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Investigating the future climate change impact in the Mediterranean basin to identify the improving durum wheat physiological characteristics

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To my sister, Marianna

The most dangerous illusion is that there is only one reality.

\- *Paul Watzlawick* -

Contents

Riassunto

Il frumento duro è una delle colture più coltivate nel bacino del Mediterraneo, con una produzione di circa 18 milioni di tonnellate durante la campagna agraria 2015-2016 (IGC, 2016). Il cambiamento climateo previsto per il prossimo futuro proprio nell'area del Mediterraneo, rappresenta una sfida per il mantenimento e/o l'incremento di produttività del frumento duro. In quest'area, le proiezioni climatehe per il medio e per il lungo periodo, indicano un aumento delle temperature, soprattutto durante il periodo estivo, e una riduzione delle precipitazioni. Ciò potrebbe avere un effetto negativo sulla produzione del frumento duro. Da alcuni decenni, i modelli di simulazione colturale stanno avendo un ruolo sempre maggiore nell'individuare le pratiche agronomiche, ma anche per indicare quali caratteristiche colturali possono essere migliorate per massimizzare la resa in un contesto di cambiamento climateo.

L'obiettivo di questo studio è stato quello di analizzare l'impatto del cambiamento climateo, previsto per il prossimo futuro, in quattro località del bacino del Mediterraneo, Firenze (Italia centrale, varietà Creso), Foggia (Italia meridionale, varietà Simeto), Santaella (Spagna meridionale, varietà Amilcar) e Sidi El Aydi (Marocco settentrionale, varietà Karim) e individuare per ciascuna di esse ideotipi di frumento duro atti ad assicurare un'elevata resa e bassa variabilità inter annuale di produzione. Lo strumento modellistico utilizzato è stato il modello di simulazione colturale *SiriusQuality*, che è stato dapprima calibrato e validato per ciascuna delle varietà considerate nelle località selezionate e, successivamente applicato. Il modello ha mostrato buone performance nella riproduzione della fenologia, della biomassa e della resa del frumento duro, con un coefficiente di Pearson (r) e un coefficiente di accuratezza (d) prossimi a 1.

Tra le tecniche gestionali che hanno un peso maggiore nel determinare la resa finale del frumento duro, sia in termini di quantità che in termini di qualità, la scelta della data di semina e della varietà sono le più influenti. Per questo *SiriusQuality* è stato applicato in ciascuna delle località considerate per investigare l'interazione genotipo x ambiente x gestione e per individuare la finestra temporale di semina in grado di ottimizzarne la resa. I risultati hanno mostrato che l'anticipo della data di semina rispetto a quella tradizionalmente utilizzata in ciascuna località, permette di ottenere una resa maggiore a discapito della qualità della granella. Inoltre, la varietà Karim si è dimostrata essere quella maggiormente produttiva.

É noto in letteratura come il frumento sia una coltura particolarmente sensibile agli stress climatei soprattutto se questi avvengono durante fasi fenologiche maggiormente sensibili come la fioritura e il riempimento della granella. Per investigare l'impatto dei cambiamenti climatei sia nel medio (2050-2070) che nel lungo periodo (2070-2090), *SiriusQuality* è stato applicato a Firenze, Foggia, Santaella e Sidi El Aydi. L'impatto del futuro cambiamento climateo è stato valutato considerando la frequenza e l'intensità del manifestarsi di tre eventi climatei stressanti per il frumento nei giorni precedenti e

successivi alla fioritura, e durante il riempimento della granella. I risultati hanno mostrato come l'impatto dei cambiamenti climatei sarà differenziato per ogni località e per periodo temporale utilizzato. Effetti positivi, in termini di quantità di granella, sono stati simulati a Firenze per tutti gli scenari e per tutti i periodi temporali e a Foggia solo per il medio futuro. Mentre effetti negativi sono previsti sia a Santaella che a Sidi El Aydi per tutti gli scenari e periodi temporali. In generale, l'incremento del manifestarsi di eventi stressanti è risultato maggiore soprattutto nei primi 10 giorni durante il riempimento della granella.

Considerando l'impatto del cambiamento climateo e la necessità di ottimizzare la resa del frumento duro, *SiriusQuality* è stato utilizzato per individuare ideotipi di frumento atti a massimizzare la resa e a ridurre il coefficiente di variazione inter-annuale di resa nel medio periodo (2050) per gli scenari climatei GISS2 e HadGEM. Per una stessa località e per uno stesso scenario climateo, gli ideotipi di frumento individuati sono descritti da diversi set di parametri varietali, tutti in grado di massimizzare la resa e ridurne la variabilità inter-annuale.

I risultati di questo studio possono essere utili per capire quale sarà l'entità del cambiamento climateo previsto nel medio e lontano futuro nell'areale del bacino del Mediterraneo. Inoltre, possono suggerire quali caratteristiche varietali possono essere migliorate per incrementare la resa del frumento.

Summary

Durum wheat is one of the most cultivated crops in the Mediterranean basin, with a production of about 18 million tonnes during the 2015-2016 growing season (IGC, 2016). The climate change expected for the near future in this area is a great challenge for the maintenance or the increase in durum wheat production. In the Mediterranean basin, the climate projections for the near and the far period indicated an increase in temperatures, especially during the summer, and a precipitation reduction. For the Mediterranean counties, this could have a negative effect on the production of durum wheat. Since some decades, crop simulation models have been playing an increasingly important role in identifying the best agronomic practices and also in indicating which crop characteristics can be improved to maximize yield in a climate change context.

The aim of this study was to analyse the impact of climate change in four locations in the Mediterranean basin, Florence (in central Italy, Creso variety), Foggia (in southern Italy, Simeto variety), Santaella (in southern Spain, Amilcar variety) and Sidi El Aydi (in northern Morocco, Karim variety) and identify for each of them durum wheat ideotype characteristics suitable to ensure high yield and low inter-annual yield variability. The crop model used was *SiriusQuality*, which was previously calibrated and evaluated for each of the varieties considered in the selected locations and then applied to investigate different aspects. The model showed good performances in the reproduction of phenology, biomass and durum wheat yield, with a Pearson coefficient (r) and a coefficient of agreement (d) close to 1.

Among the management practices that have a major role in determining the final yield of durum wheat, both in terms of quantity and in terms of quality, the choice of sowing date and variety are the most important. For this reason, *SiriusQuality* was applied in each selected location to investigate the genotype x environment x management interaction and to identify the sowing window able to optimize the yield. The advance of the sowing window compared to the traditional one, allowed to obtain a higher yield at the expense of the grain quality. Furthermore, at all locations, Karim variety was the most productive.

In literature it is well known that wheat is a culture particularly sensitive to climate stress events, especially if these occur during more sensitive phenological phases such as flowering and grain filling. To investigate the impact of climate change in both medium (2050-2070) and far (2070-2090) future, *SiriusQuality* was applied in Florence, Foggia, Santaella and Sidi El Aydi. The impact of future climate change was assessed considering the frequency and the intensity of the occurrence of three climate stress events for wheat. The results showed the impact of climate change will have spatial differences and it will be related to the used scenario. Positive effects, in terms of quantity of grain, were simulated in Florence for all scenarios and in Foggia only for the medium future. While, negative effects are expected in Santaella and Sidi El Aydi for all scenarios. In general,

the increase in the occurrence of climate stress events was more pronounced especially during the first 10 days after anthesis.

Considering the impact of climate change and the need to optimize durum wheat yield, *SiriusQuality* was used to identify wheat ideotypes able to maximize yield and reduce inter-annual yield variation coefficient during the medium future (2050) under two climate scenarios, GISS and HadGEM. For same locality and for the same climate scenario, the identified wheat ideotypes are described by different sets of varietal parameters, all capable of maximizing yield and reducing inter-annual yield variability.

The results of this study can be useful to understand the intensity of future climate change impact in the medium and in the far future in the Mediterranean basin. Furthermore, they can suggest which varietal characteristics can be improved to increase wheat yield in a climate change context.

Chapter 1

General introduction

1. Introduction

The world population is estimated to increase up to 9.1 billion people by 2050 and growth will be concentrated above all in the countries of Asia, Africa and Latin America (Godfray et al., 2010). The FAO (2014) estimates shown that to feed the population it will be necessary to increase production by 70% in 40 years, but only 10% of the increase in production may derive from an expansion of crop-growing area, the remainder part must be ensured by a considerable increase in crop productivity (Parry et al., 2011; Reynolds et al., 2011).

Consistent with FAO data (FAOSTAT, 2016), among the crops that play a fundamental role for the world's food supply, wheat is the secondo for production, after corn and before rice, with a world production of 74 million tons. The Mediterranean basin is one of the most productive areas for wheat in the world, with a production in 2016 with 21 million tons (FAOSTAT, 2016).

It is well known that wheat is particularly sensitive to extreme cold and hot temperatures during the reproductive stage (Porter and Gawith, 1999; Farooq et al., 2012) and to climate and environmental variation (Porter and Semenov, 2005). Climate change was characterized by shift in weather patterns and increase in the frequency and magnitude of extreme events. In particular, for the future, an increase in temperature and a reduction of precipitations are projected on the southern Europe (Iglesias et al., 2012; Polade et al., 2017).

Climate change represents a considerable challenge to ensure an increase in food production but it could be overcome with the selection of new wheat cultivar or adopting adaptation strategies. Among the agronomic practices, the change in timing of cultivation (sowing date and harvest date), variation in tillage practices to focus on soil water conservation and protection against soil erosion, shifts in fertilization treatments to reduce the risk of nitrogen and phosphorous leaching caused by the increased forecasted rainfall, the use of new cultivars is some of the suggested strategies to overcome climate change (Olesen et al., 2011). Moreover, the breeders are working using biotechnology and genomics to select genotypes that have high yield stability. But, the breeding process is onerous in terms of time, labour and funding requirements to determine the values of the different traits especially under the future forecasted climate conditions (Gouache et al., 2015).

In the las decades, crop simulation models are become useful tools to supporting plant breeders and to evaluate the growth, development and production behaviours of the new cultivars in different environments and using different management practices (Asseng et al., 2015; Rotter et al., 2015).

1.1. Climate change

During 1901-2005, most of Europe countries has experienced increases in surface air temperature, with an average increase of 0.9 °C in the entire the continent (Alcamo et al., 2007). Indications of changing in rainfall are evident in the frequency of drought events during spring and early summer. In the last decade, alarming reports about the stagnating crop yield growth rates in various important agricultural country, such as the wheat production in Europe have been made (Brisson et al., 2010; Tao et al., 2015). In addiction, has already been observed an increase in frequency of prolonged droughts and heat waves with major negative consequences in the broad regions of the world (Gourdji et al., 2013; Christidis et al., 2015). An example is what occurred in 2003 year in which large part of Europe was exposed to temperatures rises 3-5°C and an annual precipitation deficit of 300mm was observed. Ciais et al. (2005) have suggested that the estimate reduction of 30% over Europe in gross primary production was due to the drought observed in these year.

The International Panel on Climate Change (IPCC, 2013) has reported that the intensity of extremes events was expected to raise in the future. In particular, for Europe, in the medium-far period, a maximum temperature increase of 4.5 ° C and a minimum of 2.3 ° C are expected, with extreme values in southern Europe (Fig. 1.1a). In general, there will be a decrease in cold days and in days with frosts, while heat waves will increase in intensity, frequency and duration. For rainfall a marked reduction of their consistency is expected in the summer period, from 15-30%, mainly in Southern Europe, but will be more intense (Fig. 1.1b). For the Mediterranean basin, the forecasts have shown in average annual temperatures from 0.8 to 1.6 ° C, with greater variations in spring and summer in the medium period (2030-2050). The precipitations are generally expected to reduce from 2031, with marked seasonal variations: in summer with decreases of 5-15%, while some studies indicate an increase in frequencies and intensity in the winter period.

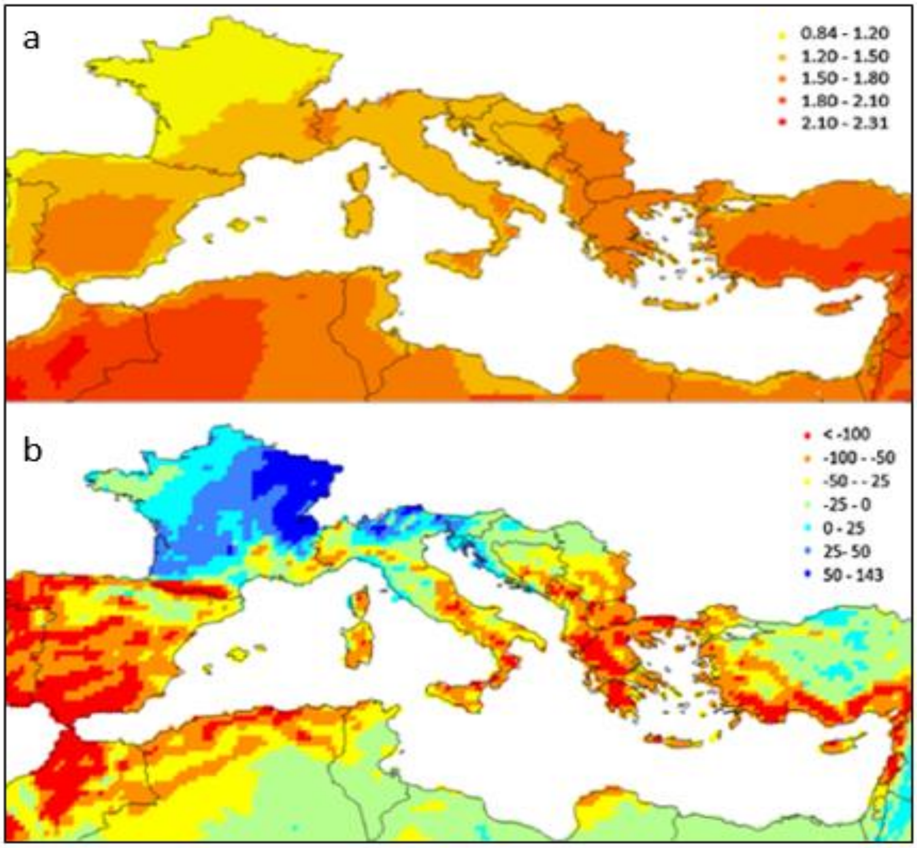

Fig. 1.1. *Spatial pattern of the average temperature (°C, a) and mean annual precipitations (mm, b) between 2000-2050 (Sadii et al., 2015)*

1.2. Durum wheat production

Among the crops most sensitive to climate change, wheat is also the one that plays a fundamental role in world nutrition. Indeed, it is the food base of more than half of the global population and is the most important crop, in terms of productivity and cultivated areas, in Europe (Semenov and Stratonovitch, 2013). Differently from common wheat, which is basically cropped everywhere in the world with the exception of the tropical areas, durum wheat is mainly cropped in 3 main basins: Mediterranean, Northern Plains between United States of America and Canada and within the desert areas of South West of United States and Northern Mexico (Fig. 1.2). There are other much smaller areas where durum wheat is cultivated between Russia and Kazakhstan, and Australia (Fig. 1.2).

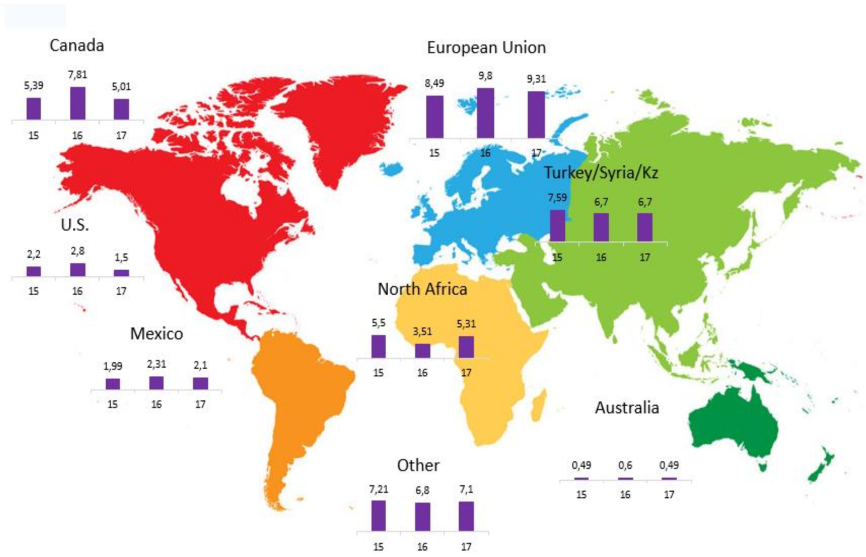

Fig. 1.2: *World durum wheat production in million tons (Souce: Int'l Grains Council April 2018 Xldata/world/durum/prod)*

The Mediterranean basin is one of the most productive areas in the word of *Triticum durum* (spp.) with a production of 18 million tons in 2015-16 (IGC, 2018). People living around the Mediterranean basin are the major users of durum wheat: pasta, couscous, bulgur and bread are the major food products. The total production, under winter cycle, in the Mediterranean Basin varies significantly because the whole crop relies on rain. In Northern Africa and Southern Europe, the agronomic yields are highly influenced by drought. Therefore, total production in one season can be around 14 million tons as for 2014-15 crop, or around 18 million tons as for 2015-16. Nevertheless, the durum wheat need of the countries of the Mediterranean Basin is higher than what is guaranteed by local productions; so, every year, more than 5 million tons reach these countries, mostly coming from North America.

Among all the countries that appear on the Mediterranean Sea, Italy is the major durum wheat producer with almost 4.0 million tons in average. Turkey and France are the followers with average of 2.7 and 1.7 million tons, respectively. Generally, smaller productions are characterizing Morocco, Algeria, Tunisia, mainly due to the effect of the dry climate that often occurs during the crop cycle. The quality of these productions varies significantly due to the weather conditions as well as the final destination of the durum wheat.

1.2.1. Wheat production under climate change

Many study of cropping systems have estimated the impact of climate change on wheat using crop simulation models (Iglesias et al., 2012; Dettori et al., 2017). Global cereal production was estimated to decrease in the second half of the century under different climate scenarios from 1 to 11% (Fischer et al., 2005; Tubiello and Fischer, 2007). Focusing on the south of Europe, the IPCC (Porter et al., 2014) has reported a yield variation ranged between -27 to +5 %. The climate change, with a reduction of precipitations, an increase in temperatures and in CO_2 concentration, could affected yield in different way. In general, in the Mediterranean basin a reduction of yield has been simulated for the future (Fig. 1.3, Saadi et al., 2015).

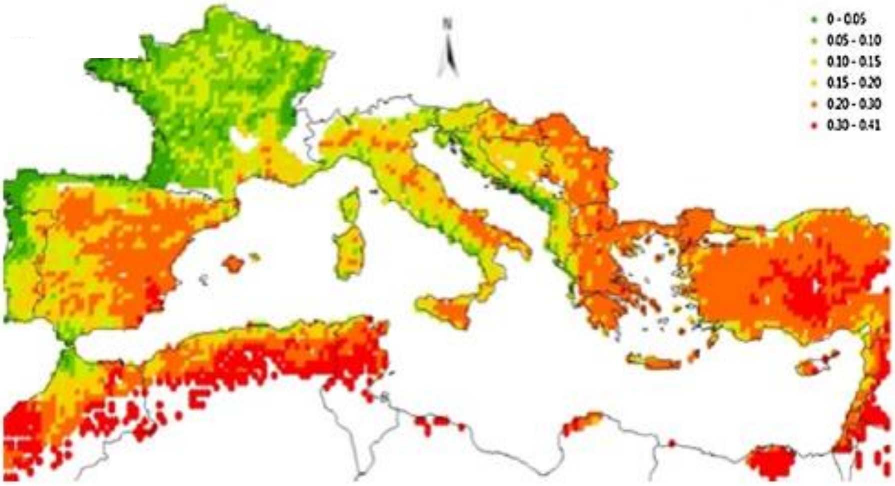

Fig. 1.3. *Spatial pattern of winter wheat relative yield losses under rainfed conditions for 2050, the later including new potentially cultivable areas in the future (Saadi et al., 2015)*

Many authors have reported increase in the crop development rate, shorten in the crop growing cycle, which reduces the time for biomass accumulation (Ventrella et al., 2012; Dettori et al., 2017). Moreover, Xiao et al. (2005) and Moriondo et al. (2016) have reported some beneficial effects of climate change on durum wheat due to the positive interaction between increased photosynthetic efficiency at high CO^2 concentration, rainfall pattern during the growing season and shortening of growth cycle. Indeed, the shortening of the growth cycle induced by higher temperatures reduce the exposure of the crop to drought and heat stress during the most sensitive phenological phases, such as anthesis and grain filling. Moreover, FACE studies have suggested that water-stressed crops will respond more strongly to elevated CO_2 than well-watered crops, because of CO_2 induced increases in stomatal resistance. This suggests that rain-fed cropping systems will benefit more from elevated CO_2 than irrigated systems (Shimono et al., 2008; Hasegawa et al., 2013).

The incidence of climate change on yield might be more emphasised by the increase of pests and diseases attacks. Indeed, changes in temperature can result in geographic shifts of pests and diseases through changes in seasonal extremes, and thus, for example, overwintering and summer survival (IPCC, 2014). When coupled with increased crop and pathogen biomass, elevated CO_2 can result in increased severity of the *Fusarium pseudograminearum* pathogen, leading to shrivel grains with low market value (Melloy et al., 2010).

Furthermore, elevated CO_2 can lower the nutritional quality of flour produced from grain cereals (Högy et al., 2009; Erbs et al., 2010).

To avoid or to reduce negative effects of climate change, in literature several adaptation strategies have been suggested. The short-terms adaptations included changing in varieties, shifting in sowing date, variation in the pesticide and in fertilization treatments (Olesen et al., 2011). Whilst, the long-term adaptations refer to major structural changes to overcome climate change. For instance, they involved the changing in land allocation and farming systems, breeding of new crop varieties, new management techniques to increase the water soil conservation.

1.3. Crop simulation models

In the mid-1960s, crop development and growth began to be represented by relative simple mathematical equations that could be encoded as crop simulation models (de Wit, 1965). Many crop models about wheat have been developed with different level of details, such as SSM-Wheat (Soltani et al., 2013), CropSyst (Stöckle et al., 2003), DDSAT (Jones et al., 2003), CESERS-Wheat (Ritchie and Otter-Nacke, 1985), *SiriusQuality* (Jamieson et al. 1998; Martre et al., 2006). Crop models simulated the crop growth and development considering the climate conditions (e.g. temperatures, rainfall, solar radiation), soil characteristics (e.g. soil texture, water content, nitrogen mineralization capacity, organic matter amount, soil layer depth), management practices (e.g. sowing date, timing and quantity of fertilization treatments) and cultivar parameters (e.g. thermal time requirements, photoperiod and vernalization sensitivity) (Fig. 1.4). The crop process included: phenology driven by temperature, photoperiod and vernalization; the biomass production by the light interception and the biomass partitioning considering the deficit or excess of water and nutrients in the soil.

Reliable model outputs required high quality of input model data for soil, weather, management and genotype characteristics. The major uncertainties are typically related to the genotype parameters and to the soil characteristics (initial soil water and soil mineral nitrogen content).

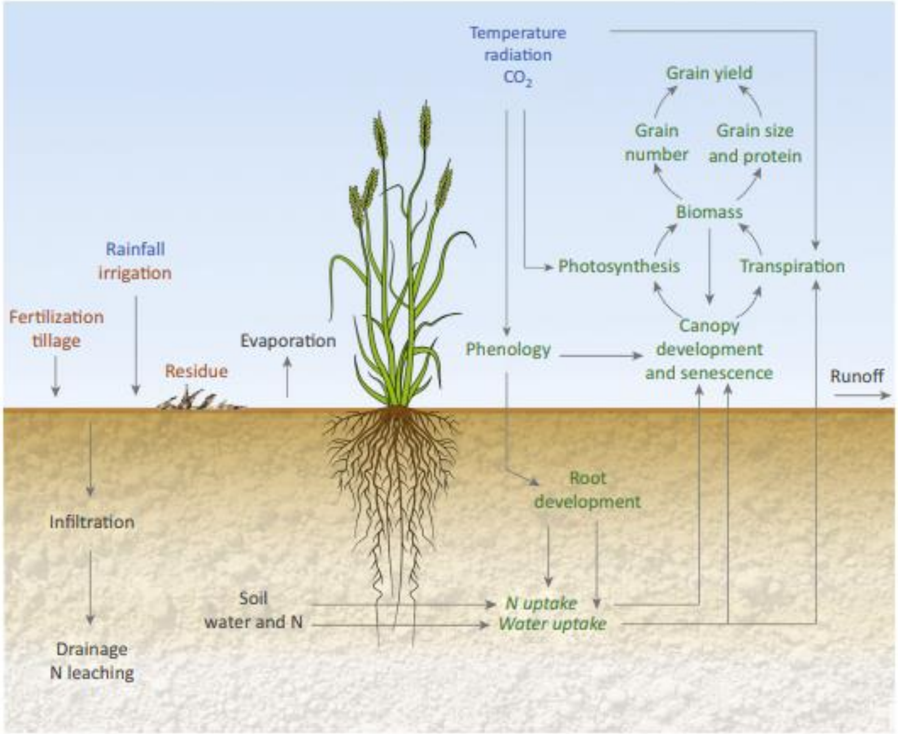

Fig. 1.4: *Simplified framework of a wheat crop model (Chernu et al., 2017)*

Nowadays crop models have commonly used to allow researchers, farmers and policymaker to evaluate the potential grains and to determine the limiting factors for yield productivity understanding the "yield gap" between the potential and farmer's yield (Hochman et al., 2013). Wheat crop models have been used to assess management impacts on crop yield, such as fertilization (Dumont et al., 2015), irrigation (Liu et al., 2007) and sowing date (Andarzian et al., 2015). Furthermore, the farming system models (which incorporate crop simulation model), can be used in the design of the strategies to reduce the agriculture impact on the environment and maintain or increase the crop production (Godfray et al., 2011).

Nowadays, the negative effects of pest and disease in the wheat production is estimated to be -28% worldwide (Oerk, 2006). Under future climate change, the negative impact of pest and disease is expected to increase (Chakraborty and Newton, 2011). For these reasons, pest and disease sub-models are need to be integrated in a lot of crop simulation models. In this way, crop models can provide more reliable information about wheat production, but also to assist decision making for farmers, such as when spray the pesticides. By now, simple crop simulation models have been employed to consider yield-loss for pest and disease (for example, aphids, weeds, eyespot and brown rust) (Rossing, 1991; Deen et al., 2003; Robin et al., 2013; Bregaglio and Donatelli, 2015).

Crop simulation models are having an increasing role to simulate the Genotype x Environment x Management (G x E x M) interactions with the aim to identify potential traits to be considered for wheat yield improvement (Martre et al., 2015) and to identify strategies to improve agronomy and breeding approaches (Chenu et al., 2017). Plant breeders are developing cultivars characterized by high yield stability, but the breeding process require a lot of time. In the last decades, crop simulation models are used to help breeders in this process selecting the plant traits connected with the plant production and describing the crop ideotype. An ideotype is an idealized plat, which is expected to ensure high yield when developed as a cultivar (Donald, 1968). Martre et al. (2015) defined the crop ideotype as "*a combination of morphological and/or physiological traits, or their genetic bases, optimizing crop performance to a particular biophysical environment, crop management, and end-use*". In crop model, an ideotype is defined as a set of varietal parameters that defined the plant growth and development with the given environmental conditions.

Moreover, modelling can help to understand the impact of future climate change on wheat production. In this contest, they are useful tools to define the future limiting productivity factors and to identify possible adaptations to offset climate drawbacks on yield (Martin et al., 2014). An important climate change factor to consider is the CO_2 concentration. A large number of crop simulation models have been tested with elevated CO_2 concentration experiments and they are able to reproduce CO_2 effects on grain yield up to 550 ppm (O'Leary et al., 2015).

1.3.1. *SiriusQuality*

SiriusQuality is a process-based model consisting of eight sub-models (modules) ((http://www1.clermont.inra.fr/siriusquality/). The modules simulate on a daily time step crop phenology (Phenology sub-model), canopy development (Leaf Layer Expansion sub-model), accumulation and partitioning of dry mass (DM; Light Interception and Use Efficiency and Dry Mass Allocation sub-models) and N (N Allocation, and Root Growth and N Uptake References sub-models), including responses to shortage in the supply of soil water (Soil Drought sub-model) and N (dealt with in the N Allocation sub-model), and accumulation and partitioning of grain DM and N (Grain sub-model). Two additional sub-model describe crop evapotranspiration and soil N and water balances.

For running, *SiriusQuality* (Fig. 1.5) needs input information such as daily weather data (e.g. minimum and maximum temperature, rainfall and solar radiation); soil characteristics and properties (e.g. layer depth, soil organic matter, N mineralization, water content); management information (e.g. sowing date, plant density, date and quantity of fertilization and irrigation treatments); varietal parameters (e.g. phyllocron, growing degree days between the phenological phases, photoperiod sensitivity, rate of leaf senescence). As outputs, the model reproduces, for instance, the daily dry mass and the grain accumulation, the N biomass and grain accumulation, the grain protein concentration and its components (gliadin and gluten), the potential and actual crop evapotranspiration, the water efficiency and the photosynthetic active radiation.

