Field Crops Research 259 (2020) 107969

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Understanding effects of genotype × environment × sowing window interactions for durum wheat in the Mediterranean basin

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ARTICLE INFO

Keywords:
SiriusQuality
Sowing window
Mediterranean environments
Durum wheat

ABSTRACT

Durum wheat is one of the most important crops in the Mediterranean basin. The choice of the cultivar and the sowing time are key management practices that ensure high yield. Crop simulation models could be used to investigate the genotype × environment × sowing window (G × E×SW) interactions in order to optimize farmers' actions. The aim of this study was to evaluate the performance of the wheat model *SiriusQuality* in simulating durum wheat yields in Mediterranean environments and its potential to explore the G × E×SW interactions. *SiriusQuality* was assessed in multiple growing seasons at seven sites located in Italy, Spain and Morocco, where locally adapted cultivars were grown. The model showed good ability in predicting anthesis and maturity date (Pearson r >0.8), as well as above ground biomass and grain yield (6 % < nRMSE < 18 %). The model was then used to find the optimal 30-day sowing window to maximize grain yields at four sites, two were located in Italy (Florence, Foggia), and the other two were in Spain (Santaella) and Morocco (Sidi El Aydi) respectively. Among the cultivars, on the average between all sowing window, Amilcar had the best performance in Foggia (+33 % compared to the traditional cultivar Simeto) and in Sidi El Aydi (+22 % compared to Karim), Karim in Florence (+19 % compared to Creso) and in Santaella (+6 % compared to Amilcar). Instead Creso and Simeto showed the lowest production at all locations. The results showed that an earlier sowing window compared to the traditional one would have a positive effect on wheat yields in all environments tested, because of increased maximum leaf area index, grain number and size, and grain filling duration. Moreover, with earlier sowing, grain filling coincides with higher soil water availability, reducing the water stress and increasing the accumulation of dry mass in grains. In cooler and wetter locations, cultivars characterized by higher leaf area index and radiation use efficiency had the higher number of grains, while in the hottest and driest locations, short-cycle cultivars with high grain dry matter potential (e.g. through enhanced "stay green" capacity) should be preferred.

1. Introduction

Durum wheat (*Triticum turgidum* L. subsp. *durum*) is one of the most important crops in the Mediterranean basin, which contributes to more than 38 % to the global durum wheat production (IGCC, 2017). In general, grain yield and quality are strongly influenced by the variability of weather conditions during the season (Porter and Semenov, 2005). Moreover, wheat is mostly sensitive to late frosts as well as to high temperatures and water deficit during the reproductive and grain filling phases (Porter and Gawith, 1999; Farooq et al., 2011; Alghabari et al., 2014). Terminal droughts could render the crop more sensitive to heat stress, as well as heat stress could be exacerbated by water stress, resulting in even more negative effects on the grain yield (Asseng et al., 2011). Such environmental conditions, typical of the Mediterranean

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https://doi.org/10.1016/j.fcr.2020.107969
Received 31 January 2020; Received in revised form 12 August 2020; Accepted 22 September 2020
Available online 7 October 2020
0378-4290/

climate, are the main climatic constraints for durum wheat yield in the Mediterranean basin (Ferrise et al., 2015).

Appropriate management practices are essential to ensure high wheat production. The sowing time and the cultivars choice are among the key factors (Connor et al., 1992; Bassu et al., 2009), since they act on the duration and timing of developmental phases and have the potential to avoid adverse environmental conditions in wheat sensitive stages (Ferrise et al., 2010; Bassu et al., 2009; Tapley et al., 2013). It is proved that the combination of optimal sowing date with early or late cultivars allows maximizing the yield and avoid stresses due to frost, heat and drought stresses around the anthesis and during grain filling (Ababaei and Chenu, 2020; Zheng et al., 2012), while favouring precipitation, temperature and radiation accumulation in the growing season (Tapley et al., 2013). Long-season cultivars may benefit from early sowing, thanks to an increased intercepted radiation during winter, thereby resulting in a higher accumulation of dry matter by the crop, while escaping terminal droughts (Zheng et al., 2012). On the other hand, this practice is not appropriate with early cultivars, when frost risk is generally high during winter or early spring (Andrarzian et al., 2015). Late sowing is usually recommended in locations with high frost risk (Connor et al., 1992), because it helps the crop to escape from frost conditions during the sensitive phases of crop growth. However, late sowing may induce a shortening of crop cycle (Sharma et al., 2008) and expose the crop to warmer and drier conditions during anthesis and grain filling (Panozzo and Eagles, 1999; Subedi et al., 2007). In the Mediterranean basin, the sowing window of durum wheat starts with the first significant rainfall after the summer season and ends when a sowing date is too late to allow the completion of the crop cycle. In the Mediterranean basin, the optimal combination of sowing window and cultivar should result in avoiding (or minimizing the impact of) frost damage during early springs as well as heat and drought conditions during anthesis and grain filling (Bassu et al., 2009; Chen et al., 2020).

It is widely recognised that wheat yield and grain quality are affected by genotype (G), environment (E), sowing window (SW) and their interactions (Sharma et al., 2008; Tapley et al., 2013; Haq et al., 2017). The complexity to test G × E × SW interactions in field experiments could be reduced by testing alternative scenarios with crop simulation models (Stapper and Harris, 1989; Chenu et al., 2017), which are able to reproduce crop growth and development, considering the interactions between soil, weather and crop management. Crop models have been largely used to extrapolate agronomic research findings over time and space (Chenu et al., 2017), to assess crops performance in response to climatic conditions (Salado-Navarro and Sinclair, 2009; Soltani et al., 2013; Dettori et al., 2017) and to identify the best management practices in a given environment (Soltani and Hoogenboom, 2007; Rozbicki et al., 2015). Several crop modelling studies have been carried out to investigate the effect of shifting the sowing date in future climatic scenarios (Moriondo et al., 2010; Dettori et al., 2017; Nouri et al., 2017) or to analyze the combination of adaptation strategies, including the shifting of the sowing date (Ruiz-Ramos et al., 2018; Giuliani et al., 2019) or to define the optimal flowering period in Australian environments (Flohr et al., 2017; Chen et al., 2020) but only few studies focused on the optimization of the sowing window in the Mediterranean basin under present climatic conditions (Bassu et al., 2009).

The objective of this study was to investigate the effects of genotype × environment × sowing window in four areas of the Mediterranean basin for current climate, by using the wheat simulation model SiriusQuality. First, the model was calibrated and evaluated in the targeted environments; then, a scenario analysis was carried out to identify the optimal sowing windows for early and late cultivars in order to quantify the impact of G × E × SW interactions on wheat growth and development.

2. Materials and methods

2.1. Experimental sites

Data were collected from field experiments carried out in seven Mediterranean locations where durum wheat (*Triticum turgidum* L. subsp. *durum*) is widely grown (Fig. 1). The experimental sites were located in Florence (43.76 °N, 11.21 °E, 42 m elevation) and Foggia (41.26 °N, 15.30 °E, 90 m elevation), in central and southern Italy, respectively, in Carmona (37.47 °N, 5.63 °W, 253 m elevation) and Santaella (37.57 °N, 4.85 °W, 238 m elevation), in southern Spain, in Marchouch (33.98 °N, 6.49 °W, 398 m elevation) and Sidy El Aydi (33.16 °N, 7.40 °W, 315 m elevation) in the north of Morocco, and in Khemis Zemamra (32.63 °N, 8.70 °W, 165 m elevation) in the south of Morocco. According to Metzger et al., 2005), the sites belong to northern (Florence) and southern (the other sites) Mediterranean environmental zone, with hot and dry summers and mild winters. Monthly maximum temperatures are in August (from 30 °C in Florence and Morocco to 32 °C in Spain), while January is the coldest month with minimum monthly temperature ranging from ~3 °C in Florence to 6 °C in Morocco. Rainfall are mainly concentrated in late autumn (Florence and Spain) and winter (Foggia and Morocco), with a secondary peak during spring in Florence and Foggia. Annual cumulated rainfall shows a clear latitudinal trend ranging from 750 mm in Florence to 350 mm in Morocco (Fig. 2).

2.2. Experimental field data

In Florence, data were collected from two rainfed experiments carried out at the University of Florence in the 2002–2003 and 2004−2005 growing seasons (Ferrise et al., 2010) with the Italian durum wheat cultivar Creso, a medium-late maturation cultivars characterized by high yield quantity and good quality. Sowing (150 seeds m^{-2}) was performed on the 11 December 2002 and 05 November 2004 (normal sowing dates), and on 27 January 2003 and 18 January 2005 (late sowing dates). Four nitrogen treatments were applied with a total amount of 0, 6, 12 and 18 g N m^{-2}; one-third of which was applied as ammonium sulphate at Zadoks' growth stage (Zadoks et al., 1974) (ZS) 15/22 (leaf 5 emerged at 50 %, 2 tillers visible) and the remaining two third as ammonium nitrate at ZS 31 (first stem node detected).

In Foggia, data were obtained from a long-term field experiment carried out at the CRA-SCA experimental farm in the periods of 1997–2000 and 2007–2013 (11 growing seasons). Data used in this study were collected on the cultivars Simeto, a medium-early maturation Italian cultivars characterized by an excellent grain quality. Crops were sown between mid-November and early January, depending on the weather and soil conditions, at a density of 400 seeds m^{-2}. Two treatments were applied each year. In the first treatment (hereafter treatment A), crops received 10 g N m^{-2} of ammonium nitrate at ZS 31, and in the second treatment (hereafter treatment B), crop residues were incorporated with 30 mm of water and crops received 15 g N m^{-2} as urea at sowing and 10 g N m^{-2} as ammonium nitrate at the ZS 31. In 2012 and 2013, crops were irrigated (both treatments) with 30 mm, during the emergence phase, and 80 mm, before anthesis, respectively. Otherwise, the crops were rainfed.

