Chapter

Wheat Phenology and Yield in a Mediterranean Scenario of Climate Change

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Abstract

Wheat is a crucial crop for food and nutritional security worldwide, but it has special importance in the Mediterranean basin. Nowadays, the wheat crop is facing significant challenges due to climate change; modification in the rainfall patterns or temperature increases are boosting the probability of yield production gaps. In this study, we evaluated the effect of winter and spring rainfall, as well as minimum and maximum temperature in these two seasons and sowing date, on multiple composes of wheat yield in the Mediterranean area. Low winter rainfall (<100 mm) together with a late sowing date (later than December 31) was described as the factor decreasing to a greater extent, wheat grain yield, yielding any tested genotype less than 4200 kg ha^{-1}. Similarly, sowing date and its interaction with minimum winter temperature decrease TGW (Thousand Grain Weight). Protein content seemed to be more influenced by crop management than by climatic conditions; even when late sowing in cold winters or rainy winters can help to achieve higher grain protein content, close to 80% of the protein data ranged between 11 and 17%. The sowing date correlates negatively with days to heading (DTH), implying that the later the sowing date, the shorter the DTH period.

Keywords: phenology, soft wheat, climate change, breeding, food security

1. Introduction

Wheat grains are one of the major sources of calories (provides 50% of the world's caloric intake) and essential nutrients for human health: proteins, minerals (Cu, Mg, Zn, P, and Fe), vitamins (B-group), and dietary fiber [1]. An average of 130 kg per capita is consumed in the Mediterranean region, and the highest is in North African countries, where it is 200 kg per capita. Every year, 12.1 thousand to 6.6 million hectares of wheat are harvested; it is the main staple crop and key to food security in the region. Despite the efforts to develop cereal agriculture and increase production, countries in the Mediterranean basin and North Africa can no longer produce enough wheat to meet their domestic demand. Today, more than 50% of the cereals consumed in those regions are imported [2].

It is well known that the Mediterranean area is one of the regions worldwide most susceptible to episodes of drought and heat [3]. This fact is aggravated by climate change, predicting the literature [4] a warmer and drier future scenario, with a shift to less uniform rainfall distributions resulting from higher temperatures [5]. According to Todaro et al. [6] and Tarín-Carrasco et al. [7], from the mid-1980s to the beginning of the twenty-first century, annual rainfall has decreased by 10–40%, with hot spots for changes in wetter periods (spring and autumn). In addition, the projections show an increase in the global temperature from 1 to 5°C, with the highest warming rates occurring in summer [8], but with more than 1°C increase in spring [9], which can severely affect winter cereals cropping. Wheat varieties have an optimal temperature between 15 and 25°C, making them highly sensitive to climate change. The annual mean temperature in a warmer region like the Mediterranean basin had been supposed to be increased by 3–4°C, which may lead to a yield reduction of 6.0 ± 2.9% [10, 11]. In addition, water scarcity will present a major limiting factor for crop production, both with respect to lowering the total amount and also due to more irregular precipitation patterns, as well as the higher evapotranspiration resulting from higher temperatures and larger vapor pressure deficit [12]. According to Ait-El-Mokhtar et al. [13], rising temperatures will lead to 20% higher evapotranspiration by 2050 and 40% by 2080.

Climate change also plays a negative impact on plant-pathogen interactions: at the level of pathogen dynamics, the environmental shifts enable pathogens to extend their geographic range, helping in their adaptation to new agroecological zones, and making easier more virulent episodes, conferring to the pathogens the ability to overcome host resistance or even to infect new host species. On the plant side, many resistance genes are temperature sensitive and/or in view of the aggressiveness of the pathogen, they become ineffective. Thus, it is known that many wheat resistance genes are temperature sensitive, including those for Hessian fly [14], rust [15], and Fusarium head blight [16]. Climate models predict that heat and drought will favor more wheat diseases in the Mediterranean region than before [17, 18]. Another important aspect of wheat is its nutritional value. Drought and heat events differentially regulate protein and starch accumulation, and mineral metabolism in wheat grains and change grain quality. These changes affect grain weight, nutrient and anti-nutrient content, fiber, protein content and composition, starch granule structure, and free amino acid composition [19], all of which are important for human nutrition. In addition to that, different agronomical practices have been adopted to ensure sustainable wheat yields across the Mediterranean basin. Thus, literature recommends some practices to increase soil water retention, such as the enhancement of soil organic matter [20], the reduction of the tillage [21], or the management of a crop rotation with legumes, irrigation or nitrogen fertilization [22, 23]. To address all the above-mentioned constraints we need to develop climate-resilient, multi-stress tolerant and nutritionally enhanced wheat varieties. This is in line with Mediterranean and global agricultural goals. However, breeding to high-yielding wheat varieties showing adequate technological quality and resistance to biotic and abiotic stresses, is not an easy task, since these traits can be negatively correlated or not correlated at all. Even so, the use of genetic diversity seems to be the key to sustaining and improving wheat varieties. The genetic variation within specific wheat genotypes that allows them to grow and yield under heat and drought stress conditions, highlights the importance of identifying traits for drought and heat tolerance, disease resistance, and high nutritional quality; hence, landraces including drought-tolerant genes that have been naturally selected over time, are a source of desirable genes for better adaptation to climate change, being a promising way to increase gene flow.