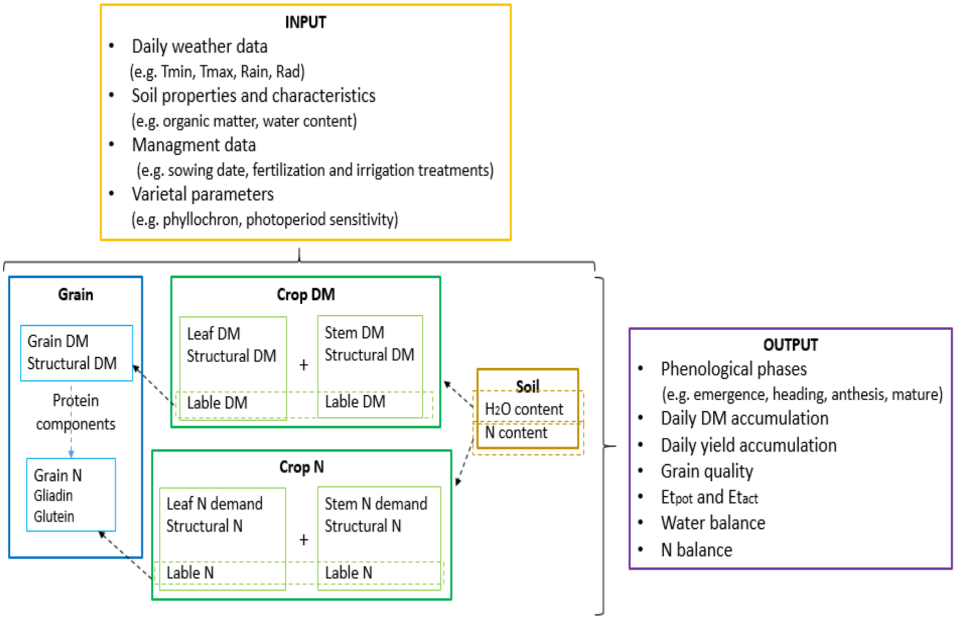

Fig. 1.5: *A simplified flowchart of SiriusQuality*

The Phenology sub-model calculates the durations of six development phases, including pre-emergence (sowing to emergence), leaf production (emergence to flag leaf ligule appearance), flag leaf ligule appearance to anthesis, anthesis to beginning of grain fill, grain filling, and maturation (Jamieson et al., 1998). The anthesis date is mainly determined by the rate of leaf production (1/phyllochron) and the final leaf number, which is calculated by day length (photoperiod) and temperature (vernalization) response sub-routines. Canopy development is simulated in the Leaf Layer Expansion sub-model as a series of leaf layers associated with individual main-stem leaves, and tiller production is simulated through the potential size of each layer.

The Light Interception and Use Efficiency sub-model calculates the amount of light intercept by each leaf layer using the turbid medium approach and uses it to produce biomass at an efficiency (light use efficiency) calculated from temperature, air CO_2 concentration, soil water deficit, leaf nitrogen content per unit surface area (specific leaf N) and the ratio of diffuse to direct radiation. The total above-ground biomass at any time is the sum of the daily rate of biomass accumulation of each leaf layer, which, in turn, is the product of LUE and intercepted photosynthetically active radiation (PAR) by the leaf layers.

Crop N uptake is driven by canopy expansion. The vertical distribution of leaf N follows the light distribution. The ratio of nitrogen to light extinction coefficients is determined by the crop N status and the size of the canopy. As for the biomass, any N not allocated to the leaves is allocated to the stem if its N concentration is less than its maximum. After anthesis, the capacity of the root system to uptake N from the soil decreases linearly with thermal time. After the end of the endosperm cell division stage, the rate of N transfer to grains is determined by the stem and leaf N concentrations and follows a first order kinetics.

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Chapter 2.

Objectives and structure

2. Objectives and structure

Considering the climate change which is already occurring in the Mediterranean basin and the economically importance of the durum wheat in this area, understand the possible effects of the climate change on the durum wheat production and to identify durum wheat ideotype characteristics are needed. For this purpose, the followed specific aims were investigated:

1. to evaluate the performance of *SiriusQuality* and to investigate the effects of Genotype x Environment x Management on Creso, Simeto, Amilcar and Karim durum wheat cultivars in Florence, Foggia, Santaella and Sidi El Aydi. In particular, the effect of changing in sowing window on yield production and grain quality were analysed.

2. to investigate the impact of climate change on durum wheat production in four sites in the Mediterranean basin considering the frequency and the intensity of three climate stress events occurred around anthesis and during the grain filling.

3. to identify durum wheat ideotype physiological characteristics in Florence, Foggia, Santaella and Sidi El Aydi able to ensure high grain production and low inter-annual yield variability under future climate change.

This thesis is structured in chapters, which were written as scientific papers. The first paper (Chapter 3) explains the crop simulation model *SiriusQuality* calibration and validation in four sites in the Mediterranean basin. In addition, the results about *SiriusQuality* application in Florence, Foggia, Santaella and Sidi El Aydi to investigate the optimal sowing window for durum wheat in these location are explained. In the second paper (Chapter 4), *Sirius Quality* was applied for the future climate change impact analyse in Florence, Foggia, Santa Ella and Side El Aydin using Cresol, Simit, Hamilcar and Karim cultivar, respectively. Moreover, three climate stress events, in terms of frequency and intensity, around anthesis and grain filling were investigated. The compensative CO2 yield effect was researched, too. The third paper (Chapter 5) shows the *SiriusQuality* application for the identification of durum wheat ideotype characteristics under tow future climate scenarios in Florence, Foggia, Santaella and Sidi El Aydi locations. For each location and scenario, clusters of ideotipes, described by different sets of varietal parameters, were found. The changed varietal parameters for the ideotyping study were selected considering the results of the second paper.

The first paper was submitted to the European Journal of Agronomy. Instead, the other two papers are in preparation.

Chapter 3.

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

Gloria Padovan, Pierre Martre, Misha A. Semenov, Simone Bregaglio, Domenico Ventrella, Ignatio J. Lorite, Cristina Santos, Marco Bindi, Roberto Ferrise, 2018. Understanding effects of genotype x environment x management interactions for durum wheat in the Mediterranean basin. European Journal of Agronomy (submitted)

Abstract Durum wheat is one of the most important crops of the Mediterranean regions. Optimal management practices are essential to ensure high yield, in particular variety choice and sowing time. Crop models could be useful tools to investigate genotype x environment x sowing window (GxExSW) interactions. The aims of this study were to evaluate the performance of the wheat simulation model *SiriusQuality* to simulate durum wheat growth and development in different Mediterranean environments and to use the model to investigate the effects of G x E x SW interactions. *SiriusQuality* was evaluated over different growing seasons at seven sites in Italy, Spain, and Morocco where locally adapted cultivars were grown. The model showed good performance in predicting anthesis date, maturity date, above ground biomass and grain yield with coefficients of agreement and Pearson coefficients of correlation close to one. To find the optimal 30-day sowing window, the four durum wheat cultivars were sown at the four sites in Italy (Florence, Foggia), Spain (Santaella), and Morocco (Sidi El Aydi) from 10 October to 5 December with an increments of 5-day shifts. The simulation results showed that an earlier sowing window could improve the grain yield, but not the grain quality, in all locations for all cultivars. Maximum leaf area index, single grain dry matter, grain number per square meter and grain filling duration where higher for the optimum sowing window than for the sowing window currently used by farmers. Moreover, the water stress during grain filling was lower at optimum sowing window compared to the traditional one.

Keywords: *SiriusQuality*, Sowing window, Mediterranean environments, Durum wheat.

3.1. Introduction

Durum wheat (*Triticum turgidum* L.subsp. durum) is the most common crop in the Mediterranean basin and the region produces over 38% of the global durum wheat production (IGCC, 2017). Grain yield and quality are strongly related to weather behaviour during the growing season (Porter and Semenov, 2005). Wheat is particularly sensitive to hot temperatures and water deficit during both the reproductive and grain filling stages (Porter and Gawith, 1999; Farooq et al., 2011; Alghabari et al., 2014). Global warming and forecasted reductions in rainfall in the Mediterranean basin (Semenov et al., 2014) is likely to affect durum wheat production. In fact, the more severe drought could render the crops more sensitive to heat stress, with a resultant negative effect on grain yield (Asseng et al., 2011). Appropriate management practices are fundamental to ensure healthy wheat development and high wheat production. Of the different factors which influence durum wheat production, sowing time and the choice of the cultivar are among the most important ones (Connor et al., 1992; Gomez-Macpherson and Richards, 1995; Turner et al., 2004; Bassu et al., 2009).

Sowing window, as a management practice, is generally aimed at avoiding or minimizing stress effects on crop performance (Tapley et al., 2013). Early sowing increases grain yield, whereas yield reduction is observed when sowing is delayed after the optimum time (Connor et al., 1992; Bassu et al., 2009; Tapley et al., 2013). Shifting the sowing date within the sowing window influences the grain yield by affecting the numbers of tillers and spikes and the duration of spike growth (Bassu et al., 2009). Moreover, the number of seed per unit area and the single grain dry mass are also affected when the sowing date is changed within the sowing window (Fischer, 1975; Tapley et al., 2013). An advantage of early sowing is that it permits an increase in the interception of solar radiance, thereby resulting in a greater accumulation of dry matter by the crop (Stapper and Harris, 1989). On the other hand, this practice is not considered favourable under conditions where frost risk during winter or early spring is predicted to be high. Instead, late sowing is usually recommended in locations with elevated frost risk (Connor et al., 1992). However, late sown crops may experience more variable temperatures, especially during the reproductive and grain filling periods, which can lead to a shorter grain-filling period (Hunt et al, 1991), a reduction of spike growth duration and an increase in spike sterility (Wheeler et al., 1996). In general, maximum yield declines before and after the optimum sowing time, and is related to stressful conditions during the grain-filling period or warmer environments with shorter growing seasons (Sharma et al., 2008).

Sowing window can be defined as the period that results in the crop flowering after the risk of frost damage but before the onset of the summer drought (Single, 1961; Fischer and Khon, 1966; Syme, 1968). In the Mediterranean basin, the sowing window for durum wheat starts with the first significant rainfall after the summer season and closes when a sowing date is too late to achieve a reasonable yield (Bassu et al., 2009).

The selection of an appropriate cultivar for a specific sowing date that will flower at the right time and under optimum environmental conditions is an important aspect to consider for maximizing grain yield. Early maturing cultivars could be at a higher risk of stem damage due to frost if sown too early (Kelley, 2001). Furthermore, they have a greater possibility to break winter dormancy sooner if delayed sowing is chosen, which in turn accelerates the crop growth, thereby resulting in freeze injury and yield losses (Holman et al., 2011). In contrast, early sowing of late maturing cultivars may result in high yields depending to the soil water content after anthesis (Gomez-MacPherson and Richard, 1995), and late sowing of late maturing cultivars may result in less yield if temperatures during late spring are higher than the historic average values (Kelley, 2001).

It has long been recognized that wheat productivity and grain quality vary considerably as a result of the 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 reproduce G x E x SW interactions can be overcome by using crop simulation models (Stapper and Harris, 1989; Chenu et al., 2017), which are able to reproduce crop growth and development, taking into account the soil-weather-crop-management dynamics. Therefore, they have been largely used to extrapolate agronomic research findings over time and space (O’Leary and Connor, 1998; Chenu et al., 2017). Moreover, they have been used to assess crop behaviours in response to different climate conditions and management practices (Salado-Navarro and Sinclair, 2009; Soltani et al., 2013; Dettori et al., 2017) or to identify the best management practices (Soltani and Hoogenboom, 2007; Rozbicki et al., 2017). Several studies have been carried out using crop simulation models to investigate the effect of shifting the sowing date under climate change (Moriondo et al.,2010; Oort et al., 2012; Dettori et al., 2107; Nouri et al., 2017) but there are only few studies regarding the optimization of the sowing window in the Mediterranean basin (Oweis et al., 2000; Bassu et al., 2009; Ferrise et al., 2010;).

In this study, the wheat crop simulation model *SiriusQuality* was used to investigate the effects of genotype x environment x sowing window in four areas in the Mediterranean basin for current climate. First, the performances of the model were evaluated at seven sites in the targeted environments. It was then used to identify optimal sowing windows for early and late maturing cultivars in Florence, Foggia, Santaella and Sidi El Aydi and to quantify GxExSW interactions.

3.2. Materials and Methods

3.2.1. Experimental sites

Data collected from field experiments, carried out in seven locations within typical Durum wheat cultivation areas (*Triticum turgidum* L.subsp. *durum*) in the Mediterranean Basin, were used (Fig. 3.1). The sites were located in Florence (43.76° N, 11.21° E, 42 m elevation) and Foggia (41.26° N, 15.3° E, 90 m elevation), in central and southern Italy, respectively, in Carmona (37.38° N, 5.58° W, 253 m elevation) and Santaella (37.51° N, 4.88° 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, 8.7° W, 165 m elevation) in the south of Morocco.

Fig. 3.1. Locations of the sites used in this study: Florence (FI) in central Italy, Foggia (FO) in southern Italy, Carmona (CA) and Santaella (SA) in the south of Spain, Marchouch (MA), Sidi El Aydi (SE) and Khemiz Zemamra (KZ) in the north of Morocco.

According to Metzger et al. (2005) Florence is classified as a northern Mediterranean environmental zone, while the remaining locations under study are classified as southern Mediterranean environmental zones. All sites were characterized by a Mediterranean climate, with warm and dry summers and mild winters but with different climate characteristics. In Florence, daily temperatures range from a maximum temperature of 30°C in August to a minimum temperature just under 0°C in January. Rainfall is evenly distributed during the year, with a total amount averaging 750 mm. In Foggia, daily temperatures range from a maximum of 31°C in August to 3.5°C in January. Rainfall is concentrated in Autumn and Winter, with a total average of 500 mm. In Santaella and Carmona daily temperatures range from 32°C in August to 4.5°C in January. The total average annual rainfall is 480 mm, and is more concentrated during Autumn and Winter, with dry Summers. In Morocco, temperatures range from 6°C in January to 30°C in July -August. Rainfall is concentrated in Winter and Spring, and is very low during the summer season, with a total annual average of 350 mm.

3.2.2. Experimental site data

In Florence, data were derived from two rainfed experiments carried out at 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 cultivar characterized by good yield quantity and quality. For each year, the seeds were sown (150 seeds m^{-2})

on either two normal sowing dates or two late sowing dates as follows: 11 December 2002 and 05 November 2004 (normal sowing dates), and 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 (GS) 15/22 (leaf 5 emerged at 50%, 2 tillers visible) and the remaining two third as ammonium nitrate at GS 31 (first stem node detectable).

In Foggia, data were obtained from a long-term field experiment carried out at the CRA-SCA experimental farm in Foggia in the periods 1997 to 2000 and 2007 to 2013 (11 growing seasons). Data used in this study were from the cultivar Simeto, a medium-early maturation Italian cultivar characterized by an excellent grain quality. Crops were sown between mid-November and early January, depending on 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} applied ammonium nitrate at GS 31, and in the second one (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 GS 31. In 2012 and 2013, crops were irrigated (both treatments) with 30 mm on 18 January and 80 mm in 2013, otherwise crops were rainfed.

In Spain, data were obtained from rainfed field varietal trials conducted in Carmona and Santaella in the period 2011 to 2015 and 2011 to 2016, respectively. Crop data used in this study were from cultivar Amilcar, a short-cycle variety characterized by high potential production and disease resistance. At both sites crops were sown between 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 to 13 g N ha^{-1}, of which 30% to 50% were applied at sowing as diammonium sulphate and the remaining in one to two splits between GS 23 (3 tillers visible) and 37 (flag leaf just visible) as urea and ammonium nitrate. In Santaella, crops received 11.5 to 18.5 g N ha^{-1} of which 20% to 100% were applied at sowing as diammonium sulphate and the remaining between GS 21 and 37 (flag leaf just visible) as urea. In Santaella, in 2012, 2014, and 2016 crops were irrigated with 30 to 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 in Marchouch (Bregaglio et al., 2015). In both years, cops 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 on 12 December. Cultivar Karim, a medium semi-dwarf high yielding cultivar, was used in all experiments in Marocco. In all 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} at GS 39 (flag leaf ligule just visible) as urea. In Kemis Zemamra crops were rainfed, in Marchouch they were fully irrigated, and in Sidi El Aydi a rainfed and fully irrigated treatments were applied. Fully irrigated crops received 40 mm every 1 to 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 Morocco, for which they were extracted from the SOIL GRIDS DATABASE (soilgrids.org). Phenological stages were collected in all experiments (Table 1). In Spain heading date was recorded, while in the other sites anthesis date was recorded. Grain yield was measured in Italy and Spain but not in Morocco, while total above ground data biomass were available in Italy and in Morocco. Total above ground N, grain N content and grain number data were available in Florence.

Table 3.1 Observed experimental data used for model calibration and validation at the seven studied sites.

Country	**Site name**	**N. environments[a]**	**Observed data**													
			Phenology[b]				**In-season**					**Final harvest**				
			01	**55**	**65**	**89**	**Leaf area index**	**Above ground biomass**	**N uptake**	**Grain yield**	**Grain N yield**	**Above ground biomass**	**N uptake**	**Grain yield**	**Grain number**	**Grain N yield**
Italy	*Florence*	16	16	0	16	16	0	64	64	64	64	16	16	16	16	16
	Foggia	22	22	0	22	22	1	0	0	0	0	0	0	22	0	0
Spain	*Carmona*	4	4	4	0	5[c]	0	0	0	0	0	0	0	4	0	2
	Santaella	5	5	5	0	4[c]	0	0	0	0	0	0	0	5	0	0
Morocco	*Sidi El Aydi*	4	4	0	4	0	0	20	0	0	0	0	0	0	0	0
	Marchouch	1	1	0	1	0	0	5	0	0	0	0	0	0	0	0
	Khemis Zemamra	1	1	0	1	0	0	5	0	0	0	0	0	0	0	0

[a] site/year/treatment combinations

[b] Growth stages: 01, emergence; 55, heading; 65, anthesis; 89, physiological maturity

[c] Estimated from the harvest date

3.2.3. The wheat crop simulation model *SiriusQuality*

The wheat crop simulation model *SiriusQuality* (http://www1.clermont.inra.fr/siriusquality/) has been used to model wheat phenology and growth in several studies covering different environmental characteristics and management practices (e.g. Tao et al., 2017; Maiorano et al., 2017; Wallach et al., 2018; Weber et al., 2018). *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 environmental conditions and crop management. The model requires daily weather data (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). Phenological stages are modeled based on the rate of leaf appearance and final leaf number modified by vernalization and photoperiod response (He et al., 2012). Canopy development is modeled 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., 1998). Biomass allocation and remobilization is modeled using a sink/source approach and sink priority rules (Jamieson et al., 1998). N uptake and partitioning is modeled using a photosynthesis acclimation model and sink priority rules (Martre et al., 2006; Bertheloot et al., 2008; Moreau et al, 2012). Grain dry mass accumulation depends on post-anthesis biomass assimilation and includes a proportion translocated from the biomass accumulated at anthesis (Martre et al., 2006). Here we used the version 2.0.2 of *SiriusQuality*. The source code and the binaries can be freely downloaded at https://forgemia.inra.fr/siriusquality.

3.2.4. Model calibration and evaluation

Because data availability varied between the selected locations (Table 1), different criteria were used to select the appropriate data with which to calibrate and evaluate the model for each location. 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. 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 evaluation. For southern Spain, data from Carmona were used for model calibration, whilst data from Santaella were used for model evaluation. 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 evaluation.

In Morocco, the weather conditions, around sowing were very dry and the observed emergence occurred average of 20 days after sowing and coincided with the first rainfall event. *SiriusQuality* simulates the emergence date, considering only the thermal time from sowing to emergence, without taking into consideration the soil humidity. Thus, to correctly simulate emergence, and consequently the other phenological stages, the sowing dates were estimated using *SiriusQuality* with a fixed sowing window (15 November to 30 December) using the algorithm described in Brisson et al., (2009), see below. Grain yield data were not available in Morocco, so the simulated yields were compared with the Moroccan durum wheat production data from FAOSTAT (2012) and the Grain Report for Morocco (2012).

Six genotypic parameters were estimated for each cultivar (Table 3.2) using a covariance matrix adaptation—evolutionary strategy (Hansen and Ostermeier, 2001) that minimized the root mean squared error (RMSE) between simulated and observed phenological and biomass data. The four cultivars have very low cold temperature requirement (Motzo and Giunta, 2007) so the response of vernalization rate to temperature (He et al., 2012) was set at a high value for all the cultivars (0.05 d^{-1} $°C^{-1}$).

Table 3.2 Name, definition, unit and value of the varietal parameters of the wheat model *SiriusQuality* calibrated for the durum wheat cultivar Creso, Simeto, Amilcar and Karim

Name	**Definition**	**Unit**	**Value**			
			Creso	**Simeto**	**Amilcar**	**Karim**
Dgf	Potential thermal time from anthesis and end of grain filling	°Cd	650	550	500	600
PlagLL	Phyllochronic duration between end of expansion and the beginning of the senescence period for the mature leaves	cm^2 lamina^{-1}	8	5	8	8
PsenLL	Phyllochronic duration of the senescence period for the mature leaves	Phylllochron	5	3	5	5
RUE	Potential radiation use efficiency under overcast conditions	g MJ^{-1} (PAR)	2.5	2.9	3.1	3.5
Dse	Thermal time from sowing to crop emergence	°Cd	93	111	125	135
Phyll	Phyllochron	°Cd	114	105	90	115
SLDL	Daylength response of leaf production	Leaf h^{-1} (daylength)	1.39	1.40	1.04	1.21

3.2.5. Model application

To analyze GxExSW interations we simulated the development and growth of the four cultivars at Florence, Foggia, Santella, and Sidi El Aydi for the period 1980-2010 sown within 30-day sowing windows ranging from October until January. For all sites, standard local management practices were identified by asking local experts in the field. The management inputs used for the simulations are summarized in Table 3.3.

Table 3.3 Sowing window, plant density (seeds m^{-2}) and fertilization treatments (g N m^{-2}) in pre-sowing and in top-dressed used for *SiriusQuality* application in Florence, Foggia, Santaella and Sidi El Aydi. The top dressed fertilization treatments were applied in tow growing stage (GS).

Site	Traditional sowing window	Sowing density	Fertilizer application (g N m^{-2})	
			Growth stage	Rate (g N m^{-2})
Florence	30Oct.-30Nov.	350	00	3.5
			30	6.0
			39	6.0
Foggia	20Nov.-20Dec.	350	00	3.6
			22	6.9
			32	3.9
Santaella	15Nov.-15Dec.	360	00	3.6
			22	6.9
			32	4.0
Sidi El Aydi	30Nov.-30Dec.	400	00	3.0
			22	3.5
			32	4.6

One hundred years of synthetic daily weather data representative of the 1980-2010 period were generated with LARS-Weather Generator (LARS-WG) (Semenov and Barrow, 1997; Semenov and Stratonovitch, 2015) calibrated at each site using a long series of daily weather data extracted from the Crop Growth Monitoring System (CGMS) of the Joint Research Centre (JRC) archive (http:// mars. jrc. ec.europa.eu). The 100 individual years generated by LARS-WG should be considered as samples representing the typical weather for the 1980-2010 period (Semenov and Stratonovitch, 2015), that in turn, should increase the significance of modelling results. All simulations were done with an atmospheric CO_2 concentration of 363 ppm.

To investigate the best sowing window-yield combination at each site and if the traditional sowing windows (TSW) are optimum for grain yield, thirty-day sowing windows were tested starting from 10 October until 5 January with 5 day increments. Within each sowing window, each year the sowing date was calculating using *SiriusQuality* with the approach described by Brisson et al. (2009). In brief, sowing occurred the first day with 10 mm of cumulative precipitation in the previous three days, an average air temperature > 10°C and a minimum air temperature > -4°C for the previous 10 days, and a soil moisture content between 0.75 to 1.2 the field capacity in the first 30 cm.

3.2.6. Statistical analysis

The accuracy of *SiriusQuality* in reproducing observed phenology, 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:

$$r = \frac{\sum_{i=1}^{n}(O_i - \bar{O}) x \, (S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2} \, x \, \sqrt{\sum_{i=1}^{n}(S_i - \bar{S})^2}} \tag{1}$$

where O_i is the observed data, $\bar{O}$ is the mean of the observed data, S_i is the simulated data, $\bar{S}$ is the mean of simulated data, and n is the number of data. Negative r values would imply that an inverse relationship exists between simulations and observations, whereas a value of zero would imply that there is no linear correlation between the simulated and observed data.

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

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

The model performance is considered perfect if the 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:

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

Values of MAE close to zero correspond to a good model performance. Finally, the index of agreement is defined as:

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}\left(|S_i - \overline{O}| + |O_i - \overline{O}|\right)^2}\right] \tag{3}$$

The numerator is the sum of the square errors and the denominator is related to the variability in the observed and in the simulated values. The *d* ranges from 0 to 1. If the model performance is perfect, then *d* = 1, indicating that the simulated data is equal to the observed data (Willmott, 1985).

To evaluate the significance G x E x M and their interactions, an analysis of variance (three way-ANOVA) was done. We considered the fertilization treatments (which were different in timing and in quantity for each site) as location characteristics, because they were linked to the soil and weather conditions of each location. To evaluate the significance of differences in yield between TSW and the sowing window producing the highest yield (OSW), a *t*-test was used.

3.3. Results

3.3.1. Model evaluation

For both the calibration and evaluation data sets, MAE for anthesis or heading date and maturty date were < 9.30 days (Table 3.4, Fig. 3.2C-E), and nRMSE for grain yield and total above ground ranged from 6% to 18% and from 10% to 32%, respectively (Table 3.4, Fig. 3.2A-D-F-G-H). The overall nRMSE for grain yield was only 5% higher for the evaluation than for the calibration data set. All d values for phenology and grain yield excepting heading date in Carmona (that is, for the site use for model calibration in Spain) were > 0.70. On average, MAE for phenological stages were only 1 days higher for the evaluation than for the evaluation data set. For the data used for model evaluation, all r and d values were > 0.80 and 0.70, respectively (Table 3.4). For grain N yield in Florence, the nRMSE was 10% (Table 3.4, Fig. 3.2A). For Morocco, the average simulated yield in rainfed conditions was in the range indicated in the FAOSTAT (2012) and the Grain Report for Morocco (2012).

3.3.2. Genotype x environment x management interactions

The growth of the four cultivars for which *SiriusQuality* was calibrated were simulated in Florence, Foggia, Santaella and Sidi El Aydi with local agronomic practices (Table 3.2) for 100 years representative of the climate of the period 1980-2010. G x E x SW interaction for anthesis date, anthesis LAI, and grain number were highly significant (p-value < 0.005). However, G x E x SW interaction for grain yield was not significant (p-value > 0.5) but G x E and E x SW interactions were highly significant (both p-value < 0.005).

Florence, Foggia and Santaella produced the highest yields, whilst Sidi El Aidy was the least productive site. In both Florence and Foggia, grain number was the principle trait contributing to yield ($r^2 = 0.79$ and 0.76, respectively), followed by LAI in Florence ($r^2 = 0.35$) and by single grain dry mass in Foggia ($r^2 = 0.33$; Supplementary Information Fig. S3.1). In Santaella and Sidi El Aydi, the principle traits were grain filling duration ($r^2 = 0.31$ and 0.56, respectively) and the grain number ($r^2 = 0.30$ and 0.53).

Table 3.4 Evaluation of the wheat model *SiriusQuality* for the calibration and evalution data sets for phenological stages, final total above ground biomass and N, final grain yield, final grain N, and gain protein concentration. *r*, pearson coefficient of correlation; MAE, mean absolute errore; nRMSE, normalized root mean squared error; *d*, index of agreement.