In Spain, experimental data were provided by the Andalusian Network of Agricultural Trials (RAEA in Spanish). For this study, data from wheat trials conducted in Carmona and Santaella in the period 2011–2015, and 2011–2016, respectively, were considered. Crop data used in this study were from the cultivar Amilcar, a short-cycle cultivar selected for high potential production and disease resistance. At both sites, crops were sown within late November and mid-December at a density of 350 and 360 seeds m^{-2} in Carmona and Santaella, respectively. In Carmona, crops received 8–13 g N ha^{-1}, of which 30–50% was applied at sowing as diammonium sulphate and the remaining in one to two splits between ZS 23 (3 tillers visible) and 37 (flag leaf just visible) as urea and ammonium nitrate. In Santaella, crops received 11.5–18.5 g

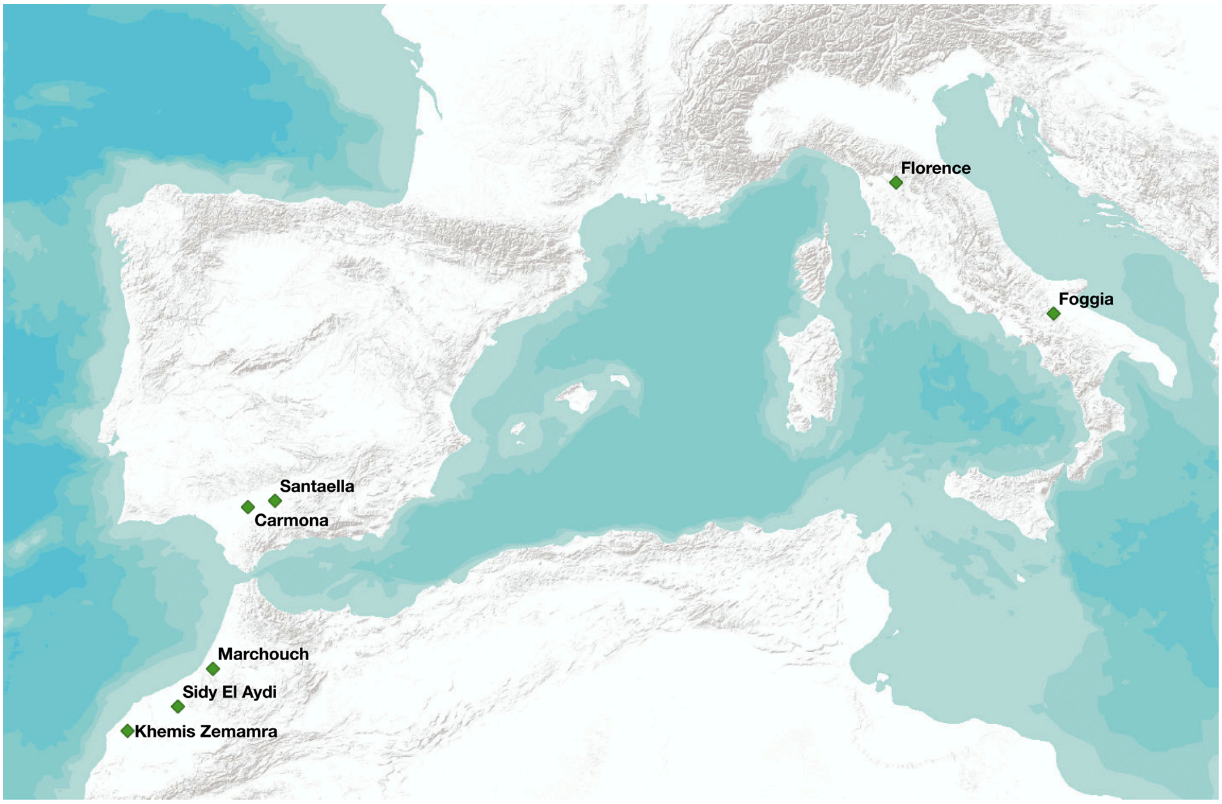

Fig. 1. Locations of the sites used in this study: Florence in central Italy, Foggia in southern Italy, Carmona and Santaella in the south of Spain, Marchouch, Sidi El Aydi and Khemiz Zemamra in the north of Morocco.

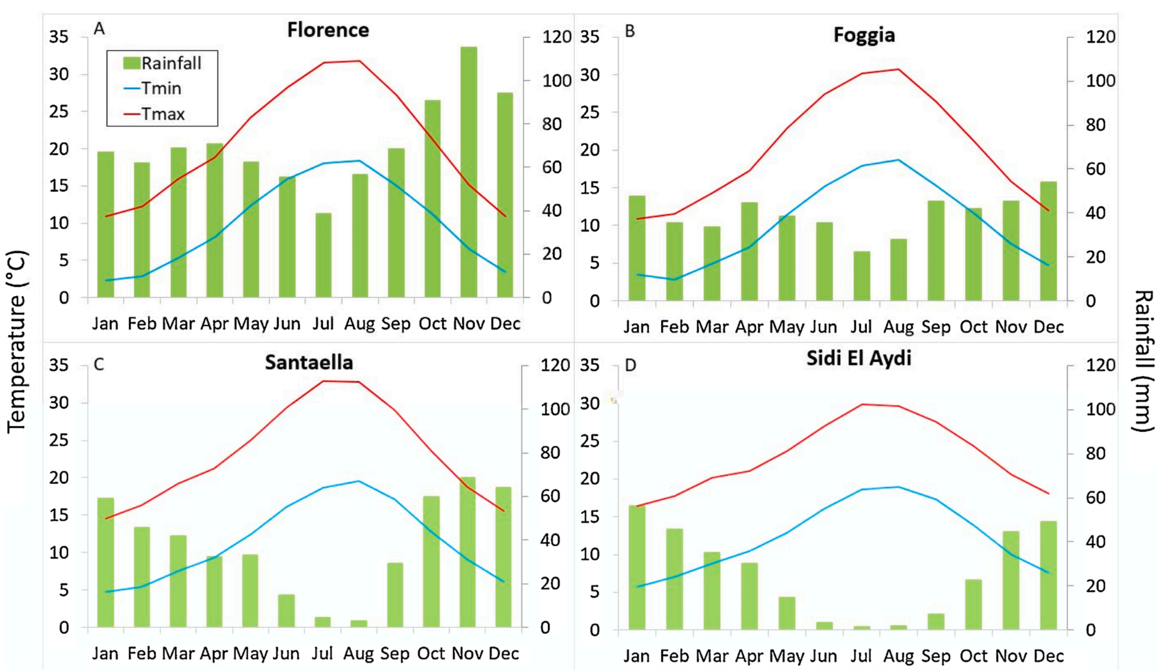

Fig. 2. Average of 100 years of monthly rainfall, minimum (Tmin) and maximum (Tmax) temperatures generated for the period 1980–2010 by LARS-WG in Florence, Foggia, Santaella and Sidi El Aydi.

N ha^{-1} of which 20%–100% were applied at sowing as diammonium sulphate and the remaining between ZS 21 and 37 as urea. In Santaella, in 2012, 2014 and 2016, crops were irrigated with 30–40 mm at crop establishment stage and in 2012, they received 80 mm on 21 March, otherwise, at both sites crops were rainfed.

In Morocco, data were obtained from field experiments carried out in the experimental stations of the National Institute of Agronomic Research of Morocco during the 2011–2012 and 2012–2013 growing seasons in Sidi El Aydi, and in 2011–2012 in Khemis Zemamra and Marchouch (Bregaglio et al., 2015). In both years, crops were sown in the second half of November in Sidi El Aydi and in the second half of December in Kemis Zemamra. In Marchouch, sowing was done on 12 December. Cultivar Karim, a medium semi-dwarf high yielding cultivar, was used in all the experiments in Morocco. In all the experiments, the sowing density was 400 seeds m^{-2}, and the crops received 18 g N ha^{-1} as diammonium phosphate at sowing and 46 g N ha^{-1} as urea at ZS 39 (flag leaf ligule just visible). In Kemis Zemamra, crops were rainfed, in Marchouch, they were fully irrigated, and in Sidi El Aydi, a rain fed and fully irrigated treatments were applied. Fully irrigated crops received 40 mm every 1–7 days depending on the crops' need.

At each location, maximum and minimum air temperature, rainfall and global solar radiation data were collected from automatic weather stations located close to the respective experimental fields. Soil properties were available for all sites except that of Morocco, for which they were extracted from the ISRIC's SoilGrids database, from the Africa Soil Information Service (www.soilgrids.org, http://africasoils.net/).

Phenological stages, such as emergence, anthesis, physiological maturity, were recorded in all the experiments following the BBCH scale (Meier, 2001). In Spain, heading dates were recorded instead of anthesis dates. Grain yield was measured in Italy and Spain but not in Morocco, while total above ground biomass data were available in Italy and in Morocco. Total above ground N, grain N content and grain number data were available in Florence.

2.3. The wheat simulation model SiriusQuality

The wheat simulation model *SiriusQuality* was used (He et al., 2012; Maiorano et al., 2017; Martre et al., 2006; Martre and Dambreville, 2018; Wang et al., 2017; http://www1.clermont.inra.fr/siriusquality/). *SiriusQuality* has been evaluated under a large range of conditions covering different environments and management practices (Ferrise et al., 2010; Tao et al., 2017; Wallach et al., 2018; Porter et al., 2019). *SiriusQuality* simulates daily wheat growth and development, including phenological stages, leaf area index, biomass and N uptake and partitioning, and soil water and N fluxes in response to the environmental conditions and crop management. The model requires as input, daily weather data (at least maximum and minimum air temperatures, solar radiation and precipitation), soil properties (organic N content, saturation, field capacity, wilting point, clay content), and management information (sowing date or sowing window, sowing density, N fertilization and irrigation rates and dates or growth stages). By default, the upper limit of evapotranspiration is given by Penman, 1948, potential evapotranspiration rate as formulated by French and Legg, 1979), which uses humidity and wind speed. However, when air vapor pressure or wind speed data are not available, as in this study, the Priestley-Taylor approximation is used. Phenological stages are reproduced according to the rate of leaf appearance and final leaf number modified by vernalization and photoperiod response (He et al., 2012). Canopy development is simulated using a leaf cohort approach and coordination rules (Martre and Dambreville, 2018), and daily biomass assimilation by each leaf cohort is simulated from photosynthetically active radiation using a radiation use efficiency approach (Jamieson et al., 1998a). Biomass allocation and remobilization is modeled using a sink/source approach and sink priority rules (Jamieson et al., 1998a). N uptake and partitioning is modelled using a photosynthesis acclimation model and sink priority rules (Martre et al., 2006; Bertheloot et al., 2008). Soil N deficit first reduces LAI expansion, and if this is not sufficient, N is remobilized from leaves, which accelerates leaf senescence and stem reserves. As for N stress, water deficit first reduces leaf expansion rate (Martre and Dembreville, 2018), then plant transpiration. More severe water deficit reduces also biomass accumulation and accelerate the rate of leaf senescence during the post-anthesis period (Semenov and Halford, 2009). Grain dry mass accumulation depends on post-anthesis biomass assimilation and includes a fixed proportion translocated from the dry mass accumulated at anthesis (25 % of leaf lamina and 10 % of leaf sheath dry mass) and a proportion (25 %) of the biomass accumulated in the stem (internodes) during the early (lag) phase of grain development (Martre et al., 2006). Dry mass is transferred to the grain at a constant rate in thermal time, thus any stress affecting (reducing) the potential duration of the grain filling, including water and N stresses, reduces the quantity of biomass translocated. All the processes are driven by non-linear responses to temperature (Wang et al., 2017) and considers the impact of heat, water and nitrogen stress on canopy senescence (Maiorano et al., 2017). The version 2.0.2 of *SiriusQuality* (https://github.com/SiriusQuality/Release) was used.

