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Heat Stress

Response of Durum Wheat Cultivars to Climate Change in a Mediterranean Environment: Trends of Weather and Crop Variables at the Turn of 21st Century

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ABSTRACT

A better comprehension and analysis of climate impacts on crop traits allows the implementation of more appropriate adaptation strategies and, therefore, a higher resilience of the future cropping systems. The aims of this study were: (i) to assess how the climate changed in the last 32 years in a Mediterranean-type climate, (ii) to understand how crop traits evolved over time in early and late durum wheat cultivars and (iii) to highlight which weather variables mostly affected the performances of diverse durum wheat varieties. To investigate this, a 32-year period (i.e., 1989–2020) was analysed, detecting possible significant trends of weather variables (e.g., air temperatures, precipitations, solar radiation) and crop traits (e.g., earliness, yield, yield components and test weight) over time in Viterbo, central Italy. Eight durum wheat varieties (4 early and 4 late cultivars) were chosen from the most used in that location. A clear upward trend of the monthly maximum air temperature during the entire growing season was revealed (0.12°C–0.21°C per year), while rainfall displayed a significant trend only for February and March. Days to heading and number of spikes per unit area showed a significant downward trend moving towards 2020. Anticipation of heading date was much more pronounced in the late cultivars than in the early ones, so that the difference between the two groups was reduced from about 10 days of 1989 to less than 6 days of 2020. Grain yield stagnated around 5 $t\,ha^{-1}$ with late varieties that proved to be as good producers as the early ones. Test weight and thousand kernel weight showed a slight increase over time. Maximum temperatures of February and March exerted a considerable influence in reducing time to heading (0.7–3.4 days for each additional °C), while the maximum temperature of May was detrimental for grain yield (−180 to −270 $kg\,ha^{-1}$ for each additional °C). Our study identified two weak points in the current durum wheat cultivation: (i) phenology is being more and more similar among modern cultivars; (ii) the number of spikes per unit area dramatically decreased in the last 30 years. Therefore, beside greater genetic diversity, a new agronomic approach, especially from seeding to the end of the tillering stage, will be required to cope with durum cultivation in the future climate scenario of the Mediterranean. The outputs of our analysis add precious information on the comprehension of climate change effects on Mediterranean cropping systems and can guide either the decision making for the management of durum wheat or its breeding activity for the future.

Summary

- A clear upward trend of the monthly maximum air temperature was detected.
- Maximum temperatures of February and March markedly shortened the pre-heading phase.
- Heading dates of early and late durum cultivars got closer over time.
- Number of spikes per unit area dramatically decreased in the last three decades.
- Grain yield was stagnating and was negatively affected by air temperature in May.

1 | Introduction

The shifts of climatological conditions, caused by climate change, are expressed by an increase in extreme weather events, abiotic stresses and global warming (Anderson, Bayer, and Edwards 2020). This pattern is threatening food security as well as the sustainability of farming systems. Given the primary role of the agricultural sector in the Mediterranean region, it is critical to identify first the expected specific risks, and then the adaptation strategies, policies and specific management tools to cope with climate change. In this regard, crop rotation, optimal sowing date, optimization of irrigation and plant nutrition, choice of cultivars with different earliness and reduced tillage practices are considered the key agronomic strategies to better achieve the sustainable development goals (Ferrise et al. 2010; Mathlouthi et al. 2022; Mathlouthi, Ruggeri, and Rossini 2022; Mihailescu and Soares 2020; Prabhjyot-Kaur, Sandhu, and Kothiyal 2024; Tapley et al. 2013).

Durum wheat (*Triticum turgidum* L. subsp. *durum* (Desf.) Husn.) has always been a key commodity of southern Europe and a staple food crop for millions of people. The Countries surrounding the Mediterranean Sea, characterised by semi-arid climates, ensure the production of nearly 50% of global durum wheat (Martínez-Moreno, Ammar, and Solís 2022). In Italy, this crop (mainly cultivated in southern and central Italy) accounted for 3.8 million tons in 2023 (53% of EU durum production), while bread wheat (and spelt) for 3.1 million tons (Eurostat 2024). Cereal production is sensitive to environmental factors and it is conditioned by drought and heat stress during the growing seasons. In general, weather variability and water availability, inducing phenological changes, can severely influence wheat cultivars in terms of grain yield and nutritional value (Kahiluoto et al. 2019; Rezzouk et al. 2022; Zahra et al. 2023). These effects, associated with the declining genetic advance and the depletion of wheat genetic basis (Chairi et al. 2018; Kuzmanović et al. 2020, 2018), are seriously hindering durum wheat production in several regions of the Mediterranean (Ceglar et al. 2021; Ferrise, Moriondo, and Bindi 2011; Zampieri et al. 2020). This geographic area, strongly relying on durum products, will likely face an issue for societies and ecosystems (Cramer et al. 2018).

The use of a multi-year dataset, including weather conditions and crop performances, is pivotal for a deep understanding of climate change effects on crops and its connection with the most effective adaptation options. Despite this, studies aiming to understand the effects of climate change on durum wheat performances and phenology by using multi-year datasets are very few and they often lead to contrasting conclusions. For example, Dettori, Cesaraccio, and Duce (2017) found a positive effect of increasing temperature and decreasing rainfall on the kernel weight of durum wheat grown in Sardinia, that is quite the opposite of what Nuttall et al. (2017) reported in their review about the relationship between wheat quality and climate change. Moreover, the recurrent finding that the medium-late genotypes often had yields comparable or even higher than those of the early varieties under typical Mediterranean climatic conditions (Chairi et al. 2018; Rossini et al. 2018), lead to speculate that additional information were needed to disentangle the complex relation existing between climate change and performances of modern durum wheat cultivars. Finally, while many studies were published regarding the effect of annual or seasonal weather variables on different wheat cultivars, at the best of our knowledge, no one analysed the climate change in each single month of durum wheat growing season and its effect on a set of cultivars divided by their growing cycle (early and late).

The objectives of this study were: (i) to assess how the climate changed at the turn of the 21st century in a typical durum growing area; (ii) to understand how crop traits evolved over time (from 1989 to 2020) in early and late durum wheat cultivars; (iii) to highlight which weather variables mostly impacted on durum wheat phenology, yield and test weight.

2 | Materials and Methods

2.1 | Meteorological Data

A 32-year period (from 1989 until 2020) has been analysed. Climatic data (e.g., average, maximum and minimum temperature, solar radiation and precipitations) were retrieved from an automatic agrometeorological station located within the experimental farm of the University of Tuscia (Viterbo, Italy, latitude 42°43′ N, longitude 12°07′ E), nearby the field plots. The analysis of the data was limited to the period from January to June, as it corresponds to the durum wheat growing season in that area. To assess the impact of climate on durum wheat phenology and yield performance, we analysed monthly temperature, precipitation and solar radiation. Additionally, we also analysed some combinations within those climatic variables (e.g., total precipitation of February and March, total radiation of April and May, etc.).