Cultivar (site or country)	**Variable**	**Calibration**					**Evaluation**				
		No. Of observations	***r***	**MAE**	**nRMSE**	***d***	***No. 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
	Final grain N yield	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

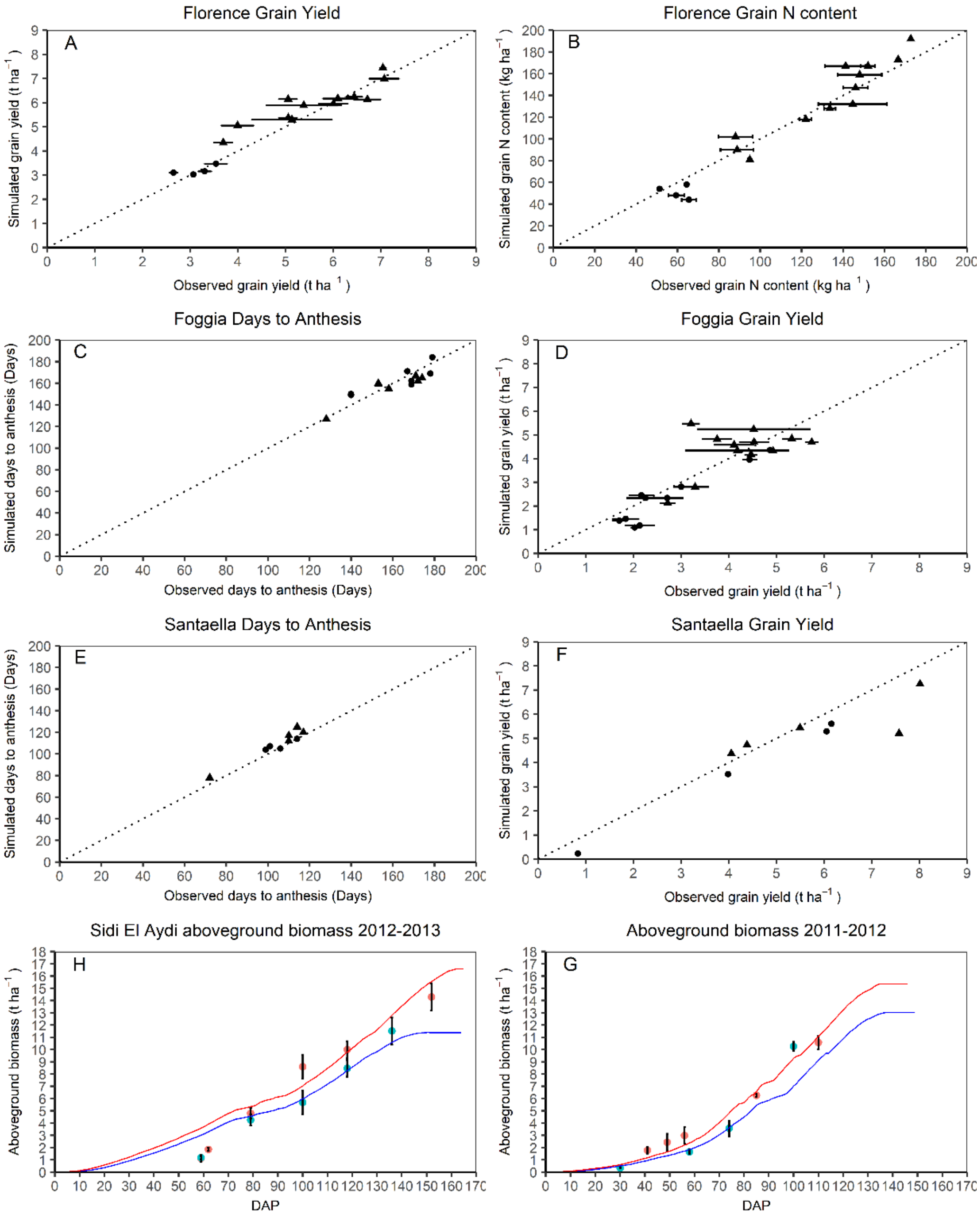

Fig. 3.2. *Simulated versus observed grain yield (t ha^{-1}) and N grain content (kg N ha^{-1}) in Florence (A, B), anthesis (Days After Planting, Days) and grain yield (t ha^{-1}) and in Foggia (C, D) and in Santaella (E, F). The point represent the model calibration, the triangles the model evaluation Simulated versus observed aboveground biomass for Morocco in Sidi El Aydi (H) for growing season 2012-13, and in Khemiz Zamamra and Marchouch for the growing season 2011-12 (G). The red line and points for irrigated treatments (used for model calibration) and blue for rainfed treatments (used for model evaluation). The error bars corresponding to n=3 replicates. Dash lines are y = x.*

3.3.3. Optimum sowing window

For all sites, an earlier sowing window compared to TSW resulted in higher simulated grain yield (Fig. 3.3). In each site, the four cultivars generally had the same behavior, namely a grain yield reduction with earlier and later sowing windows compared to the OSW. At the four sites, with TSW and OSW, Karim and Amilcar were the most productive cultivars and Creso and Simeto the less productive. At the OSW the coefficient of variation (CV) for yield was lower than for the TSW for all genotypes and for all locations (Table 3.6). Maximum leaf area index (LAI) and grain number were the highest for OSW (Fig. 3.4). Single grain dry mass was also the highest for OSW at all locations.

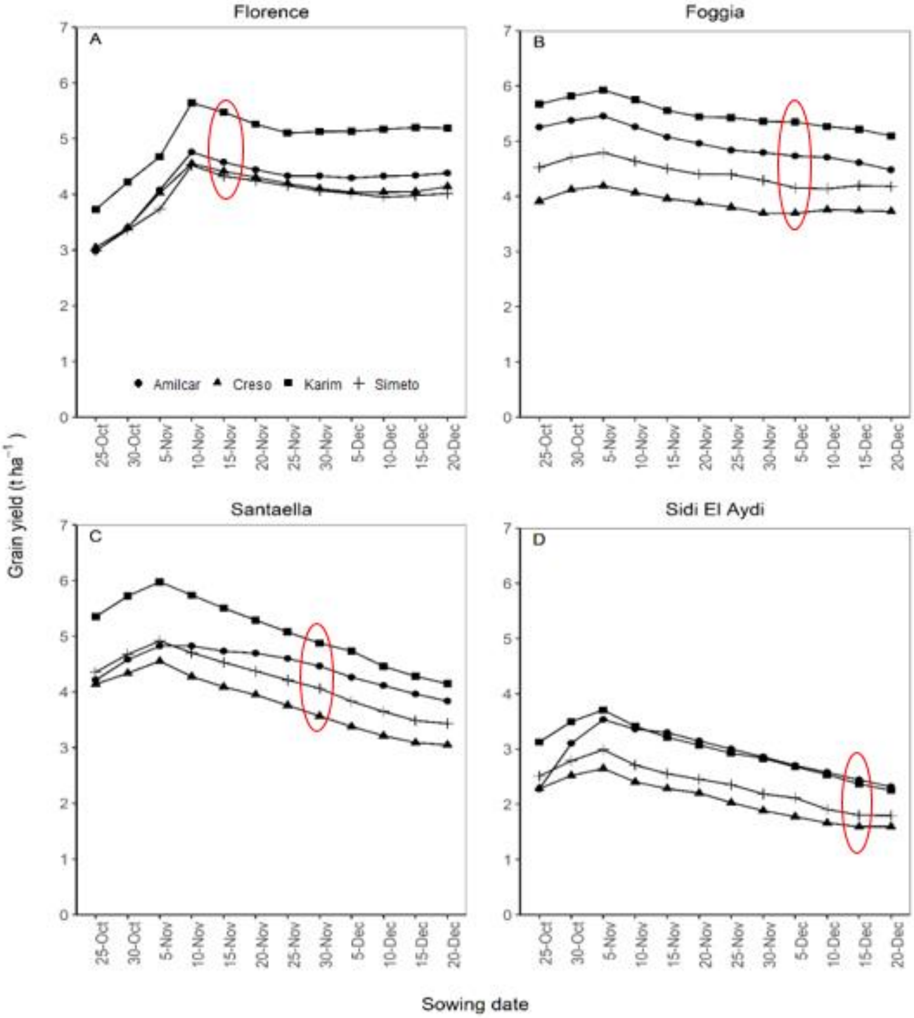

Fig. 3.3. *Simulated grain yield for the different sowing windows for cultivars Creso, Simeto, Amilcar, and Karim in Florence, Foggia, Santaella and Sidi El Aydi. The red circle indicates the yield at the traditional sowing*

In Florence, for all cultivars OSW was from 25 October to 25 November (average 10 November), compared with 30 October to 30 November for TSW (Fig. 3.3A). A low mean yield was observed for the earliest sowing window (10 October to 10 November, average 25 October), whereas yield was unaffected by the variation in sowing date within sowing windows between November and January. Cultivar Karim showed the best yield performance for all sowing windows, and at OSW, the average yield was of 5.63 t ha^{-1}. Creso, Simeto and Amilcar had very similar results for all sowing windows. Among the cultivars, the coefficient of variation (CV) for yield at OSW was reduced of 10.75% compared the CV at TSW (Table 3.5). The average evaporative drought index (EDI, Zhao et al., 2017) during grain filling was decreased of 2.60% compared to the EDI at TSW (Fig. 3.5A). Respect to the TSW, the average grain protein concentration reduction between the cultivars at OSW was 1.63% (Fig. 3.6A).

In Foggia, OSW ranged from 20 October to 20 November (average 5 November) for all genotypes (Fig. 3.3B). Karim was the most productive genotype for all sowing windows, with a yield of 6 t ha^{-1} for OSW. Creso was the least productive genotype with 4.2 t ha^{-1} for OSW. Creso and Simeto appeared less sensitive to the sowing window variation, with a maximum yield difference of 9% between the high and minimum yields. In contrast, a maximum yield difference of 13%, 14% and 18% was evident for Simeto, Karim and Amilcar, respectively. The average CV for yield between the TSW (20 November - 20 December, average 5 December) and OSW was reduced of 14.75% (Table 3.5). At OSW, during grain filling, the EDI was decreased by 5.28% compared to the EDI at TSW (Fig. 3.5B). The grain protein concentration was reduced by 8.39% compared to the TSW, too (Fig. 3.6B).

In Santaella, OSW was 20 October - 20 December (average 5 November) for all genotypes (Fig. 3.3C). Karim had the best yield performance (5.80 t ha^{-1}) for OSW, followed by Amilcar (4.92 t ha^{-1}), Simeto (4.82 t ha^{-1}) and Creso (4.55 t ha^{-1}), respectively. Karim, Creso and Simeto displayed the same yield response to sowing window, that is yield declined for sowings after OSW. For Amilcar, mean grain yield was not significantly different for sowing windows between 5 November and 30 November (ranged from 4.82 to 4.6 t ha^{-1}). Only after 10 December, simulated grain yield started to decline but with lower intensity in comparison to that of the other genotypes. The average yield CV between TSW (15 November - 15 December, average 30 October) and OSW (20 November - 20 December, average 5 December) was decreased of 28.30% (Table 3.5). The EDI during grain filling reduction at OSW was 27.92% compared the EDI at TSW (Fig. 3.5C). At OSW a grain protein concentration reduction of 6.18% compared to the grain protein concentration at TSW was observed (Fig. 3.6C).

In Sidi El Aydi the results showed that the higher mean yield was produced in the sowing period from 20 October to 20 November (average, 5 November; Fig. 3.6D). Karim had the best yield performance at the OSW with 3.70 t ha-1, followed by Amilcar (3.53 t ha^{-1}), Simeto (3.00 t ha^{-1}) and Creso (2.65 t ha^{-1}). For the earlier sowing window, both the Karim and Amilcar had the same yield performance. Instead, Creso and Simeto were less productive genotypes. After the OSW, the yield started to decrease for all genotypes. The average CV between the TSW (30 November- 30 December, average 15 December) and the OSW was reduced by 27.67% (Table 3.5). During the grain filling the EDI at OSW was reduced by 19.95% compared to the EDI at TSW (Fig. 3.5D). An average grain protein concentration reduction among the cultivars between the TSW and the OSW of 13.01% was observed (Fig. 3.6D)

Table 3.6: Average simulated days to anthesis and anthesis Day Of the Year (DOY), grain filling duration (days), yield (t ha^{-1}), the Coefficient of Variation (% CV) and t-test results between the yield distribution obtained in the traditional sowing window (TSW) and the optimum sowing window (OSW) (ns $p>0.05$; *$p<0.05$; **$p<0.001$; ***$p<0.0001$).

Site	**Cultivar**	**Anthesis date (DOY)**				**Grain-filling duration (d)**				**Grain yield (t DM ha^{-1})**				***P-value***
		Average		**%CV**		**Average**		**%CV**		**Average**		**%CV**		
		TSW	**OSW**	**TSW**	**OSW**	**TSW**	**OSW**	**TSW**	**OSW**	**TSW**	**OSW**	**TSW**	**OSW**	
Florence	Creso	128	127	1.50	1.97	45	44	4.30	9.87	4.41	4.55	29.00	27.54	ns
	Simeto	124	123	1.62	2.38	40	41	7.94	7.81	4.32	4.52	24.38	21.64	ns
	Amilcar	107	101	4.56	8.81	47	52	7.63	10.81	4.57	4.75	15.53	12.48	ns
	Karim	125	123	1.73	2.50	44	45	6.25	6.40	5.47	5.65	22.15	20.81	ns
Foggia	Creso	142	137	1.80	2.46	39	42	11.63	11.50	3.70	4.20	35.75	30.19	*
	Simeto	138	132	1.77	3.10	36	38	1.77	3.11	4.15	4.80	39.68	35.11	*
	Amilcar	122	107	2.09	9.32	42	52	8.80	15.88	4.45	4.73	28.79	23.56	**
	Karim	139	132	1.78	3.11	29	31	8.71	8.16	5.35	5.92	31.28	26.94	*
Santaella	Creso	111	95	4.04	9.59	43	51	13.24	15.39	3.56	4.55	25.62	15.51	***
	Simeto	105	88	4.46	11.37	42	50	12.21	13.47	4.06	4.92	42.41	33.62	***
	Amilcar	83	55	11.41	8.75	52	66	10.91	14.25	4.46	4.82	35.77	26.30	**
	Karim	106	89	4.65	11.41	46	54	10.65	12.97	4.87	5.80	35.66	26.19	***
Sidi El Aydi	Creso	101	80	4.76	7.19	39	49	12.98	14.49	1.60	2.65	63.06	47.22	***
	Simeto	96	72	5.36	8.61	38	46	13.13	14.44	1.80	3.00	72.89	56.50	***
	Amilcar	76	43	8.65	18.96	46	60	14.15	13.68	2.45	3.50	68.40	49.01	***
	Karim	97	73	5.36	8.47	43	51	11.44	13.52	2.35	3.70	56.00	36.54	***

3.4. General discussion

3.4.1. *SiriusQuality* evaluation

The six varietal parameters that described the four cultivars used in this study were within the range presented for wheat in the calibration of both Sirius (Semenov et al., 2014) and *SiriusQuality* (Tao et al., 2017). Moreover, considering various varietal parameters, such as the phyllochron, these were comparable to previous modelling study results using Karim, Creso and Simeto (Bassu et al. 2009; Dettori et al., 2017; Confalonieri et al., 2013). We found no published data for Amilcar. The cultivars differed for phenological and growth parameters. For instance, the phyllochron and daylength response parameters were in good agreement with the cultivar characteristics, with Amilcar and Simeto representing early and medium-early cultivars, respectively, and Creso and Karim medium-late maturation cultivars.

Considering the evaluation results, *SiriusQuality* provided a good estimation of phenology, grain yield, grain N yield and biomass dynamic. In fact, all statistical indexes used for the model evaluation showed good performances. Only in Marchouch and Foggia, *SiriusQuality* was not shown to provide excellent results for the biomass and yield, respectively. In Marchouch, the nRMSE was higher than 30%, which is considered poor (Hoogenboom, 2009). The reason was that *SiriusQuality* underestimated the biomass only at the last observed data (Fig. 3.2H) even though the remaining data were correctly simulated. Moreover, it must be taken into consideration that the observed data used for the calibration and the validation of the model were derived from field experiments that were not specifically carried out for a crop model simulation study. Thus, the low grade accuracy of the observed data did not permit a better model calibration than that given. In Foggia, there was a major discrepancy in one data set between observed and simulated yield for 2008-2009 (Fig. 3.2D) (3.2 vs 5.2 t ha^{-1}). The reason may be attributable to the wet growing season (from sowing to harvest) that occurred between 2008-2009. For this growing season, 565 mm (422mm up to 1st March) was observed, in comparison to annual average of 280 mm for remaining growing seasons. *SiriusQuality* was not able to reproduce water excess consequences that could have affected the crop in 2008-2009. Moreover, the relationship between the observed yield data and rainfall were centreed around the regression line, which was not evident for the 2008-09 yield data.

3.4.2. Genotype x environment x sowing window interactions

In the Mediterranean basin, the choice of the cultivar and the sowing date are crucial aspects for the optimization of yield (Connor et al, 1992). The results of this study indicated that either earlier or delayed sowing dates around the OSW reduced grain yield. Implementation of an earlier sowing window of about three weeks for Foggia and

Santaella and about two weeks for Sidi El Aydi, compared to the TSW, impacted positively on grain yield.

Delaying the sowing window resulted in a reduction of the crop cycle duration. The consequences included increase in water stress and reductions in cumulative intercepted solar radiance, biomass accumulation and grain weight (Heng et al., 2007; Stapper and Harris, 1989). In contrast, yield reductions associated with an earlier sowing date compared to TSW could be due to lower LAI, as found here in Florence and Sidi El Avdi and to higher water stress during grain filling.

On average crop anthesis date is advanced by 13 days and grain filling duration is 6 days longer for OSW compared with TSW, thereby resulting in a water stress reduction during grain filling. Increasing the grain filling period was shown to result in a longer period for grain growth, permitting a higher accumulation of the dry matter in the grain (Bassu et al., 2009; Semenov et al., 2009). Moreover, the anthesis date was forwarded with an average of 2 days (days of the year) in Florence, 8 days in Foggia and 22 days in both Santaella and Sidi El Aydi compared to the anthesis at the TSW (Table 3.5). Anticipating anthesis is considered favorable in avoiding stress-related events that potentially occur around anthesis at the TSW, such as high temperatures and less rainfall. Both of the latter have been shown to compromise pollen fertility, thereby resulting in higher sterility grains (Porter and Gawith, 1999). Similar results on phenology, when comparing traditional sowing date to that of an earlier optimum sowing date, have been published in Andarzian et al., (2015).

Regarding the genotypes in all locations, Karim was the most productive cultivar, followed by Amilcar. The exception was in Sidi El Aydi, where yields of both Karim and Amilcar were similar. Both Creso and Simeto were less productive in all locations and at all sowing windows. It is important to consider that Amilcar and Karim were modern varieties, selected after 1986, with higher yield potential than the older cultivars Creso and Simeto. Among the locations, Sidi El Aydi was the less productive. A reason can be attributable to the drier and the more difficult weather conditions normally observed in Sidi El Aydi (Grain Report for Morocco, 2012). In fact, a higher water stress was observed compared to the other locations during grain filling (Fig. 3.5).

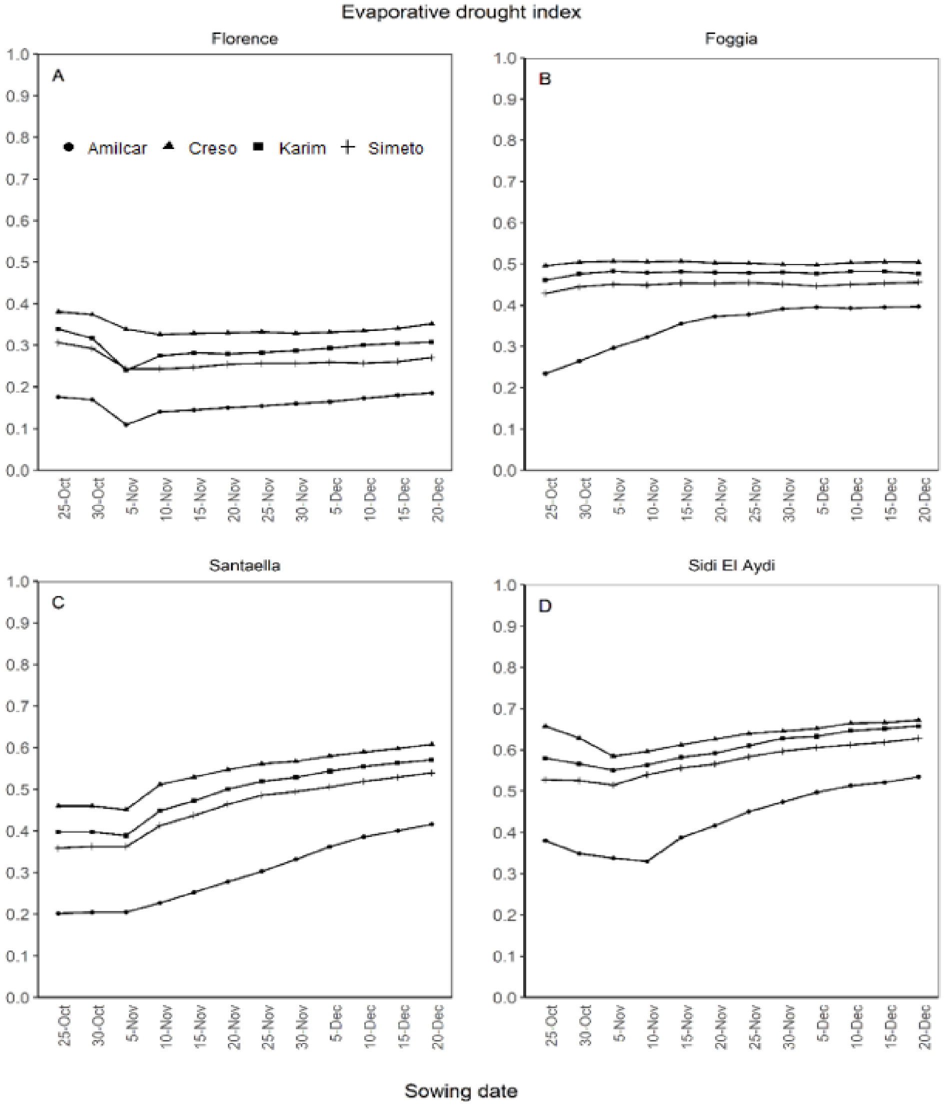

***Fig. 3.5**: Evaporation drought index during grain filling for Creso, Simeto, Amilcar and Karim cultivar in Florence, Foggia, Santaella and Sidi El Aydi.*

The yield component traits are strictly connected to each other and yield performance is a result of the compensative effect between the yield traits. For example, grain size can compensate for low grain number (Sharma et al., 2008; Gambin and Borras, 2010). Our results corroborated previous findings showing that the principle traits were able to compensate for the lower performing traits. For example, grain number and LAI compensated for the low grain weight for Karim compared with the other cultivars. For these varieties under study, the positive correlation between grain yield and principle contributory traits could be important aspects to take into consideration in order to maximize yield. Thus, appropriate management practices that maximize these principle contributory yield traits should be implemented. For instance, a useful agricultural practice for maximizing LAI could be adequate fertilization treatments in terms of quantity and timing.

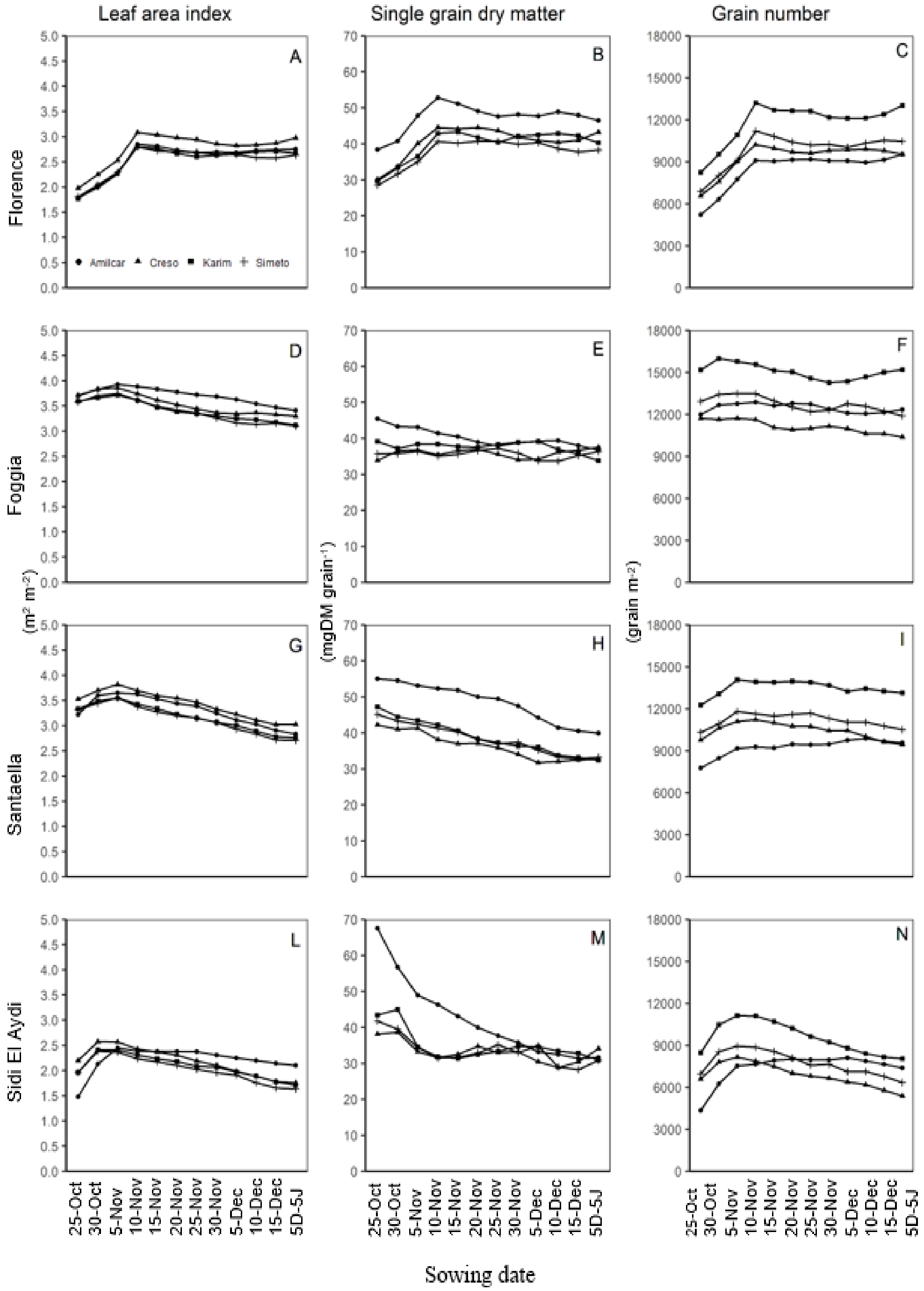

Fig. 3.4. . *Average simulated, leaf area index (LAI at anthesis), single grain dry matter (mgDM grain^{-1}) and the grain number at maturity (grain m^{-2}) in Florence, Foggia, Santaella and Sidi El Aydi for Creso, Simeto, Amilcar and Karim genotypes.*

When considering GxE interaction, it is important that the environmental conditions permit the expression of the principle traits which contribute to yield. Choosing the correct sowing window is a fine balance between different aspects, which include, for instance grain quantity and quality. At more advanced and more late sowing window, an increase in grain protein concentration was observed compared to the protein grain concentration at OSW (Fig. 3.6). This was due to the dilution effect, which implied the negative correlation between yield and grain protein concentration: a yield increase was associated to a grain protein reduction.

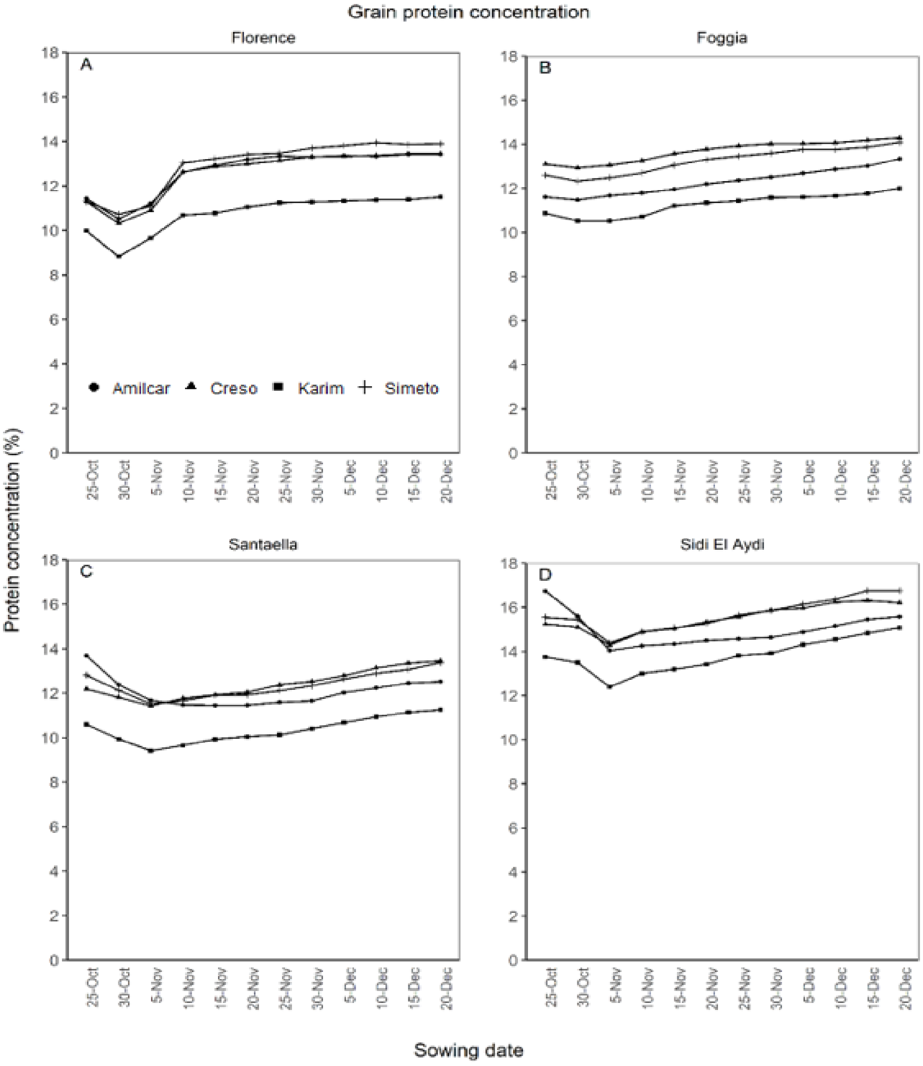

Fig. 3.6: *Grain protein concentration (%) in Florence, Foggia, Santaella and Sidi El Aydi for Creso, Simeto, Amilcar and Karim genotypes.*

Our results suggest that an earlier sowing window compared to TSW can be implemented to optimize durum wheat yield in the Mediterranean basin. The results shown that at the OSW not only increased yield but also reduced the inter annual yield variability which is a key concern in rainfed areas such as the Mediterranean basin (Khatoon et al., 2016). However, an important aspect requiring consideration is the practicality of forwarding the sowing date in Mediterranean environments (Nouri et al., 2017). In these environments, the major constraint for earlier sowing is insufficient soil moisture content before sowing, which is related to the inadequate cumulated rainfall during the summer and early autumn periods. A low water soil content has different implications to management, such as the difficult workability of the soil to prepare the field for sowing, as well as the difficulty in optimizing the nitrogen fertilization (Moeller et al., 2009). Anyway, the analysis of the evaporative drought index for the grain filling showed that the OSW water stress was not an issue for all locations. Moreover, in Florence, Santaella and Sidi El Aydi the major water stress reduction was observed at OSW compared to the other sowing windows. Instead in Foggia, among the sowing windows, water stress seemed to not be a limiting factor.

