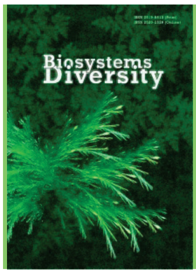

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Diagnosis of the rainfall-wheat yield relationship in the current and future climate change conditions in Eastern Algeria

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Future projections indicate that rain-fed agriculture in North Africa is among the most vulnerable in the world in the context of future climate change. This article aims to diagnose the relationship between rainfall and wheat yield in both current and future climatic situations in a semi arid agro-climatic conditions represented by the region of Bordj Bou Arreridj. For the current situation, we used 15 years (1995–2009) of recorded rainfall and durum wheat yield series. Future rainfall projections (2071–2100) were generated by the MED-CORDEX climate model version CCLM4-8-19 under RCP 6.0 scenario. Simulated data over the observed period and that of the future on the maximum evapotranspiration (ETM) of durum wheat and the water deficit (WD) accumulated over the cycle as well as future yields are obtained using a simple agro meteorological crop simulation model, previously validated. In both current and future situations, precipitations, ETM, WD and yields data are first analyzed, then yields are related by regression to three components of rainfall: annual rainfall, cumulative rainfall over the crop cycle (November–June) and cumulative rainfall during spring (March–May). In the observed climate, annual precipitation averages 382.3 ± 96.3 mm, cumulative rainfall over the crop cycle (November–June) averages 278.3 mm and cumulative rainfall during spring is 101.9 mm. These last decrease to 303.7 ± 99.4, 232.3 and 83.3 mm in the future situation. Observed yields (1995–2009) averages1.9 ± 0.64 q/ha in the observed situation and decrease to 15.5 ± 0.54 q/ha in future climate. ETM are low and WD values are high in the current climate, with a worsening of the situation in the future climate, particularly during spring. The correlation between yields and précitations is always positive in both weather conditions, but the best R^2 are 0.65 and 0.82 and concern spring rains. In semi-arid regions, cumulative rainfall towards the end of the growing season is currently impacting the grain yield of durum wheat and will become more decisive in the context of future climate change.

Keywords: durum wheat yield; recorded rainfall; future climatic and crop conditions; cumulative rainfall over the crop cycle; cumulative rainfall during spring.

Introduction

Cereal farming is an ancient activity in the Algerian agricultural community and is present in all regions of the country including the Saharan zones, with a predominance of durum wheat cultivation. It dominates the North of Algeria, and is practiced in rainy conditions on 97% of the Useful Agricultural Surface (UAS); 80% of this surface is located in the semi-arid agroclimatic zone, characterized by a lack of rainfall, irregularly distributed in space and time (Smadhi et al., 2013). Long and intense droughts during the rainy season can have serious consequences on crop and agricultural production and lack of soil moisture is considered the major constraint as it strongly affects crop growth and returns (Tramblay et al., 2020). However, production in this sector remains low and is around 31 million quintals for an average yield of 20.3 q/ha.

The Mediterranean region is considered one of the regions of the globe with the highest socioeconomic exposure to droughts that is likely to be exacerbated in the future (Gu et al., 2020). North Africa is often considered a "climate change hotspot" that has been receiving increasing attention in recent years, particularly from natural and social scientists (Diffenbaugh & Giorgi, 2012). African agriculture is likely to be the most affected due to its heavy reliance on low-income rain-fed agriculture, but especially due to its low adaptive capacity (Mertz et al., 2009). For almost all parts of North Africa, there was a significant warming trend over the last decades, more pronounced in the summer and with regard to minimum temperatures (Donat et al., 2013). Average precipitation during the rainy season, from October to March, has been decreasing over the last decades, with the greatest decrease over the Mediterranean parts of Morocco and Algeria and over parts of Libya (Nashwan et al., 2019). In the North-African region, no significant trends in wet events over the past decades have been observed (Nasri et al., 2016), against a general increase in the frequency of droughts (Hertig & Tramblay, 2017). Under (RCP) 4.5, the GCM ensemble indicates a warming of about 4 °C in summer and about 2.5 °C in winter by the end of the 21st century and a decrease in rainfall of about −10% to −20% for most of North Africa (IPCC, 2013). Droughts are shown to increase in number, duration and intensity particularly for northern Morocco and Algeria (Gao et al., 2006; Hertig & Tramblay, 2017).