2.4. Model calibration and validation

Because the availability of experimental data varied between locations, *ad-hoc* criteria were developed to calibrate/evaluate the model. For central Italy (Florence), data collected without N fertilization treatment were used for the calibration, whereas data with N fertilization treatments (6, 12 and 18 g N m^{-1}) were used for model validation. Although the parameters, except those related to stress responses (none was included in the calibration) are usually estimated with treatments close to potential production conditions, in Florence, the treatment with no fertilizer application was used, so that the rate of soil N mineralization could be estimated. For southern Italy (Foggia), treatments A and B for the growing seasons from 2006 to 2011 were used for model calibration, and treatments A and B for the growing seasons from 1996 to 1999 and 2012–2013 were used for model validation. For southern Spain, data from Carmona were used for model calibration, whilst data from Santaella were used for model validation. In Morocco, the model was calibrated using the irrigated treatments at Khemis Zemamra and Sidi El Aydi and the rainfed treatments at the three sites were used for model validation.

In Morocco, the weather conditions around sowing were very dry and the observed emergence occurred on the average of 20 days after sowing and coincided with the first rainfall event. Once the sowing date is set, *SiriusQuality* simulates the emergence date, considering only the thermal time from sowing to emergence, without taking into consideration the soil water content. Thus, to correctly simulate the observed emergence, and consequently the other observed phenological stages, the sowing dates used for the calibration process were postponed until the soil moisture was favorable for germination and plant growth. As such, sowing dates were estimated using *SiriusQuality* with a fixed sowing window (15 November to 30 December). Sowing occurred the first day within the sowing window when the soil water content of the 0−30 cm soil layer was > 75 % of the plant available water content and the cumulative precipitations over 3 consecutive days was > 10 mm. If the conditions were not met on the last day of the sowing window, then, the sowing occurred the following day. Since grain yield data were not available in Morocco, the calibration and validation of the model was performed on phenological development and above ground biomass accumulation.

Seven genotypic parameters were estimated for each cultivar (Table 1) using a covariance matrix adaptation—evolutionary strategy (Hansen and Ostermeier, 2001) that minimized the root mean squared error (RMSE) between all simulated and observed available data. The parameter values were estimated sequentially starting with phenology (Dse, Phyll, SLDL, and Dgf), then canopy development (PlagLL and PsenLL), and finally biomass accumulation (RUE). Each parameter estimation step was performed four times to estimate the uncertainty in the estimated values. When the uncertainty ranges for two or more cultivars overlapped and the differences in RMSEs between the estimated and average values was < 10 %, the average of the estimated parameter values was used. The parameter values were rounded up based on their uncertainty and influence on the model results.

2.5. Model application

To analyze G × E×SW interactions, the four wheat cultivars used in

Table 1
Name, definition, unit and value of the varietal parameters of the wheat model SiriusQuality calibrated for the durum wheat cultivars Creso, Simeto, Amilcar and Karim.

Name	Definition	Unit	Value (±st.dev.)			
			Creso	Simeto	Amilcar	Karim
Dgf	Potential thermal time from anthesis and end of grain filling	°Cd	650 ± 5.8	550 ± 10.4	500 ± 8.55	600 ± 26.9
PlagLL	Phyllochronic duration between end of expansion and the beginning of the senescence period for the mature leaves	cm^2 $lamina^{-1}$	8 ± 0.16	5 ± 0.46	8 ± 0.23	8 ± 0.12
PsenLL	Phyllochronic duration of the senescence period for the mature leaves	Phylllochron	5 ± 0.09	3 ± 0.56	5 ± 0.04	5 ± 0.14
RUE	Potential radiation use efficiency under overcast conditions	g MJ^{-1} (PAR)	2.5 ± 0.11	2.9 ± 0.05	3.1 ± 0.07	3.5 ± 0.17
Dse	Thermal time from sowing to crop emergence	°Cd	93 ± 0.8	111 ± 0.8	125 ± 2.4	135 ± 4.2
Phyll	Phyllochron	°Cd	115 ± 1.0	105 ± 0.4	90 ± 3.0	115 ± 0.7
SLDL	Daylength response of leaf production	Leaf h^{-1} (daylength)	1.405 ± 0.048	1.410 ± 0.033	1.040 ± 0.011	1.220 ± 0.007

model calibration and validation at Florence, Foggia, Santella, and Sidi El Aydi in the period of 1980–2010 were simulated, testing different 30-day sowing windows ranging from October to January. In each site, the soil type used for calibration (typical of each location) and the standard local management practices (as communicated from local experts) were adopted as inputs for the model (Table S1). The four cultivars, Creso, Simeto, Amilcar and Karim were tested in all the locations.

To be consistent with international studies, such as AgMIP and MACSUR, and provide longer time series for risk assessment due to inter-annual climate variability and climatic extremes, 100 years of daily weather were generated for all sites using the LARS-WG weather generator (Semenov and Barrow, 1997; Semenov and Stratonovitch, 2015) and the ELPIS dataset (Semenov et al., 2010) of site parameters for Europe, derived from the interpolated daily 25 km gridded meteorological dataset, Crop Growth Monitoring System (CGMS) of the Joint Research Centre for the period of 1980–2010. This latter dataset has been created for agricultural modelling applications, since the interpolation procedure adopted (van der Goot and Orlandi, 2003) accounts for the agricultural areas within a cell and makes these data representative of an agricultural area typical to this grid. CGMS was used to compute the ELPIS dataset of site parameters for the LARS-WG weather generator to enable the generation of local-scale daily climate scenarios across Europe. LARS-WG in Europe and the ELPIS 1980–2010 dataset was validated against independent meteorological dataset ECAD (Semenov et al., 2013) and demonstrated a good performance particularly for agricultural application. The 100 years generated by LARS-WG (Fig. 2) are representative samples of weather conditions in the 1980–2010 period (Semenov and Stratonovitch, 2015), and were used to increase the significance of the modelling results. All simulations were done with an atmospheric CO_2 concentration of 363 ppm (as the average of 1980–2010). At each site, to investigate the best sowing window in terms of yield (HSW), 30-day sowing windows were tested starting from 10 October until 5 January, with 5 day increments and compared with the final yield at the traditional sowing window (TSW). Within each sowing window, the sowing date was calculated year-by-year with the approach described by Brisson et al. (2009). Sowing occurred the first day when 10 mm of cumulative precipitation occurred in the previous three days, an average air temperature > 10 °C and a minimum air temperature > −4 °C in the previous 10 days, and a soil moisture content >75 % of the plant available water content in the top 30 cm soil layer. An exponential relaxation was applied on the soil water content and precipitation threshold to estimate the sowing date as the sowing date approached the end of the sowing window. If the conditions were not met on the last day of the sowing window, then sowing occurred on the following day.

To understand the changes in crop water required between the different sowing windows, the evaporative drought index (EDI); (Yao et al., 2010) was calculated during the grain-filling period. EDI is given by:

$$EDI = 1 - \frac{ET}{PET} \tag{1}$$

Where, ET and PET (mm) are the cumulative actual and potential evapotranspiration during the grain-filling period, respectively. The EDI ranged from 0 to 1. A lower EDI value means that the actual evapotranspiration demand is close to the potential, indicating an abundant water supply for the crop. An EDI value close to one means that the actual evapotranspiration is close to 0, indicating insufficient water supply to guarantee crop water need. In this study, both actual and potential evapotranspiration were computed by the crop model (Jamieson et al., 1995, 1998b).

2.6. Statistical analysis

All the statistical analyses and the model simulations were carried out using R programming environment (R core team, 2013). The accuracy of *SiriusQuality* in reproducing observed phenology, above ground biomass, grain yield and N grain yield was evaluated by considering the Pearson's correlation coefficient (*r*), the mean absolute error (MAE), the normalized root mean square error (nRMSE), and the index of agreement (*d*). The Pearson's correlation coefficient is the covariance of the two variables divided by the product of their standard deviations:

$$r = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)(S_i - \overline{S})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(S_i - \overline{S})^2}} \tag{2}$$

Where, O_i is the observed data, $\overline{O}$ is the mean of the observed data, S_i is the simulated data, $\overline{S}$ is the mean of simulated data, and n is the number of data points. Negative *r* values imply that an inverse relationship exists between simulations and observations, whereas a value of zero implies that there is no correlation between the simulated and observed data, and value close to one indicates that model predict well the variations in the observed data.

The nRMSE provides information regarding the relative difference (expressed in % of the mean value of observations) between the simulated and observed data and is given by:

$$\text{nRMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \text{x} \frac{100}{\overline{O}} \tag{3}$$

The model performance is considered excellent if nRMSE value is less than 10 %, good if it is between 10 and 20 %, fair if it is between 20 and 30 %, and poor if it is greater than 30 %. (Bannayan and Hoogenboom, 2009).

The MAE is calculated by summing the magnitudes of the errors and dividing them by the number of data:

$$\text{MAE} = \frac{\sum_{i=1}^{n}|S_i - O_i|}{n} \tag{4}$$

MAE measures the average magnitude of the absolute differences between the simulated and observed data, where all individual differences have equal weight, thus reducing the effect of outliers compared to RMSE (Yang et al., 2014). Simplifying, MAE shows how big an error that could be expected on the average from the model, thus values close to zero correspond to a good model performance.

Finally, the index of agreement (Willmott, 1981) is defined as:

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} \left(\left| S_i - \overline{O} \right| + \left| O_i - \overline{O} \right| \right)^2} \right] \quad (5)$$

Where, the numerator is the sum of the square errors and the denominator is the largest potential error from the observed mean. The index of agreement provides a measure of the agreement of the deviation of modelled and observed values from the observed mean, since the potential error (the denominator) increases when modelled and observed values deviate in the same direction (i.e. both higher or lower than the mean). The d ranges from 0 to 1, with values closer to 1 indicating better model performances.

The effects of environment, genotypes, and sowing windows on plants agronomic performances and phenological traits were analyzed fitting a three-way ANOVA (analysis of variance) model, testing all levels of factor interactions. The general pedo-climatic conditions (i.e. soil characteristic, rainfall) and agronomic practices (i.e. fertilization treatments, plant density, except sowing date) were considered as typical traits that characterize each location, and we referred to them as environmental factor (E). Data that do not fulfil the ANOVA assumption were log transformed prior to the analysis. For each location and cultivar, a *t*-test comparison between the simulated yields obtained at TSW and at HSW was carried out. Moreover, the Coefficient of Variation (CV, %) at TSW and HSW was calculated to understand the difference in the inter-annual crop variability.

A principal component analysis (PCA) considering grain filling duration (GF), leaf area index (LAI), cumulated rain during the grain filling (RAIN), photosynthetic active radiation (PAR), yield, single grain dry matter (GDM), and grain number m^{-2} (GN) was carried out on all sowing windows using R factoextra package (Kassambara and Mundt, 2019), in order to estimate the relative importance of each trait in capturing data variation and the importance of sowing windows and wheat cultivar as possible factors structuring the data.

3. Results

3.1. Model evaluation

For both the calibration and validation data sets, MAE for anthesis or heading date and maturity date were < 9.3 days (Table 2, Fig. 3C-E), and nRMSE for grain yield and total above ground biomass ranged from 6 to 18 % and from 10 to 32 %, respectively (Table 2, Fig. 3A-D-F-G-H). The overall nRMSE for grain yield was only 5 % higher in validation than in calibration data set. All *d* values for phenology and grain yield except heading date in Carmona (that is, the Spanish site) were > 0.70. On the average, MAE for phenological stages were only one day higher in calibration than in validation data set. For the data used for model validation, all *r* and *d* values were > 0.80 and 0.70, respectively (Table 2). For the protein concentration in Florence, the nRMSE was 10 % (Table 2, Fig. 3A). In Morocco, the *d* for the biomass dynamic was 0.97 (Table 2, Fig. 3G, H) and the MAE for anthesis date was 9 days (Table 2).