Considering the positive effect on durum wheat yield, an earlier sowing date is suggested in the Mediterranean basin when the weather and the soil conditions are permitting it. Specific studies investigating the soil water content could be useful to understand the possibility to adopt earlier sowing date in the Mediterranean basin.

3.5. Conclusions

SiriusQuality was calibrated, tested and applied to four different environments in the Mediterranean basin using four durum wheat cultivars. The results showed that it can be considered an adequate tool to simulate durum wheat growth and development. The application of the model suggested that the sowing windows, traditionally used in Florence, Foggia, Santaella and Sidi El Aydi, did not result in optimum grain yields. In particular, the sowing window could be moved forward in all locations with positive effects on yield in Foggia, Santaella and Sidi El Aydi. Moreover, the improved yield response of the optimal sowing window was shown to be related to different factors, including earlier anthesis date, longer grain filling, and higher values for grain number per m^2, single grain weight and LAI at anthesis, water stress reduction during grain filling when compared with results obtained with the traditional sowing window. The optimum sowing window affected in a positive way the grain quantity but not the grain quality. In fact, a reduction of the grain protein concentration is observed at the found optimum sowing window. This means that the adopted TSW in Florence, Foggia, Santaella and Sidi El Aydi represents a good compromise between grain yield quantity and quality.

In conclusion, an earlier sowing window is suggested to optimize durum wheat yield and to reduce the yield inter-annual variability in the Mediterranean basin. Considering that yield was determined by different traits, the results of the present study can be useful in breeding programs designed to select cultivars with high yield potential. Moreover, this study is also useful towards identifying the best management practices for the expression of the traits that maximize grain yield.

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Supplementary information

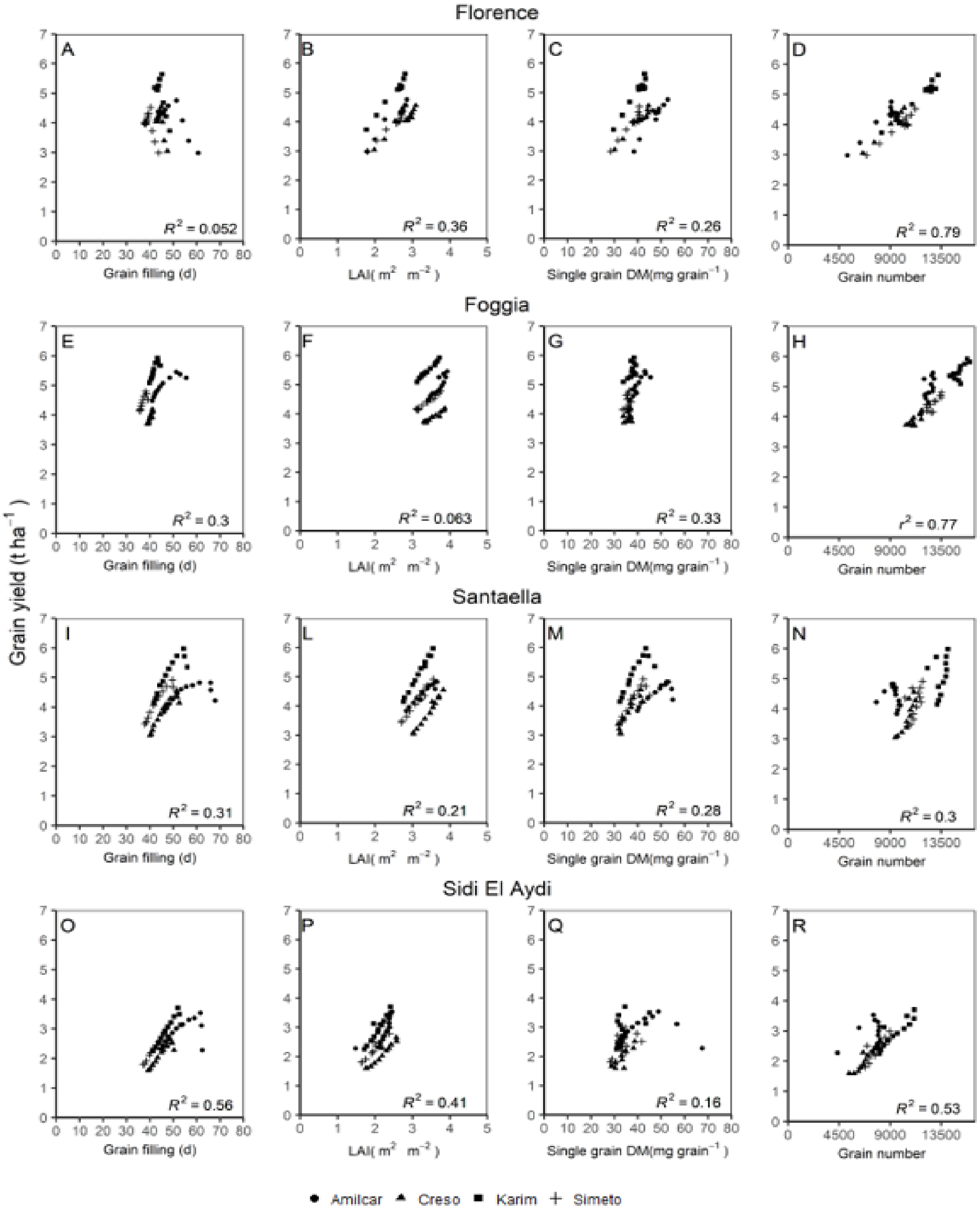

Fig. S3.1. *Relationship between grain yield, maximum leaf area index (LAI), grain number, single grain dry mass, and grain filling duration for Creso, Simeto, Amilcar and Karim in Florence, Foggia, Santaella and Sidi El Aydi.*

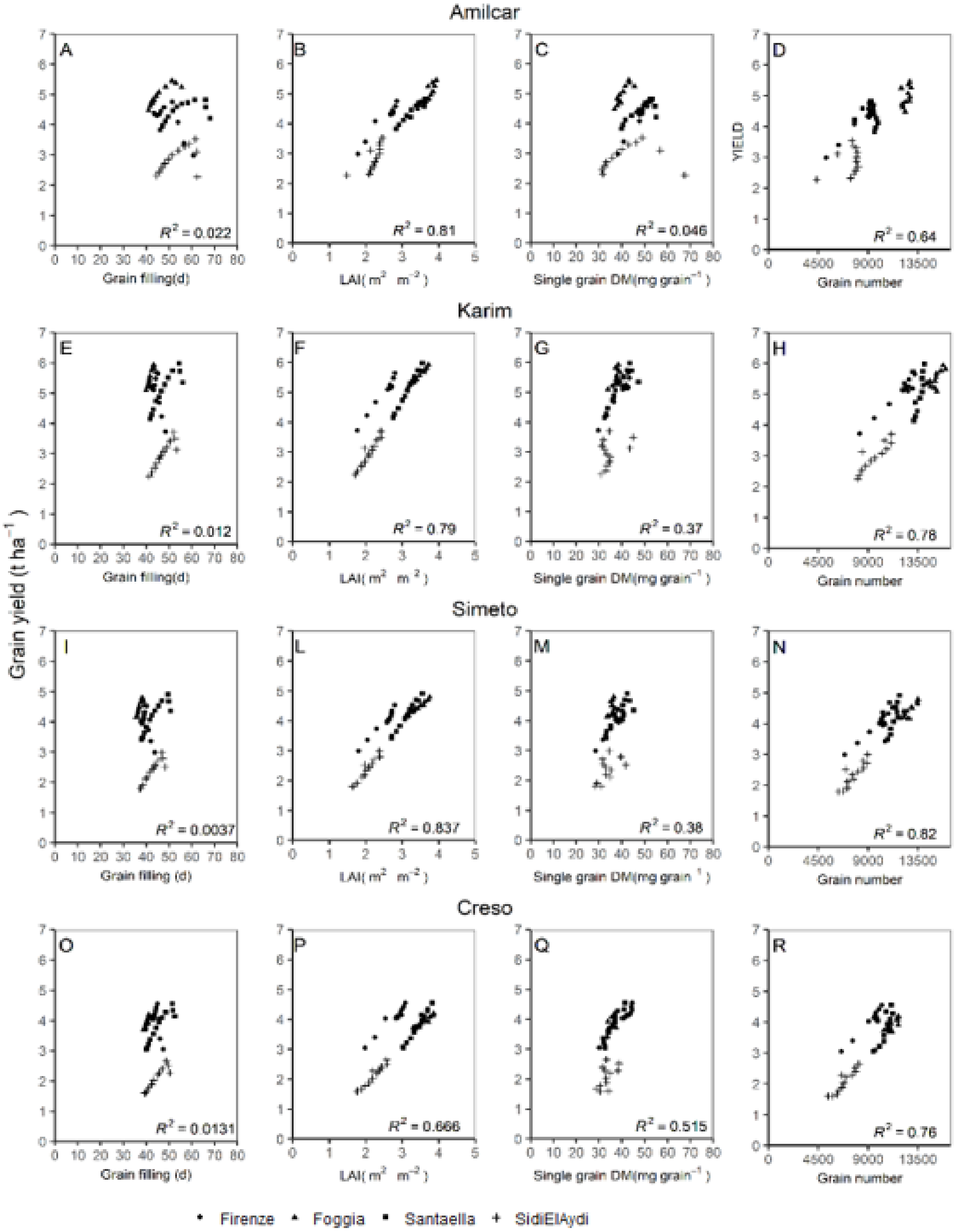

Fig. S3.2. *Relationship between grain yield, grain filling duration, maximum leaf area index (LAI), single grain dry mass and grain number for Amilcar, Karim, Simeto and Creso in Florence, Foggia, Santaella and Sidi El Aydi.*

Table S3.1

Soil properties for the field experiments used for calibration and validation of the wheat model *SiriusQuality*

Site	**Year**	**Depth (cm)**	**Sand (%vol)**	**Clay (%vol)**	**Silt (%vol)**	**Bulk density (g cm^{-3})**	**Saturation (%vol)**	**Wilting point (m^3 m^{-3})**	**Field capacity (m^3 m^{-3})**
Florence	2002-03	0-150	53.1	7.0	39.9	1.59	50.00	0.15	0.40
	2004-05	0-120	33.2	36.1	30.7	1.30	51.00	0.17	0.40
Foggia	1997-00	0-20	12.8	48.5	38.7	1.04	55.10	0.24	0.55
	2007-13	20-40	12.8	48.5	38.7	1.17	54.90	0.24	0.55
		40-60	11.1	54.4	34.5	1.27	56.20	0.24	0.56
		60-80	8.5	54.4	37.1	1.30	56.20	0.20	0.56
		80-130	8.5	54.4	37.1	1.30	56.20	0.20	0.56
Carmona	2011-15	0-25	17.67	57.31	25.02	1.27	52.10	0.33	0.45
		25-50	9.92	64.70	25.38	1.21	54.50	0.34	0.46
		50-75	15.10	57.85	27.05	1.25	53.00	0.33	0.46
		75-100	9.93	67.31	22.76	1.20	54.60	0.35	0.47
Santaella	2010-12	0-25	23.63	53.81	22.56	1.32	50.30	0.31	0.44
		25-50	20.34	52.12	27.53	1.31	50.70	0.30	0.43
		50-75	20.25	56.06	23.69	1.29	51.50	0.32	0.45
		75-100	21.01	38.75	40.23	1.41	46.80	0.23	0.38
	2013-14	0-25	18.08	54.22	27.70	1.28	51.60	0.31	0.43
		25-50	17.21	54.89	27.89	1.28	51.80	0.32	0.44
		50-75	19.37	55.92	24.71	1.28	51.60	0.32	0.45
		75-100	19.28	55.65	25.07	1.28	51.70	0.32	0.44
	2014-16	0-25	15.01	64.63	20.36	1.23	53.60	0.35	0.46

		25-50	12.44	69.27	18.29	1.22	54.10	0.35	0.46
		50-75	15.01	68.59	16.40	1.23	53.60	0.35	0.46
		75-100	13.77	67.04	19.18	1.23	53.80	0.25	0.46
Sidi El Aydi	2011-13	0-20	20.5	26.50	53.00	1.14	48.70	0.18	0.30
		20-40	17.50	36.00	46.50	1.29	48.00	0.16	0.32
		40-60	15.00	48.50	36.50	1.39	50.70	0.19	0.33
Marchouch	2011-12	0-20	12.70	50.00	37.30	1.41	51.70	0.17	0.39
		20-40	10.50	51.30	38.20	1.47	52.50	0.18	0.41
		40-60	12.40	52.30	35.1	1.54	52.30	0.17	0.40
Khemis Zemamra	2011-12	0-15	39.00	34.00	26.00	1.46	44.80	0.12	0.44
		15-30	39.00	35.00	26.00	1.46	44.90	0.12	0.44
		30-60	39.00	36.00	25.00	1.45	45.20	0.12	0.45
		60-100	39.00	35.00	26.00	1.46	44.90	0.12	0.44

Chapter 4.

Effects of climate change on durum wheat in the Mediterranean basin

Gloria Padovan, Pierre Martre, Misha A. Semenov, Sergi Costafreda Aumedes, Marco Bindi, Roberto Ferrise, 2018. (in preparation)

Abstract Wheat is particularly sensitive to heat stress during the reproductive stages. The future climate change, which is expected to be characterized by shift in weather patterns and increase in the frequency and magnitude of extreme events, could affect the wheat yield. The aim of this study was to analyze the impact of future climate change in four locations in the Mediterranean basin, Florence, Foggia, Santaella and Sidi El Aydi on durum wheat production, as simulated by the crop model *SiriusQuality*. Moreover, the frequency and the intensity of some climate stressing events around anthesis and during grain filling in the selected locations was investigated. In this study, 18 Global Climate Models were used to reproduce future climate scenarios in four locations, for the medium (2041-2060) and the far (2071-2090) future at RCP4.5 and 8.5. The results suggested that the impact of climate change could have different magnitude depending on the locations. In particular, Florence resulted the less sensitive to climate change with an increase of grain production at all scenarios, whilst Foggia was more sensitive to climate change in the far future than in the medium one. On the other hands, in Santaella and Sidi El Aydi, the major yield reduction was observed. In addition, for all locations, the increase of air CO_2 will have a positive effect contrasting the grain yield reduction caused by the higher temperatures and by the rainfall reduction. The effect of climate change on grain protein concentration was negative related with the yield production in all locations at all scenarios. The frequency and the intensity of heat stress events around anthesis and during grain filling were higher in Santaella and Sidi El Aydi compared to Florence and Foggia. In conclusion, to contrast the future climate change, adaptation strategies focus on escaping heat stress during the sensitive wheat phenological stages and the development of new cultivars tolerant to heat stress are needed.

4.1. Introduction

The Mediterranean basin is identified as a climate hot spot, in fact the climate in this area is especially responsive to climate change, as has been consistently observed in different generations of climate model projections (Giorgi, 2006). Most of the Mediterranean regions are already experiencing increase in temperatures, precipitation reduction, and increase in extreme events such as heat waves, extended drought periods, and forest fires. For the future, the climate projections in the Mediterranean regions suggested rising temperatures and lower rainfall (Asseng et al., 2015; Semenov and Stratonovitch, 2015; Polade et al., 2017) along with more severe aridity (Gao and Giorgi, 2008). Based on the outputs of 18 global circulation models (GCMs) under the representative concentration pathway (RCP) 8.5, Semenov and Stratonovitch (2015) reported for the Mediterranean basin by the end of the century an increase in mean annual temperature up to 4.5 °C (varied from + 3.1 °C to + 6.6 °C) and a decrease in annual precipitation by 15.5 % compared to the baseline (1980-2010). Among the Mediterranean regions, the greatest temperatures were expected rising in inner Spain, Greece, Algeria and Tunisia coastline (Tomaszkiewicz et al., 2016).

The agricultural productions are connected to climate change and climate variability (Zhao et al., 2017). Indeed, a precipitation reduction combined with an increase in the amount of precipitation delivered in relatively rare heavy events, and the increase of extreme warm seasons, may cause greater year-to-year variability in yields (Polade et al., 2017). In particular, the impacts of climate change on crop yield are related to the magnitude of heat stress by increasing plant water demand and shortening the growth period (Tubiello et al., 2000; Parry et al., 2005; Giannakopoulos et al., 2009).

In the Mediterranean basin, durum wheat (*Triticum turgidum* L. subsp. durum) is one of the most important crop with a production of 18 million of tons in the growing season 2015-16 (IGC, 2018). It is known that wheat is sensitive to heat stress, especially during the phenological phases strictly related to grain production, such as the anthesis stage and the grain filling period (Alghabary et al., 2014; Vara Prasad and Djananaguiraman, 2014). The impact of heat stress is a function of the magnitude and the rate of temperature increase, but also of the duration of exposure to high temperature (Farooq et al., 2011). Semenov (2009) reported that the major issue for the crop connected with the future global warming might be the increase of the frequency and the intensity of heat stress occurring around anthesis. In literature, several studies analyzed the effect of high temperatures in wheat during flowering and during grain filling (Mitchell et al., 1993; Wheeler et al., 1996; Porter and Gawith, 1999; Farooq et al., 2011). For instance, Porter and Gawith (1999) reported that maximum temperature above 31° C before anthesis induces pollen sterility, reducing the potential final grain number. Furthermore, the exposure to high temperatures more than eight days after anthesis causes a reduction in grain number or an increase number of deformed grains (Stone and Nicolas, 1995). Furthermore, high temperature during grain filling influences grain quality, in particular protein accumulation (Farooq et al., 2011).

Several studies (Ventrella et al.,2012; Semenov, 2008; Moriondo et al., 2016; Tomaszkiewicz et al., 2016; Zhao et al., 2017; Dettori et al., 2017) investigated the effects of climate change in durum wheat production using future climate projections. Future climate projections may have different effects on durum wheat production and development. In general, global wheat production was estimated to reduce about by 1-11% at the end of the century (Dettori et al., 2017; Zhao et al., 2017), but, among the studies, there were spatial differences with yield increasing in some locations (Ventrella et al., 2012; Moriondo et al., 2016; Tomaszkiewicz et al., 2016). Durum wheat yield can have some beneficial from climate change due to the positive interaction effects between the increasing photosynthetic efficiency at higher CO_2 concentration, water accumulated in the soil due to the rainfall during the autumn period and the shortening of the growth cycle due to the rising temperatures that allow the crop escaping stresses in the last part of the cycle (Moriondo et al., 2016). Instead, when the heat stress is severe, because of high temperature associated with reduction in precipitations, the impact of climate change on yield could be negative (Dettori et al., 2017).

Knowledge in crop heat stress response under future climate change are essential to analyze and to better understand what genetic characteristics might be improved by geneticists (Semenov et al., 2014). In this context, crop simulation models are useful tools to investigate crop behavior under future climate. In fact, they are able to reproduce crop growth and development under different environments and management practices. Moreover, they can indicate what genetic trails to improve with the aim to increase the wheat production under future climate change and accelerate the breeder work (Chenu et al., 2017).

In literature, many studies have addressed the impact of future climate on wheat yield, but very few of them focused on stress events during wheat growth and development (Semenov, 2015). In this study, the crop simulation model *SiriusQuality* was used to investigate the impact of climate change on durum wheat in four locations in the Mediterranean basin, namely Florence, Foggia, Santaella, Sidi El Aydi. Furthermore, to understand the impact of future climate change on durum wheat, a relation between the simulated yield and the frequency and the intensity of three climate stress events occurred around anthesis and during the grain filling period were investigated.

4.2. Materials and Methods

4.2.1. Study area and data collection

This study was carried out at four different areas in the Mediterranean region: in the Central and in the South of Italy, in the South of Spain and in the North of Morocco. In Central Italy, the experimental site was in Florence (Lat. 43.76 N, Long. 11.21 E) in which the growing season, from sowing to harvest, is from November to the end of June. The average yearly rainfall is 750 mm, 450 of these concentrating during the growing season. The minimum temperatures, below zero, are generally observed in December and January, whilst the maximum temperatures, higher than 30 °C are measured in August. Foggia (Lat. 41.26 N, Long. 15.30 E) was the experimental site in the South of Italy and it is characterized by a dry growing season (from November to the beginning of July) with a precipitation amount less than 300 mm, considering an average yearly precipitation of 500 mm. About temperatures, usually the minimum, around 0°C, are observed in January, instead the maximum, with temperatures higher than 30°C, are usually occurred in July and August. In Spain the experimental sites were in Santaella (Lat. 37.51 N, Long. 4.88 W) where the average yearly amount of precipitation is 480 mm, 350 of these are concentrated during the growing season (from December to the end of June). The minimum temperatures are usually measured just below 0°C, between January and February, and the maximum temperatures, around 35°C, are measured in July and in August. In Morocco the experimental sites were in Sidi El Aydi (Lat. 33.16

N, Long. 7.40 W) where the growing season is from November to the beginning of July. The growing season is usually dry, with a precipitation amount less than 300 mm season $^{-1}$, considering an annual average of 350 mm. The minimum temperatures, around 2°C, are observed between December and January; instead, the maximum temperatures, with peaks of above 35°C, are observed in August.

4.2.2. *Sirius Quality*

For this study *SiriusQuality* version 2.0.2 (http://www1.clermont.inra.fr/siriusquality/) is used to predict the impact of climate change for durum wheat in the Mediterranean basin. *SiriusQuality* has been used in several study for simulating wheat development and growth under different environmental and climate conditions (e.g. Maiorano et al., 2017; Webber et al., 2017; Webber et al., 2018). It is able to reproduce the plant growth and development, the nitrogen and water uptake from the soil, the nitrogen and water stress. The biomass is simulated considering the photosynthetically active radiation interception and the grain yield is calculated by partitioning coefficients from the anthesis date. The plant growth is limited by water and nitrogen availability because they influence the leaf area index (LAI). The heat stress is simulated after the emergence until the physiological maturity considering specific thresholds. *SiriusQuality* needs the weather file with the maximum and minimum daily temperature, rainfall and solar radiation; the soil profile properties; the management file with information about sowing date and plant density, fertilization and irrigation treatments; and the varietal parameters which represent the durum wheat cultivars.

SiriusQuality calibration and validation are made considering different dataset of observed data (Table 4.1). Observed data about Creso, medium-late variety, Simeto, medium-early variety, Amilcar, early variety, and Karim, medium semi-dwarf variety were collected from experimental fields carried out in Florence, Foggia, Santaella, Carmona, Khemiz Zemambra, Marchouch and Sidi El Aydi. All these durum wheat varieties are well adapted to Mediterranean environments and they are grown under rainfed conditions. The observed data concerned phenological data, such as emergence, heading, anthesis, physiological maturity, harvest dates; and productive data, such as yield and biomass. In addition, data about management practices, for example sowing date, fertilization and irrigation treatments were collected. For each location, observed weather data, such as daily minimum and maximum temperatures, rainfall and solar radiation, came from automatic weather stations placed near the experimental fields. Soil properties were available for all sites except Morocco, for which they were extracted from the SOIL GRIDS DATABASE (soilgrids.org).

Table 4.1 Experimental data used to calibrate and validate the model

Location	**Coordinates**	**Cultivar**	**Growing season**	**Growing conditions**
Florence	43.76°N 11.21° E	Creso	2002-03; 2004-05	Rainfed
Foggia	41.26°N 15.30°E	Simeto	From 1996 to 1999 and 2001-2013	Rainfed
Carmona	37.38°N 5.58°E	Amilcar	From 2011 to 2016	Rainfed and irrigated
Santaella	37.51°N 4.88°E	Amilcar	From 2011 to 2015	Rainfed and irrigated
Sidi El Aydi	33.16°N 7.40°W	Karim	2011-12; 2012-13	Rainfed and irrigated
Khemiz Zamambra	32.63°N 8.70°W	Karim	2011-12	Rainfed and irrigated
Marchouch	33.98°N 6.49°W	Karim	2011-12; 2012-13	Rainfed

The calibrated varietal parameters about Creso, Simeto, Amilcar and Karim varieties are reported in Table SI1. *SiriusQuality* provided a well performance for both calibration and validation, with a Pearson coefficient (r) and a coefficient of agreement (d) closed to 1. For phenology the Mean Absolute Error (MAE) was less than 8 days, whilst for the yield the normalized Root Mean Square Error (nRMSE) was less than 10% (Table S4.2). More details about *SiriusQuality* calibration and validation were reported in Padovan et al. (submitted).

4.2.3. Climate projections

The baseline and the future weather data were produced for each location using the weather generator LARS-WG (Semenov and Barrow 1997; Semenov and Stratonovich, 2010). First, observed weather data from each location were used to train LARS-WG, so as to identify the climate characteristics at each location. Then, the generator was applied to generate daily weather time series for the baseline (1981-2010) and two future time slices, namely medium future (MF, 2041-2060) and far future (FF, 2071-2090) according to the Representative Concentration Pathways (RCP)4.5 and RCP 8.5. Since the individual years generated for a specific time slice and location with a weather generator should be thought of as weather data samples for that time slice at that location, 100 years were generated to have a representative sampling. Future time series were created by forcing the weather generator using data from a subset of 18 Global Circulation Models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (Semenov and Stratonovitch, 2015) (Table 4.2) The selection of the 18 GCMs was made considering climate sensitivity indices (CSI) for each GCMs incorporated in LARS-WG for 21 regions as reported in Giorgi and Francisco (2000). CSI is the spatial average of differences between mean values, of temperatures and precipitations, for the future and the baseline. More details about the GCMs are reported in Semenov and Stratonovitch (2015).

Table 4.2 Global climate models (GCMs) from the CMIP5 ensemble incorporated in the LARS-WG using for this study

Research centre	**GCM**	**Grid resolution**	**Reference**
Centre of Australian Weather and Climate Research	ACCESS1-3	1.25° x 1.88°	Collier and Uhe (2012)
Beijing Climate Centre	BCC-CSM1.1	2.77° x 2.81°	Zhang et al. (2012)
Canadian Centre for Climate Modelling and Analysis	CanESM2	2.77° x 2.81°	Chylek et al. (2011)
Centro Euro-Mediterraneo sui cambiamenti climatici	CMCC-CM	0.74° x 0.75°	Bellucci et al. (2013)
CNRM-GAME & Cerfacs	CNRM-CM5	1.40° x 1.40°	Voldoire et al. (2013)
Australia's Commonwealth Scientific and Industrial	CSIRO-MK36	1.85° x 1.88°	Collier et al. (2011)
EC-Earth consortium	EC-EARTH	1.125° x 1.125°	Hazeleger et al. (2012)
Goddard Institute for Space Studies	GISS-E2-R-CC	2.00° x 2.50°	Chandler et al. (2013)
UK Meteorological Office	HadGEM2-ES	1.25° x 1.88°	Collins et al. (2011), Jones et al. (2011), Martin et al., (2011)
Institute for Numerical Mathematics	INM-CM4	1.50° x 20°	Yurova and Volodin (2011), Volodin et al. (2013)
Institute Pierre Simon Laplace	IPSL-CM5A-MR	1.27° x 2.50°	Dufresne et al. (2013)
University of Tokyo, National Institute for Environmental Studies, Japan Agency for Marine-Earth Science & Technology	MIROC5	1.39° x 1.41°	Watanabe et al. (2011), Mochizuki et al. (2012), Tatebe et al. (2012)

University of Tokyo, National Institute for Environmental Studies, Japan Agency for Marine-Earth Science & Technology	MIROC-ESM	2.77° x 2.81°	Watanabe et al. (2011)
Max Planck Institute for meteorology	MPI-ESM-MR	1.85° x 1.88°	Brovkin et al. (2013), Schmidt et al. (2013)
Meteorological Research Institute	MRI-CGCM3	1.11° x 1.13°	Tsujino et al. (2011)
National Centre for Atmospheric Research	NCAR-CCSM4	0.94° x 1.25°	Jahn and Holland (2013), Meehl et al. (2013)
National Centre for Atmospheric Research	NCAR-CESM1-CAM5	0.94° x 1.25°	Meehl et al. (2013)
Norwegian Climate Centre	NorESM1-M	1.90° x 2.50°	Bentsen et al. (2013), Iversen et al. (2013)

4.2.4. Climate change impact assessment

SiriusQuality was applied in Florence, Foggia, Santaella and Sidi El Aydi locations under the baseline and the future climate projections to evaluate the impact of climate change on durum wheat. The previously calibrated varietal parameters for Creso, Simeto, Amilcar and Karim varieties were used in the model application (Table S4.1).