On the other hand, wheat cultivars' phenology (especially crop cycle) plays an important role, modulating their tolerance to climatic variations regarding yield maintenance. Thus, days to flowering or days to maturity have an important relationship with wheat yield and are strongly influenced by temperature. However, it is important to stand out that, in a scenario of climate change with increasing temperatures, days to maturity are more severely affected than days to flowering, reducing considerably the grain-filling period and shortening, to a greater extent, the grain yield [24]. However, another important genetic trait should be taken into account regarding the relationship between wheat yield-phenology-climate change: CO2 presence influence. It has been studied that higher CO2 level in the environment significantly affects the tolerance of wheat to heat, maintaining or slightly reducing (<10%) wheat yield with a proposed temperature increase.

In this research, three decades of wheat (numerous genotypes) data are studied to determine the relationship between climate change, especially rainfall patterns and temperatures in winter and spring, grain yield and wheat phenology.

2. Material and methods

2.1 Wheat germplasm

This study was performed during 33 years with 299 field trials and an average of nine trials per year. The germplasm used were bread wheat genotypes with Portuguese and CIMMYT (International Maize and Wheat Improvement Center by its initials in Spanish) origins (parental) and predominantly spring types, even when some of them were facultative. To perform the analyses, from each field trial, were selected the five most yield productive genotypes.

2.2 Environmental conditions and field experiments

Data collection comprises the grain yield, test weight, TGW (Thousand Grain Weight) and phenological data (days to heading – DTH) from 1991 to 2024.

Field experiments were conducted in the region of Alentejo, in Portugal, which is considered the most important area in Portugal for bread wheat crop. Daily climatic data of the area (rainfall, minimum temperature and maximum temperature) were taken from the weather station whose GPS coordinates are: $38^{0}53'03.4''$N, $7^{0}08'22.0''$W, located in one of the farms used to grow most of the experiments, with no more than nine kilometers of the furthest farm (**Figure 1**).

According to the Food and Agriculture Organization (FAO, https://www.fao.org/soils-portal/data-hub/soil-classification/en/), soils in the wheat sowing area are classified as vertisols, ranging the pH between 6.8 and 7.8, showing a low organic matter content (< 1.6%), and presenting high contents of P (>200 ppm P2O5) and Ca (circa 3500 ppm Ca), and medium-high K content (between 68 and 168 ppm for K2O).

Each plot comprises six rows, 6–8 m long each (**Figure 2**), 20 cm apart, and harvest was carried out using a 1.5 m wide Nurserymaster Elite Plot Combine. Usually, all

Figure 1.
Elvas region in Alentejo (Portugal); two main locations for the experiments along the years of the study (up). National plant breeding station in Elvas in a Google Earth view in 2023 (down). https://earth.google.com/

Figure 2.
Pictures of the experiments in the national plant breeding station.

treatments were fertilized by adding 40–42 UN at sowing time and three top-dressed fertilizations (40 tillering – 60 booting - 40 heading/flowering). Weed controls were applied twice, at pre-emergence and post-emergence, and, when necessary, two antifungal treatments (stem elongation (Growth sstage-GS30-GS33) and booting (GS41-GS47)) were applied. Agricultural management also included conventional tillage treatment with moldboard plowing and disk harrowing at the beginning of the season and vibrating tine cultivation to prepare the seedbed before sowing. The seeding rate ranged between 350 and 400 g m^{-2} and sowing dates were properly recorded annually, being the earliest sowing date 13/11 (in 2001) and the latest 25/01 (in 2023).