Many studies have focused on the effects of climate variability and change on crop growth and yield (Parry et al., 2004; Xiao et al., 2008; Tao & Zhang, 2011). The most common approach is to use crop simulation models, in combination with soil and crop characteristics, to assess the potential impacts of predicted climatic conditions on farming systems, crop growth and yields, both at both continental and regional scales (Hansen et al., 2004; Moriondo et al., 2011). Wheat grown in rainfed conditions is indicated among the crops most affected by drought in future climates. The reduction in yields induced by droughts strongly depends on the phenological stage during which they occur (Pena-Gallardo et al., 2019; Vicente-Serrano et al., 2013). Early-cycle droughts induce tiller losses, while droughts that occur during the reproduction phase directly and potentially impact yield (Tramblay et al., 2020).

By focusing on rainfed cereal growing in the Algerian semi-arid agroclimatic zone, the first objective of this study is to assess the evolution in the two current and future climates of: precipitation (annual cumulative, that of the wheat cycle and spring months), the water deficit in the soil

(WDC) and crop water consumption or Maximum Evapotranspiration (ETM) of durum wheat. The second objective is to diagnose the rainfall-yield relationship of durum wheat in the two climatic situations in order to identify the rainfall component that has the greatest impact on grain yield in the future climate.

Materials and methods

Study area and climatic data. Bordj Bou Arreridj (36°04′ N 04°46′ E) is located in the Eastern High Plateaux (HPE) of Algeria (Fig. 1), straddling the Bibans mountain range which delimits the southern border of Petite Kabylie, the altitude average is around 900 m (Kourat et al., 2021). The natural environment of BBA is characterized by the succession of three geographical zones; a mountainous zone in the north with the Bibans chain, the cereal zone of the High Plains which constitutes the major part of the region and a steppe zone in the south-west, with an agro-pastoral economy. The climate is of the continental type with variable precipitation from north to south, with an annual average of 369 ± 87 mm, and the average annual temperatures are 15 ± 0.9 °C (Chourghal et al., 2016). Frosts occur from January to April and dry wind starts at the end of the spring (Baldy, 1986). The soils of the region are characterized by a heavy to very heavy texture, shallow depth and moderate organic matter content (Bouzerzour & Dekhili, 1995). The brown calcareous soils, developed on alluvium, colluvium or marl, represent the main pedological unit of the region and production systems in the region are dominated by cereals where yields are low and remain dependent on rainfall, which is both low and erratic (Baldy, 1986).

Fig. 1. Location of Bordj Bou Arreridj region, Algeria

The current climate is represented by fifteen years (1995–2009) of monthly precipitation data collected near the meteorological station in the study area. Future projections (1986–2100) were generated by MED-CORDEX climate model version CCLM4-8-19 under RCP 6.0 scenario. It is a model of the regional climate system that allows the development of a coordinated set of regional climate simulations (past and future) for all the physical components of the Mediterranean climate system with a very high resolution (up to 10 km). The RCP 6.0 was chosen because it is a scenario with stabilization of emissions before the end of the 21st century at an average level (IPCC, 2013). Three components of precipitation were calculated from monthly values for both current and future climate; the annual cumulative rainfall, the cumulative rainfall during the durum wheat cycle (November–June) and the cumulative rainfall during the spring (March–May). On these components, we calculated the statistical parameters and compared their evolution.

Maximum evapotranspiration (ETM), cumulative water deficit (WD) and future yields. The observed series of yields for the region of Bordj Bou Arreridj was provided to us by the Technical Institute of Large Crops (ITGC), which has experimental stations throughout the Algerian territory. The archival data had gaps and we were forced to consider only 15 years (1995–2009). The ITGC carries out different types of trials where the growing conditions (technical itinerary, disease control, etc.) are ideal and respected. On the water supply, the experiments are carried out under irrigated conditions, but always with controls without irrigation and it is on the latter that our collection of yield data is carried out. Different varieties of durum wheat are grown in Bordj Bou Arreridj, some are local like "Mohamed Ben Bachir" and "Boussellam", others are introduced and this is the case with the variety called "Waha". In comparison with the introduced varieties, the production of local varieties is average to quite good (from 20 to 35 q/ha). But the latter are characterized by their good drought tolerance (Laumont & Erroux, 1961).