3.2. Genotype × environment × sowing window effects

G × E × SW interactions were highly significant ($P < 0.001$) for anthesis date, leaf area index (LAI) at anthesis and grain number, while yield showed highly significant G × E and E × SW interactions (Table 3).

The PCA results suggested that different environments affected cultivars performances. For instance, whilst in Florence and in Foggia, the cultivars behaviors tended to diverge, in Santaella and Sidi El Aydi, they were more overlapped. Overall, the PC1 and the PC2 explained a high share of the total variation available in the dataset subjected to analysis (Fig. 4). In all the locations, GF, RAIN and GDM contributed largely to the first principal component (Table S2) as well as yield and LAI in Florence, Foggia, and Santaella, yield and PAR in Sidy El Aydi. The second component (PC2), differentiated the cultivars by GN and yield in all localities, followed by GDM in Florence and Sidi El Aydi, and LAI in Foggia. In general, for all locations, between GF, RAIN and GDM a positive correlation, given by acute angles (Yan and Rajcan, 2002; Yan and Kang, 2003) was observed (Fig. 4).

For all sites, an earlier sowing window compared to TSW resulted in higher simulated grain yield (Fig. 5), although in Florence, it was not statistically significant. The HSW was from 25 October to 25 November in Florence (5 days earlier than TSW), and from 20 October to 20 November in the other sites, corresponding to 25, 30 and 35 days earlier than TSW in Foggia, Santaella and Sidi El Aydi, respectively. On the average, simulated yield was from 5 % (in Florence) to 56 % (in Sidi El Aydi) higher for HSW compared to TSW, with Karim and Amilcar, as the

Table 2
Evaluation of the wheat model *SiriusQuality* for the calibration and validation data sets for phenological stages, final total above ground biomass and N, final grain yield, and final grain N. *r*, pearson coefficient of correlation; MAE, mean absolute error; nRMSE, normalized root mean squared error; *d*, index of agreement.

Cultivar (site or country)	Variable	Calibration					Validation				
		Nb of observations	*r*	MAE	nRMSE	*d*	*Nb. of observations*	*r*	MAE	nRMSE	*d*
Creso (Florence)	Anthesis date	4	0.99	3.00	2.00	0.99	4	0.99	3.00	2.00	0.99
	Maturity date	4	0.80	1.75	1.00	0.72	4	0.80	1.75	1.00	0.72
	Final total above ground biomass	4	0.93	1.37	2.39	0.60	12	0.70	1.73	9.99	0.74
	Final gain yield	4	0.81	1.30	6.00	0.80	12	0.90	0.47	10.00	0.90
	Grain protein concentration	4	0.22	10.35	4.50	0.40	12	0.93	11.39	10.00	0.95
Simeto (Foggia)	Anthesis date	10	0.94	5.2	3.89	0.93	12	0.84	7.58	5.06	0.87
	Maturity date	10	0.88	5.9	5.55	0.86	12	0.85	8.10	6.59	0.85
	Final grain yield	10	0.93	0.45	4.84	0.93	12	0.61	0.69	10.00	0.73
Amilcar (Spain)	Heading date	4	0.55	4.25	10.21	0.72	5	0.94	5.00	7.27	0.97
	Maturity date	4	0.89	5.75	10.07	0.75	5	0.90	6.89	9.14	0.75
	Final grain yield	4	0.99	0.42	18.14	0.98	5	0.88	0.74	15.03	0.87
Karim (Morocco)	Anthesis date	3	0.98	4.60	3.58	0.96	3	0.66	9.30	9.91	0.77
	Final total above ground biomass	17	0.97	0.81	23.00	0.98	13	0.95	0.787	31.50	0.96
Overall	Anthesis date	21	0.98	6.05	12.50	0.98	24	0.97	7.30	16.10	0.97
	Maturity date	18	0.97	5.85	13.42	0.97	21	0.97	6.46	17.10	0.97
	Final gain yield	18	0.97	0.89	19.25	0.97	29	0.81	0.59	20.10	0.89

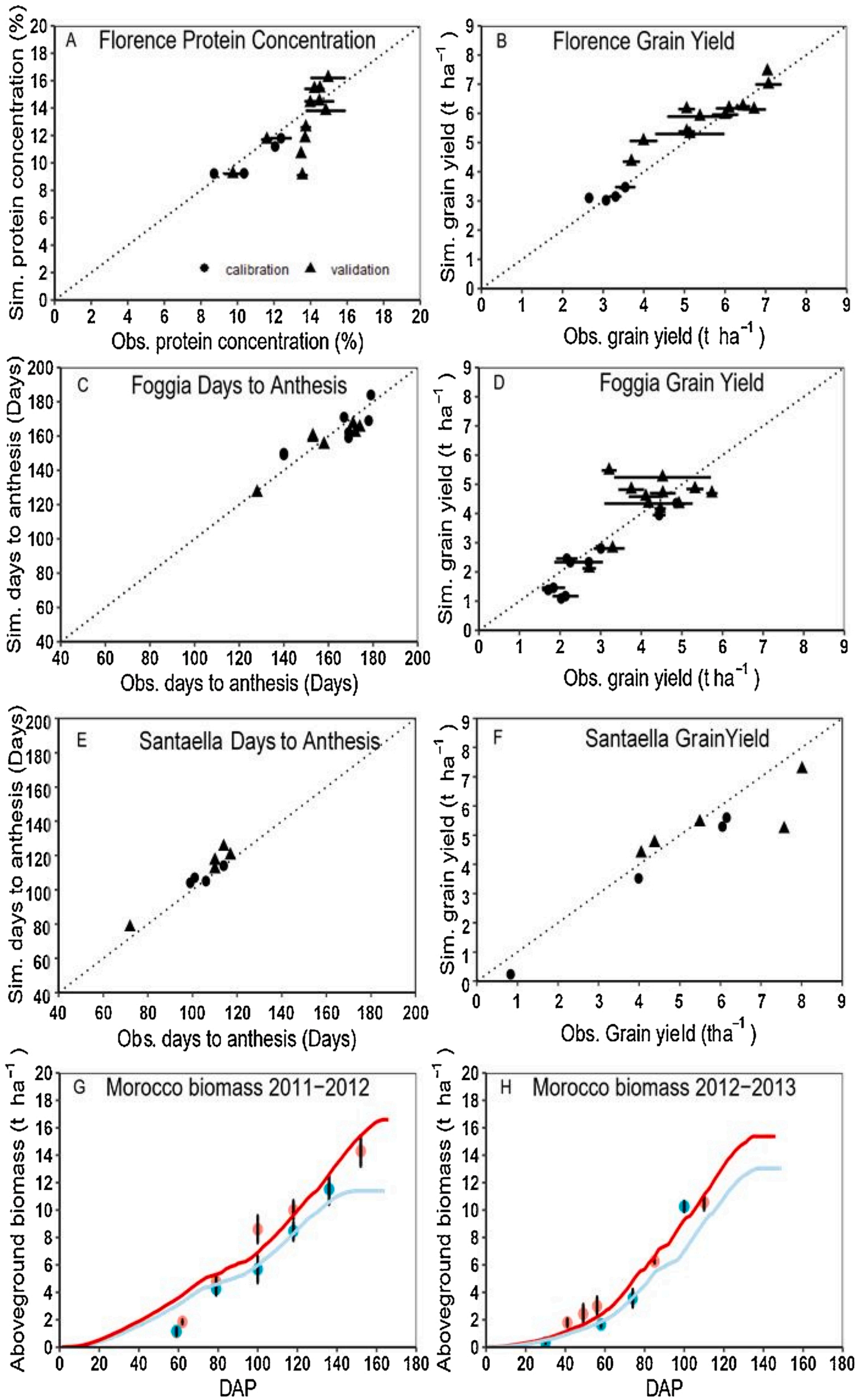

Fig. 3. Simulated versus observed grain protein concentration and grain yield in Florence (A, B), days to anthesis and grain yield in Foggia (C, D) and in Santaella (E, F), aboveground biomass in Marchouch (G) and in Sidi El Aydi (H). In A–D, circles, model calibration data set; triangles, model validation data set; dash lines, 1:1 line. In G-H, red solid lines and circles, simulations and observations for irrigated treatments (used for model calibration); blue lines and circles, for rainfed treatments (used for model validation). Observed data are means ± 1 s.d. for $n = 3$ replicates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

most productive cultivars (Table 4). Overall, further advancement of sowing windows was characterized by a pronounced yield reduction, while a smoothed decline, more accentuated in Santaella and Sidi El Aydi, was simulated in response to delaying sowing window beyond HSW.

On the average at HSW, the CV was from 8 % (in Florence) to 38 % (in Sidi El Aydi) lower than TSW (Table 4). The coefficient of variation (CV) tended to increase as the sowing window was delayed, with the exceptions of Creso in Foggia (higher CVs for the earliest and latest sowing windows) and Simeto in Florence (with no clear trend among the sowing window) and in Sidi El Aydi (decreasing trend with the delaying of sowing window). For Creso in Foggia and Simeto in Sidi El Aydi, the higher CV at HSW than TSW, was compensated by a higher average yield production which was not possible to produce at TSW.

Table 3
Analysis of variance for wheat grain yield considering Environment (E), Sowing (S) and Genotype (G) interactions.

Source of variation	df	Yield (P > F)
Environment (E)	3	<2 e-16 ***
Sowing (S)	11	<2 e-16 ***
Genotype (G)	3	<2 e-16 ***
E x S	33	<2 e-16 ***
E x G	9	<2 e-16 ***
G x S	33	0.5049
G x E x S	99	0.9983

Regarding the phenology, at all locations, the duration of the pre-anthesis phase showed a reduction with the postponement of the sowing window (Fig. 6 A, E, I, M). This response was less evident in Sidi El Aydi, with a maximum difference of 15 days for Creso among the sowing windows (Fig. 6M). Among the cultivars, Amilcar was characterized by a shorter pre-anthesis period than the other cultivars and Creso by a longer, with difference among this two cultivars of 23 days in Florence and Foggia, and of 32 days in Santaella and Sidi El Aydi. Similar trend was observed for the grain filling duration (Fig. 6B, F, *J*, N), in which a reduction of GF with the postponement of sowings was shown in Santaella and Sidi El Aydi, (on the average GF ranged from 66 days at earlier sowings for Amilcar to 33 at later sowings for Simeto). In Florence and Foggia, little variations in the duration of GF (<6 days) were observed in response to sowings, except for Amilcar (on average of 15 days). Among the cultivars, Amilcar had the longest GF and Simeto the shortest. The cumulated rain during GF varied accordingly, for which Amilcar had the highest rain accumulation and Simeto the lowest (Fig. 6C, G, K, O). Among all the locations, Florence had the highest rain accumulation during GF, with an average among sowings of 103 mm for Amilcar (Fig. 6C), instead of Sidi El Aydi, the lowest with 36 mm for Simeto (Fig. 6O). The average evaporative drought index (EDI) during grain filling was on the average, 2.6 % (Florence) to 27.9 % (Santaella) lower for HSW than for TSW (Fig. 6D, L).