2.2 | Experimental Site

Crop data analysed in this research were collected at the experimental farm of the University of Tuscia in Viterbo, Central Italy (latitude 42°43′ N, longitude 12°07′ E, altitude 310 m) from 1989 to 2020. This Research Unit was part of the National durum wheat evaluation network, coordinated by CREA (Council for Agricultural Research and Analysis of the Agricultural Economy) that, yearly, compares 30 durum wheat cultivars in rainfed conditions along the Italian peninsula.

A randomised complete block design with three replicates was used each year for the field experiment. Over the years, within the experimental site, 234 different varieties were tested in plots of 10.50 m^2 (1.5 m × 7.0 m). The sowing density was equal to 350 seeds m^{-2}, distributed in 10 rows spaced 0.15 m apart.

The soil, classified as an Ando Eutric Cambisol (FAO 1998), had an average composition of 37.6% clay, 28.6% silt and 33.8% sand (0–30 cm depth).

The growing area is characterised by a Mediterranean-type climate, with mean annual air temperature of about 14.5°C and precipitation of 790 mm. Approximately, total rainfall and average temperature during durum wheat growing season (from January to the end of June) in this area are 347 mm and 12°C, respectively.

2.3 | Crop Traits

From the total 234 varieties tested over years, data from a selection of 8 cultivars (4 early and 4 late varieties), that were those tested for more consecutive growing seasons, were processed (Table 1).

2.3.1 | Phenology

One aim of this research was to verify whether the life cycle of durum wheat varieties was affected by climate change. For this purpose, we focused on the time to reach the heading phase. According to the guidelines provided by the National durum wheat evaluation network, the heading phase was declared when at least 70% of plants in each plot (visual assessment) had spikes totally out from the flag leaf. Results were expressed as the number of days from April 1st.

2.3.2 | Grain Yield

At ripening (Zadoks 90), plants were mechanically harvested using a plot harvester (Walter—Wintersteiger, Ried, Austria).

TABLE 1 | Durum wheat cultivars examined in the study: number of years tested and their earliness.

Cultivar	Experimental years			Earliness
	First	Last	Total	
Iride	1997	2020	24	Early
Saragolla	2006	2019	14	Early
Simeto	1989	2020	32	Early
Duilio	1989	2018	30	Early
Creso	1989	2011	23	Late
Neodur	1991	2001	10	Late
Achille	2007	2018	12	Late
Dylan	2004	2017	14	Late

Grain yield was determined on the entire area of each plot, excluding the external rows (8.4 m^2). Results were reported as t ha^{-1} (13% moisture). Prior to harvest, the number of spikes m^{-2} has been determined by counting the spikes on two 1 m-long internal rows.

2.3.3 | Test Weight

A 500 g–grain sample was cleaned to determine the test weight. A 1/4 L Schopper calibrated chondrometer was used and results were reported as kg hL^{-1}.

2.3.4 | Thousand Kernel Weight

Grains in a 15 g grain sample were counted and the thousand kernel weight was determined by a proportion.

2.4 | Statistical Analysis

All statistical analyses were performed using R statistical software (R Core Team 2021).

To understand how the climate changed in the area and to assess its impact on durum wheat phenology, yield and test weight, different statistical methodologies were used:

i. The Mann–Kendall test, with the scope to verify the possible existence of a trend and its statistical significance. The test was performed for both meteorological and crop variables using the R package "Kendall". The statistical analysis was conducted referring to the period 1989–2020 for the following crop traits: heading date, grain yield, test weight, number of spikes per unit area and thousand kernel weight;

ii. Sen's Slope Estimator Test, to calculate the magnitude of the trend (Hirsch, Slack, and Smith 1982) when the output of the Mann–Kendall test showed the presence of a significant trend;

iii. A stepwise method for variable selection, based on the AIC value, to select the most significant climate variables having an impact on crop traits (Yamashita, Yamashita, and Kamimura 2007). In the case of multiple regression, we used the variance inflation factor (VIF), to detect a possible multicollinearity between the climate variables. We excluded any variables with a VIF value higher than 5 and subsequently we performed the regression analysis without the excluded variables (Liu et al. 2021).

3 | Results

3.1 | Weather Variables

Climatic trends of the 1989–2020 period were reported in Figure 1 (precipitations), Figure 2 (air temperatures) and Figure 3 (solar radiation).

