Modelling phenotypical traits to adapt durum wheat to climate change in a Mediterranean environment

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Abstract: *In water-limited environments, water is the main limiting factor of crop production, especially in rainfed crops such as durum winter wheat (*Triticum durum *Desf.). Consequently, also in climatic change projections, it is essential both to recognise characteristics in breeding programs that can lead to drought tolerance and to reduce the time needed to observe variations of these traits on crop yield. Moreover, changing in management strategies could improve crop adaptation to climate change, not considered in this approach. Crop growth models can assist breeding research in identifying these traits. The CropSyst model was parameterized for durum wheat cultivated in Southern Italy: crop characteristics were analyzed, development (grain filling duration and phenologic response to water stress), canopy expansion (specific leaf area, leaf duration and ratio between leaf and stem) and water uptake (root length). Model sensitivity was evaluated varying one parameter at a time and changing the value by ± 5, ± 10 and ± 20% of calibrated values. Wheat was simulated with past real daily climatic data (55 years, from 1952 to 2006) and future daily climatic data predicted with an HADCM3 global climatic model (100 years, from 2000 to 2100) where an average air temperature increase of +2 °C is expected as well as a CO_2 concentration of 550 ppm (IPCC, A2 scenario). Leaf area duration and specific leaf area proved to be the parameters with the greatest impacts on wheat yield, with changing in wheat yield from -20 to16% and from -38 to 35% respectively as consequence to variation for these parameters oscillating between -20 and 20%. The ratio between the leaf and the stem biomass accumulation was inversely and linearly related to grain yield. Lengthening or shortening the grain filling duration did not seem to provide benefits in term of grain yield. The "non-response" in term of grain yield to water stress highlights that the wheat crop was optimized yet in Mediterranean environment in order to maintain production stability in drought conditions which could accelerate different crop phenological stages. The variation of maximum root depth (from 0.8 to 1.2 m) did not result in any significant variation in grain yield. The changes of crop morphology could also enhance climate change adaptation.*
Keywords: *in-silico genotype, CropSyst simulation model, crop yield, specific leaf area, leaf area duration.*

Riassunto: *In ambienti a sussidio idrico limitato, è l'acqua a rappresentare il fattore limitante le produzioni, specie per colture coltivate in asciutto, come il frumento duro (*Triticum durum *Desf.). Conseguentemente, anche in vista di cambiamenti climatici, è essenziale sia individuare nei programmi di miglioramento genetico quelle caratteristiche vegetali che possono portare a tollerare meglio lo stress idrico e sia ridurre il tempo necessario per valutare gli effetti delle variazioni di questi tratti sulla produzione. I modelli di crescita colturale possono aiutare i breeders nell'individuare questi tratti. Il modello CropSyst è stato parametrizzato per il frumento duro coltivato nel Sud Italia: le caratteristiche colturali analizzate sono state: sviluppo (durata del riempimento della granella e risposta fenologica allo stress idrico), espansione della canopy (area fogliare specifica, durata fogliare e rapporto foglie-culmo) e assorbimento idrico (lunghezza radicale). La sensibilità del modello ai cambiamenti di queste caratteristiche è stata valutata variando i parametri del ± 5, ± 10 e ± 20% dei valori calibrati. Il frumento è stato simulato per il passato con dati climatici giornalieri reali (55 anni, dal 1952 al 2006) e per il futuro con dati climatici giornalieri generati con il modello climatico globale HADCM3 (100 anni, dal 2000 al 2100), prevedendo un aumento medio delle temperature di +2 °C così come una concentrazione della CO_2 atmosferica di 550 ppm (IPCC, scenario A2). La durata fogliare e l'area fogliare specifica si sono dimostrati essere i parametri con il maggiore impatto sulla produzione finale con variazioni sulla produttività del frumento rispettivamente dal -20 al 16% e dal -38 al 35% per oscillazioni di tali parametri compresi tra -20 e 20%. Il rapporto foglie-culmo della biomassa accumulata è stato inversamente e linearmente correlato alla produzione, mentre nessun effetto ha dimostrato l'allungamento o l'accorciamento della durata della fase di riempimento del seme. La mancata riposta in termini produttivi a variazioni del parametro sulla risposta fenologica allo stress idrico, evidenzia come questa coltura sia stata già ben selezionata per l'ambiente Mediterraneo al fine di mantenere una certa stabilità di produzione in condizioni asciutte, accorciando la durata delle diverse fasi fenologiche. La variazione della massima profondità radicale (da 0.8 a 1.2 m) non ha significativamente influenzato la produzione finale. Le variazioni morfologiche della coltura possono essere utili anche nel processo di adattamento ai futuri cambiamenti climatici.*
Parole chiave: *genotipo, modello di simulazione CropSyst, produzione, area fogliare specifica, durata dell'area fogliare.*

1. INTRODUCTION

In Mediterranean environments, water is the major limiting factor on field crop production, especially for crops that are not usually irrigated, such as durum winter wheat. In these envi-

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ronments, the main goal for plant breeders is to focus on the complex interaction between crop growth and water availability, in order to maximize and stabilize the commercial yield. An improvement in crop performance under drought conditions has been achieved in recent years through the selection of traits that involved, for example, anthesis-silking interval in maize (Edmaedes *et al.*, 2004), transpiration efficiency in wheat (Condon *et al.*, 2004) or modification in growth habits for many species in response to different seasonal water supply.

As reported by several authors, the major genes that control plant growth and development are the same that are involved in stress response and thus for drought adaptation. Hsiao (1973) reports that cell expansion (and therefore plant growth) is the first process that suffers in a decrement in tissue water potential. Reymond *et al.* (2003) reports that leaf elongation has a strong genetic control, influenced by the water used by the crop throughout the season. From these examples it is clear how the identification of certain traits involved in rationalization and full exploitation of crop-available water is a crucial target in breeders' research on how to improve drought resistance and/or tolerance.

Some authors (Campos *et al.*, 2004; Cooper *et al.*, 2006) underlined how research studies to improve drought resistance should follow two steps; the first is to identify candidate traits, the second is to select or to engineer new adaptation genes. For the first step, an aid to identifying candidate traits in drought resistance and/or adaptation can be given by the crop simulation models. Jordan *et al.* (1983) carried out simulations to evaluate strategies for crop improvement in drought regions by changing simple crop traits, such as root depth, maturity time and osmotic adjustment.

The response of crops to water stress conditions and changing root volume was evaluated by Jones and Zur (1984). Sinclair and Muchow (2001) analyzed a number of plant traits in maize, such as leaf size, rate of leaf appearance, stomata closure and grain growth duration in order to improve crop yield in a water-limited environment.

