unusual heat or drought can strongly depress yields (Heil et al. 2023). These events highlight the need to complement trend analyses with a focus on thresholds, for example, short episodes of >32°C during flowering or deficits in July soil moisture beyond critical levels, which disproportionately reduce yield.

Third, the interaction between heat and drought is particularly damaging. Even when precipitation totals are near average, higher evaporative demand can reduce effective soil water availability (Wollmer et al. 2016). Our finding that July soil moisture is a key determinant of yield confirms that deeper subsoil reserves are often more critical than atmospheric drought indices alone. This aligns with evidence that soil water status, not just precipitation, governs stress intensity (Wójcik-Gront 2018).

Finally, the growing variability in phenological durations observed in our dataset is important not only for mean yield but also for yield stability. Longer or shorter autumn and spring phases can shift exposure to stress, creating trade-offs between the benefits of extended growth and the risks of late frost or early summer heat. Such trade-offs reinforce the importance of adaptive strategies, particularly cultivar selection with tailored phenology, water-conserving agronomy and stress-tolerant breeding as key tools to maintain both productivity and stability under ongoing climate change (Yashavanthakumar et al. 2021; Rezaei et al. 2023; Ulukan 2024; Neupane et al. 2022).

5 | Conclusion

During the period 1968–2024, the productivity of winter wheat in the central part of the Right-Bank Forest-Steppe of Ukraine has increased significantly. However, the study reveals that warming trends, increased frequency of precipitation extremes, soil moisture shortages, shortened winter calm and growing variability in autumn and spring phenology are progressively threatening yield stability. Although average yields have increased from ~4.6 to ~7.1 t ha^{-1}, only a modest portion of interannual yield variation (~17%) is explained by temporal trends alone. Critical findings include the rise in soil moisture droughts below ~112 mm at 50–100 cm depth since 2007, especially in warm years and the strong relationship between higher yields and favourable phenological timing (later autumn cessation, earlier spring regrowth). In addition, our results show that despite higher average temperatures, not all warmer years led to low yield; it remains closely tied to how the phenological schedule aligns with periods of moisture availability and seasonal drought. Further research should focus on disentangling the relative contributions of cultivar genetics, management and climate extremes, using long-term, stage-specific field data to improve prediction and guide regionally tailored adaptation.

Author Contributions

Tetiana Grabovska: conceptualization, investigation, writing – original draft, methodology, validation, writing – review and editing, formal analysis, project administration. **Jerome Schneuwly:** investigation, writing – review and editing, validation. **Hynek Roubik:** conceptualization, writing – review and editing, supervision. **Mykola Grabovskyi:** conceptualization, investigation, writing – original draft, writing – review and editing, visualization, validation. **Mykola Lozinskiy:** investigation, writing – review and editing, visualization, validation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Supporting Information S1:** Productive soil moisture for different wheat growth stages. **Supporting Information S2:** Model variables included in the variable selection process.