Water deficits and maximum evapotranspiration in the current and future climate and future yields are simulated using a simple crop model which is a generic agro-meteorological process-oriented model which runs on a daily time scale using climatic, soil and crop data. For a sowing date fixed at November 1st; phenology is calculated on the basis of thermal time (sum of temperature) and potential yield (Y_{max}) calculation is based on the Monteith (1977) relation that, from the value of the photosynthetically active radiation (PAR), calculates the total accumulated dry matter (TDM) and then links it to the harvest index (HI).

$$Y_m = HI \cdot TDM_m \quad (1)$$

$$TDM_m = \varepsilon_c \; \varepsilon_b \; \sum \varepsilon_a \; (j) \; R_s \; (j) \quad (2)$$

where R_s is the incident solar radiation, ε_c the climatic efficiency, ε_a the absorption efficiency and ε_b the biological conversion efficiency,

In the model, the water balance is calculated by a single soil reservoir approach which leads to the estimation of the maximum evapotranspiration (ETM), and cumulative water deficit (CWD) according to the FAO reference method and finally the actual yield Y_a is simulated by the linear water-yield function developed by Doorenbos & Kassam (1979):

$$\frac{Y_a}{Y_m} = 1 - (K_Y \cdot ISH) \quad (3)$$

K_Y is the yield response factor, determined for a number of crops by Doorenbos & Kassam (1979) and WSI is the water stress index. The crop model has been validated on field data and all the steps are detailed and can be documented in Chourghal et al. (2016).

Diagnosis of the rainfall-wheat yield relationship. In order to characterize the influence of precipitation on durum wheat yield in the study area, yields are first correlated with annual rainfall, then with cumulative precipitation along the crop cycle (November–June) and finally with cumulative precipitation during the spring period (March–May). The relationship will be analyzed on the basis of the coefficient of determination whose value varies from 0 to 1; the closer it gets to 1, the stronger the link between precipitation and yield.

Results

Observed and future precipitations. In the actual climate, the maximum annual average was recorded in 2003 and was 600.1 mm. For this same total, the cumulative rainfall over the cycle is 488.8 mm and that cumulative during the spring is only 116.7 mm. Conversely, the best cumulative rainfall during the spring is 288.8 mm but corresponds to a cumulative over the cycle only of 338.7 mm and an annual cumulative of 455.1 mm. In the future climate the best annual rainfall total is only 451.7 mm, which gives a cycle total of 405.6 mm and a spring total of 136.6 mm. Conversely, the best rainfall accumulation over the spring is 150.6 mm and corresponds to a cycle accumulation of 226.9 mm and an annual accumulation of 384.8 mm.

The comparison of precipitation between observed and future climates shows that the inter-annual precipitation decreases by 78.7 mm or –20.6%, the cumulative rainfall over the wheat cycle decreases by 46 mm or –16.5% and the cumulative rainfall during the spring decreases by 18.6 mm or –18.2% (Table 1). Variability of annual rainfall is greater than that of cumulative rainfall over the cycle and cumulative rainfall during the spring in both the current and future climates. In the future situation, it is rather October which becomes the rainiest month with 53 mm and the driest month is always August with 11 mm. Figure 2 represents the evolution of the monthly inter-annual values of precipitation in the observed and future climates.

In the current climate, the wettest month is December with 54.6 mm and the driest month is August with only 6.3 mm. It should be noted that the spring months are also approaching the driest month with respectively 13.0 and 12.8 mm for April and May.

It decreases in the two situations from December to June, with a period of drought which marks the summer period in the current climate but begins in advance (February) and ends late (late August) in the future climate pointing to a remarkably dry spring (up to –65.7% in May). Conversely, monthly cumulative rainfall improves from late summer to early autumn (+52.7% in October) in future climate model.