Water availability during different wheat crop growth stages affects biomass accumulation, phenological path and yield components. Rajala *et al.* (2009), report as drought prior the pollination and terminal drought decrease net photosynthesis and stomatal conductance and, consequently, final dry biomass. Drought before pollination influences yield components, resulting in a lower number of fertile florets per number of spikes and number of grain per spike; water availability after pollination increases single grain weight, furnishing grain yield greater than well watered wheat plants. On the contrary, terminal drought reduces significantly the single grain weight compared to well watered treatment, maintaining the same number of fertile florets, but reducing the number of grains per spike: this causes a low grain yield.

Cereals use different strategies to adapt to different conditions of limited water supply (Tambussi *et al.*, 2007); this adaptation can follow two different strategies; avoiding the risk of drought disease, for example by shortening the growing cycle or improving the root system (avoidance), or tolerating the water deficit, ensuring adequate productivity also under water stress (tolerance).

Temperature is a crucial factor for wheat productivity, which determines both phenological development (Bauer *et al.*, 1984) and growth rates (Grace, 1988). Besides, temperature affects leaf appearance (Baker *et al.*, 1980), respiration (Goudriaan *et al.*, 1985), rate of grain-filling (Wardlaw, 1994), evapotranspiration and water stress (Ritchie, 1972). It is possible to link temperature to wheat response, as water stress, phenology (vegetative and reproductive stages) and physiology (photosynthesis, respiration and grain-filling). All these effects are self-correlated and it is difficult to separate their overall effect on grain yield and, consequently, identify a clear relationship between wheat productivity and temperature.

In Mediterranean environments, the wheat development and reproductive stages occur with air temperatures usually higher than the optimal. High temperatures during the grain filling stage can reduce single grain weight as reported by several authors (Savin *et al.*, 1996; Passarella *et al.*, 2002; Plaut *et al.*, 2004). This trend was confirmed also for other cereals, such as sorghum, as reported by Rinaldi and De Luca (2012), with a decrease in term of grain yield up to 20% compared to current sorghum grain yield, as result of long term simulations, the latter set to future maximum temperature increment up to 5 °C.

On the other hand, Rinaldi *et al.* (2009) reported as the response of three crop simulation models for durum wheat productivity in Mediterranean environment to temperature increment was contrasting.

Anyway, because of their dynamic response, crop simulation models also offer the opportunity to explore the effects of changing the rates of various physiological processes, driven by the simple traits previously identified for crop simulations. For example, Hoogenboom *et al.*, (1994) used the BEANGRO model to investigate the effects of changing specific leaf area (*SLA*), root portioning, rooting depth and root length, root weight on seed yield ratio and water use efficiency (*WUE*) of the common bean. PNUTGRO was used by Boote and Jones (1988) to evaluate 16 parameters on groundnut yield under rain-fed conditions over 21 years. They found that yields increased over 15% by lengthening the duration of the vegetative and reproductive phases and canopy photosynthesis.
An important issue that could be addressed by simulation models is predicting the response for the novel genotype both in different environments and for the same environment in different climatic conditions. Indeed, the evaluation of a new genotype in different conditions and over several years requires a great deal of time and human resources. It is expensive, and not entirely practical, to assess different plant germoplasms using conventional multi-site and multi-season trials. This aspect is of crucial importance in creating new genotypes whose value should be evaluated on expected future climatic scenarios, obtainable by means of global climatic models. In fact, as reported by the Intergovernmental Panel on Climate Change (Bates *et al.*, 2008), anthropogenic greenhouse gas emission, if not reduced, could lead to an increase of global surface temperature from 1.5 to 4.5 °C.
Rosenzweig and Tubiello (1996) used CERES-wheat to evaluate the effect of changes in minimum and maximum temperature on wheat yields: temperature increase involves in a contrasting path for dry biomass, with positive or negative oscillations compared to baseline simulated biomass; however, they reported from slight to high decrement in term of yield, if daily mean temperature raises from +1 to +4 °C. Semenov (2009) reported a study on wheat, using 100 years of synthetic climatic data generated by the LARS-WG stochastic weather generation and calibrated in two locations in the UK and Spain. He concluded that changes in parameters controlling the effects of water stress on leaf senescence and biomass accumulation had the largest impact on grain yield under drought (up to 70% in yield compared with control), whereas phyllochron and grain weight did not improve yields.
The aim of this study is to analyze the effects of variations in different traits of durum wheat on grain yield as affected by future climate change, also if in this approach adaptation strategies, crop management are not considered.

2. MATERIALS AND METHODS

2.1 The simulation model

CropSyst is a multi-year, multi-crop, daily time-step cropping system simulation model, used to simulate soil water budget, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water and salinity (Stockle *et al.*, 2003).
The simulation of crop development is based on thermal time which is necessary to reach a given growth stage, taking into account average air temperature above a base temperature and below a cut-off temperature.
Potential biomass is calculated from the crop potential transpiration-dependent biomass production, multiplying the biomass-transpiration coefficient with the potential transpiration, the latter divided by the daytime mean atmospheric vapour deficit. This relationship, however, shows an important weakness; at low VPD it predicts infinite growth.
To overcome this problem, a second estimate of unstressed biomass production is calculated multiplying the radiation-use efficiency by the daily amount of crop-intercepted photosynthetically active radiation. During each time step, the potential rate is taken as the minimum between the two potential biomasses. The actual biomass is calculated from the potential biomass for which water or nitrogen limitation determines a reduction.
The increase of leaf area during the vegetative period, expressed as leaf area per unit soil area (leaf area index, *LAI*) is calculated from the model by the ratio between the specific leaf area (*SLA*) and the cumulated aboveground biomass, the latter multiplied by the partitioning coefficient for the biomass of the leaves.
Root growth in CropSyst is described in terms of root depth and root density. Root depth is synchronized with leaf area growth and influenced by water or nitrogen concentration.
Grain yield simulation depends on cumulated

Layer	Depth (m)	Sand (%)	Clay (%)	Silt (%)	Permanent wilt point (m^3/m^3)	Field capacity (m^3/m^3)	Bulk density (t/m^3)	Vol. WC at -1500 J/kg (m^3/m^3)	Vol. WC at -33 J/kg (m^3/m^3)	pH
1	0.20	12.9*	43.7*	43.4*	0.22*	0.44*	1.20*	0.25**	0.41**	8.5*
2	0.40	12.9*	43.7*	43.4*	0.22*	0.44*	1.20*	0.25**	0.41**	8.5*
3	0.60	12.9*	43.7*	43.4*	0.22*	0.44*	1.20*	0.25**	0.41**	8.5*
4	0.70	9.6*	54.6*	35.8*	0.30*	0.44*	1.45*	0.30**	0.44**	8.5*
5	1.13	21.5*	34.6*	43.9*	0.19***	0.35***	1.29***	0.19***	0.35***	8.5*
6	1.35	34.4*	27.7*	37.9*	0.16***	0.30***	1.35***	0.16***	0.30***	8.5*

* Measured

** Computed by CropSyst model from user specified value

*** Estimated from texture

Tab. 1 - Values of parameters, describing the soil characteristics, used to perform the simulation in the study area (Foggia).
Tab. 1 - Valori dei parametri delle caratteristiche del suolo, usati per la simulazione nell'area di studio (Foggia).

plant biomass and the relative harvest index, modified according to the water and nitrogen stress intensity that occur during flowering and grain filling.