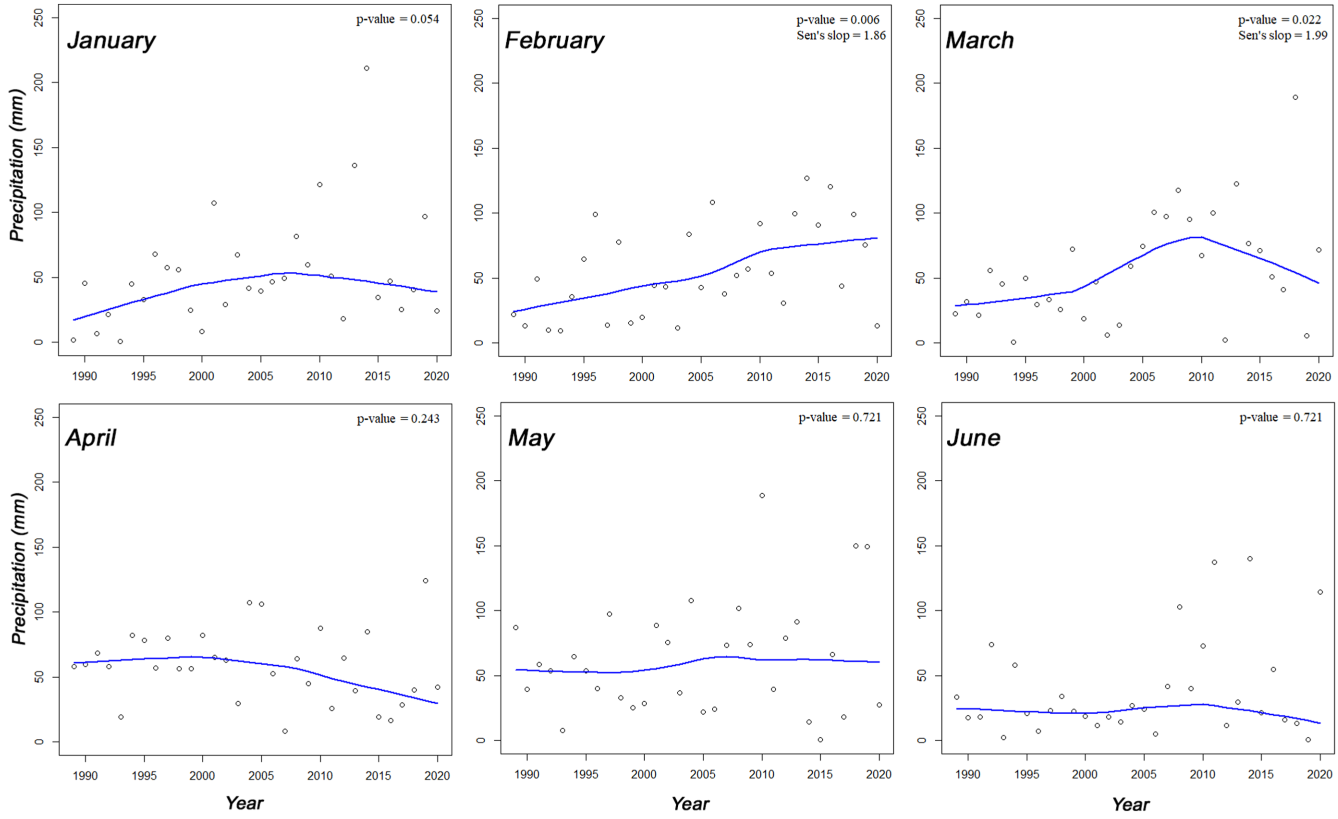

FIGURE 1 | Trends in monthly precipitation of the analysed time series (1989–2020). Open dots are the values, while the blue lines depict the trends.

3.1.1 | Precipitations

Significant trends in monthly precipitations were clearly detected just for February and March (p-value = 0.006 and 0.022, respectively), with a magnitude of about +2 mm per year. As for the other months, precipitations in January increased over time (p-value = 0.054), while they decreased in April (p-value = 0.243) and remained substantially unchanged in May and June (p-value = 0.721).

3.1.2 | Air Temperatures

Generally, mean air temperature remained stable over time, except for April and June (Figure 2). More in detail, average air temperature of April significantly rose up from 1989 to 2020 (+0.13°C per year, p-value = 0.0003). A similar trend was found for June, with a significant increase of 0.1°C per year (p-value = 0.0098).

As for maximum temperatures (Figure 2), all trends were significant and rising, except for May. Trends of February, March and April showed a continuous increase (+0.15°C, +0.12°C and +0.21°C per year, respectively), while those of January and June peaked around the year 2000 and then maintained a constant level.

Finally, no significant trend was found for minimum temperatures (Figure 2).

3.1.3 | Solar Radiation

Generally, monthly solar radiation remained stable over time, except for April (Figure 3), in which it significantly rose up from 1989 to 2020 (+2.8 MJ m^{-2} per year, p-value = 0.002).

3.2 | Crop Traits

The time needed to reach the heading date progressively decreased moving towards 2020 for early and late cultivars, with the line becoming steeper after 2010, as shown in Figure 4. Specifically, the heading date shifted backwards by 0.28 days per year in the early cultivars (more than 1 week in 32 years) and 0.37 days per year in the late cultivars (more than 11 days in 32 years). The Mann–Kendall test was highly significant also for some cultivars (Table 2). Specifically, the heading dates of Duilio and Simeto advanced by 0.3 days per year, while the late cultivar Dylan even by 1.2 days per year.

The number of spikes per unit area constantly decreased from 1990 to 2020 in both types of cultivars, with the post-2005 trend line showing a shallower slope (Figure 4). On average, the early and late cultivars showed a reduction of 6.4 and 10.7 spikes m^{-2} per year, respectively. All the early cultivars, except Saragolla, highlighted a significant and negative trend during time (Table 2). Iride resulted the most impacted cultivar, with a reduction of 8.3 spikes m^{-2} per year, while the most resilient was Simeto (−6.3 spikes m^{-2} per year). The Mann–Kendall test was highly