Table 1
Averages and standard deviations of the three components of precipitation in the current and future climates and average relative differences between the two situations

Precipitations, mm	Observed climate (1995–2009), average ± standard deviation	Future climate (1986–2100), average ± standard deviation	Relative difference, %
Annual	382.3 ± 96.3	303.7 ± 99.4	–20.6
Cumulative precipitation along the crop cycle	278.3 ± 87.6	232.3 ± 70.9	–16.5
Cumulative precipitation during the spring period	101.9 ± 62.5	83.3 ± 45.1	–18.2

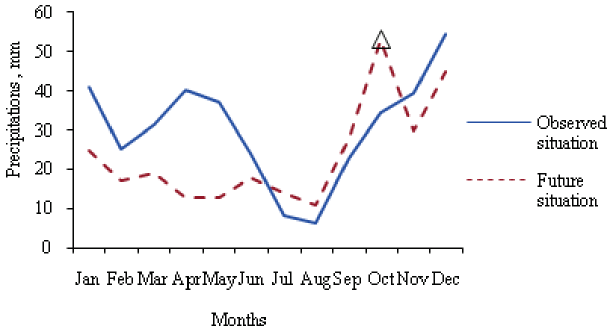

Fig. 2. Monthly precipitation in observed (1995–2009) and future (2086–2100) climatic situations

Maximum evapotranspiration, water deficit and durum wheat yields between actual and future climate. Values of ETM and WD in actual and future climate are indicated in Table 2. In the current climate the ETM takes low values. An average of 255.5 mm indicates a very limited water consumption of the cultivation of durum wheat in the semi-arid region of Bordj Bou Arreridj. It decreases further in future climatic conditions to the value 172.3 mm or –32% with greater variability. The cumulative water deficit over the crop cycle is positively very significant indicating that the water needs of wheat are not covered even at 50% in the current climate. Its value increases further in the future climate (+288.8 mm) due to the decrease in precipitation.

Table 2
Averages and standard deviations of the cumulative crop evapotranspiration and water stress in the current and future climates and average relative difference between the two situations

Precipitation, mm	Actual climate (1995–2009)	Future climate (2086–2100)	Relative difference, %
Cumulative maximum crop evapotranspiration (ETM), mm	255.5 ± 30.4	172.3 ± 28.7	–32.6
Cumulative water stress deficit (WD), mm	273.4 ± 65.2	288.8 ± 58.7	+5.6

Yields in the current climate are higher than those projected in the future under the RCP 6.0 scenario (Fig. 3). The maximum value is 30 q/ha in the current climate against only 15 q/ha in the future situation. In the observed climate grain yields of durum wheat have an average of 19.2 q/ha with a standard deviation of 6.4 q/ha. It decreases in the future climatic conditions to reach an average of 11.3 ± 2.9 q/ha (i.e. a decrease of –41.1, Table 3). The decrease in durum wheat grain yields under future climatic conditions is mainly due to two factors; on the one hand the decrease in the accumulation of dry matter due to global warming, a parameter not dealt with in this study but sufficiently documented by other researches carried out under similar pedoclimatic conditions, and on the other hand increase in the value of the water deficit in the soil, which negatively impacts the water consumption of the plant.

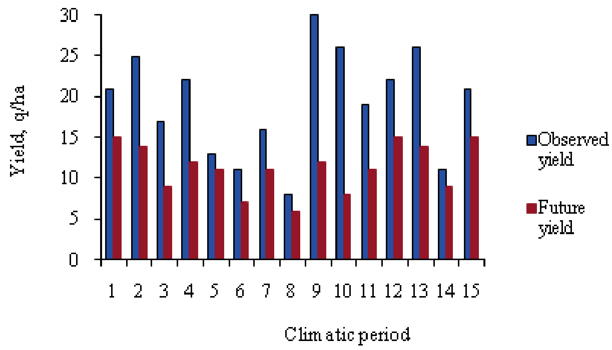

Fig. 3. Durum wheat grain yield in actual climate (1980–2009) and future climate conditions (2086–2100)

Table 3
Average and standard deviation of the yields data in the current and future climate conditions and average relative difference between the two climatic situations

Climatic situations	Average, q/ha	Standard deviation, q/ha	Relative difference between observed and future situation, %
Actual climate (1995–2009)	19.2	6.4	–41.1
Future climate (1986–2100)	11.3	2.9	

Yield in relation to future change in precipitation. The regressions between the three components of precipitation and yields in the two observed (to the left) and future climates (to the right) are grouped in Figure 4.