The first step adopted by CropSyst to estimate dry biomass is to calculate the potential biomass, deriving from optimal conditions in terms of water supply. Actual biomass is estimated by replacing the potential transpiration (*Tp*) with actual transpiration (*Tact*) as a consequence of water limitation. The ratio between *Tact* and *Tp*, both derived by model outputs, was used to calculate the water stress index (*WSI*), in order to show whether the variation in crop parameters can influence grain yield in relation to different *WSI* levels. If *Tact* fits with *Tp*, the *WSI* is equal to 1 (no stress), whereas the value 0 indicates the maximum stress.

The CropSyst version used for this research was 4.05.05. Durum wheat crop parameters for the Simeto cultivar were obtained from previous calibration activity in the same location (Donatelli *et al.*, 1997; Garofalo *et al.*, 2009).

The yearly output considered in this study were the peak of *LAI*, grain yield, aboveground dry biomass, potential transpiration and actual transpiration. In addition, *WSI* and flowering-maturity duration were also used to evaluate model sensitivity to crop parameter changes.

For each simulation output (100 years), the mean value, standard deviation and coefficient of variation (*CV*) as ratio between standard deviation and mean were calculated.

2.2 Location and climate

The pedo-climatic conditions chosen for this study are representative of the Mediterranean environment, as well as the durum wheat cultivar (Simeto) which is widely used by local farmers.

The site used was near Foggia (Apulia region, Italy; 41° 27' lat. N, 15° 04' long. E, 90 m asl); the soil is a vertisol of alluvial origin, Typic Calcixerert (Soil Taxonomy 10th, USDA, 2006). In Tab.1 the soil crop input for the CropSyst simulation are shown. The climate is "accentuated thermo-Mediterranean" (FAO-UNESCO, 1963) classification, with minimum temperatures below 0 °C in the winter and maximum temperatures above 40 °C in the summer. Annual rainfall (mean 550 mm, considering a 50-year long period) is mostly concentrated during the winter months and class "A pan" evaporation exceeds 10 mm d^{-1} in summer (average of maximum daily values recorded in July and August).

A "*past*" simulation, representing the reference period or the baseline, was carried out with measured daily climatic data (55 years, from 1952 to 2006). A "*future*" long term simulation (100 years) was performed using daily climatic data predicted by the Joint Research Centre (Ispra, Italy) with an HADCM3 global climatic model and IPCC A2 scenario. These data were statistically downscaled to a 50 km grid for a better adaptation to real conditions, from 2000 to 2100 (Pizzigalli *et al.*, 2012). These climatic data were used in previous works at different time frames (30 years) (Rinaldi and De Luca, 2012; Ventrella *et al.*, 2012), but in this specific sensitivity analysis the main focus is about average climatic behaviour of XXI century.

2.3 Crop model traits

Traits concerning wheat drought avoidance and tolerance were examined, as described below, varying one parameter at a time and changing the value for each trait by ± 5, ± 10 and ± 20% of calibrated values.

2.3.1 Specific Leaf Area (SLA)
SLA represents the mean leaf area per unit of dry leaf weight; it measures leaf density or relative thickness (Hunt, 1982). As it is influenced by environment and growth stages, it is a useful variable for characterising the development of photosynthetic apparatus of crop plants. An increase in the leaf area development of a cereal crop is associated with an increment in water use efficiency (Lopez-Castaneda and Richards, 1994). Indeed, an increase in leaf area affects soil surface shading and reduces soil water evaporation, increases weed competition for solar radiation capture (Coleman *et al.*, 2001) and permits a more stable transpiration in case of low pressure deficit (Fischer, 1979). Lopez-Castaneda *et al.* (1995) showed that an increase in *SLA* on wheat was due to leaf area increase more than a reduction of leaf weight; this was accompanied by greater photosynthesis activity, as reported by Richards (2000). Xinyou *et al.* (1999) identified at least three chromosomal regions associated with genotypic variations for *SLA* in barley. Moreover, Rebetzke (2004) indicates that there is the possibility of an increased *SLA* in new wheat genotypes, with a possible variation of about 20%.
The calibrated value of *SLA* was 17 $m^2 kg^{-1}$.

2.3.2 Leaf Duration (LD)
Leaf duration represents the time that elapses between the appearance and senescence of a new green leaf. This parameter, coupled with *SLA*, greatly influences the amount of photosynthetically active leaf dry matter, crucial for solar radiation interception and plant biomass accumulation.
An increase in leaf duration is one of the key strategies used to improve grain yield under water-limited conditions (Triboi and Triboi-Blondel, 2002). Simon (1999) crossed 4 wheat cultivars, observing variations of 33% in leaf duration after breeding between crossed varieties as a consequence of heritability. The same author pointed out that breeding work in improving leaf duration is slow and that consequently, any further research should be carried out in this way.
The effect of leaf duration on yield in wheat was evaluated changing the calibrated value of 720 growing degree days (*GDD*).

2.3.3 Ratio between leaf and stem (RLS)
This parameter adjusts the proportion of cumulative biomass that is partitioned to green leaf area production as the crop accumulates biomass during the active growth stage. It is used to determine the amount of green area index produced in a day. CropSyst, according to the dry biomass calculated in the previous day, estimates the daily green area, using *SLA* and *RLS* coefficients. This parameter is reported as the basis for grain yield production in wheat (Jaradat, 2009). Results for grain yield as a consequence of variations in stem and leaf partition are not easy to predict; a greater allocation of dry matter to the stem could increase the translocation to the grain during the grain filling period. On the other hand, a greater leaf surface would allow a better pattern for light interception and transpiration.
In CropSyst, *RLS* is a coefficient used in the calculation of new green leaf area produced in a day: it is inversely related to green leaf area.
RLS was changed in this simulation by ± 20%, a range that is between the genetic variation in leaf surface observed by Shearman *et al.* (2005) and the genetic variation for stem cumulated dry matter as reported by Jaradat (2009).