The model was run using the 18 GCMs in the four sites considering the CO_2 air concentration of 487 and 531ppm for the medium period and 541 and 758 ppm for the far period under RCP 4.5 and 8.5, respectively. In addition, using the 18 GCMs, a fixed CO_2 concentration of 360 ppm (the baseline CO_2 concentration) was used to understand the role of the fertilizing effect of enhanced CO_2 in the yield production under future climate conditions (Yield_360).

Table 4.3 shows the soil properties and characteristics in order to provide the soil data required by the crop simulation model. The soil data for Foggia and for Santaella came from experimental fields; for Florence came from the Regional soil database of Tuscany; for Sidi El Aydi from SOIL GRIDS DATABASE (soilgrids.org). In Florence the soil is loam, with an extractable water (difference between water at field capacity and water at wilting point) at the top soil of 14 cm cm^{-1}. In Foggia and in Santaella the soil is classified as clay, with an extractable soil water of 18 cm cm^{-1} for Foggia and of 11.7 cm cm^{-1} for Santaella, which had, respectively, the higher and the lower soil water extractable at top soil compared to the other location. The soil in Sidi El Aydi is clay-loam with an extractable soil water of 14 cm m^{-1}.

Table 4.3 Physiological and chemical soil characteristics at Florence, Foggia, Santaella and Sidi El Aydi for the top soil.

Parameters	Florence	Foggia	Santaella	Sidi El Aydi
Sand (%_vol)	34.94	12.80	13.75	19.50
Silt (%_vol)	39.06	38.70	19.33	49.75
Clay (%_vol)	26.00	48.60	66.95	31.25
Bulk density (gcm^{-3})	1.51	1.17	1.23	1.26
Field capacity (m^3m^{-3})	30.00	42.00	46.75	31.00
Wilting point (m^3m^{-3})	16.10	24.00	35.05	17.00
Saturation (%)	42.70	55.00	53.85	48.70

For each location, the traditional agronomic management practices were used. In Florence the durum wheat sowing is usual from the 1stNovember to the 20th December, with 320 seeds m^{-2}. The fertilization treatments are carried out in pre-sowing with 35 kg

N ha^{-1}, at the beginning of stem elongation and at the flag leaf appearance with 60 kg N ha^{-1}. In Foggia the sowing is usually between the 20th November and the 10th December, using 350 seeds m^{-2}. The fertilization treatments are applied in pre-sowing with 36 kg N ha^{-1}, during tillering with 69 kg N ha^{-1} and at the beginning of stem elongation with 39 kg N ha^{-1}. In Santaella the sowing of the durum wheat is commonly from the 15th November to the 20th December with 360 seeds m^{-2}. The fertilization treatments are made in pre-sowing with 35 kg N ha^{-1} and at stem elongation with 80 kg N ha^{-1}. In Sidi El Aydi the sowing date is normally between the 25th October and the 20th December, using 350 seeds m^{-2}. The fertilization treatments are applied in pre-sowing with 30 kg N ha^{-1}, at the beginning of tillering with 35 kg N ha^{-1} and during the leaf flag appearance with 46 kg N ha^{-1}.

4.2.5. Climate stressing event evaluation

In this study, the impact of climate change was investigated considering the occurrence of different climate stresses in the most sensitive phenological phases, around anthesis and during the grain filling (Porter and Gawith, 1999; Farooq et al., 2011). For this, the impact of climate change on yield simulated by the model was analyzed in relation with the frequency and the intensity of three climate stress events. The selected stress events were a result of literature research. The stress events considered were: to have at least one day with maximum temperature above 31°C during 5 days before anthesis (S1) (Wheeler et al., 1996); to have at least one day with maximum temperature higher than 27 °C during 10 days after anthesis (S2) (Mitchell et al., 1993; Stone and Nicolas, 1995); to have at least one day with the maximum temperature exceeding 35 °C during grain filling (S3) (Tahir and Nakata, 2005). Moreover, the effect of stresses was also connected with their duration. For this reason, the intensity of the three event occurrence was considered, too. The frequency was calculated considering the occurrence at least of one day during the 100 synthetic daily weather generated, with temperatures higher than the selected thresholds for the selected period. Whilst, the intensity of events, was calculated, only in the years in which the stress event was happened, as mean of the day number in which the temperature threshold was overcame during the considered period for the 100 daily synthetic daily weather data.

4.2.6. Statistical analysis

A t-test analyze between the yield simulated under future climate change and the baseline and between the yield simulated under future scenarios and the yield simulate under future scenarios with fixed CO_2 was calculated. Moreover, the relationship between the frequency and intensity of stress events and the final yield production and grain protein concentration was investigated.

4.3. Results

4.3.1. Weather projections

All the future projections suggested a general increase in the temperatures and a general reduction of rainfalls respect to the baseline for the Mediterranean basin, with difference rate depending on locations, scenarios and future period and seasons (Fig. 4.1). In particular, for all locations, the RCP8.5 for the far future (2071-2090), showed the highest maximum and minimum temperature raising and the highest rainfall reduction. The temperature was observed to increase especially during summer season (maximum temperatures, Tmax up to +2-3°C in the MF and up to +3-5°C in the FF), but also during spring and autumn seasons (Tmax up to +1-2°C in MF, and Tmax up to +2-3 °C in FF). The highest variation up to + 6°C of Tmax was predicted in Florence for RCP8.5 FF, whilst the high variation up to +5°C of minimum temperature (Tmin) was predicted in Florence and in Foggia for RCP8.5 FF. Instead, in Foggia and in Santaella, Tmax variation was up to +5.5°C and in Sidi El Aydi was +4.5°C. For the Tmin, the variation was up to +4.5°C and +4°C for Santaella and Sidi El Aydi, respectively, for RCP8.5 FF.

In comparison to the baseline, the precipitations were expected to reduce especially during the summer period (June-August) in Florence (-23% in RCP4.5MF, -24% in RCP4.5FF, -23% in RCP8.5MF, -39% in RCP8.5FF) and Foggia (-20% in RCP4.5MF, -25% in RCP4.5FF, -26% in RCP8.5MF, -43% in RCP8.5FF). In Santaella, the major reduction was during the summer period (-46% in RCP4.5MF, -43% in RCP4.5FF, -47% in RCP8.5MF, -59% in RCP8.5 FF) and during the autumn (September-November; -19% in RCP4.5MF, -25% in RCP4.5FF, -22% in RCP8.5MF, -37% in RCP8.5 FF). In Sidi El Aydi the precipitation reduction was more accentuated in spring (March-May; -18% in RCP4.5MF, -17% in RCP4.5FF, -21 in RCP8.5MF, -33% in RCP8.5FF) and in summer (-30% in RCP4.5MF, -31% in RCP4.5FF, -35 in RCP8.5MF, -43% in RCP8.5FF). Except for Santaella, the results suggested an increase in precipitation, in particular periods of the year, for the other location. In Florence an increase in precipitation was expected in winter for the RCP4.5FF, 8.5MF and FF (+2%, +3%, +4%, respectively). In Foggia, a precipitation increase for all scenarios was observed in March (+16% in RCP4.5MF, +22% in RCP4.5FF, +12 in RCP8.5MF, +8% in RCP8.5FF), whilst in Sidi El Aydi it was observed during autumn for RCP4.5MF and FF (+7% and 1%, respectively).

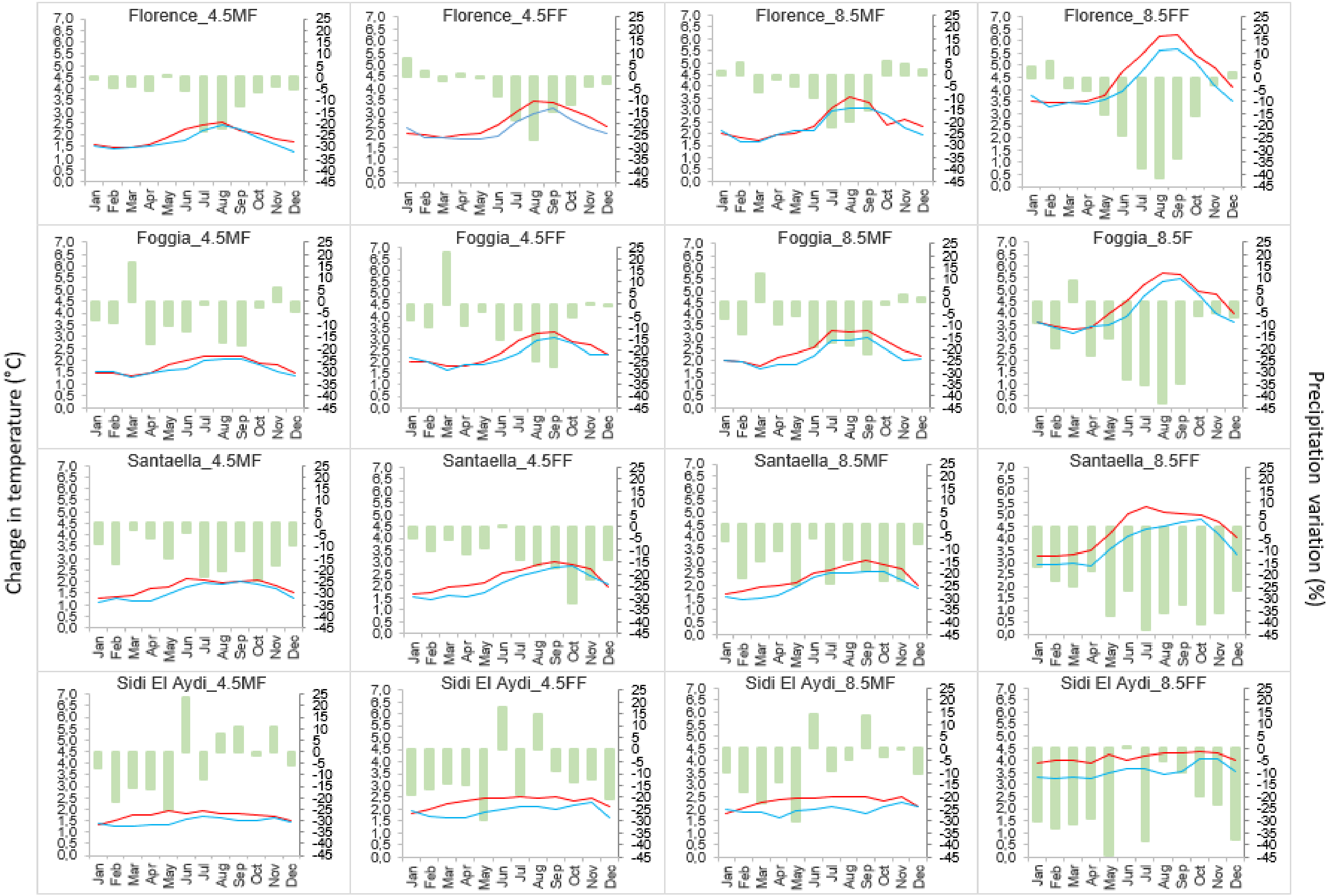

***Fig. 4.1**: Changes in median monthly temperatures (°C, average of 18 GCMs) and rainfall (%, average of 18 GCMs) in the medium and far period (M, 2041-2060; F, 2071-2090) with 4.5 and 8.5 RCP, respect to the baseline (1981-2015) for Florence, Foggia, Santaella and Sidi El Aydi locations*

4.3.2. Impact of climate change on yield and phenology

The results showed that the climate change affected the grain yield with different intensity in the considered locations (Fig. 4.2A, Table 3.4). Furthermore, the frequency and the intensity of climate stressing events were negatively related with the grain yield production (Fig. 4.3, 4.4).

Florence was the less prone location to future climate change with a general yield increased. The maximum yield raising was expected at RCP 4.5 for the far future (+27%) and at RCP 8.5 for the medium future (+27%). In Foggia the results suggested a yield reduction about 8% for the RCP 4.5 in the medium future, a little increase for RCP4.5 in the far period (+3%) and a yield risen of +11% for RCP 8.5 in the far future. An average yield reduction about 9% compared to the baseline was observed in Santaella for all scenarios. Sidi El Aydi resulted to be the most sensitive to climate change with a maximum yield reduction of -27.5 % for the far period at RCP 8.5.

The CO_2 increase had a positive effect on yield quantity. Indeed, Table 4.4 shows that at fixed CO_2 concentration of 360 ppm for all future scenarios, the grain yield was reduced compared with the same simulations made using the appropriate CO_2 concentrations for the scenarios. In particular, the yield decrease was greater in the far period for RCP 8.5, with a loss of -28.60% in Foggia, -26.40% in Santaella and Sidi El Aydi. Instead in Florence, the higher yield variation was observed for RCP8.5 at the medium period (-13%).

Considering the grain protein concentration (Fig.4.2B), the results suggested a reduction of protein concentration in Florence and Foggia for all scenarios compared to the baseline, with major reduction for the far future at RCP 8.5 (-43% and -14%, respectively). Whilst, in Santaella and Sidi El Aydi was observed an increase of the grain protein: in Santaella the highest protein raising of +12%, was observed at RCP 8.5 FF, in Sidi El Aydi at RCP 4.5 FF (+44%). A positive relationship between the frequency and the intensity event S3 was observed at all locations (Fig.4.5, 6).

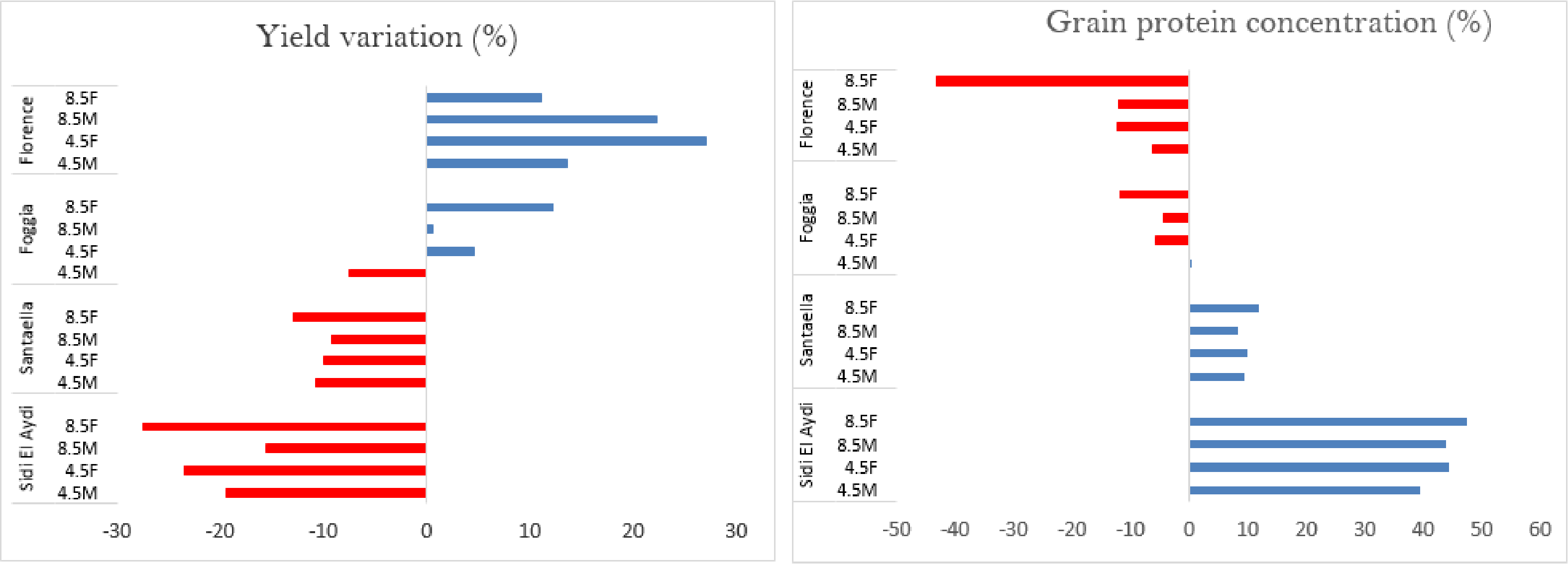

***Fig. 4.2**: Average yield variation (A, %, average of 18 GCMs) and average grain protein concentration (B, % average of 18 GCMs) respect to the baseline yield in the medium and far period (M, 2041-2060; F, 2071-2090) with 4.5 and 8.5 RCP, respect to the baseline (1980-2015) for Florence, Foggia, Santaella and Sidi El Aydi locations.*

Table 4.4 Average yield (Yield, t ha^{-1}, mean of 18 GCMs) for scenarios 4.5M, 4.5F, 8.5M and 8.5F considering the CO_2 concentration of 487, 531, 541, 758 ppm respectively, the average yield considering a fixed CO_2 concentration of 360 ppm (Yield_360) and the average yield variation (%) between them. p-value was calculated between the Yield and the yield simulate at baseline, and between the Yield and the Yield_360.

Site	**Scenario**	**Yield (t ha^{-1})**	**p-value Yield-Baseline**	**Yield_360 (t ha^{-1})**	**p-value Yield-Yield_360**	**Variation (%)Yield-Yield_360**
Florence	4.5MF	4.65	***	4.40	***	-5.60
	4.5FF	5.20	***	4.65	***	-10.50
	8.5MF	5.20	***	4.50	***	-13.50
	8.5FF	4.65	***	4.60	***	-1.10
Foggia	4.5MF	4.05	***	3.50	***	-13.70
	4.5FF	4.54	*	3.80	***	-16.40
	8.5MF	4.40	*	3.60	***	-18.30
	8.5FF	4.90	***	3.50	***	-28.60
Santaella	4.5MF	4.00	*	3.55	***	-11.10
	4.5FF	3.95	***	3.50	***	-13.15
	8.5MF	4.10	*	3.35	***	-16.80
	8.5FF	3.90	**	2.90	***	-26.40
Sidi El Aydi	4.5MF	1.90	***	1.70	**	-9.95
	4.5FF	1.60	***	1.40	***	-13.15
	8.5MF	1.80	***	1.55	***	-12.10
	8.5FF	1.25	***	0.95	***	-26.40

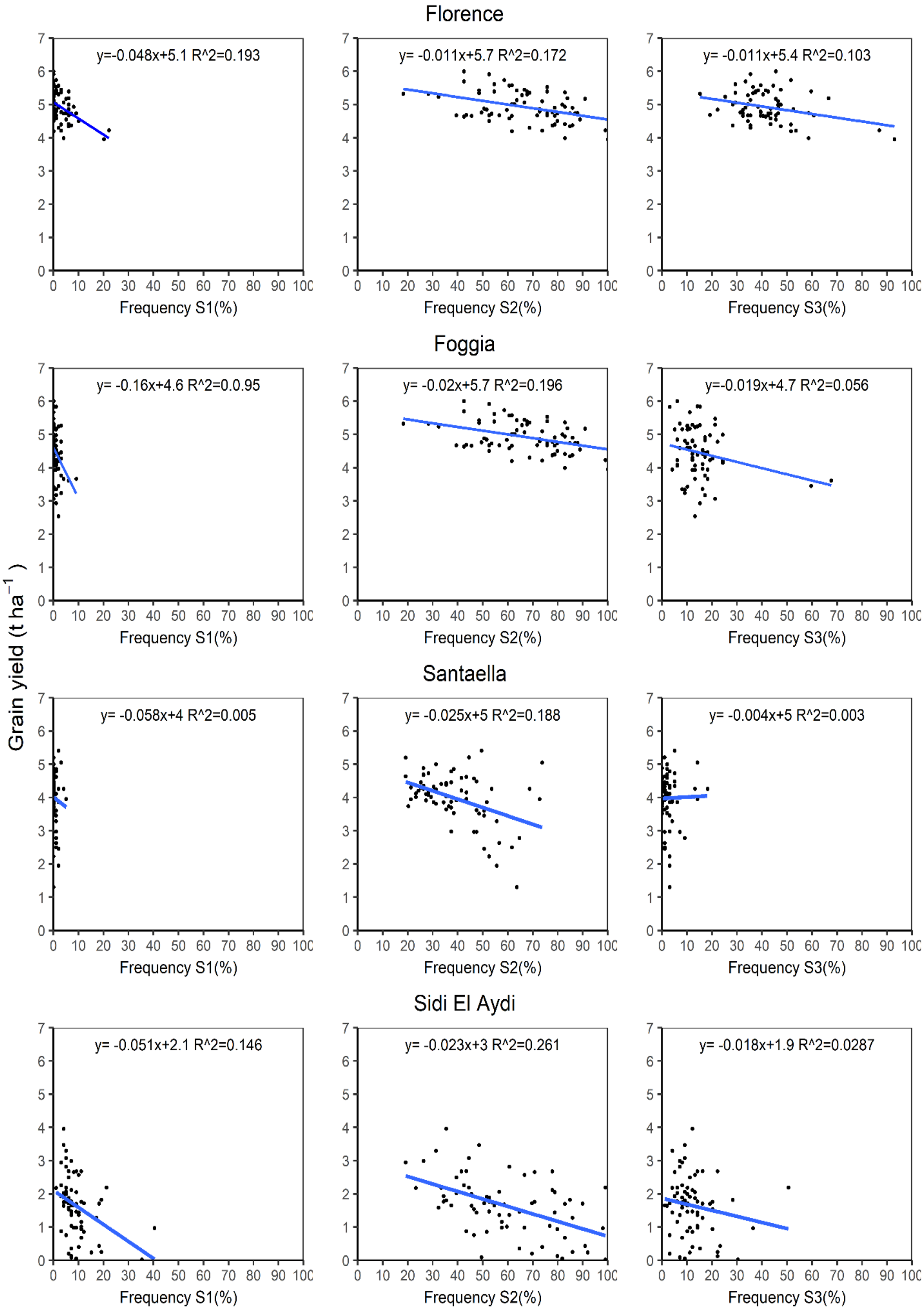

***Fig. 4. 3**: Relationship between average grain yield (t ha^{-1}) and average frequency of climate stressing events (%) S1, S2 and S3 for Florence, Foggia, Santaella and Sidi El Aydi for the future weather conditions.*

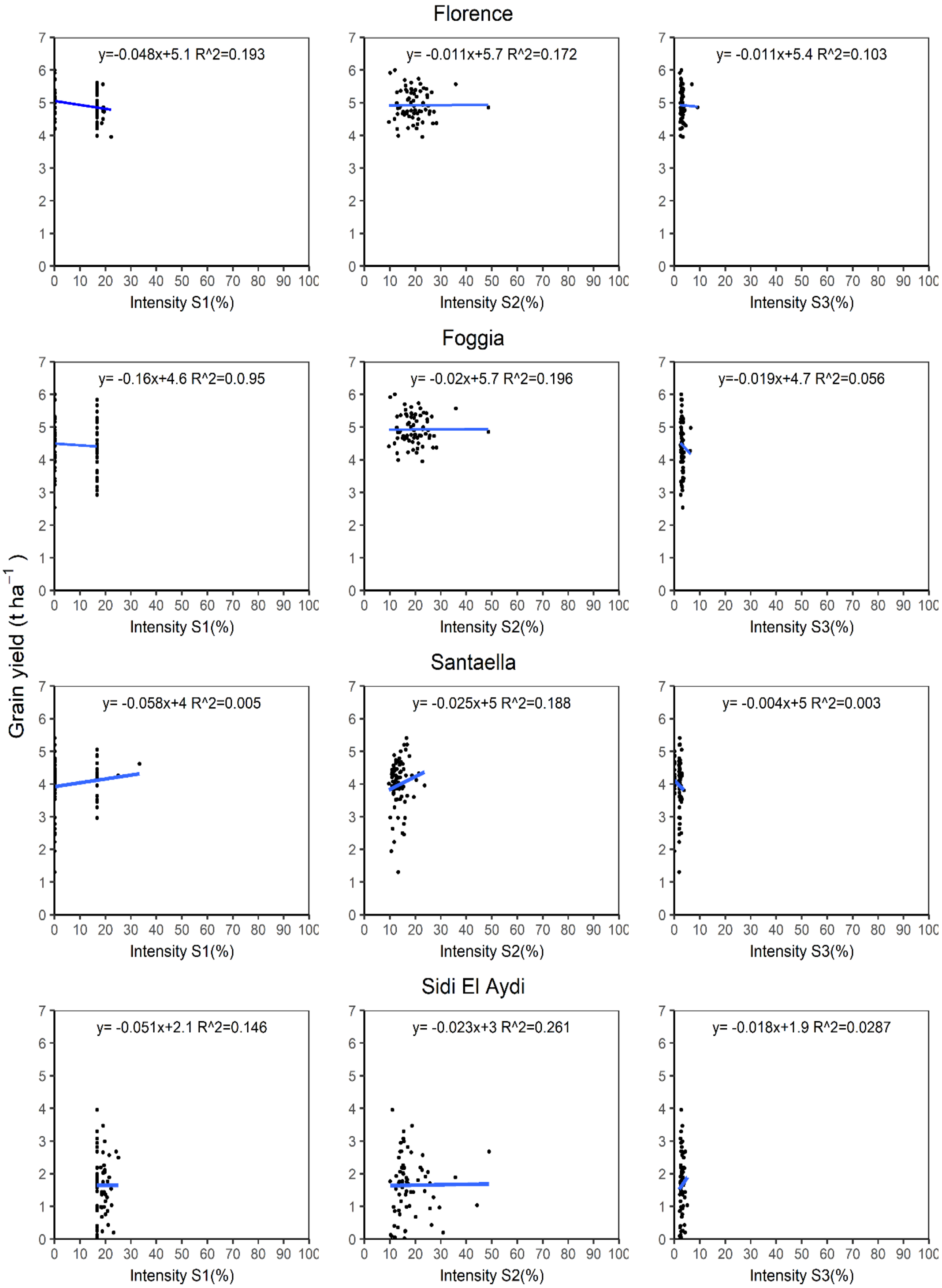

Fig. 4.4: *Relationship between average grain yield (t ha^{-1}) and average intensity climate stressing events (%) S1, S2 and S3 for Florence, Foggia, Santaella and Sidi El Aydi under future climate conditions.*

Under future climate change, an earlier anthesis and a reduction of the wheat cycle was observed at all location (Table 4.5). The anthesis date was anticipated respect to the baseline in a range between 11 at medium future for RCP 4.5 to 30 days at far future for RCP 8.5 in Florence, Foggia and Santaella. Instead, in Sidi El Aydi, the major anticipation was by 11 days for the far future at RCP 8.5. At far future for RCP 8.5, the major cycle reduction compared to the baseline was observed with 28 days in Florence, 25 days in Foggia, 32 days in Santaella and 23 days in Sidi El Aydi. In Florence and in Foggia the grain filling under future climate change was close to the grain filling at baseline (±2 days) for all scenarios. Instead, a major grain filling reduction of 8 days and 12 days was observed at RCP 8.5 at medium future for Santaella and Sidi El Aydi respectively.

Table 4.5 Average anthesis (Ant, day of the year) and physiological maturity (Mat, day of the year) date and grain filling duration (GF, days) in Florence, Foggia, Santaella and Sidi El Aydi for the baseline (1980-2010), the medium (2041-2060) and far period (2071-2090) with 4.5 and 8.5 RCP.