2.3 Measurements

During the wheat life cycle, both plant height (cm) and DTH were recorded. After the wheat harvest grain yield, TGW (in grams) and test weight (kg hl^{-1}) were also taken, as well as total N content in grain by means of NIRs technology, but only from 2002 on. Protein content (%) was obtained by multiplying the total N content by 5.7 [25].

2.4 Statistical analyses

Temporal trends in climatic variables were assessed following a Theil-Sen regression. Visual exploration of the data showed non-linear trends between response variables (grain yield, thousand-grain weight, test weight, and N content) and predictors (i.e., year of sowing, date of sowing and climate variables). GAMs were used to account for these non-linear relationships [26]. To assess potential interactive effects between date of sowing and climate, the interaction between both types of variables was tested in the model. The date of sowing was measured as the number of days lasting since November 1 for each year. Climate variables (average minimum and maximum temperatures and cumulative rainfall) were calculated for winter (December, January and February) and spring (March, April and May). Models were fit using reduced maximum likelihood (REML) and non-informative smooths were manually penalized one by one, refitting the model each time. After selecting the most parsimonious model, variables concurvity and model fit were assessed. All analyses were conducted in R v4.4.2 [27].

3. Results

Our results showed significant temporal trends in climate variables during the period studied (**Figure 3**). Maximum winter (December, January and February) and minimum spring (March, April and May) temperature significantly increased at a rate of 0.03 and 0.02°C $year^{-1}$, respectively. Maximum temperatures in spring tended to increase marginally, while minimum temperature in winter fluctuated enormously, showing differences of more than 3°C in consecutive years on several occasions. Regarding the rainfall, winter rainfall mainly ranged between 70 and 250 mm (24 out of 33 years were in this range), with 4 years with extremely low values (< 50 mm), while spring rainfall range was narrower, with almost all years between 50 and 200 mm. No temporal trends were observed for rainfall.

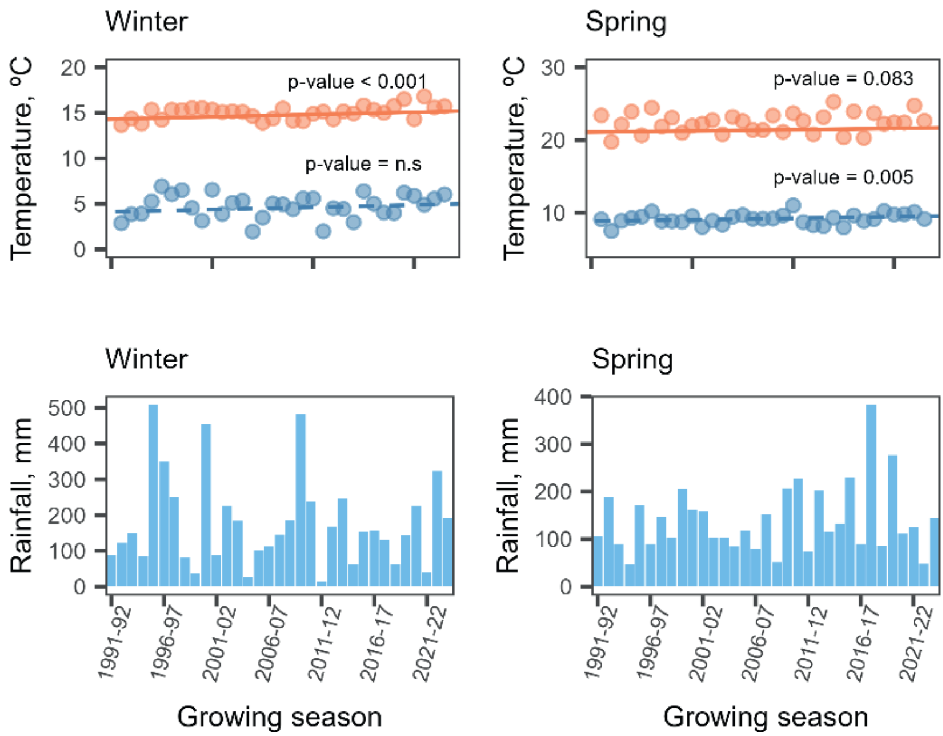

Figure 3.
Winter (left-up) and spring (right-up) maximum and minimum temperature, and winter (left-down) and spring (right-down) rainfall diagrams of the 33 years of study in the experimental area. Solid lines represent significant temporal trends following the Theil–Sen approach.