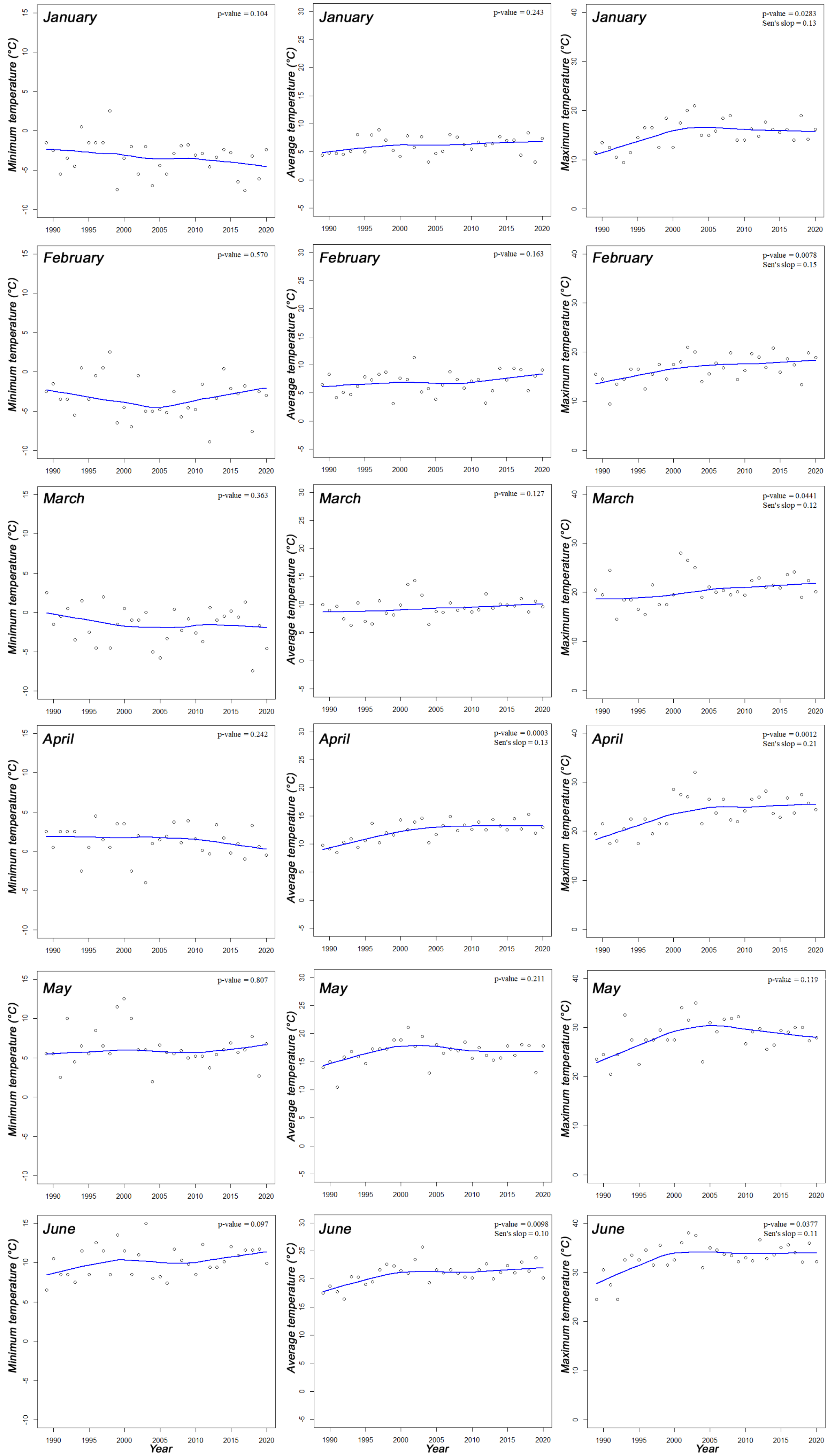

FIGURE 2 | Trends in monthly minimum, average and maximum air temperatures of the analysed time series (1989–2020). Open dots are the values, while the blue lines depict the trends.

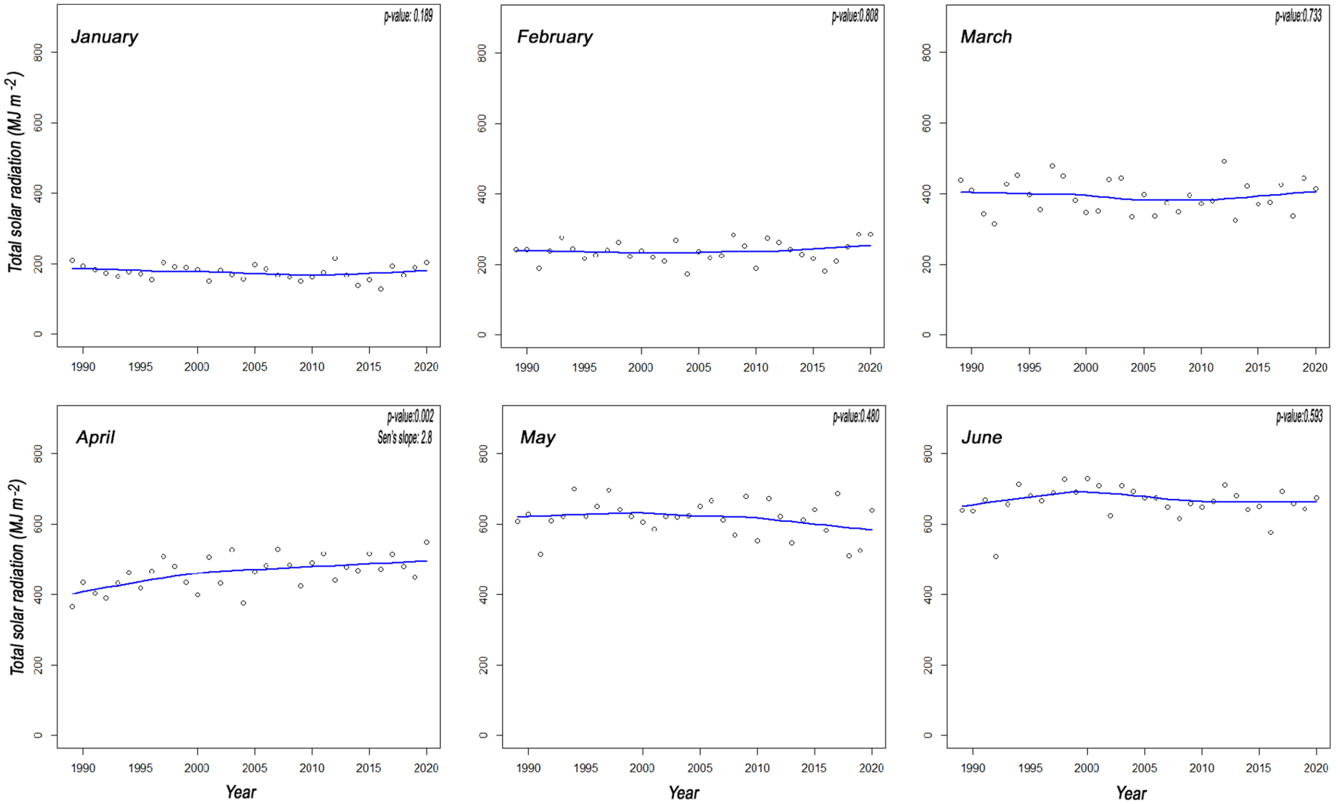

FIGURE 3 | Trends in monthly solar radiation of the analysed time series (1989–2020). Open dots are the values, while the blue lines depict the trends.

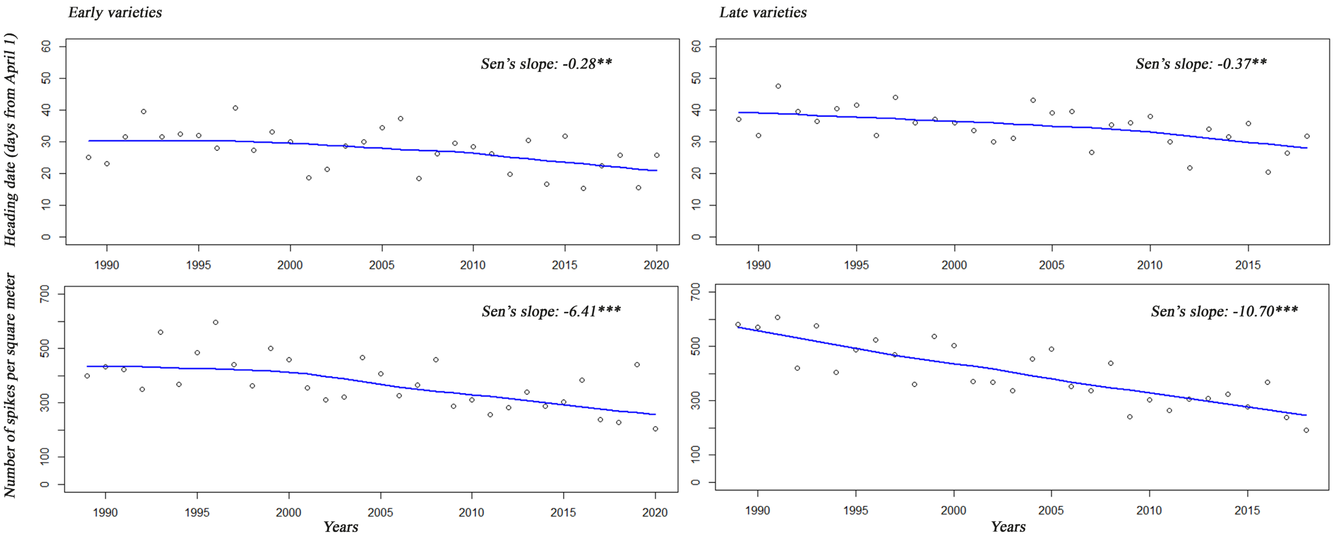

FIGURE 4 | Trends in heading date and number of spikes per unit area for grouped early and late cultivars. Open dots are the values, while the blue lines depict the trends.

significant also for two late cultivars: Creso and Dylan, showing a reduction of 13 and 13.7 spikes m^{-2} per year, respectively.