2.3.4 Grain filling duration (GFD)
Conflicting results in terms of the beneficial effects on grain yield emerged with regard to the length of the grain filling phase. Evans and Fisher (1999) suggested that an increased grain-filling period is a possible trait to increase wheat yield. By contrast, Ehdaie (1995) showed that there was a negative association between yield and the length of period from anthesis to maturity in different cultivars of wheat. Further, Semenow and Shewry (2011) reported that heat stress around flowering produced significant yield losses in wheat growing in North Europe.
In CropSyst, grain yield is calculated as the biomass at harvest multiplied by the harvest index adjusted for sensitivity to water stress that occurs during grain filling. An increase in the grain filling period potentially enhances the amount of biomass accumulated by the crop by transpiration or intercepted radiation. Generally, grain filling occurs during low water soil storage and/or low water supply and therefore lengthening in this phenological stage may determine a reduction in terms of harvest index.
The grain filling duration was changed by ± 20% using a calibrated value of 560 *GDD*, whereas genetic variations for *GFD* were reported to be ±

40% by various authors (Akkaya *et al.*, 2006; Robert *et al.*, 2001).

2.3.5 Phenological response to water stress (PRWS)

Temperature is the primary environmental factor controlling development of wheat, whereas other factors, such as water, play a secondary but still important role (Bauer *et al.*, 1984; Baker *et al.*, 1986; McMaster, 1997; McMaster *et al.*, 1999). McMaster and Wilhelm (2003) report that several wheat cultivar within a water stress treatment, reached all growth stages earlier under water stressed conditions except for emergence and jointing. Moreover, in almost every case, cultivars achieved each growth stage at different times within a water treatment, with differences among cultivars of 43.8% when referred to a mean value of *GDD* required to attain maturity.

In CropSyst, water stress tends to increase the crop canopy temperature, which may accelerate the accumulation of degree days needed to reach different phenological stages. In particular, this coefficient (set as 1 for the calibrated crop) is a part of the *Tmax* calculation actively perceived by the crop; the greater this value, the quicker the crop reaches different phenological stages.

2.3.6 Maximum root depth (MRD)

Maximum root depth is a crop model parameter that influences water soil extraction from the deepest layers; the model simulates the attainment of this value at the beginning of senescence in unstressed plants and it is used to estimate the effective root depth for each day, taking into account the actual canopy expansion.

As reported by Tripathi and Mishra (1986), wheat root depth can extend more than 1.50 m also in rain-fed conditions. In this sensitivity analysis, *MDR* calibrated value of 1 was changed between 0.8 and 1.2 m.

3. RESULTS

During the wheat growing period it is possible to observe as *future* winter minimum (*Tmin*) and maximum temperature (*Tmax*) are always greater than in the *past*, with a mean temperature (*Tmean*) 1.03 °C higher. In March and April the *past* scenario has a *Tmean* slightly greater than the *future* (0.64, on average), whereas *Tmean* was similar in May. On the contrary, in *future* June, the increase is 1.8 °C for *Tmin* and 2.7 °C for *Tmax*.

Globally, it is possible to assess that during the crop growth season, +1°C is the average increase in term of temperature, compared to the *past*, with the greater raise during the grain filling stage, and cumulated rain predicted by the climatic model is lower than the *past* of only 13 mm.

The first simulation was carried out using the calibrated crop parameters in order to compare "*past*" vs "*future*" climatic scenarios. Daily average temperatures (*Tmean*) in the previous 50 years (*past*) and in the next 100 years (*future*) in the A2 scenario are shown in Fig. 1. From wheat sowing to flowering, the *past* climate was characterized by a *Tmean* slightly lower if compared with *future*; this explains the gap of 11 days between *past* and *future* flowering dates. In the second part of growing cycle, *Tmean* in *past* and *future* scenarios were very similar and the time elapsed from sowing to grain maturity was 147 days in the *past* and 152 in the *future* scenario.

CropSyst simulated in the *future* an average of 2700 kg ha^{-1} (± 383 kg ha^{-1}) of wheat grain yield, slightly greater if compared to 2567 kg ha^{-1}(± 322 kg ha^{-1}) derived from the simulation made for the previous 50 years (*past*). Same trend is reported by Ventrella *et al.* (2012), which indicated wheat yield increment of 11% compared to the baseline, after long term simulation with CERES-wheat model set to future increment in term of T_{max} (projected for 30 years) equal to 2.3 °C. This

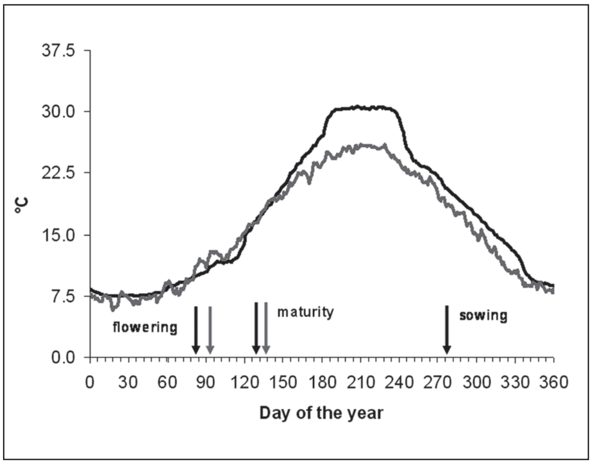

Fig. 1 - Daily mean temperature for the future (black line) and past (gray line). In graph are reported the flowering and grain maturity time, for the future (black arrow) and for the past (gray arrow). Sowing date is the same for all scenarios.
Fig. 1 - Temperatura media giornaliera per il futuro (linea nera) e per il passato (linea grigia). In grafico sono riportate le date di fioritura e maturità, per il futuro (freccia nera) e per il passato (freccia grigia). La data di semina è la stessa per tutti gli scenari.

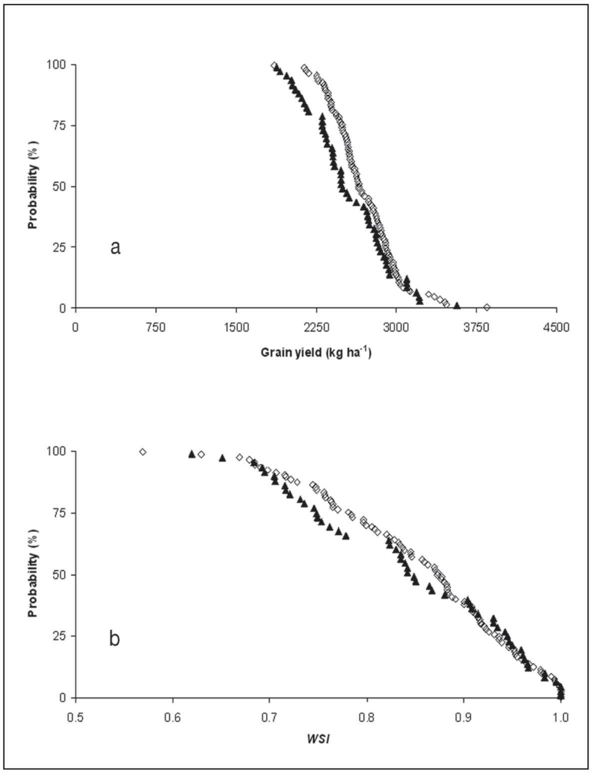

Fig. 2 - Cumulative distribution functions of probability to exceed values of grain yield (a) and Water Stress Index (*WSI*) (b), for the *past* (full triangle) and for the *future* (empty rhombus).
Fig. 2 - Funzioni di distribuzione cumulata della probabilità di eccedere valori di produzione di granella (a) e Water Stress Index (WSI) (b), per il past *(triangolo pieno) e per il* future *(rombo vuoto).*