The temporal dynamics of the studied variables are presented in **Figure 4**. Regarding grain yield, it is observed that this variable shows an increasing tendency along the years of the experiments, only interrupted by a substantial valley noticed between the years 2000 and 2010. A similar evolution is observed in TGW, with a decrease in the recorded data of this variable during the first decade of the twenty-first century (**Figure 4**). However, test weight shows a clear increase up to the year 2000, when the growth stabilizes, with the values really close to 83 kg hl^{-1}. Regarding the protein, a linear growth is observed in the data, starting in values lower than 10% in the mid-1990s and finishing in the last years of the study in values above 15% (**Figure 4**).

Wheat yield was influenced by maximum temperature, both in winter and spring, with a negative effect (**Table 1**). Including the sowing date in the model, wheat grain yield was highly influenced by the interaction of winter rainfall and sowing date. Thus, **Figure 5** shows how November (early) and December (medium) sowings were barely influenced by winter rainfall, while January (late) sowings produced a reduction of yield when winter rainfall was scarce. The model predicted a reduction of about 70% in yield in low winter rainfall (~40 mm), as compared to high winter rainfall (~250 mm), corresponding to the *10th and 90th* percentile.

Supporting the temporal dynamics results for test weight (**Figure 4**), only two of the studied climatic variables were significant: spring rainfall (p-value <0.001), which positively influences test weight, and winter minimum temperature when

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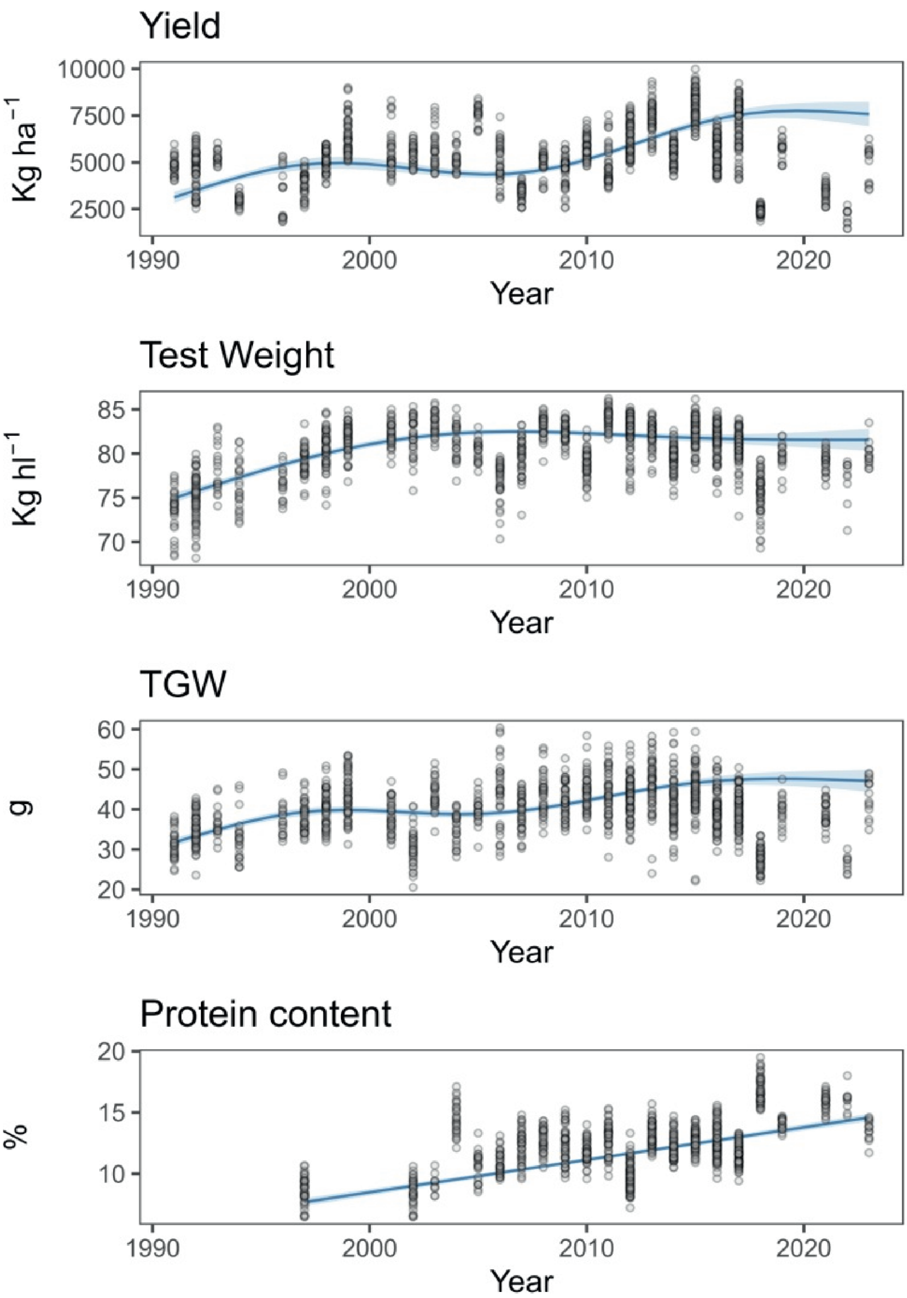