The thousand kernel weight (TKW) showed a positive trend for both early and late cultivars, but the Mann–Kendall trend test revealed statistical significance only for two late cultivars. More in detail, Achille's TSW showed an increase by 1.9 g per year, while Dylan by 1.2 g, as shown in Table 2.

As for yield and test weight, the Mann–Kendall trend test never revealed a statistical significance. Despite this, a general increase in test weight was detectable for all cultivars, while grain yield fluctuated around 5 t ha^{-1} and it appeared more stable in early cultivars as compared to late ones from 2005 to 2011. However, soon after that period, the yield of late cultivars rapidly reached again the values of the other varieties.

3.3 | Assessment of Climate Change Impacts

The relationship between meteorological data and crop variables was studied first for each group of cultivars (early and late) and, subsequently, for each variety.

Several climate variables were entered into the model, to build up a representative regression model, able to highlight the weather variables which majorly impacted on each crop trait.

TABLE 2 | Output of the Mann–Kendall trend tests for heading date, number of spikes per unit area, and thousand kernel weight (TKW) in early and late cultivars. Where significant, Sen's slope value is reported.

	Heading date	Number of spikes m^{-2}	TKW
Early cv			
Iride	Ns	−8.33**	ns
Saragolla	Ns	ns	ns
Simeto	−0.30*	−6.34***	ns
Duilio	−0.31**	−7.03***	ns
Late cv			
Creso	Ns	−13.00***	ns
Neodur	Ns	ns	ns
Achille	Ns	ns	1.91**
Dylan	−1.18*	−13.70**	1.20*

Abbreviation: ns, not significant.
*Significant at $p<0.05$; **Significant at $p<0.01$; ***Significant at $p<0.001$.

3.3.1 | Impact of Weather Variables on Crop Phenology

The regression analysis between heading date and the selected weather variables is reported in Table 3.

On average, maximum temperatures of February and March resulted in good indicators of the time to heading of the early cultivars. Particularly, Saragolla and Simeto evidenced a significant negative relationship with maximum temperature of March, while Iride and Duilio with a maximum temperature of February. For these genotypes, the regression indicated a reduction in time-to-heading period from 1.2 (Simeto) to 2.3 (Saragolla) days for each additional °C.

In general, the late cultivars highlighted a significant negative relationship with the maximum temperature of April. However, the only one cultivar that showed a significant *p*-value for this weather variable was Creso (less than 1 day of reduction in time-to-heading for each additional °C). On the contrary, Achille and Dylan highlighted a significant negative relation between heading date and maximum temperature of March. Particularly, Dylan highlighted both a very low *p*-value ($p<0.001$) and a high coefficient of determination ($R^2=0.67$).

Monthly precipitation and solar radiation did not influence the heading date of durum wheat cultivars.

3.3.2 | Impact of Weather Variables on Grain Yield

The regression analysis between the selected weather variables and grain yield is reported in Table 4. Almost all the weather variables showed a negative relationship with the grain yield. Maximum temperature of May and solar radiation of April and May were the best predictors of the final grain yield, especially

TABLE 3 | Regression analysis between different weather variables and the heading date of single and grouped early cultivars and late cultivars. Slope ± standard error.

	Max temp. (February)	Max temp. (March)	Max temp. (April)	Multiple R^2
Early cv				
Iride	−1.6 ± 0.6*	ns	ns	0.25
Saragolla	ns	−2.3 ± 1.1*	ns	0.29
Simeto	ns	−1.2 ± 0.3**	ns	0.30
Duilio	−1.27 ± 0.4**	ns	ns	0.27
Average	−0.9 ± 0.4*	−0.7 ± 0.4*	ns	0.35
Late cv				
Creso	ns	ns	−0.90 ± 0.3**	0.35
Neodur	ns	ns	ns	ns
Achille	ns	−2.6 ± 0.8*	ns	0.49
Dylan	ns	−3.4 ± 0.7***	ns	0.67
Average	ns	ns	−1.1 ± 0.3***	0.38

Abbreviation: ns, not significant.
*Significant at $p<0.05$; **Significant at $p<0.01$; ***Significant at $p<0.001$.

TABLE 4 | Regression analysis between different weather variables and the grain yield of single and grouped early and late cultivars. Slope ± standard error.

	Max temp. (February)	Max temp. (April)	Max temp. (May)	Radiation (Feb.–Mar.)	Radiation (Apr.–May)	Precipitation (Feb.–Mar.)	Precipition (Apr.–May)	Multiple R^2
Early cv								
Iride	ns	ns	−0.27 ± 0.08**	ns	−0.19 ± 0.04***	ns	−0.01 ± 0.01**	0.68
Saragolla	ns	ns	ns	−0.1 ± 0.04*	−0.1 ± 0.04*	ns	ns	0.49
Simeto	ns	ns	−0.15 ± 0.07*	ns	ns	ns	ns	0.15
Duilio	ns	ns	−0.2 ± 0.06**	ns	ns	ns	ns	0.28
Average	ns	ns	ns	ns	−0.08 ± 0.03*	ns	ns	0.20
Late cv								
Creso	ns	ns	ns	−0.13 ± 0.05*	ns	−0.01 ± 0.01*	ns	0.28
Neodur	ns	ns	ns	ns	ns	ns	ns	ns
Achille	0.34 ± 0.12*	0.38 ± 0.1*	ns	−0.13 ± 0.05*	ns	ns	ns	0.74
Dylan	ns	ns	ns	ns	−0.16 ± 0.04**	ns	ns	0.59
Average	ns	ns	−0.18 ± 0.07**	ns	ns	ns	ns	0.22

Abbreviation: ns, not significant.
*Significant at $p < 0.05$; **Significant at $p < 0.01$; ***Significant at $p < 0.001$.

for the early varieties. Analysing the regressions for each cultivar, Iride only showed both a significant *p*-value and a high coefficient of determination ($R^2 = 0.68$) of the model, as well as a more complex response to the climatic conditions. For this cultivar, the regression indicated a yield reduction of 270 and 190 kg ha^{-1} for each additional°C in May and for each additional MJ m^{-2} of radiation in April and May, respectively. Simeto and Duilio showed greater resilience to maximum temperature of May, with 150 and 200 kg ha^{-1} for each additional °C, respectively. The grain yield of Iride showed a negative relationship with the total rain of April and May, with a yield reduction of only 10 kg ha^{-1} for each additional mm of precipitation.