Regression between annual rainfall and yield (a) is characterized by a low R^2 of 0.43 in the current situation, which decreases further in the future climate (0.32), with a very large dispersion of the points with respect to the regression line.

The regression between cumulative rainfall over the wheat cycle and yield (b) shows an R^2 of 0.59 in the observed climate against a value of 0.41 in the future climate. The dispersion of the points with respect to the regression line becomes less remarkable in comparison with the previous case. The cumulative rainfall regression during the spring-yield (c) records the best R^2 value with 0.65 in the current climate and the remarkable value of 0.82 in the future situation. The points are well distributed around the dispersion line with a much lower dispersion.

Discussion

The comparison between precipitations in the current situation and future climatic conditions projected according to MED-CORDEX climate model version CCLM4-8-19 under RCP 6.0 scenario indicates a decrease in precipitations in eastern Algeria both in the cumulative quantity and in its distribution over time confirming previous findings (IPCC, 2019, 2022).

The decrease in precipitation calculated in our study has already been documented by previous studies on the Mediterranean and North African region (Giorgi & Lionello, 2008; Paeth et al., 2009; Schilling et al., 2020).

Conversely, in Bordj Bou Arreridj the end of summer and the beginning of autumn seem to benefit in the future from a remarkable increase in rainfall. Tanasijevic et al. (2014) show that summer rainfall over Europe may decrease, while a slight increase is predicted for parts of North Africa and the Middle East.

In the region of Bordj Bou Arreridj the quantity of precipitation and its distribution explain perfectly the durum wheat yield level and its interannual variability. The correlation between yields and precipitations is always positive. The R^2 is low for annual rainfall. It improves for the cumulated rainfall on crop cycle and becomes very significant in the relation which links the accumulated precipitation during the spring period to yields, especially in the future climate conditions. This confirms the importance of the rainfall factor in this region well known by the occurrence of drought at the end of growing season (Baldy, 1986), which often coincides with flowering and grain formation stages on which the durum wheat grain yield depends (Bensalem, 1993) and those are also the most sensitive stages to drought (Bouzerzour & Dekhili, 1995).