Figure 4.
Temporal dynamics of wheat grain yield (kg ha^{-1}), test weight (kg hl^{-1}), thousand grain weight (g) and protein content (%) of wheat genotypes during 33 years of study in Alentejo region (Portugal).

interacting with sowing date. **Figure 5** shows how early and medium sowing (November and December) barely affect test weight values in any type of winter (warm and cold; 10th and 90th percentile, respectively), while late sowing (January) can cause a decrease of about 50% in test weight when winter minimum temperatures are low (10th percentile). In the case of TGW, minimum and maximum spring

Component	Term	Estimate	Std error	t-value	p-value
Parametric coefficients	Intercept	22985.4	1206.3	19.1	<0.001
	Max. Temp. Winter	−640.1	72.8	−8.8	<0.001
	Max. Temp. Spring	−357.8	19.5	−18.4	<0.001
Component	**Term**	**edf**	**Ref. df**	**F-value**	**p-value**
Smooth terms	Interaction Sowing and Rainfall Winter	6.5	7.3	120.7	<0.001
	Year of sowing	4.0	4.0	268.0	<0.001
Adjusted R-squared: 0.637, Deviance explained 0.642.					

Table 1.
GAM Yield model showing the linear effect of maximum temperature in winter and spring and rainfall in spring and non-lineal effects of year of sowing and the interaction between date of sowing and precipitation on winter.

temperature influenced it positively and negatively, respectively (p-value <0.001 in both cases). The interaction of minimum winter temperature with sowing date indicates the high sensitivity of TGW to a cold winter when late sowing (January) takes place (**Figure 5**).

Finally, spring rainfall negatively influenced the protein content, while winter rainfall positively affected it (p-value <0.001 in both cases). In case of the interaction of minimum winter temperature with sowing date, protein content seems to increase with late sowing in cold winters (**Figure 5**), showing about a 50% increase in protein content in a cold winter compared to a hot winter.

Regarding the phenological data, DTH was proven to be highly correlated in a negative way with the sowing date (**Figure 6**), which implies that the longer the sowing date, the shorter the DTH period, shortening, therefore, the period to generate biomass.

4. Discussion

Our results are in accordance with the literature regarding not only the irregularity in the rainfall patterns between years [28] but also the domination of the rainy months each year [29]. Thus, as González-Hidalgo et al. [29] previously stated for the Spanish mainland, in Portugal, rainfall distribution shows a clear dominance in autumn-winter regarding not only the amount (usually higher amount in winter than in spring) but also the irregularity, which greatly affects the behavior of wheat crop. Taking into account the data presented in **Figure 3**, the decrease in the yield and TGW could be explained by the small amount of winter rainfall in the first decade of 2000 years, combined with lower winter temperatures; the best example of this combination is the year 2004–2005, with averaged rainfall and minimum temperature in winter below 50 mm and 3°C, respectively.