The grain yield of the grouped late cultivars was influenced only by the maximum temperature of May. This relationship highlighted that each additional °C produces a yield reduction of 180 kg ha^{-1} ($R^2 = 0.22$). Achille is the only cultivar that showed a complex yield response to the climatic conditions (e.g., a positive relationship with the maximum temperatures of February and April and a negative one with the solar radiation of February and March).

3.3.3 | Impact of Weather Variables on Number of Spikes per Unit Area

The regression analysis between the selected weather variables and spikes per unit area is reported in Table 5. On average, the number of spikes per unit area for early cultivars is greatly and negatively related to the maximum temperature of March. Specifically, each additional °C in that month produced a decrease of 14 spikes m^{-2}. Iride was the most sensitive, with 17 spikes m^{-2}. Simeto was the only early cultivar that showed a significant and negative relationship between spikes per unit area and the maximum temperature of February.

The late cultivars appeared to be reactive to the maximum temperature of April. Indeed, each additional °C in that month produced the same decrease of early cultivars in March (14 spikes m^{-2}). However, two cultivars, namely Neodur and Dylan, showed a strong reduction in spike number per unit area with the increase of maximum temperature of February and March, respectively.

3.3.4 | Impact of Weather Variables on Thousand Kernel Weight

Thousand kernel weight of the grouped early cultivars showed a significant positive relationship ($R^2 = 0.39$) with the maximum temperature of March (1.5 g per each additional°C) and a negative one with the maximum temperature of May (−1.1 g per each additional°C), as shown in Table 6. All the early cultivars showed a positive and significant relation with the maximum temperature of March and a negative one with the maximum temperature of May (except Saragolla). Simeto and Duilio showed also a positive relationship between the kernel weight and the total radiation and precipitation of February and March, while only for Simeto was found a weak negative relationship with the precipitation of April and May.

The grouped late cultivars confirmed the same relationship that the early ones had between the kernel weight and the maximum temperature of March and the maximum temperature of May. Dylan only showed a simple relationship between the kernel weight and the maximum temperature of March, while Creso had the most complex response. Thousand kernel weight of Neodur evidenced no relationship with any of the tested weather variables.

3.3.5 | Impact of Weather Variables on Test Weight

Both grouped cultivars highlighted a statistically significant relationship between test weight and the solar radiation of

TABLE 5 | Regression analysis between different weather variables and the number of spikes per unit area of single and grouped early cultivars and late cultivars. Slope ± standard error.

	Max temp. (February)	Max temp. (March)	Max temp. (April)	Radiation (Feb.–Mar.)	Precipitation (Feb.–Mar.)	Multiple R^2
Early cv						
Iride	Ns	−16.8 ± 6.6*	ns	−6.6 ± 3*	−1 ± 0.3**	0.40
Saragolla	Ns	ns	ns	ns	ns	ns
Simeto	−13.9 ± 5.3*	ns	ns	ns	−0.47 ± 0.2*	0.28
Duilio	Ns	−14.6 ± 5.7*	ns	ns	ns	0.20
Average	Ns	−13.8 ± 5*	ns	ns	−0.5 ± 0.2*	0.27
Late cv						
Creso	ns	ns	−15.4 ± 5**	ns	−1.1 ± 0.36**	0.48
Neodur	−22.6 ± 9.1*	ns	ns	ns	ns	0.41
Achille	ns	ns	ns	ns	ns	ns
Dylan	ns	−30.5 ± 10.9*	ns	ns	ns	0.40
Average	ns	ns	−14.1 ± 4.5**	ns	−0.77 ± 0.24**	0.47

Abbreviation: ns, not significant.
*Significant at $p < 0.05$; **Significant at $p < 0.01$.

TABLE 6 | Regression analysis between different weather variables and the thousand kernel weight of grouped early cultivars and late cultivars. Slope ± standard error.

	Max temp. (March)	Max temp. (May)	Radiation (Feb.–Mar.)	Precipitation (Feb.–Mar.)	Precipitation (Apr.–May)	Multiple R^2
Early cv						
Iride	1.4 ± 0.6*	−1.5 ± 0.6*	ns	ns	ns	0.26
Saragolla	2.2 ± 0.6**	ns	ns	ns	ns	0.52
Simeto	2.2 ± 0.4***	−1.6 ± 0.4***	0.53 ± 0.21*	0.06 ± 0.02*	−0.04 ± 0.02*	0.28
Duilio	1.9 ± 0.4***	−1.5 ± 0.4**	0.6 ± 0.25*	0.06 ± 0.02*	ns	0.52
Average	1.5 ± 0.4***	−1.1 ± 0.3**	ns	ns	ns	0.39
Late cv						
Creso	1.9 ± 0.4***	−2 ± 0.4***	0.67 ± 0.26*	ns	ns	0.62
Neodur	ns	ns	ns	ns	ns	ns
Achille	5.6 ± 1.3**	ns	ns	0.1 ± 0.03*	ns	0.68
Dylan	3.6 ± 1.2*	ns	ns	ns	ns	0.43
Average	1.5 ± 0.4***	−1.6 ± 0.4***	0.6 ± 0.2**	0.05 ± 0.02*	ns	0.52

Abbreviation: ns, not significant.
*Significant at $p < 0.05$; **Significant at $p < 0.01$; ***Significant at $p < 0.001$.

June (Table 7), but the coefficient of determination was weak ($R^2 = 0.24$–0.25).

4 | Discussion

The results showed in this study are based on a long series of data collected in 32 years at the turn of the 21st century under a Mediterranean-type climate and represent a tremendous source of information to understand how the climate has changed in that period and how these changes affected the phenology and grain yield of durum wheat.

4.1 | Weather Variables

The analysis of climate data through the Mann–Kendall test revealed the presence of a clear and significant upward trend for

TABLE 7 | Regression analysis between different weather variables and the test weight of single and grouped early cultivars and late cultivars. Slope ± standard error.

	Max temp. (March)	Radiation (June)	Precipitation (June)	Multiple R^2
Early cv				
Iride	ns	ns	ns	ns
Saragolla	ns	ns	−0.04 ± 0.02*	0.32
Simeto	ns	0.4 ± 0.1**	ns	0.24
Duilio	0.36 ± 0.2*	0.25 ± 0.1*	ns	0.35
Average	ns	0.37 ± 0.1**	ns	0.24
Late cv				
Creso	ns	0.4 ± 0.1**	ns	0.33
Neodur	ns	0.2 ± 0.06*	ns	0.53
Achille	1.2 ± 0.5*	ns	ns	0.41
Dylan	ns	ns	−0.04 ± 0.02*	0.29
Average	ns	0.3 ± 0.1**	ns	0.25

Abbreviation: ns, not significant.
*Significant at $p < 0.05$; **Significant at $p < 0.01$.

the maximum air temperature, during almost the entire growing cycle of durum wheat. If we consider the months of April and June, an increasing and significant trend was also observed for the mean air temperature. On the contrary, no significant trend was detected for minimum temperatures.