difference could be explained by the time elapsed between grain filling and grain maturity for both scenarios. In fact, CropSyst estimated 30 vs 33 days for wheat to gain the grain maturity, in the *past* and in the *future*, respectively. As reported in Fig. 2a, the fiftieth percentile oscillates between 2480 for the *past* and 2650 kg ha^{-1} for the *future* while the minimum wheat yield in this environment was similar for both climatic scenarios and equal to about 1800 kg ha^{-1}. This trend is confirmed by the cumulative probability to exceed *WSI* values (Fig. 2b), which shows that for both time series, the actual crop transpiration simulated by the model is always greater than the 60% of potential crop transpiration. Fig. 2b also indicates that for both simulated periods the previously "calibrated" wheat is well suited to this environment, since already at the fiftieth percentile, actual transpiration exceeds 80% of potential transpiration in the *past* and *future* scenarios.

3.1 Specific Leaf Area

Variations in *SLA* determined a high impact on grain yield. In fact, tuning *SLA* from -20% to +20% of input, a large range of variation in grain yield (from -37.8% to 34.7%) was observed, with yield of 2074 and 3027 kg ha^{-1}, respectively (Tab. 2). The coefficient of variation was, respectively, 15.1 and 12.9% for -20% and 20% in *SLA* changes. Moreover, a small variation of this parameter caused significant variations in wheat productivity; a -5% change in *SLA* caused a reduction in yield of about 8.7% if compared with the average yield for the calibrated crop (2701 kg ha^{-1}), whereas an increase in productivity of about 10% was observed if *SLA* was increased of 5%.
Tab. 2 shows that the response of this parameter was influenced by water stress (*Tp* and *Tact*). When the *WSI* is high (*Tact* is different from *Tp*) the yield obtained from the simulation with high *SLA* values was greater if compared with that obtained with calibrated or low *SLA* values (Fig. 3).

3.2 Leaf Duration

The lengthening of the "active" leaves duration during crop cycle produces a delay of senescence and, consequently, has a positive effect in increasing grain yield. In fact, the model simulated a rise of about 20% (3130 kg ha^{-1}) in response to an increase in *LD* of 20%. This linearity is also maintained in the other steps of *LD* variation, whereas an increase of 10% and

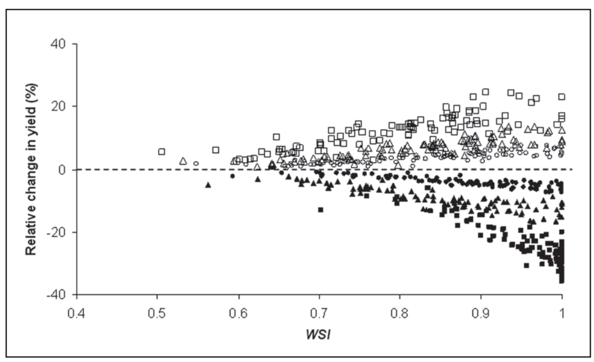

Fig. 3 - Relative change in grain yield in response to a -20% (full square), -10% (full triangle), -5% (full circle), +5% (empty circle), +10% (empty triangle) and +20% (empty square) variation of Specific Leaf Area (*SLA*, base value = 17 kg m^{-2}) versus *WSI* (0 = maximum stress; 1 = no stress).
Fig. 3 - Variazione relativa della produzione di granella in risposta a modificazioni del -20% (quadrato pieno), -10% (triangolo pieno), -5% (cerchio pieno), +5% (cerchio vuoto), +10% (triangolo vuoto) e +20% (quadrato vuoto) dell'Area Fogliare Specifica (SLA, valore di riferimento = 17 kg m^{-2}) rispetto al WSI (0 = massimo stress; 1 = assenza di stress).