In this regard, the recorded data for this study also confirms the previously stated by the literature, the increase of the temperature, both in winter and spring (about >1°C), and the broader irregularity regarding winter temperature (**Figure 1**) [30–32]. In their study, Asseng et al. [33] indicated that the increase in temperature negatively affects wheat yield, with an estimated reduction of 6% per Celsius degree of increment. However, most of the revised literature deals with the importance of spring temperature, especially what concerns to maximum temperature in late

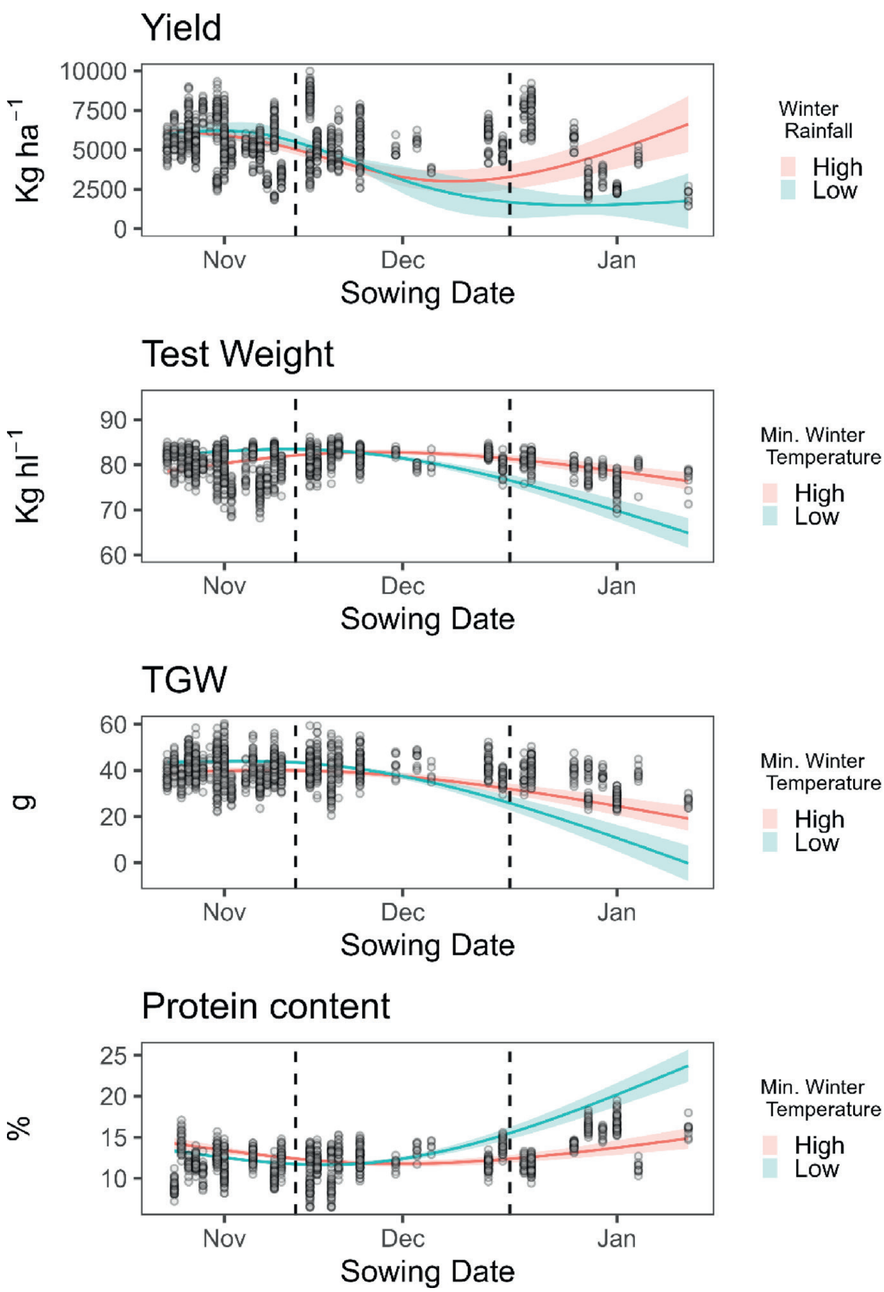

Figure 5.
GAM results on grain yield (kg ha^{-1}) influenced by winter rainfall – sowing date interaction (up). Test weight (kg hl^{-1}), TGW (g), and protein content (%) influenced by the interaction minimum winter temperature – sowing date. Lines depict high and low winter rainfall and minimum temperature corresponding to 10th and 90th percentile of the climatic record during the studied period.

spring or the date of the last spring freeze [34–37], but scarce literature deals with the importance of winter rainfall and temperatures, especially in the Mediterranean basin. In our case, even when spring rainfall and temperature were important predictors of grain yield (max. Temperature and rainfall), test weight (rainfall), TGW