Similar trends were found by other authors who analysed seasonal or annual temperatures along Italy in different periods (Poggi et al. 2022; Toreti et al. 2010; Toreti and Desiato 2008). For example, Toreti et al. (2010), analysing climate data retrieved from 49 Italian weather stations for the period 1961–2006, found a significant warming in Central and Southern Italy, during spring season, with slopes ranging from 0.023°C per year to 0.025°C per year. We found higher magnitudes (from 0.12°C to 0.21°C per year) but it must be considered that our data refer to: (i) monthly temperatures, (ii) a specific location and (iii) a shorter and different period of time (1989–2020). Indeed, Cerlini et al. (2022), investigating the phenological response of two willow species to temperature variability in Central Italy from 2005 to 2018, reported values similar to those we obtained (increases from 0.10°C to 0.17°C per year for maximum temperature of March).

Toreti and Desiato (2008), applying the Mann–Kendall test to the annual anomalies of average Italian temperatures, indicated a turning point in 1981. Indeed, the authors estimated an average temperature decrease of 0.031°C per year from 1961 to 1981, followed by an increase of 0.053°C per year from 1982 to 2004 and an overall increase of 0.96°C in 44 years. Accordingly, we found a general warming from1989 to 2020 (+0.1°C per year for April and June).

Conversely, Poggi et al. (2022) reported that mean annual air temperatures have steadily and significantly increased since 1952 in Northern Italy, with a breakpoint in 1989. Specifically, the mean temperature before and after the breakpoint was, 12.7°C and 14.1°C, respectively (+1.4°C). The presence of a shift point in the mid/late 80s for air temperatures was already verified at national (Matzneller et al. 2010) and European levels (Twardosz, Walanus, and Guzik 2021).

The positive and significant trend of the solar radiation in April, was consistent with the trends of the average and maximum temperature in that month, thus corroborating the well-known relationship between these two climatic variables (Bristow and Campbell 1984). The increase of solar radiation reported in this work agrees with the trend described for the Piedmont region during the 1990–2016 period (Manara et al. 2019).

Except for February and March, we did not find any significant trend in the monthly precipitation amount. This output is consistent with other studies conducted over time on climate change in Italy. For instance, Ciccarelli et al. (2008), analysing a large set of 50-year weather data (1952–2002) in north-western Italy, found that precipitation time series displayed no significant trend. Toreti et al. (2009) showed that, in central Italy, only the winter precipitation series was not stationary from 1961 to 2016. Moreover, the authors found a change point in 1988. Before 1988, the series was stationary, while after 1988 the trend was positive, with a slope of 0.087 per year. This trend is similar to that we observed for the winter months of January and February in our location.

Because of stable or decreasing precipitations in spring (April and May) and the parallel increasing air temperatures, the monthly evapotranspiration in that period showed an upward trend, highly significant in April (data not shown).

4.2 | Crop Traits

As for crop variables, days to heading and number of spikes per unit area were the only measured durum wheat traits showing a significant trend over time. Both variables evidenced a clear downward trend moving towards 2020 for grouped types of cultivars (early and late).

Our results on heading date agree with many studies which modelled wheat phenology against the climate change scenario and estimated or observed the reduction of the time-to-flowering over years (Dettori, Cesaraccio, and Duce 2017; Isidro et al. 2011; Poggi et al. 2022; Sadras and Monzon 2006). Interestingly, we provided additional details on the magnitude of this trend in different cultivars. Anticipation of heading date was much more pronounced in Dylan (late cultivar, −1 day per year) than in Simeto and Duilio (early cultivars, −0.3 day per year) so that, over time, heading dates of these varieties tended to be closer. This was probably one of the reasons why, in different Mediterranean countries, some reports showed late cultivars performing equally well or even better than the early ones (Chairi et al. 2018; Rossini et al. 2018). Besides the effects of climate change, the depletion of genetic variability (as a consequence of the modern breeding), was the other factor that contributed to make durum wheat varieties more and more similar to each other (Chairi et al. 2018; Henkrar et al. 2016; Kahiluoto et al. 2019). Thus, the widening of the genetic base of cultivated material, resorting to wild relatives or landraces, will be essential to obtain durum wheat varieties suited to face the hard challenges of the future scenario (Ceoloni et al. 2017; Kuzmanović et al. 2021, 2019; Rossini et al. 2020).

Starting from Nazareno Strampelli (1866–1942), the reduction of the vegetative phase was one of the most important targets of the breeding activity on both bread and durum wheat in Italy, in the attempt to escape the terminal heat and drought (De Vita et al. 2007; Giorgi 2014). In fact, due to global warming, these two abiotic stresses have more and more represented a major constraint for wheat cultivation in the Mediterranean environment. Some authors suggested that a shorter pre-flowering period, exacerbated by the projected rise in air temperatures, could be beneficial for winter cereals, because it should allow the grain filling phase to develop in better climatic conditions (relatively cooler), thus neutralising the negative effect of increasing temperatures in the post-anthesis period (Moriondo and Bindi 2007; Sadras and Monzon 2006). However, our results highlighted that, together with a shortening of the pre-heading phase, a marked reduction of the number of spikes per unit area occurred in the last 30 years. This was due to the positive relationship between days to heading and number of tillers per plant (Al-Karaki 2012; Giunta et al. 2018) that we also found for all types of cultivars (data not shown). Since durum wheat yield under Mediterranean climatic conditions is determined mostly by the number of spikes per unit area (García del Moral et al. 2003; Moragues et al. 2006; Royo, Nazco, and Villegas 2014), our findings suggest that screening durum genotypes just for earliness could not be a winning strategy for the future. Moreover, a reduced number of tillers was repeatedly associated with limited root development (Bektas, Hohn, and Waines 2016; Chen et al. 2020; Motzo, Attene, and Deidda 1993; Narayanan et al. 2014), thus making plants more susceptible to drought. Thus, agronomic practices (e.g., fertilisers and biostimulants application) aiming to enhance vegetative and root vigour from seeding to the completion of the tillering stage should be deeply investigated to (re)adapt farming practices to the new crop phenology (Rossini, Ruggeri, and Rossini 2024).