Traits	Units and calibrated values	Perturbated values %	Peak of LAI $m^2\ m^{-2}$	Grain yield $kg\ ha^{-1}$	Above ground dry biomass $kg\ ha^{-1}$	Potential transpiration mm	Actual transpiration mm	WSI	Flowering-Maturity days
SLA	***$m^2\ kg^{-1}$ 17***	***-20 (13.6)***	1.6 (13.6)	2074 (15.1)	7000 (15.2)	128 (16.7)	120 (14.8)	0.95 (6.6)	54 (7.9)
		-10 (15.3)	2.0 (10.9)	2443 (12.6)	8264 (12.6)	188 (13.2)	159 (13.7)	0.85 (11.8)	54 (7.9)
		-5 (16.2)	2.3 (9.8)	2591 (12.1)	8783 (11.9)	176 (13.8)	153 (13.5)	0.88 (10.6)	54 (7.9)
		+5 (17.9)	2.8 (8.1)	2804 (12.0)	9541 (11,5)	202 (12.6)	168 (13.7)	0.84 (12.4)	54 (7.8)
		+10 (18.7)	3.0 (7.5)	2884 (12.3)	9829 (11.6)	213 (12.2)	174 (13.9)	0.82 (13.0)	54 (7.8)
		+20 (20.4)	3.4 (6.5)	3027 (12.9)	10354(11.9)	234 (11.5)	185 (14.4)	0.80 (14.0)	54 (7.8)
LD	***°C d 720***	***-20 (576)***	2.3 (9.7)	2177 (12.4)	7380 (12.5)	175 (13.9)	153 (13.5)	0.88 (10.6)	54 (7.9)
		-10 (648)	2.4 (9.2)	2451 (11.8)	8316 (11.6)	183 (13.4)	157 (13.5)	0.86 (11.2)	54 (7.8)
		-5 (684)	2.5 (9.1)	2578 (11.8)	8753 (11.6)	186 (13.3)	159 (13.5)	0.86 (11.5)	54 (7.8)
		+5(756)	2.6 (8.9)	2816 (12.2)	9564 (11.7)	191 (13.4)	161 (13.6)	0.85 (11.7)	54 7.9)
		+10 (792)	2.6 (8.8)	2927 (12.5)	9940 (11.9)	192 (13.0)	162 (13.6)	0.85 (11.8)	54 (7.9)
		+20 (864)	2.6 (8.6)	3130 (13.2)	10633 (12.5)	195 (12.8)	164 (13.6)	0.85 (11.9)	54 (7.8)
RLS	***$m^2\ kg^{-1}$ 3.10***	***-20(2.5)***	2.9 (9.7)	2872 (12.8)	9777 (12.2)	207 (13.1)	170 (14.0)	0.83 (12.8)	54 (7.8)
		-10 (2.8)	2.7 (9.3)	2786 (12.3)	9471 (11.9)	197 (13.1)	165 (13.8)	0.84 (12.2)	54 (7.8)
		-5 (2.9)	2.6 (9.1)	2741 (12.1)	9314 (11.7)	193 (13.2)	163 (13.7)	0.85 (11.8)	54 (7.9)
		+5 (3.3)	2.4 (8.8)	2657 (11.8)	9016 (11.5)	184 (13.2)	158.(13.4)	0.86 (11.2)	54 (7.8)
		+10 (3.4)	2.4 (8.6)	2616 (11.6)	8872 (11.4)	181 (13.2)	156 (13.3)	0.87 (10.9)	54 (7.8)
		+20 (3.7)	2.2 (8.4)	2532 (11.4)	8579 (11.2)	173 (13.2)	152 (13.1)	0.88 (10.3)	54 (7.9)
GFD	***°C d 560***	***-20 (448)***	2.5 (9.0)	2707 (11.0)	9177 (10.9)	170 (13.8)	151 (13.5)	0.89 (10.1)	48 (8.4)
		-10 (504)	2.5 (9.0)	2704 (11.8)	9173 (11.6)	179 (13.3)	156 (13.4)	0.88 (10.9)	51 (8.1)
		-5 (532)	2.5 (9.0)	2702 (11.9)	9171 (11.6)	184 (13.3)	158 (13.5)	0.87 (11.2)	53 (8.0)
		+5 (588)	2.5 (9.0)	2699 (11.9)	9168 (11.6)	194 (13.1)	163 (13.6)	0.85 (12.2)	55 (7.8)
		+10 (616)	2.5 (9.0)	2697 (11.9)	9167 (11.6)	198 (12.9)	165 (13.6)	0.84 (12.3)	57 (7.6)
		+20 (672)	2.5 (11.9)	2694 (11.9)	9164 (11.6)	208 (12.8)	168 (13.8)	0.82 (12.8)	59 (7.4)
PRWS	***- 1***	***-20 (0.8)***	2.5 (9.0)	2701 (11.9)	9170 (11.6)	189 (13.2)	160 (13.5)	0.86 (11.6)	54 (7.8)
		-10 (0.9)	2.5 (9.0)	2701 (11.9)	9170 (11.6)	189 (13.2)	160 (13.5)	0.86 (11.6)	54 (7.8)
		-5 (0.95)	2.5 (9.0)	2701 (11.9)	9170 (11.6)	189 (13.2)	160 (13.5)	0.86 (11.6)	54 (7.8)
		+5 (1.05)	2.5 (9.0)	2700 (11.9)	9170 (11.6)	189 (13.2)	161 (13.6)	0.86 (11.6)	54 (7.9)
		+10 (1.1)	2.5 (9.0)	2700 (11.9)	9169 (11.6)	189 (13.2)	160 (13.5)	0.86 (11.5)	54 (7.9)
		+20 (1.2)	2.5 (9.0)	2700 (11.9)	9169 (11.6)	189 (13.2)	160 (13.5)	0.86 (11.5)	54 (7.8)
MRD	***m 1.0***	***-20 (0.8)***	2.5 (9.1)	2669 (12.3)	9076 (11.8)	188 (13.2)	157 (13.9)	0.84 (12.3)	54 (7.8)
		-10 (0.9)	2.5 (9.0)	2690 (12.0)	9137 (11.7)	188 (13.2)	159 (13.7)	0.85 (11.8)	54 (7.8)
		-5 (0.95)	2.5 (9.0)	2696 (12.0)	9155 (11.6)	189 (13.2)	160 (13.6)	0.85 (11.6)	54 (7.8)
		+5 (1.05)	2.5 (8.9)	2704 (11.9)	9180 (11.6)	189 (13.2)	161 (13.5)	0.86 (11.5)	54 (7.8)
		+10 (1.1)	2.5 (8.9)	2706 (11.9)	9188 (11.5)	189 (13.2)	161 (13.5)	0.86 (11.4)	54 (7.8)
		+20 (1.2)	2.5 (8.9)	2710 (11.8)	9198 (11.5)	189 (13.1)	161 (13.4)	0.86 (11.4)	54 (7.8)
Simulation results with calibrated values			**2.5 (9.0)**	**2701 (11.9)**	**9170 (11.6)**	**189 (13.2)**	**160 (13.5)**	**0.88 (11.5)**	**54 (7.8)**

SLA = Specific Leaf Area; *LD* = Leaf Area Duration; *RLS* = Ratio between Leaf and Stem; *GFD* = Grain Filling Duration; *PRWS* = Phenological response to water stress; *MRD* = Maximum Root Depth; *LAI* = Green Leaf Area Index; *WSI* = Water Stress Index.

Tab. 2 - Mean values and variation coefficients (bracket), for some outputs simulated by CropSyst in 100 years for the future, in response to change in cultivar parameters. For perturbated values in brackets are reported specific values of each traits used in the simulation.

Tab. 2 - Medie e coefficienti di variazione (in parentesi), di alcuni output derivanti dalla simulazione di CropSyst per 100 anni futuri, in risposta della variazione dei parametri colturali. Per i parametri variati (terza colonna) in parentesi sono riportati i valori specifici di ciascun tratto usato nella simulazione.

5% resulted in an average value for grain yield of 2927 and 2816 kg ha^{-1}, respectively (Tab. 2). A decrease of yield of 19.4, 9.3 and 4.5 % if compared with the calibrated crop (2701 kg ha^{-1}) was simulated by the model, consequence to a reduction in *LD* of 20, 10 and 5%, respectively. The variability in grain yield over the years (*CV*) was between 13.2 observed in *LD* +20% and 11.8% recorded in *LD* -10 and -5%; this variation in *LD* did not influence crop *Tp* and *Tact* in any significant way, keeping the *Tp* (175 mm for -20%; 195 mm for 20%) and *Tact* (153 mm for -20%; 164 mm for +20%) close to the values obtained with the calibrated crop parameter (189 mm for *Tp* and 160 mm for *Tact*).
The model used *LD* to calculate the dry biomass gained for every day, but not to estimate the different phases length: consequently, the time elapsed between grain filling and grain maturity resulted similar in the *LD* variation and equal to 54 days.
Fig. 4 shows that increasing water stress (low *WSI*), the crop with high *LD* values produced more yield; for instance, when the *WSI* is approximately 0.6, the crop with *LD* -20% suffered a yield decrease of 10% if compared with the calibrated crop, whereas crops with *LD* +20% showed a relative change in yield of about 7%.