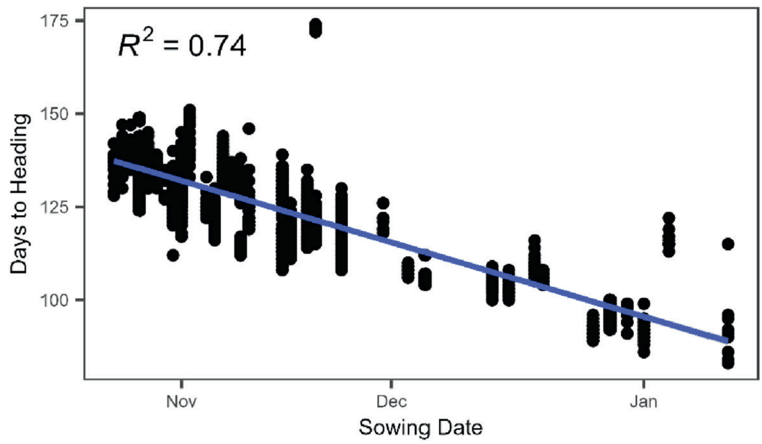

Figure 6.
Correlation between days to heading and sowing date measured as the number of days lasting since November 1 for each year.

(max. temperature) and protein content of the grain (max. temperature), the main factors affecting the studied parameters come from the winter. Thus, winter rainfall enormously influences grain yield, more than any other studied factor, as stated before (**Figures 4** and **5**), especially when late sowing takes place, bringing to light the great importance of winter rainfall and soil water accumulation for plant development during the spring season. In addition, minimum winter temperature determines, to a great extent, TGW, with an observed decrease in years with cold winter temperatures (**Figure 4**) and exacerbated in years with late sowing (**Figure 5**). This is probably due to slow plant growth in the first steps of the plant cycle, shorting importantly the period of time with appropriate temperature for the plant development; in Mediterranean areas, all the parameters that can compromise or highly influence vegetative growth have important consequences in the final yield of the crop, that is why all winter factors can severely influence final grain yield.

In the case of test weight, the more stable recorded data could be explained because test weight measures the adaptation capacity of a genotype to the environment where it is grown; in this sense, our data evidence that test weight is a more fixed value because it compensates the effects of the climate [38], while TGW, being one of the most important yield components, is highly dependent of the climatic season [39]. In addition, the heritability of the TGW trait is considerably higher than that of test weight in winter cereals [40].

Protein content is also influenced by rainfall and temperature, especially minimum winter temperatures, with a positive effect of colder winter on late sowing protein content. This is in accordance with the previously stated: the colder the winter is, the shorter the leaves formation, and so, the amount of assimilates necessary to maintain the foliage of the plant, which means the biomass. On the contrary, flag leaf and subsequent leaves, barely affected by winter cold, will create photo-assimilates to fill the grains, with no losses for biomass maintenance. With reference to protein content, it is well known that this variable is highly dependent on crop management, especially to N application (product, rate, timing, etc.) [41, 42].

Talking about crop management, interestingly, in our results, regarding the interaction of winter rainfall and sowing date, the highest yields were found with late sowing in rainy winter (90th percentile); this fact led us to think that by using irrigation systems, rainy winter can offer the best results in yield, even with late sowing. This fact is really interesting because late sowings can reduce the risk of eventual accidents in the field (storms, drought, diseases, late frosts, etc.) and can also reduce the use of herbicides during the cropping, decreasing both environmental pollution and crop incomes. However, it is necessary to take into account that in Mediterranean winter cereal systems, maturation occurs mostly on similar dates irrespective of the sowing date, and this is due to maximum spring temperatures, which accelerate maturation. In this regard, a late sowing date implies a shorter DTH period, with the resultant reduction in the vegetative period. A reduction of the vegetative period can decrease both leaf area index and root size, causing a reduction in the grain filling and so affecting negatively gross primary production. The decrease in gross primary production is observed in this study by means of yield (**Table 1**) and TGW reduction, similar to what was previously stated by Gitelson et al. [43].

5. Conclusions

To sum up, winter rainfall patterns and, especially minimum winter temperatures influence in a very important way wheat phenology and grain yield in the Mediterranean area, even more than the same parameters in spring. Sowing date interaction with winter rainfall can be used as a predictor of grain yield, while TGW is more influenced by sowing date interaction with minimum winter temperature. In the context of winter maximum temperatures increasing, late sowing (January) date could be a good practice to wheat growing under irrigation without compromising grain yield.

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Conflict of interest

The authors declare no conflict of interest.

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