	Florence			**Foggia**			**Santaella**			**Sidi El Aydi**		
	Ant	**Mat**	**GF**	**Ant**	**Mat**	**GF**	**Ant**	**Mat**	**GF**	**Ant**	**Mat**	**GF**
Baseline	130	174	44	136	172	36	85	136	51	88	132	44
4.5MF	119	162	43	127	161	34	75	122	47	87	125	37
4.5FF	114	159	45	123	159	36	71	118	47	85	121	36
8.5MF	111	156	44	123	158	35	71	117	46	83	119	36
8.5FF	99	146	47	111	147	36	61	104	43	77	109	32

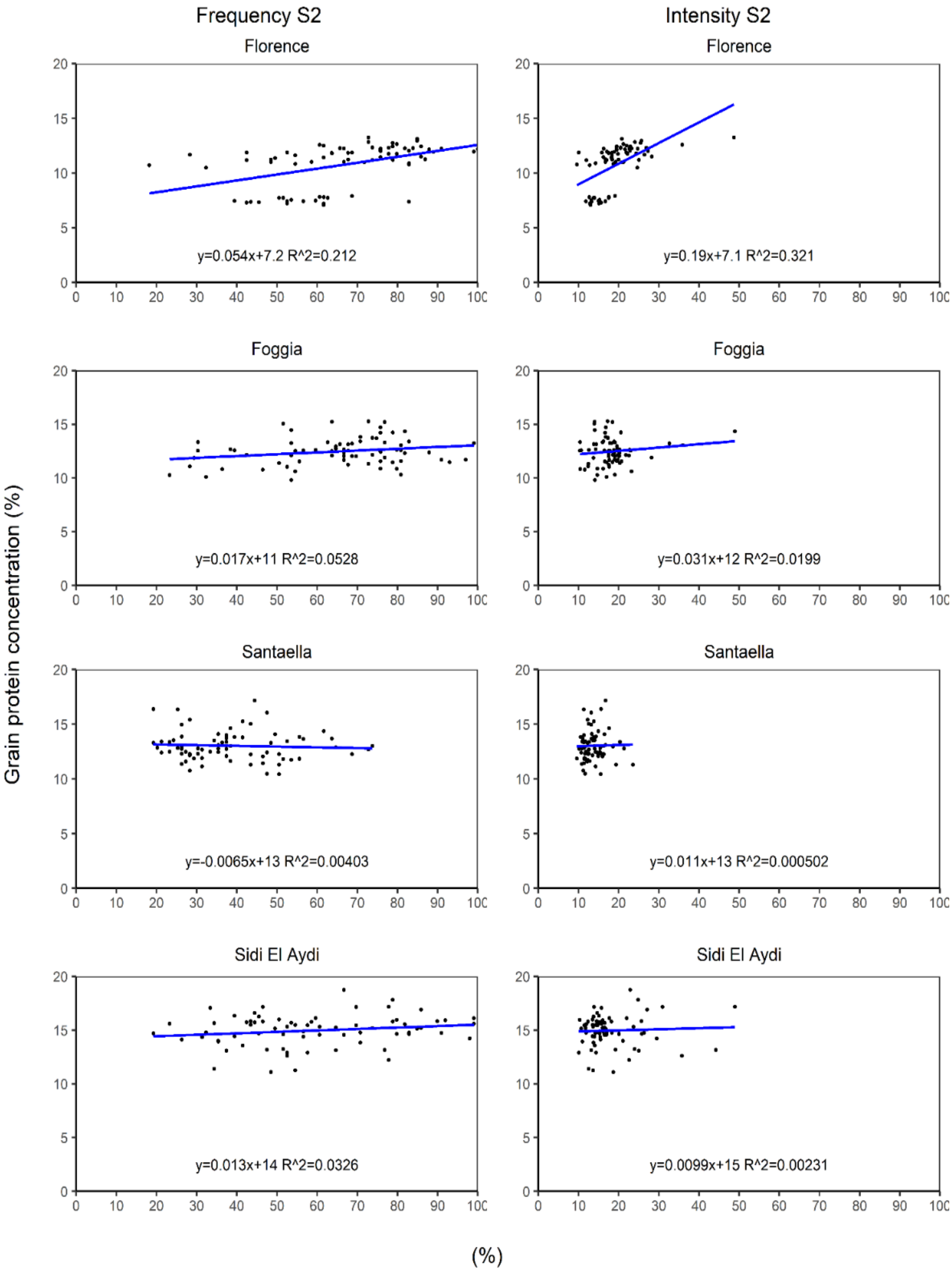

Fig.4.5: *Relationship between the average gain protein concentration (%) and the average frequency of S2 stress event (%) on the right and relationship between the average grain protein concentration (%) and the average intensity event S2 (%) on the left for Florence, Foggia, Santaella and Sidi El Aydi for the future weather conditions.*

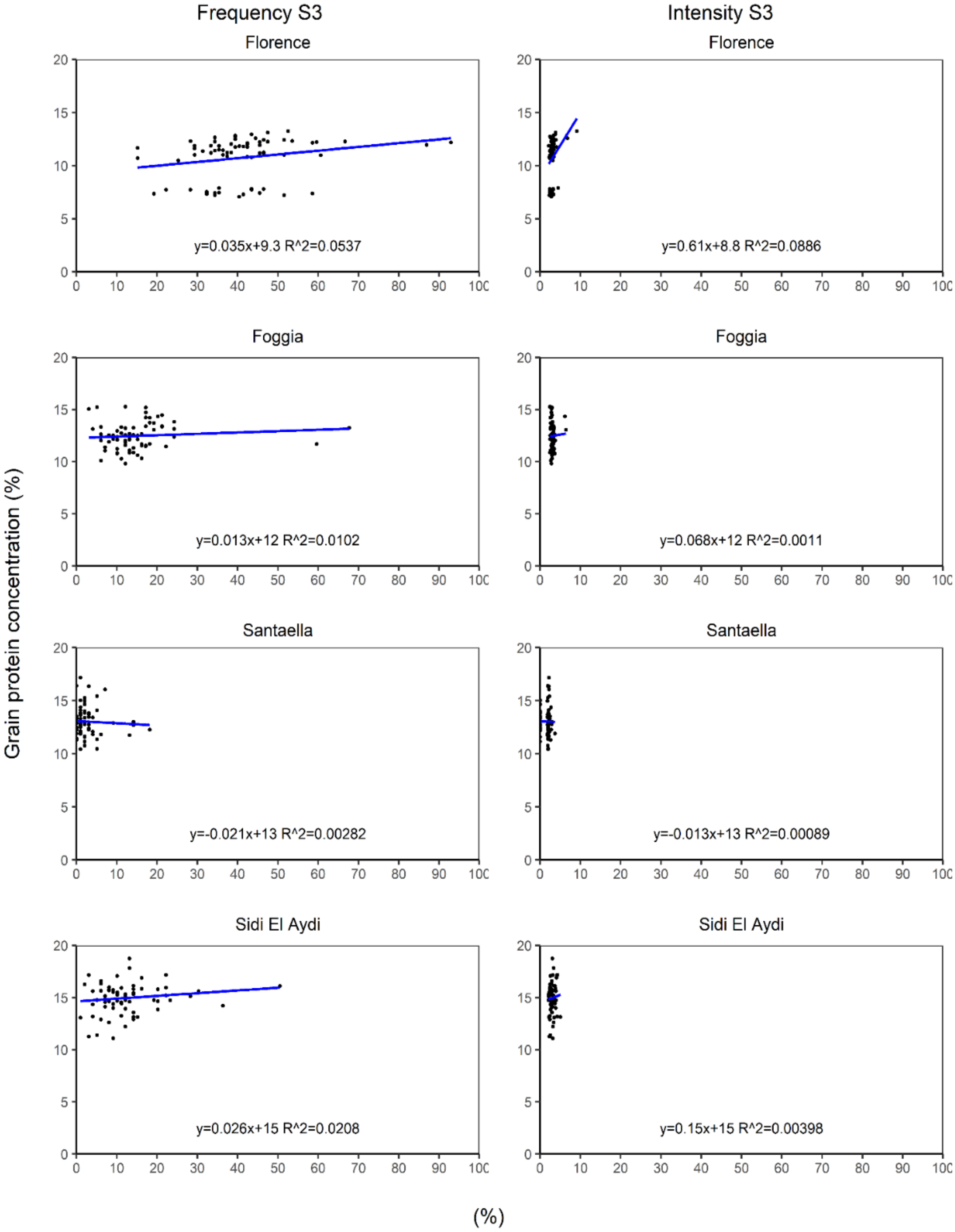

Fig.4.6*: Relationship between the average gain protein concentration (%) and the average frequency of S3 stress event (%) on the right and relationship between the average grain protein concentration (%) and the average intensity event S3 (%) on the left for Florence, Foggia, Santaella and Sidi El Aydi for the future weather conditions.*

4.3.3. Climate stressing event impact

As for the yield, the results about the frequency of climate stressing events and their intensity showed difference among the locations (Fig. 4.7, Table 4.6).

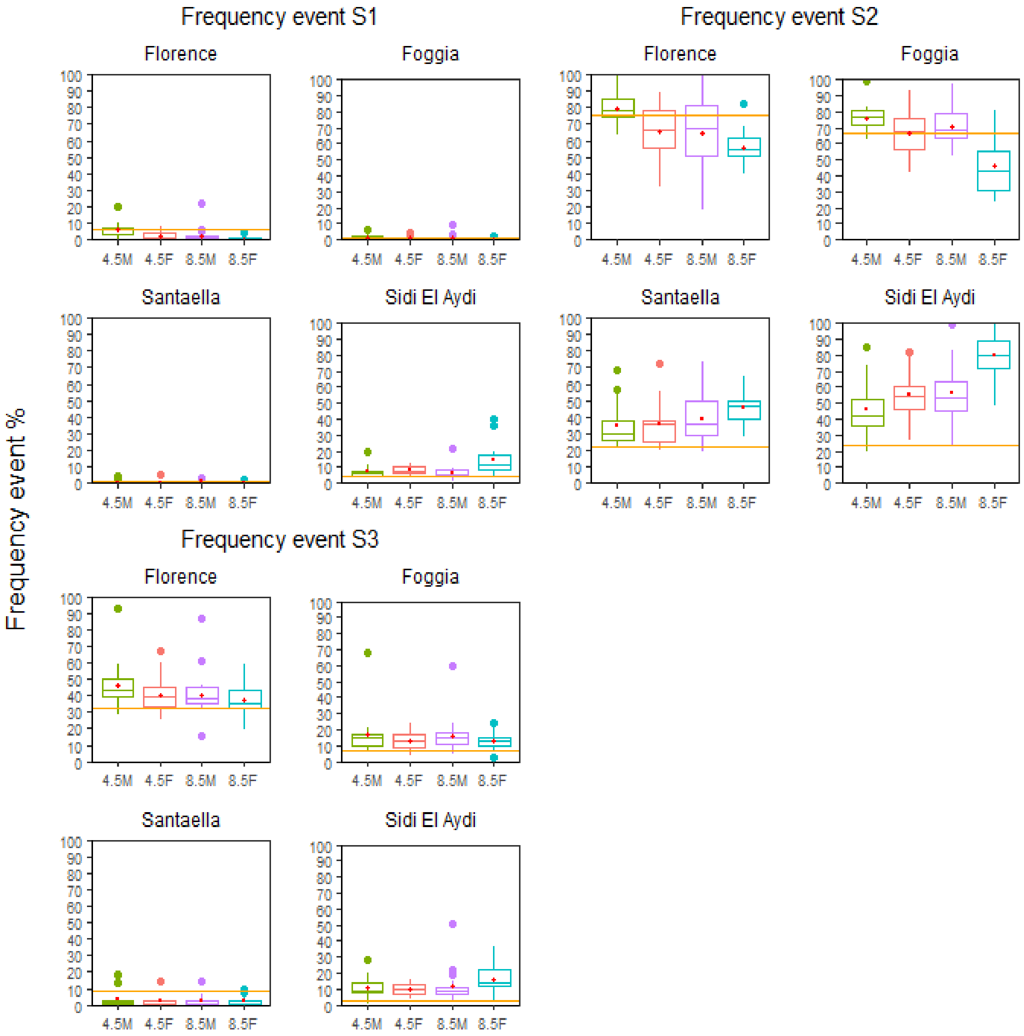

Fig. 4.7: *S1, S2, S3 average climate stressing event frequency (%) in Florence, Foggia, Santaella and Sidi El Aydi in the medium and in the far period (M, 2041-2060; F, 2071-2090) with 4.5 and 8.5 RCP. The orange line represented the average probabilities at baseline period (1980-2010); the red points were the mean of the box plot.*

The S1 event, in Florence, Foggia and Santaella showed a reduction or no difference in the frequency to have at least one day with Tmax up to 31 °C 5 days before anthesis compared to the baseline for all scenarios. Instead, in Sidi El Aydi an increase of the frequency by 97% under RCP 4.5 and by 260% in RCP 8.5 was observed in the FP compared to the baseline. For the intensity of S1 event, a reduction in Florence (about -30% for all scenarios), no variation in Foggia and an increase in Sidi El Aydi was observed in all scenarios compared to the baseline (Table 4.6). In Santaella, the S1 event was not observed during the baseline instead for the future the results shown the occurrence of the event and consequently a higher increase of the intensity event (Fig.4.7, Table 4.6).

Table 4.6: Average variation intensity of S1, S2, S3 events (%, average of 18 GCMs) respect to the baseline intensity events in the medium and far period (MF, 2041-2060; FF, 2071-2090) with 4.5 and 8.5 RCP, respect to the baseline (1980-2010) for Florence, Foggia, Santaella and Sidi El Aydi locations.

Location	Scenarios	S1	S2	S3
Florence	4.5MF	-30.00	+7.50	+13.60
	4.5FF	-33.30	-12.15	-0.75
	8.5MF	-32.50	-18.00	-2.30
	8.5FF	-33.30	-35.30	-9.00
Foggia	4.5MF	0	+17.55	+12.95
	4.5FF	0	-0.20	+5.00
	8.5MF	0	+13.45	+13.45
	8.5FF	0	-20.00	+5.70
Santaella	4.5MFF	+17.75	+16.10	+12.20
	4.5FF	+19.00	+17.70	+2.25
	8.5MF	+15.66	+22.50	+7.00
	8.5FF	+15.66	+33.36	+7.85
Sidi El Aydi	4.5MF	+9.45	+42.40	+42.80
	4.5FF	+9.90	+50.40	+40.40
	8.5MF	+2.40	+63.80	+41.40
	8.5FF	+16.20	+143.90	+72.40

For the S2 event, in Florence was predicted an increase of frequency to have at least one day with Tmax above 27 °C during 10 days after the anthesis for the RCP4.5 in the medium period and a general reduction for the other scenarios respect to the baseline. Furthermore, the intensity of S2 event was in general expected to reduce in Florence for the future. In Foggia, the average results showed an increase of the probability of S2 event during the medium period for both RCP, a no variation respect the baseline for the far period at RCP4.5 and a reduction for RCP8.5. The same dynamic was observed for the event intensity, with an increase of the intensity event of +7.50% in Florence for the medium period for RCP4.5 and a reduction in average of 30% for the other scenarios compared to the baseline. In Foggia, was expected an increase of intensity event S2 for the medium period with +17.55% in PCR4.5 and +13.45% in RCP8.5 compared to the baseline (Table 4.6). In Santaella and in Sidi El Aydi, was expected a general raised of the S2 event frequency respect to the baseline, above all for the far period at RCP8.5, with an average frequency of +106% and +230% respectively. The intensity of event was observed to increase respect to the baseline with a maximum of +33.36% at RCP8.5 for the far period in Santaella and +143.90% at RCP8.5 for the far period in Sidi El Aydi.

In general, the results suggested an increase of the probability of S3 event manifestation in Florence, Foggia and Sidi El Aydi and a reduction in Santaella (Fig.4.7). In Florence and in Foggia, the maximum probabilities were observed during the medium period (+44% and 27% for Florence; +138% and +130% for Foggia respect the baseline, at RCP4.5 and RCP8.5 respectively). In Sidi El Aydi the highest frequency was observed in RCP8.5 for the far period with +16.5% compared to the baseline. Instead, in Santaella, the results suggested a general reduction of the frequency of S3 event respect the baseline. About intensity events, except for Florence in which was observed an increase only for the medium period at RCP4.5, for the other locations a raise intensity event was suggested for the future (Table 4.6). Sidi El Aydi was resulted as the location with the higher increase intensity event with +72.40% for the far period at RCP8.5.

4.4. General discussion

Our results demonstrated that the severity of climate change impact in the Mediterranean basin will be strongly affected by spatial and temporal patterns of climate. In fat, the impact analyze of climate change suggested different weather behaviours in relation with locations and with the future projections. In general, the results suggested a more evident grain yield reduction in Santaella and Sidi El Aydi compared to Foggia and Florence. The results are consistent with Olesen et al. (2011) which have reported a decrease of winter crop production (e.g. winter and spring wheat) in the southern areas in the southern Europe and with Iglesias et al. (2012) who reported a reduction of crop production for the Mediterranean basin, especially for the south of Spain.

The results of this study might be interpreted as a combination of durum wheat growth cycle duration, anthesis date advance and of the future climate change that is projected in the Mediterranean basin. The climate change could have contrasting effects. For instance, stress events, such as high temperatures and rainfall reduction, increase the crop development rate, shortening the growing cycle and decreasing the biomass accumulation. But, the accelerating crop development could lead to more favourable climate conditions for the crop growth. In reverse, the CO_2 concentration enrichment increases the water and radiation use efficiency reducing the impact of climate change (Ferrise et al., 2011; Moriondo et al., 2016).

The results showed a general shortening of the wheat growing cycle (Table 4.5) and they were in agreement with those of Dettori et al. (2017), Semenov (2009), who found a general crop cycle reduction for winter cereals in response to climate change. The reduction of the crop growing season is one of the most accepted evidence of the impacts of climate change and it is also one of the primary causes of projected decreases in yield (Dettori et al., 2017; Parry et al., 2005). An interesting aspect to consider was that the yield increased in Florence and in Foggia was associated with a grain filling duration close to the baseline (± 2 days). Instead, a grain filling reduction from 3 to 7 days for Santaella and from 6 to 12 days for Sidi El Aydi was associated to a reduction of the yield. Yang et al. (2002) and Shah and Paulsen (2003) found a grain filling reduction due to high temperatures of 45-60%. The positive relation between yield and grain filling duration (Fig. 4.8) was an important aspect to consider for improving the durum wheat yield under climate change (Evans and Fischer, 1999; Semenov et al. 2009). Indeed, a longer grain filling will potentially increase the radiation interception amount and, consequently the grain yield. Instead, high temperatures accelerated the leaf senescence, reducing photosynthesis (Harding et al., 1990; Yang et al., 2002; Zhao et al., 2007). In addition, an advance of the anthesis date compare to the baseline was observed (Table 4.7). This fact permitted to escape from more severe heat stress around anthesis that could compromise grain production (Porter and Gawith, 1999). Thus in Santaella and in Sidi El Aydi, the adoption or the selection of varieties characterized by a long grain filling and with the capacity to "stay green" could reduce the negative impact of future climate change. The "stay green" of a crop is the capacity to extend the duration of leaf senescence and maintain green the leaf area longer after anthesis (Silva et al., 2000).

The future projections showed a stronger rainfall reduction in Santaella and in Sidi El Aydi during the durum wheat growing season than in Florence and in Foggia. In these latter sites an increase or low-reduction in rainfall in winter and in early spring (Fig.4.1) suggested a positive effect on yield. Indeed, the water stored in the soil during winter could be available for the crop in the late spring, closed to the anthesis date. This soil water availability could contrast the effects of the high temperature, permitting to have a normal grain filling duration. The rainfall increase observed in Sidi El Aydi (Fig.4.1) did not affected the grain yield because it occurred at the end of the growing season (June) or after the end of growing season (August and September).

The results about precipitations, suggested that the yield increasing in Florence and Foggia was due not only to the positive effect of the CO_2 concentration and the longer grain filling, but also to the increase in precipitations during the autumn and winter seasons. This might be suggested that under limited water stress conditions, durum wheat could be able to overcame the raising temperatures. Whilst, the yield reduction in Santalla and Sidi El Aydy was the consequence of the less precipitation projected and of the incapacity of elevated CO_2 to contrast the simulated high temperatures.

The yield increased or reduction was connected to the frequency and intensity of stress events, too. In particular, the stress event S2 was more related to the yield than the other stress events. In fact, at the reduction of S2 was associated a yield increased. This mean that the stress events occurred 10 days after anthesis had more consequences on yield than the stress events occurred 5 days before anthesis or in the latter during grain filling. Stone and Nicolas (1995) reported that significant reduction in grain number was observed when heat stress occurred 10 days after anthesis, instead no significant relation was observed if heat stress occurred 10-30 days after anthesis. But, it is also important to considered that the wheat response to heat stress in the period around anthesis and during grain filling depends on the variety (Stone and Nicolas, 1995; Hays et al., 2007; Farooq et al., 2011). However, instead of the reduction of probabilities of stress events, the intensity was observed to increase especially after anthesis and during grain filling. The extension of stress events magnified the stress damage in the crop (Farooq et al., 2011). Using or selecting for early durum wheat varieties, able to escape from hot climate conditions, can reduce the frequency and the intensity of stress events around anthesis.

The simulation with a fixed CO_2 concentration of 360 ppm has allowed to understand the mitigation rule of the CO_2 under climate change on the durum wheat production. A lot of studies (Xiao et al., 2005; Ventrella et al., 2012; Moriondo et al., 2016) have attributed the positive effect of climate change on crop yield to the elevated CO_2. Our results have confirmed these hypotheses and they are consistent with Zhao et al. (2015), shown that without an increase of the CO_2 concentration (Table 4.4) a pronounced reduction of yield has been predicted under future climate change.

Porter and Gawith (1999) reported that not only the quantity but also the quality of the grain could be reduced, in particular the protein content, if wheat was exposed to heat stress. The results confirmed the opposite relation between yield quantity and the grain protein concentration. Indeed, in Florence and in Foggia, in which a positive impact of climate change was suggested, a reduction of grain protein concentration was observed. Instead, in Santaella and in Sidi El Aydi, the grain protein was suggested to raise under future climate change. For these last locations, the increased of protein was only a concentrative effect due to the yield quantity reduction. Corbellini et al. (1997) reported that under heat stress, even if this was an increase in grain protein concentration, their functionality was compromised and, consequently, the end-use quality. In addition, the results suggested, consistent with Castro et al., (2006), that grain protein concentration was more related to stress events when they occurred earlier during grain filling than during all grain filling period.

In this modelling study, the acclimation process was not take into account. Wheat has the capacity to acclimate the heat events (Barlow et al., 2015) and this aspect is important to considerate under future climate change conditions, because it could mitigate the effect of high temperatures. Indeed, heat shock events may reduce the impact of high temperatures after the heat shock event (Stone et al., 1995). This thermos-tolerance capacity was correlated with a protein group known as heat shock proteins (Blumenthal et al, 1994).

Strategies to improve wheat heat stress tolerance and to contrast high temperatures are required under future climate change. Among the agronomic practices, the irrigation and fertilization treatments, and the cultivar choice have been suggested by different authors as adaptation options (Olesen et al. 2011; Zhao et al., 2015; Dettori et al., 2017). For instance, Zhao et al. (2015) have reported that considering irrigation treatment, drought stress is avoided with a positive impact of climate change on wheat yield. Another strategy could be the breeding improvement with the selection of ideotypes with physiological, morphological characteristics and traits for the adaptation to grow under water supply and high temperature (Olesen et al., 2011; Semenov et al., 2009). Among the traits that could be modified, a longer grain filling duration, a longer leaf stay-green and the efficiency of water extraction were the most considered (Tao et al., 2017).

4.5. Conclusion

This study shown the impact of climate change on the durum wheat considering 18 climate change projections in the Mediterranean basin using *SiriusQuality*. The magnitude of the impact of climate change on durum wheat production and the frequency and the intensity of stress events will have spatial difference and it is strictly connected with the future weather projections. The results of this study have indicated that the impact of climate change might been interpreted considering the interaction between the weather patterns, the CO_2 concentration and the advanced phenology.

In Florence and in Foggia the impact of future climate could be less negative than in the other locations. In particular, a yield increased was observed in Florence under all scenarios, instead in Foggia yield increase was simulated for the far future. Whilst, in Santaella and in Sidi El Aydi a higher yield reduction was simulated. In addition, in this last two locations, a more pronounced rainfall reduction was observed in the future. The effect of future climate change on grain protein concentration was negative related with the grain production, with an increase in grain protein concentration associate to a reduction of yield and vice versa.

In general, for all these locations, an increase of the frequency of stress events was suggested, with a major increase during the 10 days after anthesis, which could have negative consequences in the final grain quantity and quality. About the stress events intensity, its increase was suggested in all location except in Florence. Moreover, our results have confirmed the important rule of the CO_2 enrichment to contrasting the effects of raising temperatures and rainfall reduction on wheat yield, especially in the far future.

In conclusion, considering the forecasted increase of stress events in the future, adaptive and tolerance strategies, such as irrigation treatments, and genetic improvement are needed to contrast the effects of climate change in the Mediterranean basin.

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Supplementary Information

Table S4.1 Name, definition, unit and value of the varietal parameters of the wheat model *SiriusQuality* calibrated for the durum wheat cultivar Creso, Simeto, Amilcar and Karim

Name	**Definition**	**Unit**	**Value**			
			Creso	**Simeto**	**Amilcar**	**Karim**
Dgf	Potential thermal time from anthesis and end of grain filling	°Cd	650	550	500	600
PlagLL	Phyllochronic duration between end of expansion and the beginning of the senescence period for the mature leaves	cm^2 lamina^{-1}	8	5	8	8
PsenLL	Phyllochronic duration of the senescence period for the mature leaves	Phylllochron	5	3	5	5
RUE	Potential radiation use efficiency under overcast conditions	g MJ^{-1} (PAR)	2.5	2.9	3.1	3.5
Dse	Thermal time from sowing to crop emergence	°Cd	93	111	125	135
Phyll	Phyllochron	°Cd	114	105	90	115
SLDL	Daylength response of leaf production	Leaf h^{-1} (daylength)	1.39	1.40	1.04	1.21

Table S4.2: Evaluation of the wheat model *SiriusQuality* for the calibration and evalution data sets for phenological stages, final total above ground biomass and N, final grain yield, final grain N, and gain protein concentration. *r*, pearson coefficient of correlation; MAE, mean absolute errore; nRMSE, normalized root mean squared error ; *d*, index of agreement.

Location	**Variable**	**Calibration**				**Evaluation**			
		r	**MAE**	**nRMSE**	***d***	***r***	**MAE**	**nRMSE**	***d***
Florence	Anthesis date	0.99	3.00	2.00	0.99	0.99	3.00	2.00	0.99
	Maturity date	0.80	1.75	1.00	0.72	0.80	1.75	1.00	0.72
	Final total above ground biomass	0.93	1.37	2.39	0.60	0.70	1.73	9.99	0.74
	Final gain yield	0.81	1.30	6.00	0.80	0.90	0.47	10.00	0.90
	Final grain N yield	0.22	10.35	4.50	0.40	0.93	11.39	10.00	0.95
Foggia	Anthesis date	0.94	5.2	3.89	0.93	0.84	7.58	5.06	0.87
	Maturity date	0.88	5.9	5.55	0.86	0.85	8.10	6.59	0.85
	Final grain yield	0.93	0.45	4.84	0.93	0.61	0.69	10.00	0.73
Spain	Heading date	0.55	4.25	10.21	0.72	0.94	5.00	7.27	0.97
	Maturity date	0.89	5.75	10.07	0.75	0.90	6.89	9.14	0.75
	Final grain yield	0.99	0.42	18.14	0.98	0.88	0.74	15.03	0.87
Morocco	Anthesis date	0.98	4.60	3.58	0.96	0.66	9.30	9.91	0.77
	Final total above ground biomass	0.97	0.81	23.00	0.98	0.95	0.787	31.50	0.96
Overall	Anthesis date	0.98	6.05	12.50	0.98	0.97	7.30	16.10	0.97
	Maturity date	0.97	5.85	13.42	0.97	0.97	6.46	17.10	0.97
	Final gain yield	0.97	0.89	19.25	0.97	0.81	0.59	20.10	0.89

Chapter 5

Designing durum wheat ideotypes for the Mediterranean basin under future climate conditions

Gloria Padovan, Pierre Martre, Misha A. Semenov, Marco Bindi, Roberto Ferrise, 2018. (in preparation)

Abstract Food security under future climate change is the new challenge that farmers, breeders and agronomist have to overcome in the next years. The increase in the food demand is expected to increase about 70% by 2050. Durum wheat is one of the major crop cultivated in the Mediterranean basin which was described as a climate "hot spot". To ensure enough and stable wheat production under future climate, new varieties with specific physiological characteristics are needed. Crop simulation models can be used to design and test in silico new wheat ideotypes with specific characteristics for target locations and future climate scenarios. In this study, the crop simulation model *SiriusQuality* was used to identify the physiological characteristics of durum wheat ideotypes in Florence, Foggia, Santaella and Sidi El Aydi under future climate conditions, for the medium period (2050s) at RCP 8.5 as projected by GISS-E2-R-CC and HadGEM2-ES. The results suggested that, in the same location and under the same scenario, different sets of varietal parameters due to high yield quantity and stability. Moreover, early, medium and late ideotype varieties belonged at the same ideotype clusters. The results suggested that the improving durum wheat varieties need to have an earlier anthesis date and a longer grain filling compared to the actual varieties. In addition, a reduction in the rate of leaf senescence to maintain a longer crop "stay green" capacity could be an effective adaptive strategy for increasing the grain filling duration. In conclusion, under future climate change, in the selected locations, the durum wheat ideotypes can be described by different sents of varietal parameters.

5.1. Introduction

By 2050 the global food demand is expected to increase connected with the global increase population (IPCC, 2014; Gerland et al., 2014) and with the diet and food consumption changings (Godfray et al., 2010; Tilman et al., 2011; Kastner et al., 2012). The challenge of food security and supply will be more difficult to overcome because of the future climate change and weather increase extremes event expected (Ray et al., 2015). In the last decade, alarming reports about the stagnating crop yield growth rates in various important agricultural country, such as the wheat production in Europe have been made (Tao et al., 2015; Brisson et al., 2010; Lobel et al., 2009). In addition, an increase in frequency of prolonged droughts and heat waves with major negative consequences in the broad regions of the world has already been observed (Christidis et al., 2015; Gourdji et al., 2013; IPCC, 2013). The IPCC (Porter et al., 2014) suggested that future climate change may progressively increase the inter annual variability of the major crop (wheat, rice and maize) yields in Europe, in particular a crop productivity decreases was forecast in the Mediterranean basin (Tomaszkiewicz et al., 2017; Iglesias et al., 2012; Olesen et al., 2011).