The simulated LAI showed an increasing trend until the HSW (4.86 in Florence, 3.62 in Foggia, 3.56 in Santaella and 2.36 in Sidi El Aydi at the HSW), then it remained constant in Florence (Fig. 7A) while decreased in the other locations (Fig. 7 E, I, M). Differences in LAI among the cultivars were minor, except for Simeto in Foggia, Santaella and Sidi El Aydi. The cumulated PAR was almost unchanged in Florence, while it decreased after the HSW in Foggia. A clear increase was observed until HSW in Santaella and Sidi El Aydi, followed by a slight reduction in Santaella (Fig. 7 B, F, I, N).

The final GN at maturity had an increasing trend until the HSW (on average at HSW 10,986 grain m^{-2} in Florence, 12,656 in Foggia, 10,732 in Santaella and 8842 in Sidi El Aydi) and then it remained constant, with the exception of Karim in Florence (Fig. 7D), Creso and Simeto inFoggia (Fig. 7H), and Creso and Karim in Sidi El Aydi (Fig. 7P) that showed a reduction. Among the cultivars, Karim had the highest GN at all locations and Creso the lowest, except in Florence, where Amilcar, Creso and Simeto had overlapped dynamics.

Overall, the GDM at maturity was the highest for Amilcar (on average 47.24 mg $grain^{-1}$ in Florence, 40.18 in Foggia, 48.23 in Santaella, 41.95 in Sidi El Aydi), followed by Creso, Karim and then Simeto. In Foggia the dynamics among the cultivars and the sowing windows were similar (Fig. 7G). In Florence, the other cultivars showed an unchanged behavior among the sowings (Fig. 7C), except for Amilcar. In Santaella and Sidi El Aydi, a reduction trend was observed from the earlier to later sowings (Fig. 7K, O).

4. Discussion

4.1. *SiriusQuality* evaluation

The value of seven varietal parameters describing the four wheat cultivars used in this study were within the literature range for Sirius (Semenov et al., 2014) and *SiriusQuality* (Tao et al., 2017). Moreover, they were comparable to previous modelling studies with Karim, Creso and Simeto (Bassu et al., 2011; Dettori et al., 2017; Bregaglio et al., 2015). No published parametrization for Amilcar cultivar was found.

SiriusQuality provided a good estimation of phenology, grain yield, grain N yield and biomass dynamics. All statistical indexes used in the model evaluation denoted good model performances, with satisfactory nRSME values according to Bannayan and Hoogenboom (2009). In Marchouch, *SiriusQuality* well reproduced the observed phenology and biomass accumulation. The high RMSE for the aboveground biomass was due to the underestimation of the last observed data under rainfed conditions, which was higher than the observed data in the irrigated treatment. Although the model in Morocco was calibrated and validated on phenological development and aboveground biomass, the simulated average yield in rainfed condition were in the range of 1.1-2.4 t ha^{-1}, in agreement with FAOSTAT (2012) and the Grain Report for Morocco (2012) for those areas.

In Foggia, there was a major discrepancy between observed and simulated yield in 2008–2009 (3.2 vs 5.2 t ha^{-1}). The reason may be attributable to the large amount of rainfall that occurred in the first months of 2009 (i.e., two heavy 3-day rainfall events in January and March, with 70 and 50 mm, respectively) that may have caused anaerobic soil conditions. *SiriusQuality* was not able to reproduce the consequences of such extreme events. This may have also affected the results of the scenario analysis in Foggia, where simulated yields could be higher than expected as a result of similar rainfall events in the generated weather series. Nonetheless, since these events occurred some months after sowing, their impact was common to all the sowing windows tested, therefore relative differences among sowing dates should be compensated.

4.2. Genotype × environment × sowing window effects

PCA results confirmed different response scenarios depending on the location and crop cultivars. The northern locations allowed a more clear distinction among cultivars performances, which is likely due to less climate stressful conditions. The interaction between environments and genotypes directly affected the expression of the plant traits which actively contributed to the yield. In general, the traits most positively associated with the yield were the GN and GDM, highlighting their key role in the final yield production (Sharma et al., 2008; Borràs-Gelonch et al., 2012). In the dry Mediterranean environments, indeed, cultivars characterized by the combination of higher GN and longer GF associated to early-flowering, as Karim and Amilcar, could be a useful strategy to guarantee a good yield. In Foggia, the yield is mainly led by GN, suggesting that for this environment, grain weight could be increased while maintaining the number of grains. Another important aspect was the positive correlation between GF, RAIN, and GDM, emphasizing the importance of water availability during GF for sustaining the growth of the grain (Royo et al., 2006).

Wheat yield is determined by the combination of the number of grains (GN) and the final grain dry matter (GDM) (Sharma et al., 2008; Borràs-Gelonch et al., 2012). These two characters depend on different factors and are determined in different periods of the crop cycle. The GN depends on the conditions during spike growth (in the last part of the pre-anthesis phase) and it is strongly correlated to the biomass accumulated at anthesis (Fischer, 2011; Zhang et al., 2019). The GDM is positively affected by the duration of the pre-anthesis phase and the maximum LAI, which in turn, determines the quantity of intercepted PAR (Rivera-Amado et al., 2019), and by the photosynthetic efficiency of the crop (Fischer, 2011). After the anthesis, the number of grains no longer varies, and the final yield is a function of grain dry mass. This is a cultivar-specific trait, which mainly depends on the duration of the grain filling and on the rate of grain growth. Stressful events, primarily temperatures and water stress, may negatively affect both GN and GDM,

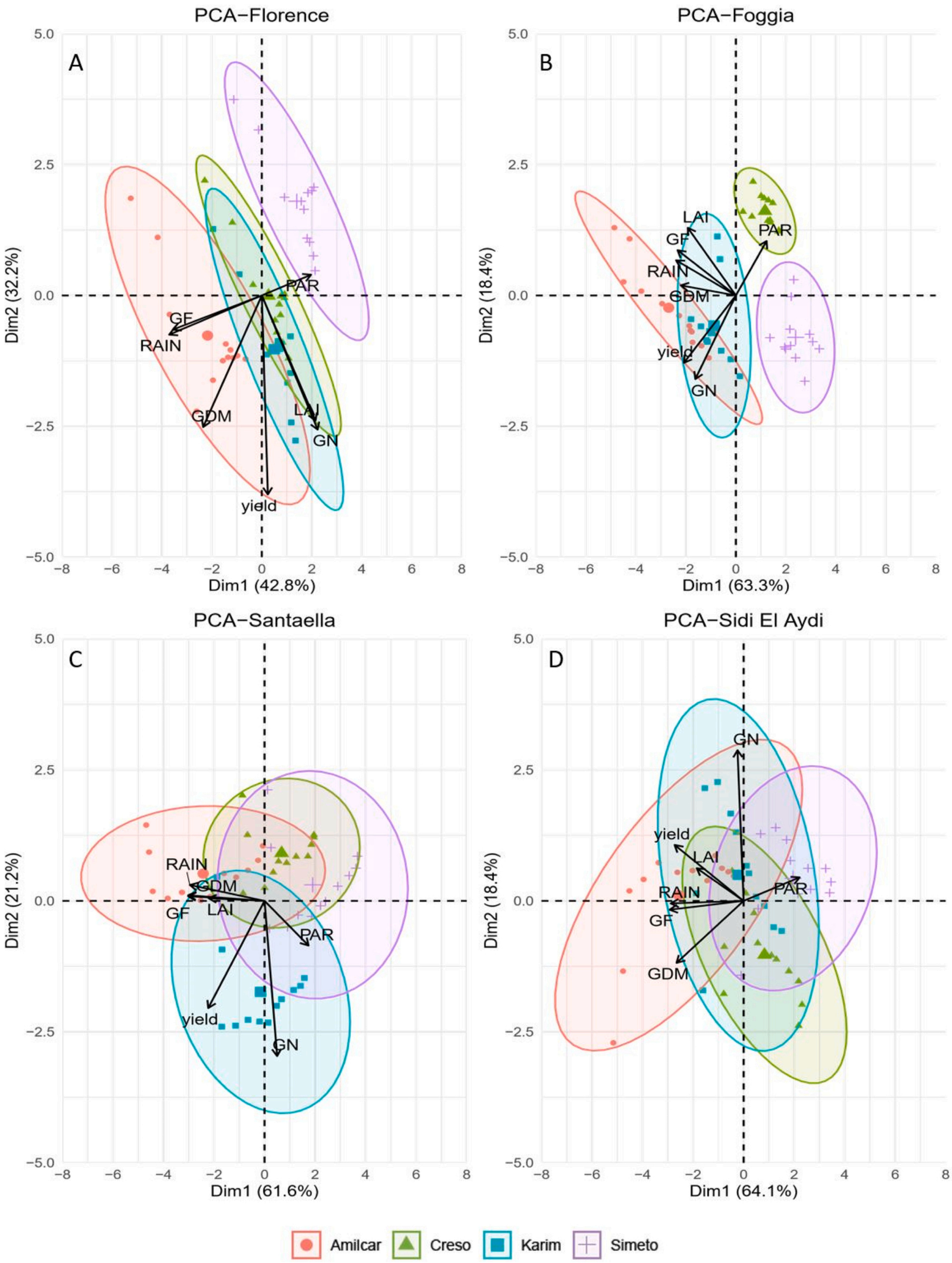

Fig. 4. Principal component analysis (PCA) projections on axis x and y, respectively PC1 and PC2 (%) for Creso, Simeto, Amilcar and Karim varieties in Florence (A), Foggia (B), Santaella (C) and Sidi El Aydi (D).

thus reducing the accumulation of dry mass in the grains (Fischer, 2011).