3.3 *Ratio between leaf and stem*

CropSyst simulations reported that at -20% of calibrated value, grain yield increased by 6.3%, whereas an increase at +20% determined a

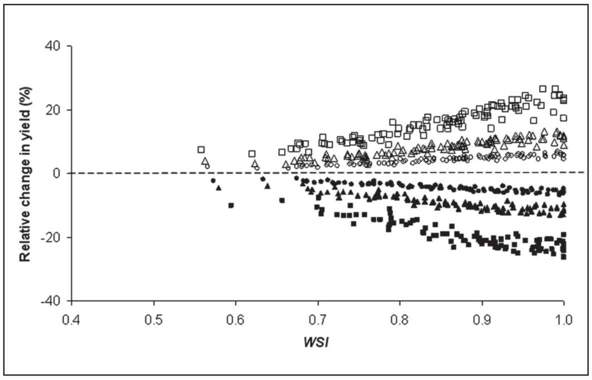

Fig. 4 - Relative change in grain yield in response to a -20% (full square), -10% (full triangle), -5% (full circle), +5% (empty circle), +10% (empty triangle) and +20% (empty square) variation in Leaf area Duration (*LD*, base value = 720 growing degree days) versus *WSI* (0 = maximum stress; 1 = no stress).

Fig. 4 - Variazione relativa della produzione di granella in risposta a modificazioni del -20% (quadrato pieno), -10% (triangolo pieno), -5% (cerchio pieno), +5% (cerchio vuoto), +10% (triangolo vuoto) e +20% (quadrato vuoto) della Durata dell'Area Fogliare (LD, valore di riferimento = 720 gradi giorno) rispetto al WSI (0 = massimo stress; 1 = assenza di stress).

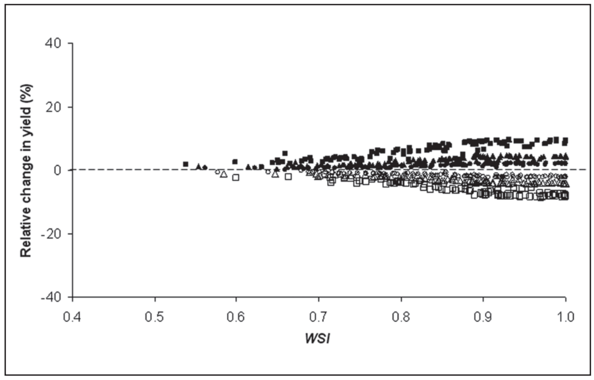

Fig. 5 - Relative change in grain yield in response to a -20% (full square), -10% (full triangle), -5% (full circle), +5% (empty circle), +10% (empty triangle) and +20% (empty square) variation in Ratio between Leaf and Stem (*RLS*, base value = 3.10 m^2 kg^{-1} versus *WSI* (0 = maximum stress; 1 = no stress).

Fig. 5 - Variazione relativa della produzione di granella in risposta a modificazioni del -20% (quadrato pieno), -10% (triangolo pieno), -5% (cerchio pieno), +5% (cerchio vuoto), +10% (triangolo vuoto) e +20% (quadrato vuoto) del Rapporto Area Fogliare/ Peso del Culmo (RLS, valore di riferimento = 3.10 m^2 kg^{-1}) rispetto al WSI (0 = massimo stress; 1 = assenza di stress).

reduction in grain yield of 6.3%. Halving the changed value for *RLS* also halved the relative change in yield (Tab. 2). Thus, the existence of a linear proportionality of *RLS* with grain yield suggests breeding programs improving the wheat plant "stem vs leaves" proportion.

The water stress level influenced productivity at the variation of this parameter very poorly, as reported in Fig. 5; in fact, at high values of water stress (*WSI* between 0.5 and 0.6), the maximum gap in yield between the modified crop (-20 and +20% of *RLS*) and the calibrated crop was only ±2.5%.

3.4 Grain filling duration

This parameter did not influence wheat yield productivity. In fact, considering the two extreme values for attainment of physiological maturity (2204 vs 2428 *GDD*), the yield oscillated between 2707 kg ha^{-1} (*GFD* -20%) and 2694 kg ha^{-1} (*GFD* +20%) (Tab. 2), with *CV* ranging between 10.9 and 11.6 for -20 and 20% in *GFD*, respectively. Variation in time necessary to reach the grain physiological maturity from the start of grain filling, resulted different among wheat trait alterations; 11 days was the maximum gap, observed between -20 and 20% in *GFD*. A reduction in *GFD* had as a consequence the soil moisture preservation, thanks to the less transpired crop water; on average, water saving was about 10 mm, an amount not particularly large, but enough to prevent water stress in the final phase of crop cycle.

The variation in terms of productivity, as a consequence of changes in *WSI*, was the same for all the six levels of modified crop parameter. In fact, the grain yield response, considering the grain filling-maturity stage time, was slightly affected by water stress, but considerably influenced by air temperature. Even though the lengthening of period from grain filling to maturity would let to increase the time to allocate the dry matter to the grain, it is more probable that the crop would suffer for high temperatures. Therefore, the response in term of yield and yield variation compared to the calibrated value at different level of *WSI*, was similar for all perturbed traits.

3.5 Phenological response to water stress

The modification of *PRSW* in the calibrated crop (with 1 as calibrated value) did not produce variation in grain yield (Tab. 2). In fact, grain yield values with the modified *PRSW* were constantly around 2701 kg ha^{-1}, with a *CV* value of 11.9 over the total years; the shortening of crop development due to variations in *PRWS* was only 2 days for flowering, peak *LAI* and

physiological maturity dates between the two extremes (+ and – 20% of *PRWS*). The time from grain filling to maturity remained 54 days, because all phenological stages were shifted among modified traits (Tab. 2). This trend was also confirmed by the yield response to *WSI*, which resulted almost identical in all water stress conditions.
From these observations, it is possible to conclude that wheat crop was yet optimized in breeding programs in Mediterranean environments and it is able to maintain constant production also in drought conditions.