Despite the significant reduction of spikes per unit area, grain yield evidenced a substantial stagnation in the last 3 decades (around 5 t ha^{-1}). This was probably due to the compensations among yield components that cause the phenotypic plasticity of wheat and its grain yield stability. In particular, the increase of thousand kernel weight over time could be a major cause of the yield stability, despite the trend resulted significant only for some late cultivars. Another possible explanation is that CO_2 increase in the atmosphere could have counteract the negative effect of a reduction in spikes' number per unit area. Several studies have reported that an elevated CO_2 has a beneficial effect on wheat yield due to an increased net photosynthetic rate, water use efficiency, kernel number per spike, thousand kernel weight and harvest index (Ainsworth and Long 2021; Aranjuelo et al. 2013; Wang et al. 2022). Other authors pointed out yield stagnation around Europe identifying, as its beginning, a different year according to the country: from 1989 of Spain to 1999 of Germany, going via 1994 of Italy (Brisson et al. 2010; Peltonen-Sainio, Jauhiainen, and Laurila 2009; Schauberger et al. 2018). The main three reasons mentioned to justify crop yield stagnation are: (i) a decrease in genetic progress, (ii) changes in agricultural practices and (iii) greater frequency of biotic and abiotic stresses (Le Gouis, Oury, and Charmet 2020). From this latter point of view, studies aiming to seek resilient wheat genotypes will have a dramatic importance for global food safety and security (Giovenali et al. 2023; Rossini et al. 2024; Tounsi et al. 2024).

Even though a slight increase, especially in test weight, was perceptible over time for all types of cultivars, no significant trend was found for quality features of grains (protein content was not shown because it has never shown a significant trend). To the best of our knowledge, no trend analysis, based on long data series, was performed so far on test weight of durum wheat. Conversely, various studies were performed to understand if quality traits changed according to the year of cultivar release (e.g., comparative analysis between old and modern durum varieties), thus estimating the genetic gain obtained over time. The consensus is that grain protein percentage experienced a decreasing trend with the time of release due to a dilution effect (i.e., heavier grains of modern cultivars), while test weight did not change (De Vita et al. 2007; Motzo, Fois, and Giunta 2004; Subira et al. 2014). Anyway, these results are not comparable with our findings because we used only post-Green Revolution varieties. Besides their variation over time, both quality indices usually remained above the standards required by the pasta industry (test weight $\geq$ 80 kg hL^{-1} and protein concentration $\geq$ 12.5%).

4.3 | Impact of Weather Variables on Crop Traits

The weather variables that mostly influenced crop traits were air temperature and solar radiation, while precipitation did not have any significant effect on durum wheat performances, especially on grain yield. This result was unexpected, because grain yield and quality were often significantly affected by the typical interannual rainfall variability of the Mediterranean climate

(Garrido-Lestache, López-Bellido, and López-Bellido 2004; López-Bellido et al. 1996; Rossini et al. 2018). However, the few studies that can be found in the literature on durum wheat, show highly variable and contrasting outcomes. Particularly, Royo, Nazco, and Villegas (2014) analysing long-term climatic variables of 22 Mediterranean countries, showed that rain during grain filling (April to June) negatively and significantly affected the number of grains m^{-2}. Seddaiu et al. (2016), through a correlation analysis between the meteorological variables and grain yield obtained over 20 years (1995–2014), indicated the rain of March and April among the monthly meteorological variables influencing durum wheat yield in central Italy (negative and positive correlation coefficient, respectively). Conversely, Dalla Marta et al. (2015) demonstrated that rainfall in March positively and significantly affected grain yield in central Italy, while weather conditions in April did not. Finally, Tappi, Nardone, and Santeramo (2022), collecting 14-years data series in southern Italy, reported that precipitation had a negative effect on durum wheat yields.

The regression analysis we applied for the relationships between agronomic traits and long-term climatic variables showed that the critical periods for durum wheat phenology and yield in central Italy are in late winter-early spring and in mid spring. Specifically, the maximum temperatures of February and March exerted a considerable influence in reducing time to heading in early cultivars ($p < 0.001$), while maximum temperatures of March and April had the same effect for late cultivars ($p < 0.001$). The maximum temperatures of March and April had a detrimental effect for number of spikes per unit area, respectively for the early and late cultivars. The grain yield appears to be negatively influenced by the maximum temperature of May and by the solar radiation from April to May. Our results are perfectly consistent with those of Dalla Marta et al. (2015) that indicated March and May as the most critical months for durum wheat phenology and production in central Italy and with the prevision model indicating the solar radiation as the main factor to estimate wheat yield in Spain (Hernández-Barrera and Rodríguez-Puebla 2017). According to variety, we found an anticipation of the heading date from less than 1 day to about 3 days for each additional °C. This range is congruent with the values projected for winter cereals in response to a 2°C increase in temperature: from 1.2 days in Tunisia to 12.2 days in Serbia (Moriondo and Bindi 2007). Generally, the outcomes from the present study agree with the widely accepted opinion that cereal phenophases experienced an anticipation, mainly during spring (Mo et al. 2016; Oteros et al. 2015; Tao et al. 2014).

5 | Conclusions

Our multi-year analysis showed that climate changed rapidly and clearly from the end of eighties onward. The significant upward trends in maximum air temperature indicated a general warming during the entire durum wheat growing season. The maximum temperatures of February and March markedly and negatively influenced the length of pre-heading period in early cultivars, while the same effect had the maximum temperature of March and April on late cultivars. As a result, heading dates constantly anticipated, especially in late cultivars, thus leading to a reduction of the difference in growing cycles among varieties. At the same time, a significant reduction in the number of spikes per unit area was observed over time.

Grain yield was negatively affected by the maximum temperature of May and solar radiation and did not evidence a clear trend over time, fluctuating around 5 t ha^{-1}. Under the climatic conditions of central Italy, late varieties proved to be as good producers as the early ones.

Our results suggest that appropriate genetic and agronomic approaches, focused on specific critical phenophases, should be adopted to improve durum wheat production in the Mediterranean environment.

Particularly, a short-term strategy should be based on the assessment and development of new plant nutrition strategies tailored to the "new wheat phenology". For example, the application of new fertilisers and/or biostimulants from seed treatment to the tillering stage as well as before the critical periods for the determination of the yield will have to be deeply investigated, as a valid approach to alleviate the heat and drought stress. At the same time, a mid/late-term plan should aim to broaden the genetic basis of durum wheat as a prelude to ensure a diverse and resilient durum landscape for the future.

Author Contributions

Angelo Rossini: formal analysis, methodology, writing – original draft, data curation. **Roberto Ruggeri:** investigation, writing – original draft, methodology, writing – review and editing, formal analysis, data curation, supervision. **Andreina Belocchi:** methodology, resources. **Francesco Rossini:** conceptualization, resources, writing – review and editing, visualization, data curation.

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Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are available on request from the authors.

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