In our study, Florence, Foggia and Santaella showed comparable yield levels. Foggia and Santaella produced a higher GN because of increased photosynthetic rates as a consequence of greater LAI and intercepted PAR. Compared to other locations, the radiation was the main limiting factor in Florence, as indicated by the low cumulated PAR, despite the long growing cycle. This led to lower LAI development and biomass accumulation at anthesis, which is associated to fewer grains. However, the greater soil water availability during the grain filling, allowed the accumulation of larger dry mass in grains (the highest GDM among locations), thus leading to similar yield in Foggia and Santaella. In Sidi El Aydi, high temperatures and reduced rainfall were the main limiting factors. Because of the high temperatures, the pre-anthesis

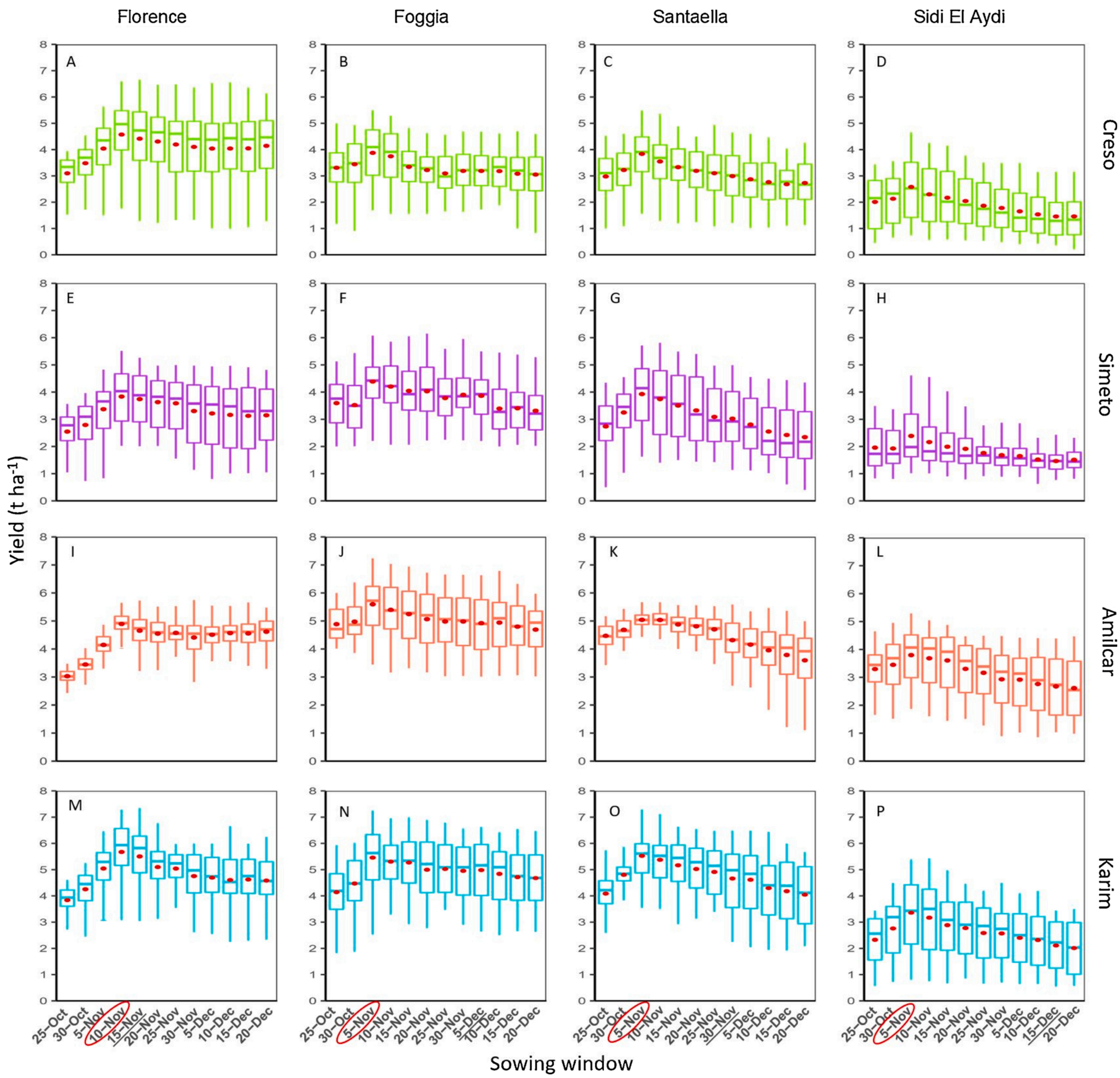

Fig. 5. Box plot of simulated grain yield for the different sowing windows for the durum wheat varieties Creso, Simeto, Amilcar, and Karim in Florence (A, E, I, M), Foggia (B, F, J, N), Santaella (C, G, K, O) and Sidi El Aydi (D, H, L, P). Lower and upper box boundaries represent 25th and 75th percentiles, respectively, line inside, the box median. The upper and lower whiskers represent Q1-1.5IQR and Q3 + 1.5IQR, where Q1 and Q3 are the 25th and 75th percentiles respectively, and the IQR is the interquantile distance. Labels are the central day of the relevant 30-day sowing window. Red circles indicate HSW, underlined dates the TSW. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

phase was the shortest. This caused the lowest LAI and biomass accumulation, and fewer simulated grains for all the cultivars. In this location, the timing and the duration of the grain filling were decisive to guarantee appropriate soil water availability, to sustain the accumulation of grain dry mass.

The high-yielding cultivars, Amilcar and Karim, were the most productive in all the locations according to the simulations. Based on the calibration results, these cultivars showed the highest radiation use efficiency, in agreement with other studies that reported modern high-yielding cultivars to have enhanced radiation-use efficiency when compared with old cultivars (Calderini et al., 1997; Shearman et al., 2005). Besides, the results indicated that these two cultivars reached higher yields with different contribution of GN and GDM to the yield. In Karim, the greater RUE allowed to set the highest GN at anthesis and sustain their growth during GF. This was particularly evident when compared with simulated performances of Creso, which showed similar length of the growing cycle, LAI and cumulated PAR as Karim, but had the lowest RUE and GN. Amilcar had the shortest simulated cycle among the cultivars. Although a slightly higher LAI that compensated the lower incoming radiation simulated for this cultivar, the GN at anthesis was lower than Karim. However, given its earliness, the weather conditions experienced during grain filling were more favorable in terms of temperature and precipitation than for the other cultivars. Despite Amilcar had the smallest thermal requirements for grain filling (Table 1), the lower temperature during GF prolonged this phase. In turn, this increased the soil water availability because of the greater rainfall accumulated during the phase when compared to the other cultivars. As a result, Amilcar was the cultivar with the highest single grain dry mass, thus offsetting the effect of a reduced number of grains. These characteristics were particularly advantageous in the hotter and drier site (Sidi El Aydi), where the grain growth of long-cycle cultivars was simulated in more stressful conditions, limiting GF duration and final grain size. In Florence, where cooler and wetter conditions also occurred later in the growing season, Karim benefited from a longer growing cycle that

Table 4
Average simulated anthesis date, grain filling duration and grain yield obtained in the traditional sowing window (TSW) and in the highest yield sowing window (HSW), *P* value of *t*-test between grain yield distribution in TSW and HSW and coefficient of variation (CV) of grain yield distributions. ns, $P > 0.05$; *, $P < 0.05$; **, $P < 0.001$; ***, $P < 0.0001$. DOY, day of the year.

Site	Cultivar	Anthesis date (DOY)		Grain filling (Days)		Grain yield				
						Average (t ha^{-1})		*P*	CV (%)	
		TSW	HSW	TSW	HSW	TSW	HSW		TSW	HSW
Florence	Creso	121 ± 2	120 ± 2	44 ± 4	45 ± 4	4.41 ± 1.27	4.57 ± 1.20	ns	28.85	26.28
	Simeto	116 ± 2	114 ± 3	39 ± 5	40 ± 5	3.74 ± 0.94	3.83 ± 0.98	ns	25.04	25.53
	Amilcar	99 ± 4	93 ± 2	48 ± 3	51 ± 5	4.66 ± 0.52	4.91 ± 0.34	ns	11.58	7.61
	Karim	117 ± 9	115 ± 3	44 ± 3	45 ± 3	5.50 ± 1.13	5.67 ± 1.10	ns	20.69	19.44
Foggia	Creso	134 ± 2	129 ± 3	39 ± 4	41 ± 5	3.18 ± 0.74	3.88 ± 0.99	*	23.31	25.72
	Simeto	130 ± 2	124 ± 4	31 ± 4	34 ± 5	3.86 ± 0.80	4.40 ± 0.80	*	20.73	18.41
	Amilcar	114 ± 2	99 ± 5	42 ± 4	51 ± 7	4.92 ± 1.03	5.58 ± 0.92	*	20.93	16.41
	Karim	131 ± 2	124 ± 4	41 ± 3	43 ± 3	4.98 ± 1.11	5.45 ± 1.15	*	22.31	21.10
Santaella	Creso	103 ± 4	88 ± 9	43 ± 6	51 ± 8	3.10 ± 0.90	3.88 ± 0.92	*	30.33	24.56
	Simeto	97 ± 5	81 ± 10	38 ± 6	47 ± 8	3.02 ± 1.05	3.92 ± 1.15	**	34.80	29.31
	Amilcar	77 ± 8	51 ± 15	52 ± 6	66 ± 9	4.31 ± 0.67	5.04 ± 0.27	**	15.68	5.43
	Karim	98 ± 5	82 ± 10	46 ± 5	54 ± 7	4.66 ± 1.13	5.52 ± 0.94	***	24.32	17.04
Sidi El Aydi	Creso	94 ± 5	74 ± 6	39 ± 4	49 ± 8	1.45 ± 0.80	2.60 ± 1.19	***	54.93	46.34
	Simeto	89 ± 5	67 ± 6	33 ± 5	42 ± 7	1.52 ± 0.37	2.40 ± 1.00	***	25.83	42.13
	Amilcar	70 ± 6	41 ± 8	46 ± 6	62 ± 8	2.67 ± 1.03	3.80 ± 0.92	***	38.61	24.41
	Karim	89 ± 5	68 ± 6	42 ± 5	52 ± 7	2.11 ± 0.90	3.40 ± 1.30	***	43.09	38.97