3.6 Maximum root depth
This trait influenced grain yield, especially when it was reduced. If we consider the minimum root length value (0.8 m) set at -20% of the *MRD* calibrated value, the variation in grain yield was -5.0%. This gap was smaller with an increment in *MRD*, with a decrease in grain yield of 2.1% and 0.9% for -10 and -5% variations in *MRD*, respectively, with no water saving in terms of crop consumption (Tab. 2). Increasing the *MRD*, some limited advantages in terms of yield were observed; from 1.5 to 2.6% in grain yield improvement with an *MRD* rise from 5 to 20%.
Despite the fact that the benefits in terms of average yield are not so remarkable, an increase in *MRD* ensured the same level of relative change in yield in response to variations in *WSI* (Fig. 6). This is of particular importance, because in water-limited environments, water stress conditions will become more frequent: thus, a trait that requires improvement in cereal breeding programs is the ability of new varieties to explore a larger soil volume and to extract more water.

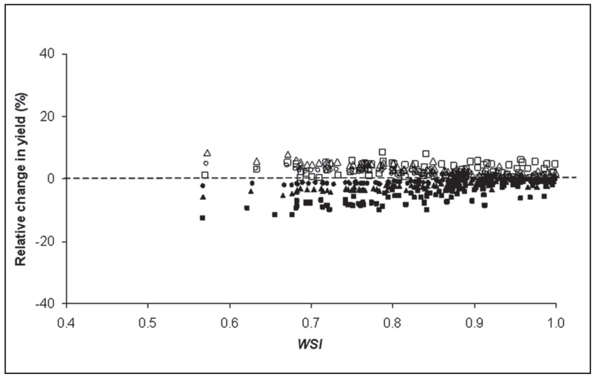

Fig. 6 - Relative change in grain yield in response to a -20% (full square), -10% (full triangle), -5% (full circle), +5% (empty circle), +10% (empty triangle) and +20% (empty square) variation in Maximum Root Depth (*MRD*, base values = 1.0 m) versus *WSI* (0 = maximum stress; 1 = no stress).
Fig. 6 - Variazione relativa della produzione di granella in risposta a modificazioni del -20% (quadrato pieno), -10% (triangolo pieno), -5% (cerchio pieno), +5% (cerchio vuoto), +10% (triangolo vuoto) e +20% (quadrato vuoto) della Massima Profondità Radicale (MRD, valore di riferimento = 1.0 m) rispetto al WSI (0 = massimo stress; 1 = assenza di stress).

4. DISCUSSION

The sensitivity analysis carried out with future climatic data allowed to assess the genetic wheat traits more sensitive in grain yield forecasting and water supply conditions.
SLA, *LD* and *RLS* were the traits whose alteration produced the greatest impact on grain yield. These traits modified leaf activity, increasing the surface (as in the case of *SLA*), renewing the leaves (*RLS*) or extending the biomass accumulation period through the lengthening of leaf vitality (*LD*).
The greatest contribution of *SLA* in raising wheat grain yield is the increase of water transpired by the crop; at a constant value of transpiration water efficiency (implemented as a crop parameter), the cumulated biomass is linearly related to water use. At *SLA* +20%, both *Tp* and *Tact* increased by 24% and 15%, respectively, a small change if compared with the *Tact* reported for the calibrated crop (160 mm, Tab. 2), but enough to raise grain yield by 12%. This improvement in productivity is greater than that reported by Semenov (2009) in England and Wales, where an increase or reduction in leaf surface area did not seem to introduce benefits for the wheat yield. Compared to the calibrated crop, wheat with a higher *SLA* can adapt better to the *WSI*; in the same stress conditions, plants with a greater *SLA* are able to extract more water if compared with the calibrated crop, with a rise in yield productivity at the same level as *WSI*.
Tp and *Tact* were similar in calibrated and modified crop when *RLS* value was reduced. However, the improvement in simulated grain yield was significant. The leaf surface area responds to changes in *RLS* and this outcomes a faster emission of new green leaves, consequence of new cumulated biomass. At high levels of water stress simulated by the model, calibrated and *RLS* modified crops showed the same yield response, because the green leaves reduced photosynthetic activity and, consequently, new biomass for crop growth and leaf emission; however, at optimal levels of water supply, more green leaves mean greater productivity.

The observations on wheat showed that cultivars with a "stay-green" trait let the plant to maintain more green leaves, especially in a post-anthesis phase and/or in drought conditions. Furthermore, they have a high grain yield and biomass (Christopher *et al.*, 2008; Foulkes *et al.*, 2007; Richards, 2006). Increasing *LD*, CropSyst simulations confirmed the results reported in literature, also in cases with lower values of *WSI* (greater water stress).

Traits that could vary the phenological length of crop cycle in response to water stress (*PRWS*) or part of it (*GFD*) did not produce significant variations in grain yield, also as a consequence of different *WSI*. Foulkes *et al.*, (2007) reported similar results for two populations of wheat under drought conditions, whose variations in yield were not correlated to variations in flowering or grain filling dates in response to water stress. Similar conclusions, in a study on the response of wheat productivity to variations in simple traits, were obtained by Semenov (2009) using pedo-climatic data from two locations in the UK and Spain. On the contrary, Ehdaie (1995) showed that there was a negative correlation between yield and the length of the period from anthesis to maturity among eight wheat cultivars under water-deficit conditions. Similarly, Sinclair and Muchow (2001), reported that shortening the crop growth duration of maize caused a significant decrement in grain yield. Our opinion is that Simeto wheat cultivar characteristics had been well fitted for Southern Italy environment, with an optimal phenology under existing conditions; current climatic conditions, probably, already correspond to an extreme condition for the crop, already adapted to this environment. Therefore, the climate change predicted for the *future*, with a global warming of about +2°C, would not result in variations on the final yield, also in response to variations in *WSI*.

Changing the maximum root depth, some advantages were achieved in the model simulation; increasing the *MRD*, wheat *Tp* and *Tact* did not change, since the largest amount of water extraction occurred in the first 0.8 m of soil depth (not shown) due to the root density distribution simulated by CropSyst. Besides, root water conductance is linked to fraction cover and so an increase in water availability does not correspond to a proportional increment in water transpired by the crop, if this is not allowed by a higher transpiring plant surface. The effects of *MRD* were slightly more effective in the *future* years when water stress will be more severe.

5. CONCLUSIONS

From this work, some consideration about the main traits that should be considered in durum wheat breeding programs emerged; the specific leaf area, the leaf area duration and the ratio between leaf and stem dry matter partition resulted the more sensitive traits on grain yield. However, it is necessary to underline that the phenotypical crop response is a consequence of an interaction between genetic traits and the environment where these traits are emphasized; the environment could shift genetic breeding work on some determined traits rather than others; alternatively, agronomical practices could improve the final yield. For this reason, it would be useful to introduce in the simulations also variations in the pedo-climatic conditions and agronomical practices, in order to examine the responses of variation of genetic traits to a larger range of combinations and so, to suggest the best breeding programs.

Finally, a more multi-disciplinary approach is also desirable (agronomists, breeders, plant physiologists) to better adapt crop genotypes to future climate changes.

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