The Mediterranean basin is one of the most productive areas for wheat in the world with 21 million of tones (FAOSTAT, 2016). It is among the areas defined as climate "hot spots" (Giorgi, 2006), so it is considered very sensible to future climate change. In fact, the IPCC (2014) has reported a yield variation ranged between -27 to +5 % under future climate projections in the south Europe. In literature it is well known that wheat is particularly sensitive to extreme and hot temperatures during the reproductive stage (Saini et al., 1983; Marcellos and Single, 1984; Porter and Gawith, 1999; Farooq et al., 2012; Alghabari et al., 2014; Vara Prasad and Djanaguiramn, 2014), thus future climate change will be a great challenge for wheat production.

In view of expected population growth, the future climate, the limited possibility to extend crop-growing area because of land availability, the limited water resources, it is unlikely that agriculture can produce enough food without using new wheat varieties, adaptation or tolerant strategies (Olesen et al., 2011; Rotter et al., 2015; Ewert et al., 2015). Among adaptation practices, some authors suggested the changing in the agronomical practices (Olesen et al., 2011) as well as the development of climate resilient crop cultivars (Tao and Zhang, 2010; Challinor et al., 2014; Semenov and Stratonovitch, 2015). Among the agronomic practices, the variation of sowing date, the change in tillage practices to increase soil water conservation, the selection of optimal fertilization practices and the choose of the appropriate cultivar are the most suggested to overcome the future climate change (Olesen et al., 2011, FAO, 2010). The plant breeders are increasing the use of biotechnology and genomic techniques to develop cultivars that have greater yield production and stability in our current production systems (Mir et al., 2012). Furthermore, uncertainties of climate change projections are causing particular challenges in the train selection for future climate conditions (Semenov and Stratonovich, 2015). Moreover, it is onerous in terms of labor, analyses and time to select the appropriate traits (Gouache et al., 2016). In the last few decades, crop simulation models have been important tools for evaluating new cultivars (Marcaida et al., 2014; Gouache et al., 2016) and support plant breeding in the selection of crop traits to improve yield stability and quantity (Li et al., 2012; Rotter et al., 2015). Under future climate change, the lower yield is expected because of the reduction of the growing cycle due to the high temperatures and water scarcity (Olesen and Bindi, 2002; Fisher et al., 2007; Iglesias et al., 2012).

Semenov and Stratonovitch (2015), Martre et al. (2015), Rotter et al. (2015), Tardieu and Tuberosa (2010), Hammer et al. (2006) have suggested that crop simulation models provide a rational framework to design and test *in silico* new wheat ideotypes optimized for target environments and future climate conditions. An ideotype is an ideal plant which is expected to produce high quantity or quality of yield when developed as a cultivar (Donald, 1968). Martre et al. (2015) reported that the concept of ideotype can be extended, not only in breeding process, but also to the research of the best crop phenotype to grow in given environments, with define cropping system and for targeted end uses. In modelling, an ideotype is described as a set of varietal parameters that define growth and development of a crop with given environmental conditions (Fig.5.1, Rotter et al., 2015).

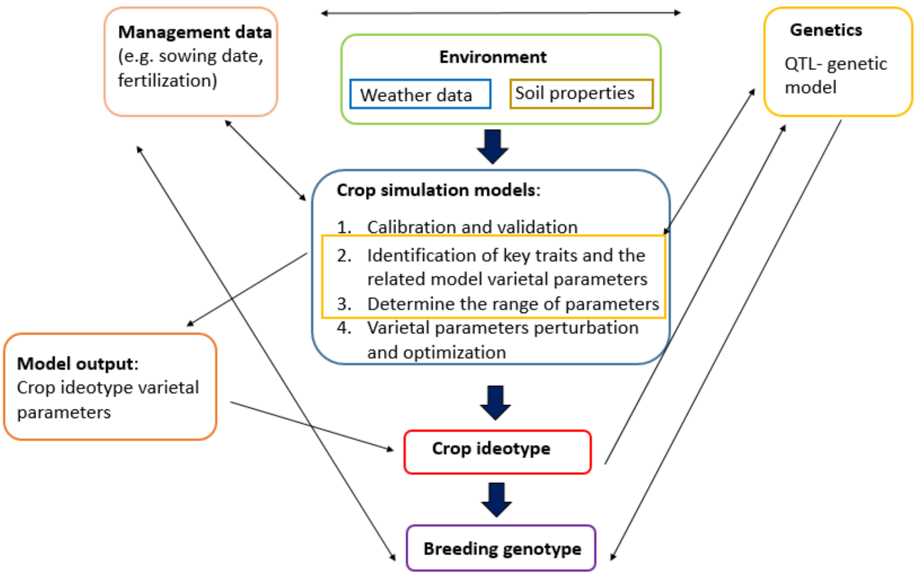

Fig 5.1: *Model-based framework processes for the breeding genotype (modified from Porter et al., 2015)*

In this study, *SiriusQuality* crop simulation model is used to select varietal parameters for describe four durum wheat ideotypes under future climate projections in Florence, Foggia, Santaella and Sidi El Aydi. *SiriusQuality* was used in several studies for reproducing the wheat growth and development under different environmental conditions and to describe a barley ideotype (Martre et al., 2007; He et al., 2012; Tao et al., 2017). Two Global Climate Models (GCMs) with different climate sensitivity, HadGEM2-ES and GISS-E2-R-CC for RCP 8.5 in the medium period (2050) are used. The aim of this study was to describe the durum wheat ideotype characteristics able to reduce the grain yield inter annual variability and ensure high yield production in the selected locations.

5.2. Materials and Methods

5.2.1. Case studies

Four different areas are chosen to represent four different agro-climate conditions in the Mediterranean basin: Florence (43.76° N, 11.21°E), in the Central of Italy; Foggia (41.26°N, 15.30°E), in the South of Italy; Santaella (37.51°N, 4.88°W), in the South of Spain; Sidi El Aydi (33.16°N, 7.40°W), in the North of Morocco. All these sites have been classified to have a Mediterranean climate, with hot and dry summer and mild winter, but they belong to different environmental zone (Metzger et al., 2005). Florence belongs to the Mediterranean North environmental zone, instead Foggia, Santaella and Sidi El Aydi belongs to the Mediterranean South environmental zone. Florence is characterized by an average yearly rainfall of 750 mm, concentrated during spring and autumn. The minimum temperature is generally observed between December and January, with temperature values below 0°C, whilst the maximum temperatures are measured in July and August with values above 30 °C. In Foggia the annual average rainfall is about 500 mm, concentrated in spring and autumn. The minimum temperatures around 0°C are generally observed in January, whereas the maximum temperatures, higher than 33°C, are measured in August. In Santaella and Carmona the average yearly amount of precipitation is 480 mm. About temperatures, the minimum temperatures are usually measured just below 0°C, between January and February, and the maximum temperatures, around 35°C, are measured in July and in August. In the North of Morocco, Sidi El Aydi, is characterized by annual average precipitations of 350 mm, concentrated in winter and spring. The minimum temperatures, around 2°C, are observed between December and January, instead maximum temperatures, with peaks of above 35°C, are observed in from June to August.

5.2.2. Simulation setup

5.2.2.1. *SiriusQuality* calibration and evaluation

For the ideotype study, the crop simulation model *SiriusQuality* version 2.0.2 (http://www1.clermont.inra.fr/siriusquality/) was adopted. *SiriusQuality* needs daily weather data, a soil description, management input to reproduce wheat growth and development. The model simulates the phenology based on the phyllochron and the final leaf number. The biomass accumulation is reproduced considering the photosynthetically active radiation (PAR) and the grain growth is calculated from the biomass using simple partition rules after the anthesis date. The potential crop growth is limited by nitrogen and water availability.

SiriusQuality is calibrated and evaluated using observed data came from experimental field carried out in Florence, Foggia, Santaella, Carmona, Sidi El Aydi, Marchouch and Khemiz Zemambra. Phenological stages were collected in all experiments. For each location, observed data about different *Triticum durum (spp)* cultivars are used: Creso in Florence, Simeto in Foggia, Amilcar in Santaella and Karim in Sidi El Aydi. Creso, a medium-late variety selected in 1973 by ENEA Centre, is characterized by good yield quantity and quality. Simeto is a medium-earlier variety selected in 1988 by ProSeme and it is characterized by an excellent grain quality. Amilcar, selected by Monsanto-CIMMYT, is a short-cycle variety characterized by high potential production and disease resistance. Karim, which come from the CIMMYT wheat program, is a medium semi-dwarf high yielding variety selected in 1985.

SiriusQuality provided a well performance in the reproduction of phenology, yield, biomass and N grain content in Florence, with Pearson coefficient (r) and coefficient of agreement (d) close to 1. More detail about *SiriusQuality* calibration and evaluation are reported in Padovan et al. (submitted).

5.2.2.2. SiriusQuality application

SiriusQuality is applied using the usual management practices for each location, such as the sowing window and the fertilization treatments. In Florence the durum wheat sowing is set from 1stNovember to 1th October, with 320 seeds m^{-2}. The fertilization treatments are carried out in pre-sowing with 35 kg N ha^{-1}, at the beginning of stem elongation and at the flag leaf appearance with 60 kg N ha^{-1}. In Foggia the sowing is set from 20th November to 20th December, using 350 seeds m^{-2}. The fertilization treatments are applied in pre-sowing with 36 kg N ha^{-1}, during tillering with 69 kg N ha^{-1} and at the beginning of stem elongation with 39 kg N ha^{-1}. In Santaella the sowing window is set from 15th November to 15th December with 360 seeds m^{-2}. The fertilization treatments are made in pre-sowing with 35 kg N ha^{-1} and at stem elongation with 80 kg N ha^{-1}. In Sidi El Aydi the sowing window is set from 30th November to 20th December, using 350 seeds m^{-2}. The fertilization treatments are applied in pre-sowing with 30 kg N ha^{-1}, at the beginning of tillering with 35 kg N ha^{-1} and during the leaf flag appearance with 46 kg N ha^{-1}.

The soil data about texture and physical characteristics used for the model application came from field experiments for Foggia and Santaella. Instead for Florence came from the Tuscany Regional dataset and for Sidi El Aydi from SOILGRIDS DATABASE (soilgrids.org).

The future climate scenarios are made by two global circulation models (GCMs), UK Meteorological Office (HadGEM2-ES) (Jones et al.,2011; Collins et al., 2011; Martin et al., 2011) and Goddard Institute for Space Study (GISS-E2-R-CC) (Chandler et al., 2013). The spatial grid resolution is respectively of 2.00° x 2.50° and of 1.25° x 1.88°. The periods 2050s with the emission scenarios of Representative Concentration Pathway (RCP) 8.5 are selected from the Couple Model Inter-comparison Project Phase 5 (CMPI5). The GISS model represents the relative cold scenarios, instead the HadGEM2 model is the relatively hot scenarios. The CO_2 concentration is assumed to be 541 ppm. As described by Semenov et Stratonovitch (2015), the climate projections are down-scaled for the selected sites using LARS-WG weather generator. LARS-WG is previously calibrated using long series of weather data extracted from the Crop Growth Monitoring System (CGMS) of the Joint Research Centre (JRC) archive (http:// mars. jrc. ec.europa.eu). Then, local-scale daily baseline weather data and climate scenarios data for the future period are generated by LARS-WG (Semenov and Stratonovitch, 2015). Finally, 100 sample years of future daily weather data are used for the simulations. The 100 individual years generated by LARS-WG should be considered as samples representing the typical weather for the far future (2071-2090) (Semenov and Stratonovitch, 2015), that in turn, should increase the significance of modelling results.

5.2.3. Varietal parameter selection for the ideotyping process

Six varietal parameters, considered the most promising to improve wheat yield under future climate conditions, are used for the ideotyping process. They can be divided in two groups: the parameters related to phenology and those related to canopy growth. The varietal parameter ranges of variation are presented in Table 5.1.

Table 5.1: Range of variation for the optimization of the varietal parameters for the ideotyping process

Varietal parameters	Description	Range of variation	Calibration value			
			Creso	Simeto	Amilcar	Karim
SLDL	Daylength response to photoperiod (leaf h^{-1})	1.-2 [a]	1.39	1.40	1.04	1.21
P	Phyllochron (°C days)	70-140 [b]	114	105	90	115
Dgf	Grain filing duration (°C)	450-900 [c]	650	550	500	600
AreaPL	Maximum potential surface area of penultimate leaf lamina (cm^2 $lamina^{-1}$)	20-40 [d]	30	30	30	30
MaxDSF	Maximum rate to acceleration of leaf senescence in response to soil water deficit	2.5-5 [e]	4.5	4.5	4.5	4.5
RatioFLPL	Ratio of flag leaf to penultimate leaf lamina surface area	0.6-1.3 [f]	0.9	0.9	0.9	0.9

[a] Giunta et al., 2001; [b] Ishag et al., 1998; [c] Akkaya et al., 2006; [d]Alvaro et al., 2008; [e]Fois et al., 2001; [f] Tao et al., 2017

Phenology

The Phyllocron (P), the thermal time during the grain filling period (Dgf) and the day length response (SLDL) are strictly connected with the phenological durum wheat development. The P is defined as the thermal time required for the appearance of successive leaves and in *SiriusQuality* is the major driver for the phenological development (Jamieson et al., 2007). Changing the P and the SLDL, the appearance of leaves was altered and consequently the final leaf number, the rate of the biomass accumulation and, therefore, the entire crop cycle, in particular the anthesis date. An appropriate anthesis date is essential for the yield maximization (Richards, 1991), in fact, if stress events happen around anthesis, the final production could be compromised. Porter and Gawith (1999) reported that stress events around anthesis cause the abnormal development of ovary and anthers, which affect the floret fertility and, consequently, the final grain number. Moreover, at the beginning of grain filling, high temperatures influence the development of the endosperm which reduces the maximum grain weight (Hawker and Jenner, 1993; Farooq et al., 2011). In *SiriusQuality*, the Dgf duration is calculated considering the thermal time accumulated between the anthesis date and the physiological maturity (Jamieson et al., 1998b). Evans and Fisher (1999) have suggested that the increase of Dgf duration is a possible trait for increase the grain yield in wheat. Indeed, the Dgf increasing allow to increase the amount of radiation intercepted by the crop, and, as a result, by the grain. *SiriusQuality* considered two sources for the biomass accumulation in the grain during Dgf: the new biomass produced from the intercepted radiation and the translocation of 25% of the biomass accumulated at anthesis considering a rate proportional to Dgf.

Biomass production

For the canopy, the parameters which are taken into account were the maximum potential surface area of the penultimate leaf lamina (AreaPL), the maximum rate of leaf senescence in response to soil water deficit (MaxDSF) and the ratio of the penultimate leaf lamina surface area (RatioFLPL). The AreaPL and the RatioFLPL are varietal parameters connected with the quantity of the solar radiation intercepted by the crop. They also affected the plant transpiration demand (Semenov et al., 2014).

The MaxDSF is a parameter related to the “stay green” of a crop. The “stay green” is the crop capacity to extend the duration of leaf senescence and maintain green the leaf area longer after anthesis (Silva et al., 2000; Triboi and Triboi-Blondel, 2002).

5.2.4. Statistical analysis

For the ideotyping process, a specific algorithm to select the best parameter combination for the optimization of the grain yield was used. The used algorithm was the Non Dominated Sorting Genetic Algorithm (NSGA-II) (Deb et al., 2002). The NSGA-II is a multidimensional genetic algorithm and as all the genetic algorithms, it is inspired to the biological evolution and to the Darwinian evolutionary concepts (Holland J.H., 1984).

The algorithm works considering sampling in the search space a sample called population. For this study, every sample is described by a set of varietal parameters selected with the aim to maximize the yield. Among the samples in the population, the samples with the higher fitness for the objective to optimized (respect to the mean of the population) are selected to create a new population. Thus, each population is obtained by creating so called offspring search points from the best individuals in the previous population This process is made for the number of generation selected. The final samples represent the best sets of varietal parameters able to maximize the grain yield.

For each location, among the best samples, 10 hypothetical ideotypes are selected considering the inter-annual coefficient of variation (CV). A CV for the yield minor of 10% is used in Florence, Foggia and Santaella. Instead for Sidi El Aydi, a CV < 20% is used because of the greater yield variation simulated under future climate conditions which have not permitted to have CV <10%. For each location and scenario, between the samples belonging to the 95th percentile, 10 hypothetical ideotypes with the highest yield were selected. Then, they were divided in clusters in relation with their phenotypic responses (anthesis date, grain filling duration and final leaf number) using the cluster method ward.D2 (Suzuki and Shimodaira, 2006; Murtagh and Legendre, 2014).

5.3. Results

5.3.1. Future scenarios

During the medium period (2040-2060) under the GISS and the HadGEM climate change scenarios, an increase in maximum and minimum temperatures (Tmax, Tmin) are projected in all locations, with a major raising for HadGEM compared to the baseline. Instead for the precipitations, an annual cumulated reduction compared to the baseline is observed in Florence, Foggia and Sidi El Aydi, whilst in Santaella an annual rainfall increase is projected, with major intensity for HadGEM compared to the GISS scenario (Fig. 5.2).

In Florence an annual Tmax increase of 1.66 °C and of 3.42°C, and a Tmin increase of 1.55°C and of 2.93°C respectively for GISS and HadGEM compared to the baseline are forecasted. About the precipitations, an annual reduction of 3% and of 4.5% for GISS and HadGEM, respectively, is forecasted in comparison with the baseline. But, considering the single scenarios, there are differences in the monthly distribution of precipitations (Fig. 5.2). For instance, for GISS scenario raising rainfall is observed during winter and spring months, instead for HadGEM the precipitation increased is only in spring. For both scenarios, in August and September the greater rain reduction is observed.

In Foggia an annual Tmax and Tmin increase respect to the baseline respectively of 1.55 and 2.01 °C for GISS scenario and of 3.42 and 2.93 °C for HadGEM scenario are observed. About the rainfall, no variation compared to the baseline was projected for the

GISS scenario, instead a rainfall increase of +5% was forecasted for the HadGEM scenario. For both scenarios, the maximum rain raising is forecasted in March. Instead, for GISS scenario the higher rain reduction was forecasted in April (-30%) and in May (-19%); whilst for HadGEM scenario the major rain reduction is observed in June (-19%) and in August (-18%) (Fig. 5.2).

For Santaella is observed the higher temperature increase respect to the other locations. In particular, an annual Tmax and Tmin raising respectively of 1.70°C and 1.68°C for the GISS scenario and of 3.60°C and 2.5°C for HadGEM scenario compared to the baseline is suggested. In this location is forecasted the major annual precipitation reduction compared to the baseline, about 9% for GISS and about 12% for HadGEM scenarios. For GISS scenario, the results shown a major rainfall reduction, about -20%, in February, May, August, September and October. Whilst, for HadGEM, the major reduction about -35% is forecasted in June, July and December.

For Sidi El Aydi an annual Tmax and Tmin increase compare with the baseline, respectively of 1.83°C and 1.78°C for GISS scenario and of 2.72°C and 2.41°C for HadGEM are forecasted. About the precipitations, an annual reduction of 1.4% for GISS and of 10% for HadGEM is suggested. In April, May, August and September, the results shown the higher rain reduction for GISS scenario (Fig.5.2). Instead, for HadGEM scenario, the major rainfall reduction is forecasted in March and in May.

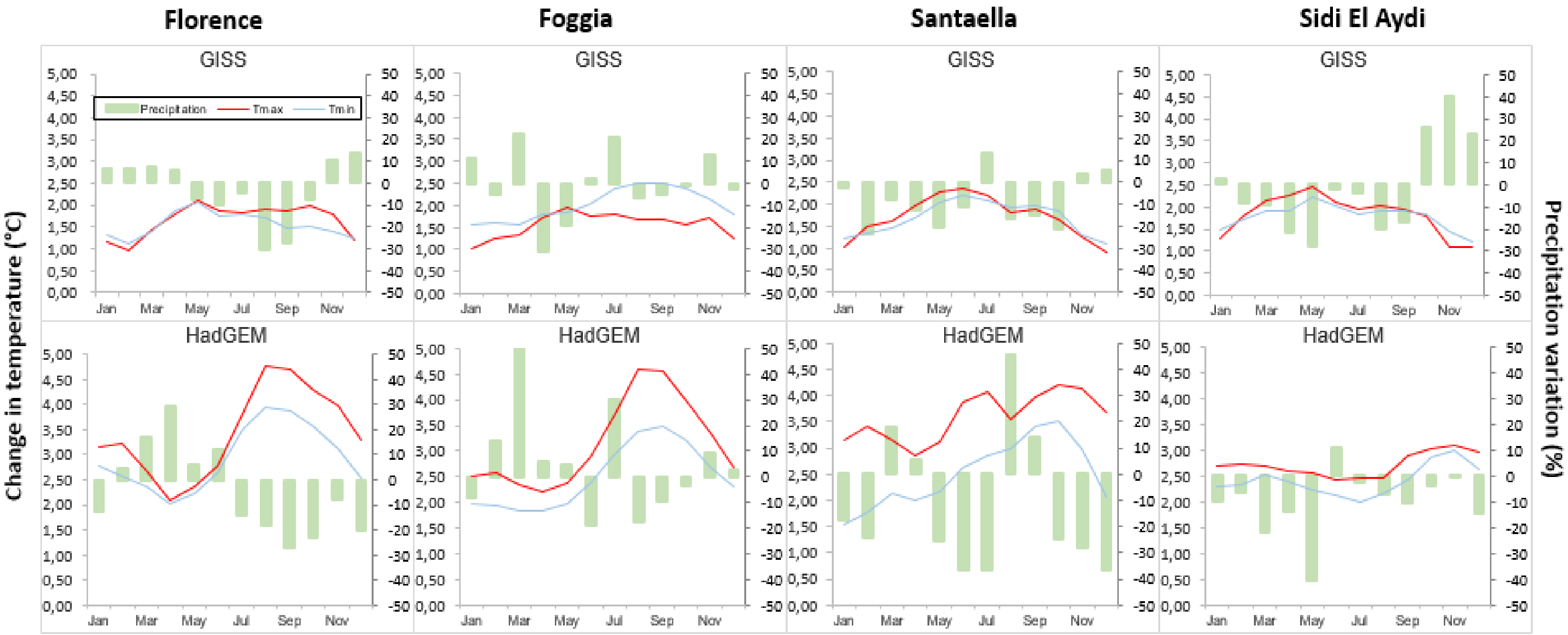

Fig. 5.2: *Changes in monthly temperatures and rainfall (%) in the medium period (2050s) at 8.5 RCP, respect to the baseline (1981-2015) for Florence, Foggia, Santaella and Sidi El Aydi locations for the GISS and HadGEM scenarios.*

5.3.2. Ideotype yield and phenological response

The results about the yield obtained using the ideotype varietal parameters shown a general yield increase for both scenarios in all locations compared to the results obtained using the unchanged varietal parameters (Fig.5.3, 4). Moreover, in Florence and in Foggia, a higher yield increase was suggested under GISS scenario than in HadGEM scenario. Whilst in Santaella and in SIdi El Aydi, the highest yield was simulated under HadGEM scenario (Fig.5.2)

Considering the ideotype varietal parameters, Florence was the location with the lower yield increase compared to the unchanged varietal parameters, with +30% for the GISS scenario and +11% for the HadGEM scenario. In Foggia a similar average yield increase about +56% for GISS scenario and about +57% for HadGEM scenario was suggested with the ideotype varietal parameters. In Santaella, an average yield raising about +62% and +73% is projected for GISS and HadGEM scenarios respectively. In Sidi El Aydi, is expected an increase in yield variation of +46% at GISS scenario and about +95% for HadGEM scenario. The highest average yield was simulated in Foggia for both scenario (6.8 and 8.2 t ha^{-1}, respectively). Whilst Sidi El Aydi had the lowest average simulated yield for both scenario (4.5 and 5.4 t ha^{-1}).

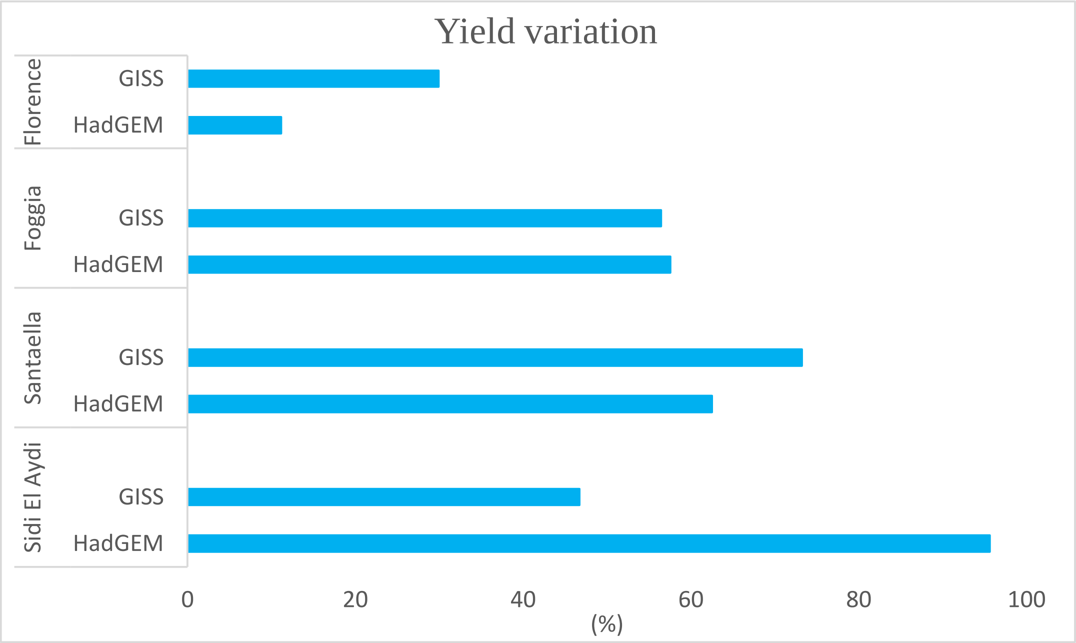

***Fig. 5.3**: Average yield variation (%) between the yiled simulated with ideotypes and with calibrated varietal parameters for Florence (Creso), Foggia (Simeto), Santaella (Amilcar) and Sidi El Aydi (Karim) under RCP8.5 for GISS and HadGEM scenarios at 2050.*

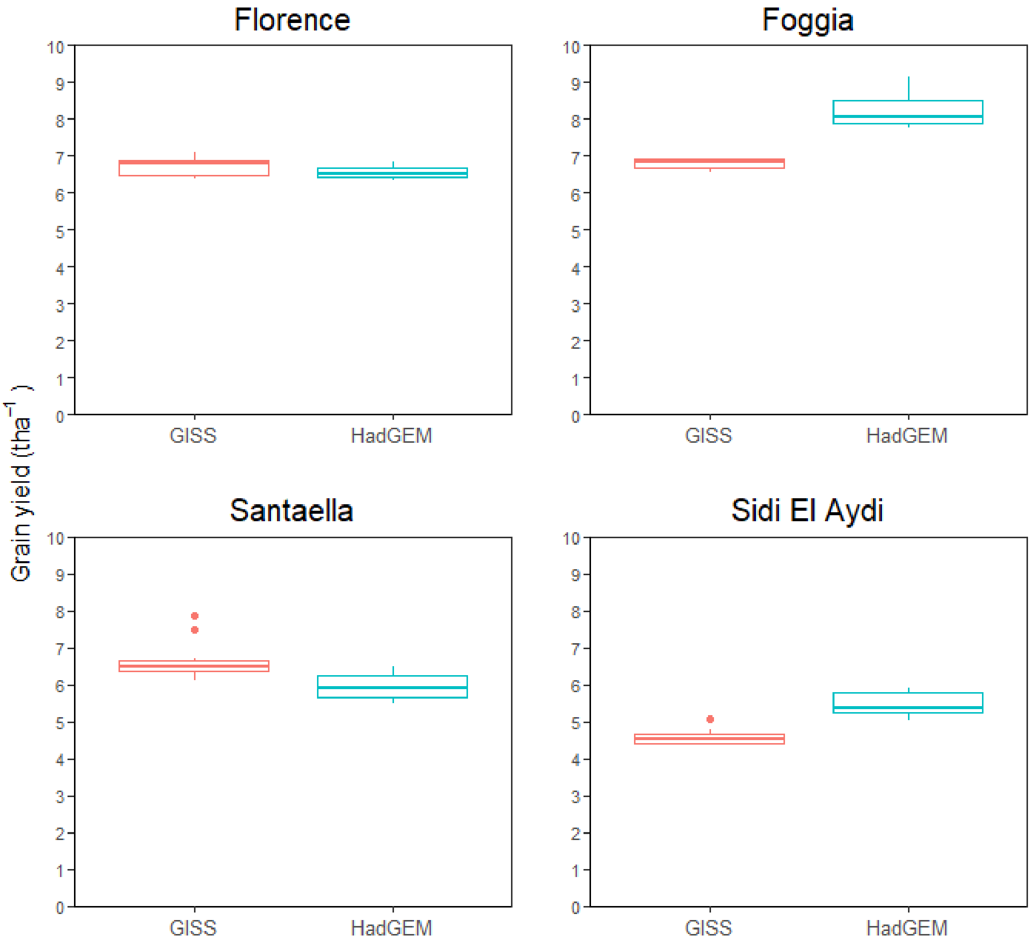

Fig. 5.4: *Box plots of simulated yield (t ha^{-1}) using the ideotype parameterts in Florence, Foggia, Santaella and Sidi El Aydi for the future climate scenarios GISS and HadGEM at RCP 8.5 for the medium period (2050s).*

As for the varietal parameters, the ideotypes differed in the anthesis date, pre-anthesis and grain filling duration were observed for the same scenario in the same location (Table 5.2). In all locations, the cluster analysis founded clusters characterized by early and late anthesis samples.