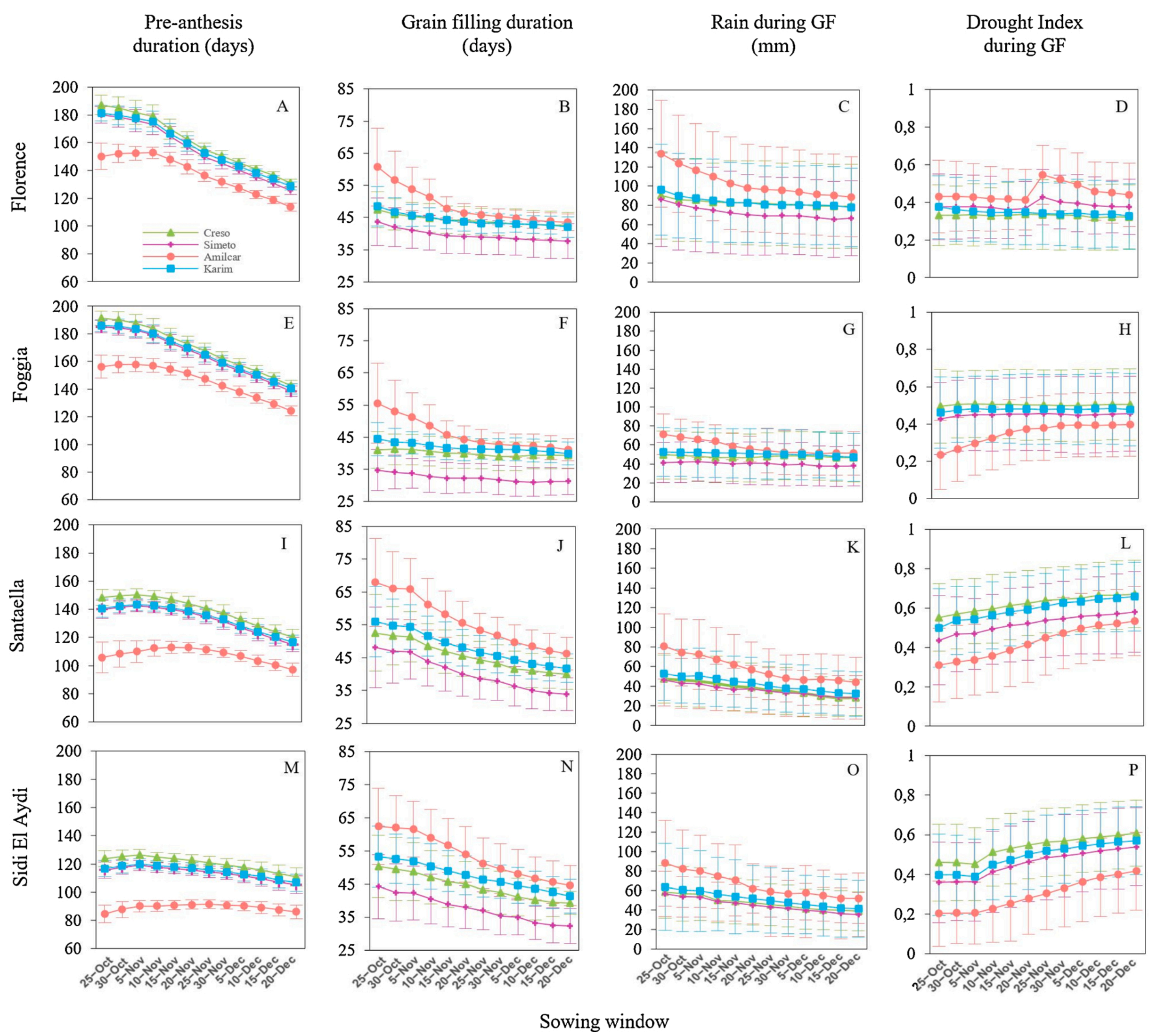

Fig. 6. Average of pre-anthesis period, grain filling duration, cumulated rainfall during the grain-filling period and drought index calculated during the grain filling period for the durum wheat varieties Creso, Simeto, Amilcar and Karim in Florence (A–D), Foggia (E–H), Santaella (I–L) and Sidi El Aydi (M–P). Data are means for 100 years of synthetic wheather data. Labels are the central day of the relevant 30-day sowing window.

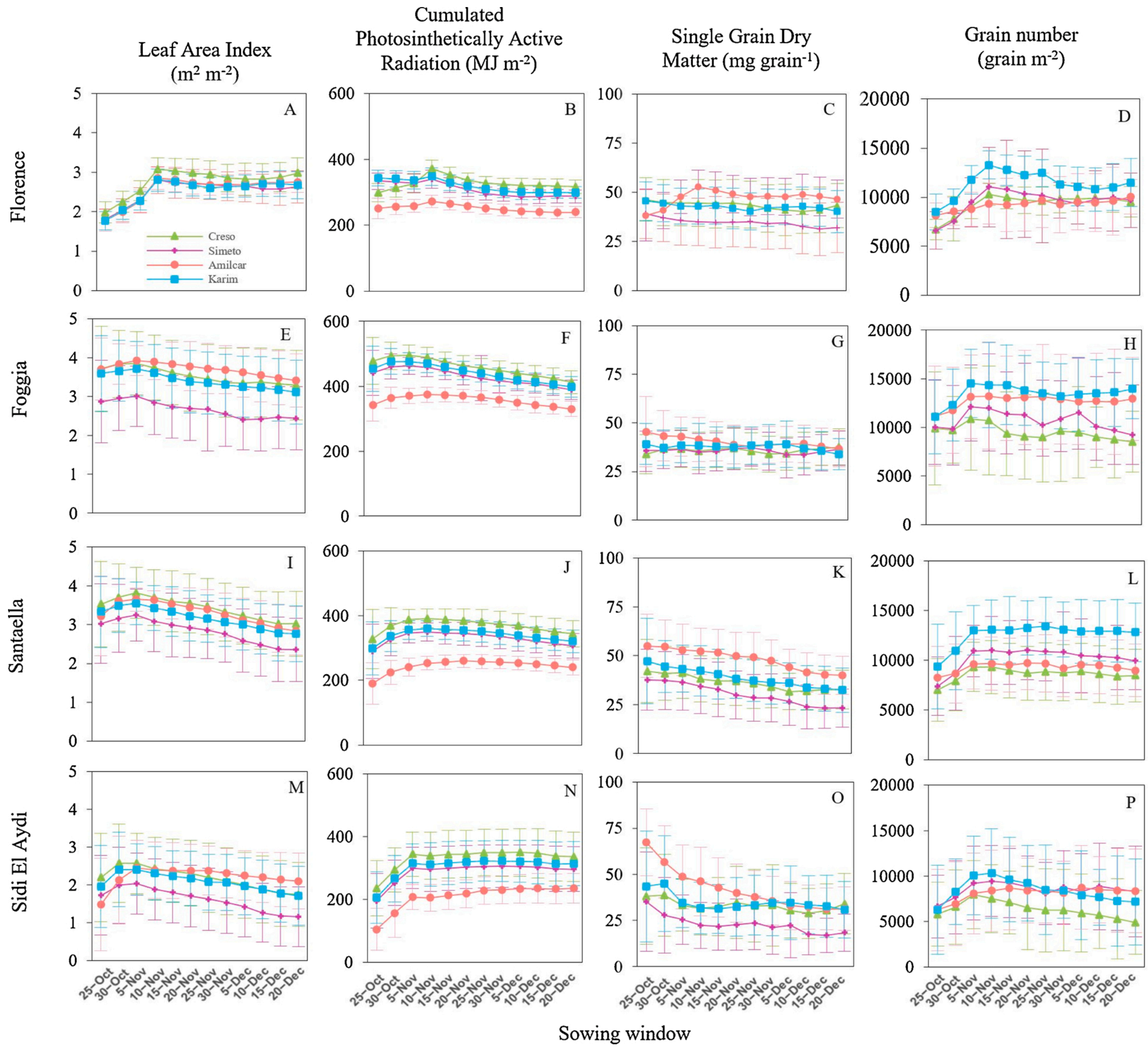

Fig. 7. Simulated leaf area index at anthesis, cumulative photosynthetic active radiation from emergence to maturity, single grain dry matter at maturity and the grain number m^{-2} in Florence (A–D), Foggia (E–H), Santaella (I–L) and Sidi El Aydi (M–P) for the durum wheat varieties Creso, Simeto, Amilcar and Karim. Data are means for 100 years of synthetic wheather data. Labels are the central day of the relevant 30-day sowing window.

allowed producing more GN, while assuring a good GDM.

The higher simulated yield at HSW could be ascribed to the optimal combination of factors for GN and GDM. At very early sowing windows, the limited incoming radiation and the lower LAI negatively affected the accumulation of biomass at anthesis and the GN that resulted the most limiting factor to high yield in all the locations. By delaying the sowings window beyond HSW, a general shortening of the growing cycle was simulated, with a reduction in the maximum LAI and small changes in GN set at anthesis. On the contrary, the grain filling was gradually shortened because of higher temperature (Fischer, 2011), resulting in reduced period for grain growth and lower accumulation of dry matter in grains (Bassu et al., 2009; Semenov et al., 2014). This effect was less pronounced in the northern locations because of the different response of the length of the pre-anthesis phase to shifts in sowing windows. In Florence and Foggia, the length of the pre-anthesis phase was proportionally reduced with sowing window, causing the timing of anthesis to be substantially unchanged in Florence or postponed by a few days in Foggia. On the contrary, in Santaella and Sidi El Aydi, the duration of the pre-anthesis phase in response to sowing window varied slightly, leading to a consistent progressive delay of the anthesis date. This determined warmer conditions during grain filling, which was shortened. Furthermore, rainfall accumulated during the crop growing season was lower, especially in the grain filling period. Thus, HSW simulations beneficiated by enhanced soil water availability during GF, as suggested by the lower simulated drought index during GF and the higher soil water content at maturity (Fig. 6 and S3), that sustained the accumulation of biomass in grains. It could be concluded that the earlier anthesis date at HSW compared with TSW allowed the avoidance of stressful conditions during the grain filling, which was characterized by lower temperature and higher water availability.

The results indicated that environment, genotype and sowing window contributed differently to the determination of final yield across locations, with different factors affecting final GN and GDM. An important role was played by the length of the pre-anthesis phase and by the maximum LAI that affected the amount of intercepted radiation, and in turn, the biomass accumulated at anthesis and the final number of grains. Advanced sowing may represent a practical solution to lengthen the duration of the phase as well as the adoption of cultivars characterized by high LAI and RUE in order to increase crop photosynthesis that allows the production of more biomass and grains (Reynolds et al., 2012).

Management strategies based on early sowing and the use of short cycle cultivars may produce effective result in enhancing yield, since they limit stressful conditions during grain filling, with lower temperature that favor the lengthening of the phase and the accumulation of dry mass in grains. Moreover, the introduction of irrigation practices in driest environments might reduce late-season water stresses and increase wheat yield (Silva et al., 2000). This practice may be even more important under future climate change scenarios, for which increased drought is prospected in the Mediterranean basin (Ruiz-Ramos et al., 2018; Webber et al., 2018). Also, the selection of cultivars with enhanced "stay green" capacity may be suggested for breeding, since they can maintain longer the green area and the photosynthetic activity during grain filling, thus increasing the final GDM (Fischer, 2011).

An important aspect to consider is the practicality of anticipating the sowing date in Mediterranean wheat area (Nouri et al., 2017). In these environments, the major constraint for early sowing is the insufficient soil moisture content, which is related to the few accumulated rainfall during summer and early autumn. *SiriusQuality* takes into account, the soil water content in setting the sowing date, and the results suggested that earlier sowing dates could be beneficial in current climatic conditions in the selected locations, also considering specific soil properties and characteristics. This might not be the case under future climate, where the period of water scarcity may be extended towards autumn. Under this scenario, problems during germination may occur with negative implications for the agronomic management practices such as difficulties in soil workability for sowing, as well as in optimizing nitrogen fertilization (Moeller et al., 2009).

The advantage of simulation modelling in reducing experiment time is unquestionable, as well as its effectiveness in providing helpful information, to identify the best management practices leading to enhanced yield and to identify promising crop traits for crop improvements (Rötter et al., 2015; Chenu et al., 2017). However, to increase the model robustness, continuous improvement in the understanding and simulation of the plant-soil system processes is needed. As such, the lack of accurate and specific dataset for modelling study is a well-known gap of knowledge, and the need to create a data-sharing network has become more pressing to improve crop model performances (Rötter et al., 2011).