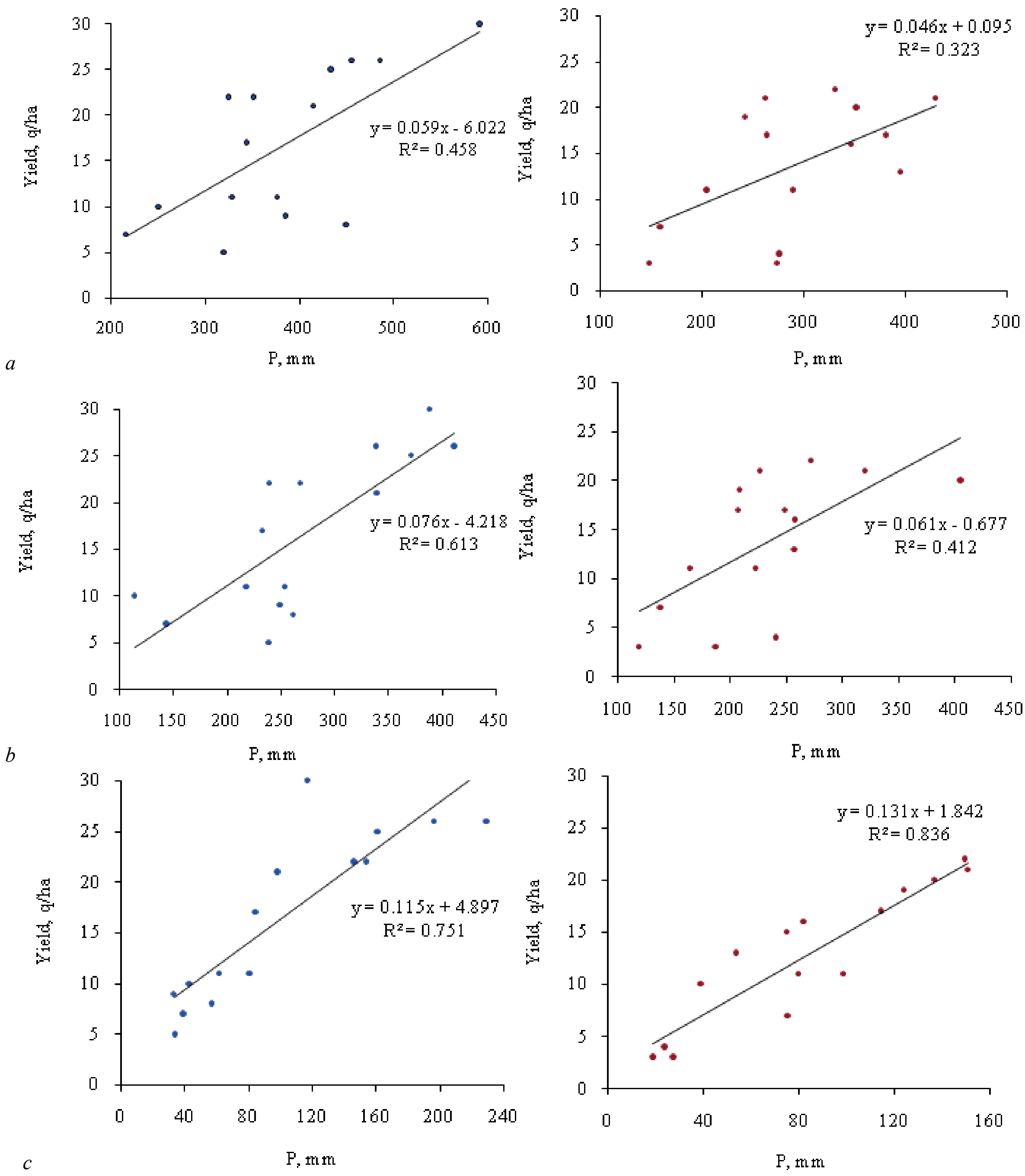

Fig. 4. Regression between precipitations and durum wheat yield in the current and future situations: *a* – annual precipitation; *b* – cumulative precipitation on the crop cycle versus yields; *c* – spring precipitation versus yields

Studies on winter wheat in the Mediterranean region show that global warming induces an advancement in the appearance of phenological stages accompanied by a shortening of their duration (Mo et al., 2016; Rezaei et al., 2018) which results in a lower accumulation of total dry matter, which in combination with stress water induces reduction in yields (Giannakopoulos et al., 2009; Moriondo et al., 2011).

In Algeria, the effect of warming and the future decrease in rainfall induce a negative water balance with a high Water Stress Index (WSI) and a low cumulative maximum evapotranspiration, which leads to a drop of (–36%) in the yield of durum wheat, if sowing is done late (Chourghal & Hartani, 2020).

Conclusion

Bordj Bou Arreridj, which is located at the semi-arid bioclimatic level, is indicated to become even more arid by the projections of the MED-CORDEX climate model version CCLM4-8-19 under RCP 6.0 scenario. In the future, precipitation will be characterized by; a decrease in the annual total, a greater increase in variability over time and above all by a reorganization of monthly and seasonal distribution. Increases in precipitation are projected from the end of summer until the beginning of autumn against long periods of drought, which will particularly affect spring, making the cumulative rainfall during this period much lower. The water consumption (ETM) of wheat will decrease and the water deficit in the soil (WDC) will be intense, which will inevitably and potentially impact the accumulation of total dry matter and the final yield grain (Ya). The present study confirms that this last parameter is more related to the spring rainfall than to the annual total and on the cycle, because this period coincides with the reproductive phase in wheat, a period very sensitive to water stress. This relationship will be even closer in the future climatic context and yields are projected to decrease sharply due to the periods of droughts indicated to be more severe, more frequent and longer during the spring.

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