In Florence, under GISS scenario, the earlier anthesis date, and also the shorter pre-anthesis period, was observed for cluster1, which had the longer grain filling period (GF) (about +10 days compared the other clusters). Cluster2 and 3 had the same GF, but different cluster3 had a later anthesis date about 15 days. Under HadGEM conditions, the earlier anthesis was observed for cluster1 (57 and 35 days before cluster2 and 3, respectively), but it had the longer GF (+32 days compared the others). The latest cluster2 had the same GF duration of the medium cluster3.

Table 5.2: Median of the anthesis date, pre-anthesis period (days), grain filling duration (GF,days), maximum leaf area index (LAI, cm^2cm^{-2}), the final leaf number, the biomass at anthesis and the cumulative Photosynthetic Active radiation up to anthesis (PAR, MJ m^{-2}) for the different selected clusters for each location and each GCMs, GISS and HadGEM (GI and HG, respectively)

Site/cluster	**Anthesis date**	**Pre-anthesis period (days)**	**GF (days)**	**LAI (cm^2cm^{-2})**	**Final leaf n°**	**Anthesis biomass (kg ha^{-1})**	**PAR (MJ m^{-2})**
Florence GI							
CL1	3 Apr	144	59	2.88	12.49	5.28	227.28
CL2	25 Apr	166	42	3.19	11.91	7.28	312.25
CL3	13 May	183	43	2.85	12.36	8.96	366.84
Florence HG							
CL1	12 Mar	128	71	3.07	12.63	5.09	202.29
CL2	8 May	154	42	2.71	15.04	10.86	435.84
CL3	16 Apr	162	43	3.20	14.17	8.01	324.84
Foggia GI							
CL1	21 May	162	33	3.10	9.97	11.88	323.15
CL2	12 May	154	37	3.44	10.50	12.45	326.26
CL3	9 May	150	45	3.08	9.65	13.65	358.38
CL4	4 May	145	40	3.65	11.73	14.72	386.93
Foggia HG							
CL1	5 Apr	120	53	3.50	11.71	9.24	259.77
CL2	14 May	159	35	4.04	11.23	15.22	397.31
Santaella GI							
CL1	20 Apr	142	35	3.27	12.72	8.32	258.46
CL2	2 Apr	123	40	2.49	13.73	11.04	361.53
Santaella HG							
CL1	8 Apr	131	39	2.85	13.05	6.05	193.77
CL2	4 Mar	95	55	2.87	13.32	10.60	328.24
CL3	22 Mar	114	50	2.93	14.28	8.04	265.25
Sidi El Aydi GI							
CL1	27 Mar	107	50	2.23	12.50	8.23	289.75
CL2	8 Apr	120	44	1.77	12.47	9.37	328.35
CL3	31 Mar	115	50	2.28	11.87	10.73	339.66
Sidi El Aydi HG							
CL1	1 Apr	105	42	1.92	11.74	6.11	206.80
CL2	31 Mar	84	46	2.34	12.11	8.60	277.59

In Foggia, under GISS condition, the earliest anthesis date was observed for cluster4, 17 days before the later anthesis date simulated in cluster1. The other clusters, 2 and 3, had medium anthesis date compare the other two. But, cluster3 had the longer GF. Under HadGEM conditions, cluster1 was characterized by an earlier anthesis of 40 days and a longer GF about 20 days compared to the cluster2.

In Sanatella, under GISS conditions, the tow clusters simulated an earlier, cluster2, and a later, cluster1, anthesis. The differences between the anthesis was about 18 days. Whilst, the GF of the cluster1 was only 5 days short than GF of cluster2. For HadGEM, the three cluster showed an early (cluster2), medium (cluster3) and late (cluster2) anthesis date. From and early to a late anthesis, a short GF was observed.

In Sidi El Aydi, under GISS scenario, tow early and one late anthesis dates were observed in the three clusters. The earlier anthesis, cluster1 and 2, differed about 3 days for the anthesis and had the same GF. Cluster2, with the late anthesis (about 8 days) had a GF shorter of 5 days compared the others. Under HadGEM scenario, cluster1 had a later anthesis, about 36 days, but a shorter GF only about 4 days compared to the cluster2.

5.3.3. Ideotype varietal parameters

Considered the cluster results (Fig.5.5), the results are presented divided in clusters. The median of the varietal parameters that described the different selected clusters of ideotypes were presented in Table 5.3.

In Florence, the ideotypes were divided in 3 clusters for both GISS and HadGEM scenarios. Cluster1 was low sensitive to photoperiod (SLDL), as cluster2, but it had a lower phyllochron (P) than cluster2. Moreover, the thermal time required for the grain filling (Dgf) in cluster1 and 3 was similar about 743 °C and it was higher about 170 °C compared to cluster2. The potential surface area of penultimate leaf (AreaPL) was close to 27 cm^2 $lamina^{-1}$ for cluster1 and 3, instead for cluster2 was above 30 cm^2 $lamina^{-1}$. The ratio of flag leaf development (RatioFLPL) and the maximum rate of acceleration of leaf senescence (MaxDSF) was higher in cluster3 than in the others. For HadGEM scenario the cluster1 had both lower SLDL and P than other clusters, but it had higher Dgf (+234 and +165 °C compared to cluster2 and 3, respectively). Cluster3 was characterized by a higher SLDL, P, AreaPL and MaxDSF compared the others.

In Foggia, the ideotypes were divided in four clusters under GISS scenario and in tow clusters under HadGEM scenario. Under GISS scenario, the clusters3 and 4 had very similar SLDL, Dgf, AreaPL, RatioFLPL but different P. Cluster2 was characterized to have higher Dgf than others, but a lower AreaPL and RatioFLPL. Cluster1 had the highest SLDL and AreaPL, but the lowest P. The MaxDSF was around 4.3 for cluster1, 3 and 4, whilst cluster 2 had the lowest value. For HadGEM scenario, cluster1 had higher SLDL and P compared to cluster2, but lower Dgf about 30 °C. Both classes had similar RatioFPL and MaxDSF, but cluster1 had a higher AreaPL (+5 cm^2 $lamina^{-1}$).

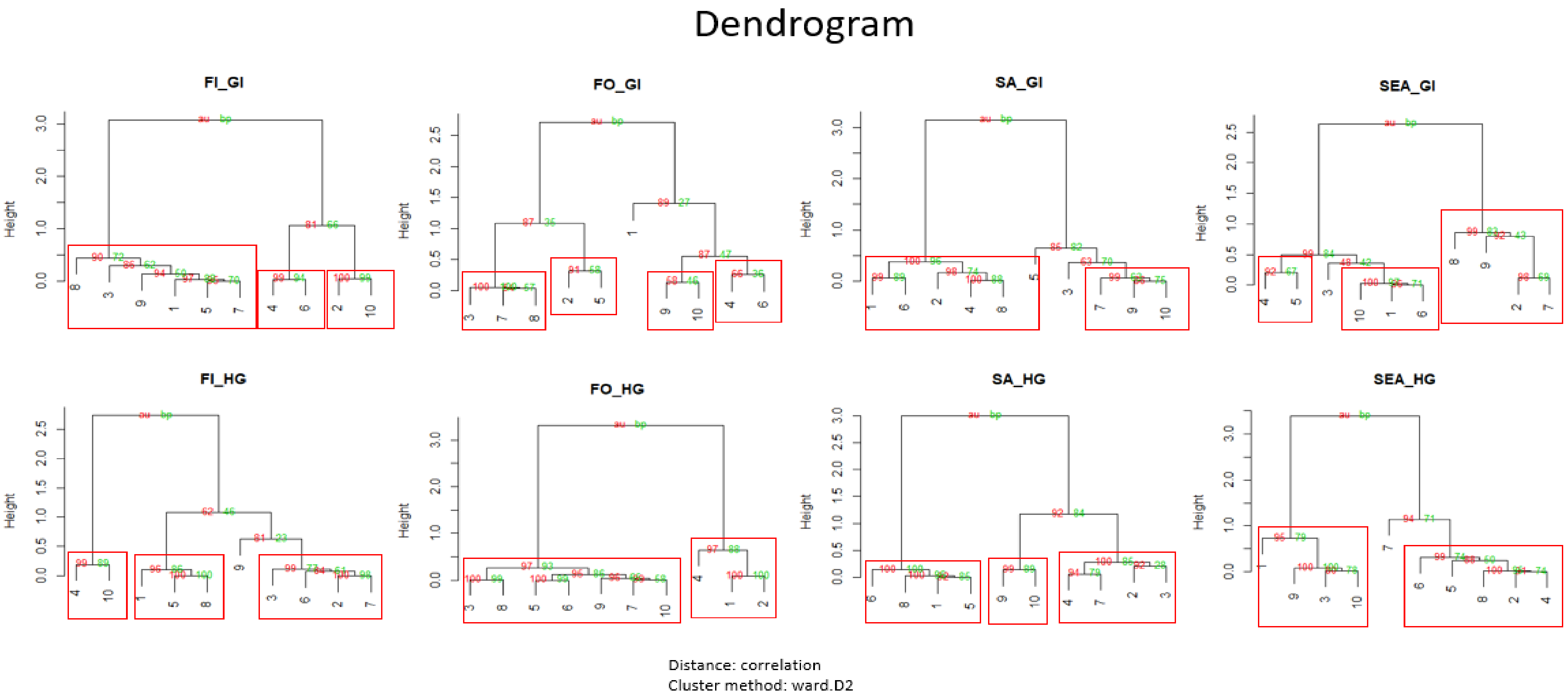

Fig. 5.5*: Cluster dendogram for Florence, Foggia, Santaella, Sidi El Aydi for both scenarios, GISS and HadGEM. Red boxes to be place around significant clusters (alpha=0.95). The green numbers are the Bootstraps Probability (bp), the red numbers are the Approximately Unbiased p-value (au)*

Table 5.3: Median of the SLDL (Leaf h^{-1}), P (°C), Dgf (°C), AreaPL ($cm^2 lamina^{-1}$), RatioFLPL, MaxDSF for the different clusters (CL) selected for each location and each GCMs, GISS and HadGEM (GI and HG, rispectively)

Site/Cluster	SLDL	P	Dgf	AreaPL	RatioFLPL	MaxDSF
Florence GI						
CL1	1.26	81.29	748.61	25.51	0.90	2.81
CL2	1.29	112.45	572.84	33.31	0.89	3.17
CL3	1.66	134.63	739.00	26.86	1.02	3.81
Florence HG						
CL1	1.19	86.69	765.11	25.80	1.12	2.53
CL2	1.60	37.46	602.62	36.41	0.92	4.10
CL3	1.49	113.02	531.28	29.34	0.94	3.57
Foggia GI						
CL1	1.55	135.69	459.17	27.26	1.02	4.37
CL2	1.57	115.45	499.54	27.12	0.92	4.52
CL3	1.25	120.15	660.85	23.57	0.91	2.76
CL4	1.81	90.87	564.89	29.86	0.77	4.35
Foggia HG						
CL1	1.58	128.44	480.45	30.67	0.91	3.44
CL2	1.31	73.27	510.14	25.96	0.96	3.41
Santaella GI						
CL1	1.69	135.97	434.12	34.42	0.78	3.55
CL2	1.71	92.40	411.47	20.13	0.70	2.74
Santaella HG						
CL1	1.54	120.68	441.74	23.49	0.96	1.71
CL2	1.49	77.36	594.12	22.98	0.79	3.24
CL3	1.72	93.98	575.71	25.13	1.02	3.25
Sidi El Aydi GI						
CL1	1.49	118.90	649.50	34.55	1.03	2.51
CL2	1.53	103.19	648.11	27.53	0.74	2.91
CL3	1.59	124.85	730.65	26.06	0.87	4.16
Sidi El Aydi HG						
CL1	1.45	128.17	551.42	25.87	0.77	3.74
CL2	1.38	84.90	548.23	25.28	0.95	3.81

For Santaella, under GISS scenario were identified tow clusters, whilst in HadGEM scenario three clusters. Under GISS scenario, the clusters differenced for the P, the AreaPL, and the MaxDSF, instead the other parameters had similar values. Cluster2 was characterized by a higher P about 43 °C compared to cluster1, and about a higher AreaPL about 14 cm^2 lamina^{-1}. Under HadGEM scenario, cluster2 had the higher P but the lower Dgf (-153 °C compared to the Dgf of cluster1). Cluster1 was characterized by a lower P and the higher Dgf, but not so far from Dgf of cluster3. All clusters had similar AreaPL.

In Sidi El Aydi were selected three cluster under GISS scenario and tow under HadGEM scenario. In GISS scenario, cluster1 and 3 had similar SLDL, Dgf and a lower MaxSDF compared to cluster2. This one, had the highest Dgf (+ 81 compared Dgf of cluster1 and 3). Cluster1 had the highest AreaPL, above 30 cm^2 lamina^{-1}. Under HadGEM scenario, cluster1 and 2 had similar Dgf, around 550 °C, AreaPL (25 cm^2 lamina^{-1}), MaxDSF, but they differed for the SLDL and the P. In particular, cluster2 was characterized by a higher SLDL and P than cluster1.

5.4. Discussion

In this study, different wheat ideotypes were selected for the yield maximization and for the reduction of the inter-annual variability at 2050s for the RCP8.5 as projected by the two GCMs, GISS and HadGEM. The results suggested that in each location and under each single climate projection, various ideotype varietal parameter sets with different phenotyping characteristics can be defined. Besides, all of them led to the yield maximization and the reduction in the inter-annual variability.

The genotype characteristics of wheat ideotypes were clustered based on the phenotype characteristics with the intent to provide information that could be useful for the genetic improving studies. The ecophysiological ideotypic traits that were modified in this work are, according to some authors (Semenov et al., 2015; Tao et al., 2017), the most relevant traits for improving crop yield under future climate change. Moreover, some of these traits were selected as those that must be improved to overcame or to reduce the future impacts of climate change on wheat in the study sites (Chapter 4).

For each location and scenario, the selected clusters, characterized by different varietal parameter sets, suggested that under future climate conditions, different phenotyping expressions can be used. Indeed, the results showed that clusters with early anthesis date associated with a long grain filling period and the clusters with late anthesis date associated with short grain filling duration led, in any case, to the yield maximization.

In *SiriusQuality* the grain growth is calculated from the total biomass using simple partitioning rules and considering the rate of assimilation of the grain structural dry mass. The 25% of the biomass produced during the pre-anthesis phase was translocated into the grain. The grain daily dry matter demand connected with the rate of the grain structural dry mass accumulation, which depends on the labile leaf blade dry matter (the common pool of dry matter) was considered too. A longer pre-anthesis period permitted to have more time for the interception of solar radiation which could increase the dry matter allocation into the grain (Miralles at al., 2000). Coherently with different studies (Richards, 1992; Alvaro et al., 2008), we found significant relationship between time until anthesis and biomass accumulation at anthesis. In fact, the photosynthetically active radiation (PAR) intercepted up to anthesis date was higher for the clusters with a longer pre-anthesis phase than the clusters with a shorter pre-anthesis phase (Table 5.2). For the daily biomass assimilation, *SiriusQuality* takes into consideration both PAR and the light use efficiency, thus, the higher cumulated PAR, the greater accumulated biomass up to anthesis (Table 5.2). The high yield produced with a longer pre-anthesis phase associated with a shorter grain filling, is probably due to the more efficient grain increase rate, connected with a major biomass quantity translocated from pool to grain. While, a shorter pre-anthesis phase, which permit to accumulate a reduced biomass compared to a longer pre-anthesis phase, was compensated by a longer grain filling duration longer than 5-7 days. It is well known that a longer grain filling allows to increase firstly the intercepted solar radiation and then the biomass translocated into the grain, therefore increasing the grain weight (Evans and Fisher, 1999). Indeed, in our case, a longer grain filling allowed to assimilate more grain mass and compensate the lower biomass translocation from pool.

Considering the results of Chapter 4, in which was described that the frequency and the intensity of stress events were major around anthesis under future climate conditions using unchanged varietal parameters, a general earlier anthesis date was expected compare to the baseline to escape from climate stress events. Apparently, the algorithm results did not consider the possibility to have both a longer vegetative phase and a longer grain filling duration. This was probably due to the fact that with this combination the weather conditions during a longer grain filling were not favourable for the crop growth.

In Santaella and Sidi El Aydi, the early anthesis date explained above, was more evident compared to Florence and Foggia. The reason was that in these locations the temperature increased, compared to the baseline, was more accentuated than in Florence and in Foggia (Fig.5.2).

In *SiriusQuality*, the anthesis date depends on the leaf appearance, which in turn is connected with the day-length response of leaf production (SLDL), and the phyllochron, i.e. the thermal requirements for the leaf development. The response of vernalisation rate to temperature, which is normally used by the model to reproduce the leaf appearance, was not considered in this study because all varieties do not require vernalisation. The photoperiodic sensitivity should receive a particular attention since it could alter the vegetative and the stem elongation periods (Slafer and Rawson, 1994). The stem elongation phase affects the number of fertile floret at anthesis, because of the quantity of assimilates translocated into the grain and, so, thereby to the final yield production (Gonzàlez et al., 2003; Miralles and Richards, 2000). Accordingly, the results of the genetic algorithm application suggested that early or late anthesis can be simulated using different combinations of parameters related to photoperiodic sensitivity and phyllochron. For instance, in Florence under both conditions, GISS and HadGEM, the early-anthesis cluter1 was characterized by both a lower SLDL and a lower phyllochron than the cluster2 and cluster3, in which a progressive reduction of photoperiod sensitivity and phyllochron was observed. Instead, in Sidi El Aydi under HadGEM projection, a similar anthesis date (31th March and 1st April) and the same number of final leaves were reproduced by different photoperiodic sensitivity and phyllochron for cluster1 and cluster2. In *SiriusQuality,* the crop photoperiodic response is positively correlated with the final leaf number, which also depends on the potential leaf number calculated in response to day-length and on maximum and minimum value of leaf number set as cultivar parameters. Once defined the final leaf number, the phyllochron regulates the duration of the leaf appearance up to the anthesis date. In general, a high SLDL, which corresponds to a low photoperiodic sensitivity, could increase the final leaf number (but it depends on the potential leaf number) and a high phyllochron increase the period for the leaf appearance, because of the high thermal time requirement, thus the anthesis was later than an anthesis simulated with a lower phyllochron.

The duration of the grain filling was connected with the “stay green” crop capacity (Silva et al., 2000). A major “stay green” capacity indicates a higher plant capacity to maintain the CO_2 assimilation and photosynthesis (Borrell et al., 2001) for a longer time. In general, in Florence and in Sidi El Aydi, at longer grain filling duration corresponded a lower leaf senescence. This implied that the extension of the “stay green” of the crop during the grain filling was adopted as adaptive strategy, since a low rate of leaf senescence ensured a longer grain filling duration. Instead, in Santaella and in Foggia, a higher leaf area of the penultimate leaf and of the flag leaf resulted in a longer grain filling duration. In this case, the strategy could foresee the increase of the leaf area for intercepting the solar radiation during the grain filling, despite of a higher leaf senescence rate compared to the clusters with short grain filling. However, the ideotype values of the rate of leaf senescence (MaxDSF) were lower than the calibrated values. An unrealistic very long grain filling was observed in Florence for cluster1 projected by HadGEM scenario (71 days). This result was associated to two parameters, a low ratio of leaf senescence and a high flag leaf area, which both permitted to maintain the crop capacity to intercept solar radiation and to translocate the assimilates into the grain for a longer time. Moreover, this very long duration of the grain filling was connected to a shorter pre-anthesis period than the other clusters in Florence. This particular combination of varietal parameters had allowed to have a so long grain filling.

The penultimate leaf surface area (AreaPL) and the ratio of flag leaf development (RatioFLPL) are both connected with the penultimate leaf and flag leaf surface area capacity to intercept solar radiation. The low penultimate leaf and flag leaf surface area observed especially in Foggia, in Santaella and in Sidi El Aydi might be a response to dry environments characterized by final growing season drought. Indeed, a larger leaf area could be responsible for a higher water loss, because of a raised evapotranspiration (Tao et al., 2017). Instead, in other favourable conditions, probably met because of the occurrence of phenology, the increase of these two parameters could allow to intercept major quantitative of light and, consequently, to raise the photosynthesis rate and thus to accumulate more biomass.

The new ideotypes were the results of "genotype x environmental characteristics", where the environmental conditions correspond to the future climate projection. Thus, the clusters represented the adaptive characteristics of these cultivars under future climate conditions.

Nevertheless, it is worth noting that in this study we did not take into account the management practices, such as the changing in the sowing date, the use of irrigation treatments and the changing in the fertilization quantity. The crop management is not often considered in crop ideotyping study. We suppose that greatest productivity could be expected if genetic improvement and agronomic practices are put together (Duvick et al., 2004; Martre et al., 2015).

SiriusQuality is currently being adopted in different studies (Martre et el., 2015; Wang et al., 2017; Tao et al., 2018) and also in ideotype studies (Martre et al., 2006; Tao et al., 2017). In this study *SiriusQuality* is used as a tool to reproduce the reality in a simplified way and to identify the durum wheat ideotype characteristics under future climate change Although we believe that the ideotype traits selected in this study for Florence, Foggia, Santaella and Sidi El Aydi could be used by breeders in genetic development programs, the results of this study need to be carefully interpreted. Indeed, this approach had some limitations due to the use of a single crop simulation model and due to the complexity of the result analysis which takes into account different aspects and simulated processes. We agree with those authors (Rotter et al., 2011; Martre et al., 2015; Wallach et al., 2016) who suggest the use of multiple model approach for ideotype studies for assessing and reducing uncertainties in crop simulations. Another limitation was that *SiriusQuality* does not consider the crop response to raising CO_2 in the Light Use Efficiency and in the water use efficiency simulation. The positive effect of the raising CO_2 and the shift of the phenological phases combined with the increase in leaf surface area of the penultimate leaf and of flag leaf and a longer pre-anthesis period lead to raise the radiation use efficiency and thus to intercept more solar radiation. Consequently, a higher biomass was produced and potentially major quantity of biomass could be translocated into the grain. *SiriusQuality* considered the influence of the increasing CO_2 in the simulation of the Light Use Efficiency (linear increase of LUE with the CO_2 increasing), but using a fix value of increased biomass related to the raising CO_2.

One of the emerging message from the analysis was that under future climate change in the Mediterranean basin, the improving durum wheat varieties need to have an earlier anthesis date and a longer grain filling compared to the actual varieties. Moreover, the increase in the grain growth rate have to be considered in a breeding program especially for its high heritability in wheat (May and Van Sanford, 1992; Mov and Kronstrad, 1994), while it is generally accepted that the grain filling duration largely depends on environmental conditions (Royo et al., 2000; 2006), and its heritability is medium to low (Egli, 1998). However, genetic variability exists for both traits in durum wheat (Gebeyehou et al., 1982; Royo et al., 2006), thus they can be improved under a breeding program. Furthermore, different strategies can be used to increase the grain filling duration, such as the reduction in the rate of leaf senescence to maintain a longer crop "stay green" capacity. In addition, the increasing in the leaf surface area of the penultimate leaf and the flag leaf allowed to increase the interception of the solar radiation during the grain filling, or, on the other hands, to reduce the leaf surface area of the penultimate leaf and the flag leaf to reduce the crop water transpiration, such as in Foggia, Santaella and Sidi El Aydi. To this regard, we believe that further research is required to discover whether among the actual wheat population there are varieties that, because of their natural adaptation to the changing climate, already included all or part of the characteristics analysed in this study and that could be effectively included in an ambitious breeding genetic program.

5.5. Conclusions

Under future climate conditions, *SiriusQuality* and the genetic algorithm suggested different sets of varietal parameters to ensure the yield maximization with a low inter-annual coefficient of variation. Moreover, this study showed that wheat ideotypes can be characterized by different phenotyping aspects: early, medium and late anthesis. Furthermore, in general, an early anthesis correspond to a long grain filling duration, and late anthesis to short grain filling duration.

Compared to the calibrated varieties, the idotypes were characterized to have an earlier anthesis date and a longer grain filling duration. Moreover, they had a lower ratio of leaf senescence and, in general, a lower surface of penultimate area.

The results of this study were difficult to explain and interpret because of the complexity of the traits interactions and the way in with *SiriusQuality* reproduces the processes in which the selected varietal parameters were involved. Despite of this, the information concerned the variety characteristics that could be improved to ensure an adequate grain production under future climate change can be considered in a genetic breeding program.

To increase the robustness of the ideotypes selected by the crop models, a continuous improvement of the processes simulated by the crop models is needed. In addition, a constant and continuous exchange of information about the needs and issues of farmers and geneticists is essential to identify which features need to be improved. For example, in this study we considered the management practices normally used in the considered locations to select the characteristics to be improved in the wheat. But, considering the use of other management practices, such as those suggested to reduce the impact of climate change (e.g. the changing in the sowing date, the use of irrigation treatments), the durum wheat ideotypes may have different characteristics compared to those identified in this study.

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Chapter 6

General conclusions

6. General conclusions

In this thesis, the crop simulation model *SiriusQuality* was used as tool to investigate the genotype x environment x management interaction, the impact of future climate change and to described the wheat ideotype characteristics to ensure high yield production and low inter-annual yield variability in Florence, Foggia, Santaella and Sidi El Aydi. During the calibration and the evaluation processes, SiriusQuality showed good performance and it confirmed itself as useful tool able to reproduce wheat growth and development in different environments and management conditions in the Mediterranean basin.

The first SiriusQuality application to investigate the genotype x environment x management, suggested that the tradictional sowing window used in Florence, Foggia, Santaella and Sidi El Aydi could be moved forward in all location with positive effects on yield quantity and yield inter-annual variability. But, at the end, the traditional sowing window resulted as a good compromise between yield quantity and quality. In fact, advanced sowing window reduce the grain protein concentration. The increase in the grain quantity using advance sowing window was due to different factors, including earlier anthesis date, longer grain filling, and higher values for grain number per m^2, single grain weight and LAI at anthesis, water stress reduction during grain filling when compared with results obtained with the traditional sowing window.

The second model application to investigate the impacts of climate change on durum wheat, showed that the impact of future climate change will have spatial differences and it might be interpreted considering the interaction between the weather patterns, the CO_2 concentration and the advanced phenology. In Florence and in Foggia the impact of climate change might be less negative than Santaella and Sidi El Aydi. In these last locations, a higher reduction in precipitations was observed in the future compared Florence and Foggia. During the 10 days after anthesis, the major increase of the frequency of stress events was suggested in all locations. Moreover, the increase in the intensity of stress events was observed in all location except in Florence. In addition, the positive CO_2 rule to contrast the climate change was confirmed.

Considering the results of the *SriusQuality* applications, the model was finally used to identify the durum wheat ideotype characteristics under future climate change. Different sets of varietal parameters to ensure the yield maximization with a low inter-annual coefficient of variation were selected. Moreover, wheat ideotypes can be characterized by different phenotyping aspects: early, medium and late anthesis, but in any case earlier than the anthesis simulated with no ideotype cultivars, associated with different grain filling duration. It is useful and interesting understand if there are already durum wheat varieties with all or some of the identified characteristics to help and accelerate the genetic breeding program.

In this thesis, the incidence of pests and diseases was not take into account, but it is an important aspect to consider, especially under future climate change. Indeed, some pests and diseases could benefit from the raising temperatures and have a more negative incidence in the final production than now. Moreover, also in the application of the forward sowing window, pests and diseases could have negative effects, because of the higher temperatures compared the temperature at the traditional sowing window, during the first crop growth and development stages

Moreover, during the ideotype selection, the use of the suggested management practices to overcame climate change, such as an earlier sowing window, fertilization or irrigation treatment applictions, can be useful to undestand if these managment practices let to an effective yield increase. Another important aspect to consider is the grain quality, which was not take in to account in the ideotype selection. For this, it is suggested to include in the ideotype studies the characteristics that not only let to a yield maximization, but to a maximization of the grain quality, too.

The results of this thesis can be useful to help breeders to select durum wheat varieties able to ensure high yield quantity and stability under future climate change in the Mediterranean basin. However, to increase the robustness of the selected ideotypes by the crop models, a continuous improvement of the processes simulated by the crop models is needed. Furthermore, a constant and continuous exchange of information about the needs and issues of farmers and geneticists is essential to identify which features need to be improved

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Picture on the cover:

"Wheat field with ladybug", 2018, Claudio Leolini

Picture on the back cover:

"Wheatfield with Lark", 1887, Vincent van Gogh, Van Gogh Museum di Amsterdam.

"Wheatfield with Crows", 1890, Vincent van Gogh, Van Gogh Museum di Amsterdam.

"A Wheatfield with Cypresses", 1889, Vincent van Gogh, National Gallery, London

"Wheatfield under thunderclouds", 1890 , Vincent van Gogh, Museo Vincent van Gogh, Amsterdam