5. Conclusions

In this study, a crop model was used to analyze the effect of environment, genotype and sowing window on wheat yield in the Mediterranean basin. The results indicated that different strategies, depending on the location, could be used to increase wheat yield. In hotter and drier environments, where temperature and water are the main limiting factors, it is crucial that grain filling occurs earlier in the season to guarantee a longer duration of this phase, due to lower temperature and adequate soil water availability for sustaining the grain growth. In such environments, short cycle cultivars may perform better than medium and long cycle cultivars, particularly for earlier sowing. On the other hand, in cooler and wetter environments, short-cycle cultivars may have reduced yield potential because of the shorter pre-anthesis phase, which would limit the accumulation of biomass and reduce the grain number. In these environments, medium and late cultivars may perform better.

CRediT authorship contribution statement

Gloria Padovan: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Pierre Martre:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Mikhail A. Semenov:** Conceptualization, Methodology, Resources, Writing - original draft, Writing - review & editing. **Alberto Masoni:** Formal analysis, Writing - original draft, Writing - review & editing. **Simone Bregaglio:** Resources, Writing - review & editing. **Domenico Ventrella:** Resources, Writing - review & editing. **Ignacio J. Lorite:** Resources, Writing - review & editing. **Cristina Santos:** Resources, Writing - review & editing. **Marco Bindi:** Conceptualization, Methodology, Writing - review & editing. **Roberto Ferrise:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Camilla Dibari:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge financial support from the following sources: FACCE JPI MACSUR2 through the Italian Ministry for Agricultural, Food and Forestry Policies (D.M. n. 24064/7303/15); the European Union's Horizon 2020 research and innovation program under the Grant Agreement No. [727247]; the Biotechnology and Biological Sciences Research Council, through the Designing Future Wheat (DFW) program (BB/P016855/1); the AgriDigit-Agromodelli project (DM n. 36502 of 20/12/2018), funded by the Italian Ministry of Agricultural, Food and Forestry Policies and Tourism; the project PR.AVA2018.051 (Innova-Clima) funded by the European Regional Development Fund (FEDER).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2020.107969.

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Supplementary Information

Understanding effects of genotype × environment × sowing window interactions for durum wheat in the Mediterranean basin

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Table S1. Traditional sowing window, sowing density, N fertilization treatments used for *SiriusQuality* application and soil characteristics in Florence, Foggia, Santaella and Sidi El Aydi.

Site	Sowing window	Sowing density (seeds m^{-2})	N fertilizer application		Soil characteristics				
			Growth stage	Rate (g N m^{-2})	Depth (cm)	Sand (% vol)	Clay (%vol)	Saturation (%vol)	Bulk density (g cm^{-3})
Florence	30Oct.-30Nov.	350	00 30 39	3.5 6.0 6.0	0-150	53.1	7.0	50.00	1.59
Foggia	20Nov.-20Dec.	350	00 22 32	3.6 6.9 3.9	0-20 20-40 40-60 60-120	12.8 12.8 11.1 8.5	48.5 48.5 54.4 54.4	55.10 54.90 56.20 56.20	1.04 1.17 1.27 1.30
Santaella	15Nov.-15Dec.	360	00 22 32	3.6 6.9 4.0	0-25 25-50 50-75 75-100	23.63 20.34 20.25 21.01	53.81 52.12 56.06 38.75	50.30 50.70 51.50 46.80	1.32 1.31 1.29 1.41
Sidi El Aydi	30Nov.-30Dec.	400	00 22 32	3.0 3.5 4.6	0-20 20-40 40-60	20.5 17.50 15.00	26.50 36.00 48.50	48.70 48.00 50.70	1.14 1.29 1.39

Table S2: Principal components score for the analyzed variable in Florence, Foggia, Santaella and Sidi El Aydi

	Florence		**Foggia**		**Santaella**		**Sidi El Aydi**	
Variables	**Factor loadings**							
	PC1	**PC2**	**PC1**	**PC2**	**PC1**	**PC2**	**PC1**	**PC2**
LAI	0.31	-0.41	-0.36	0.45	-0.35	0.01	-0.29	0.18
GF	-0.53	-0.11	-0.44	0.30	-0.48	0.02	-0.46	-0.05
GN	0.33	-0.44	-0.30	-0.56	0.08	-0.79	-0.03	0.85
GDM	-0.35	-0.43	-0.41	0.07	-0.48	0.03	-0.42	-0.35
Yield	0.03	-0.65	-0.39	-0.45	0.35	-0.55	-0.43	0.31
PAR	0.29	0.07	0.23	0.36	0.27	-0.23	0.35	0.13
RAIN	-0.55	-0.13	-0.45	0.23	-0.47	0.08	-0.46	-0.01

Table S3. Average maximum daily canopy temperature between crop emergence and physiological maturity and cumulated rainfall between crop emergence and anthesis for the traditional (TSW) and the highest yield (HSW) sowing windows in Florence, Foggia, Santaella and Sidi El Aydi for the durum wheat varieties Creso, Simeto, Amilcar and Karim.

Site	Cultivar	Maximum daily canopy temperature (°C)		Cumulated rainfall (mm)	
		TSW	HSW	TSW	HSW
Florence	Creso	17.72 ± 0.28	17.57 ± 0.30	584.92 ± 119.64	599.92 ± 117.67
	Simeto	17.16 ± 0.33	17.03 ± 0.32	575.41 ± 117.63	588.26 ± 118.59
	Amilcar	16.58 ± 0.27	16.36 ± 0.26	531.64 ± 107.33	535.48 ± 111.36
	Karim	17.53 ± 0.27	17.37 ± 0.26	578.21 ± 118.86	590.64 ± 117.94
Foggia	Creso	17.31 ± 0.32	17.40 ± 0.30	311.43 ± 73.15	362.16 ± 74.83
	Simeto	16.64 ± 0.32	16.74 ± 0.28	305.33 ± 72.40	355.94 ± 75.34
	Amilcar	15.45 ± 0.30	15.54 ± 0.25	287.84 ± 71.09	314.99 ± 47.00
	Karim	17.04 ± 0.30	17.82 ± 0.22	306.52 ± 72.29	342.22 ± 75.48
Santaella	Creso	20.16 ± 0.32	19.57 ± 0.27	328.49 ± 107.19	359.83 ± 108.26
	Simeto	19.12 ± 0.34	19.67 ± 0.28	321.39 ± 105.76	351.43 ± 106.41
	Amilcar	19.14 ± 0.31	18.53 ± 0.25	298.06 ± 101.63	307.91 ± 99.35
	Karim	19.39 ± 0.35	20.05 ± 0.27	323.15 ± 105.85	352.33 ± 106.25
Sidi El Aydi	Creso	21.067 ± 0.47	20.42 ± 0.31	248.48 ± 81.54	261.82 ± 82.64
	Simeto	20.74 ± 0.45	20.16 ± 0.33	242.20 ± 78.44	253.84 ± 81.28
	Amilcar	20.28 ± 0.47	19.74 ± 0.33	233.89 ± 73.72	207.79 ± 76.70
	Karim	21.00 ± 0.48	20.46 ± 0.31	242.89 ± 78.41	254.98 ± 81.55

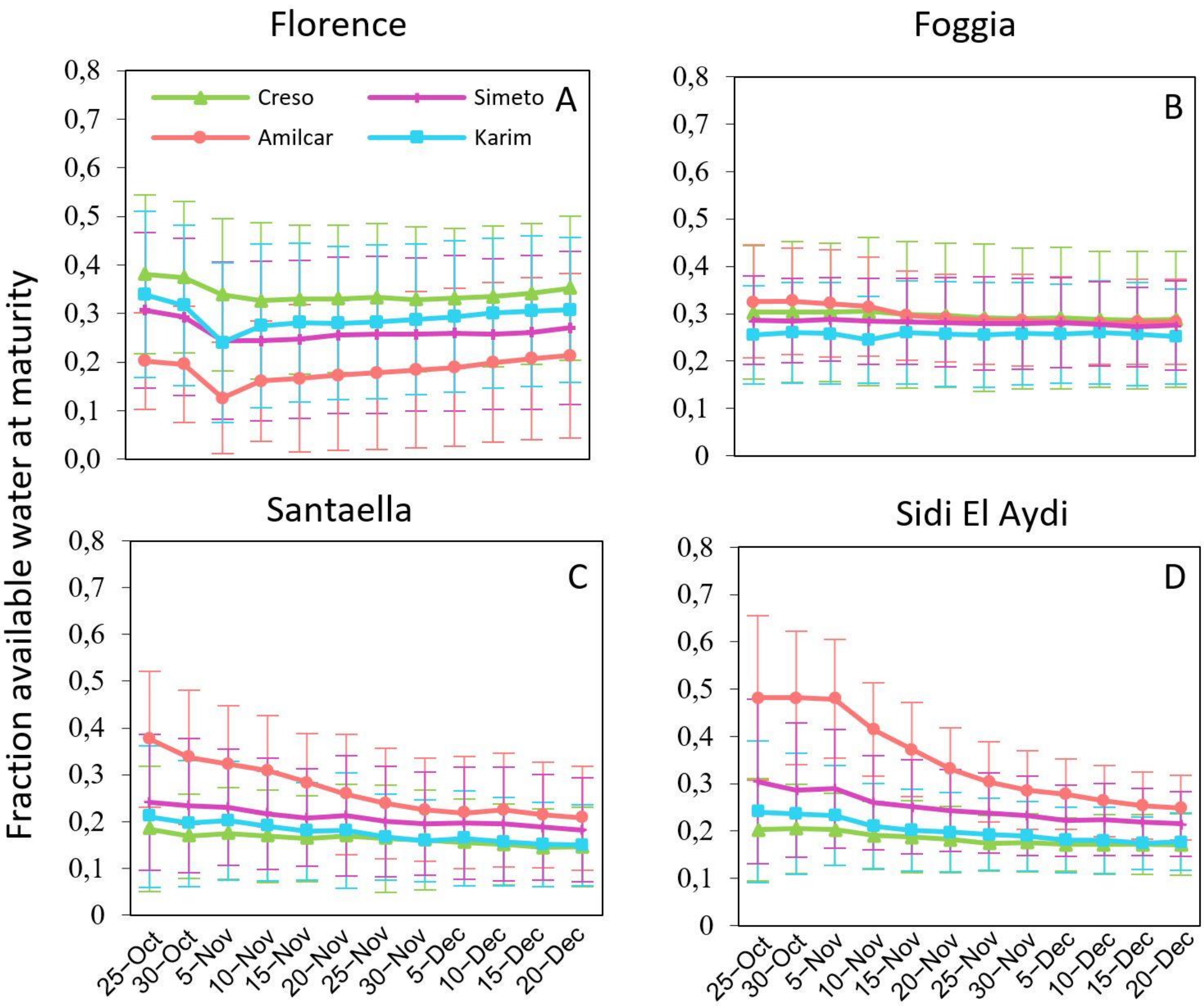

Fig. S1. Average of the fraction of available water for the plant in the soil at maturity for the durum wheat varieties Creso, Simeto, Amilcar and Karim in Florence (A), Foggia (B), Santaella (C) and Sidi El Aydi (D). Data are means for 100 years of synthetic wheather data. Labels are the central day of the relevant 30-day sowing window.