Consumptive use of green and blue water for winter durum wheat cultivated in Southern Italy

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4 authors:

Domenico Ventrella
Council for Agricultural Research and Agricultural Economy Analysis

Luisa Giglio
Council for Agricultural Research and Agricultural Economy Analysis

Monia Charfeddine
Council for Agricultural Research and Agricultural Economy Analysis

Anna Dalla Marta
University of Florence

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Domenico Ventrella[1,*], *Luisa Giglio*[1], *Monia Charfeddine*[1], *Anna Dalla Marta*[2]

Abstract: *In this study at the regional scale, the model DSSAT CERES-Wheat was applied in order to simulate the cultivation of winter durum wheat (WW) and to estimate the green water (GW) and the blue water (BW) through a dual-step approach (with and without supplemental irrigation). The model simulation covered a period of 30 years for three scenarios including a reference period and two future scenarios based on forecasted global average temperature increase of 2 and 5 °C. The GW and BW contribution for evapotranspiration requirement is presented and analyzed on a distributed scale related to the Puglia region (Southern Italy) characterized by high evaporative demand of the atmosphere. The GW component was dominant compared to BW, covering almost 90% of the ETc of WW. Under a Baseline scenario the weight BW was 11%, slightly increased in the future scenarios. GW appeared dependent on the spatial and temporal distribution of rainfall during the crop cycle, and to the hydraulic characteristics of soil for each calculation unit. After considering the effects of climate change on irrigation requirement of WW we carried out an example of analysis in order to verify the economic benefit of supplemental irrigation for WW cultivation. The probability that irrigation generates a negative or zero income ranged between 55 and 60% and climate change did not impact the profitability of irrigation for WW as simulated for the economic and agro-pedoclimatic conditions of Puglia region considered in this study.*
Keywords: *irrigation, water productivity, model simulation, climate change.*

Riassunto: *In questo studio realizzato su scala distribuita il modello DSSAT CERES-Wheat è stato utilizzato per simulare la produzione di frumento duro e stimare i consumi di "green water" (GW) e "blue water" (BW) mediante un approccio a 2 stadi basato su simulazioni effettuate con e senza irrigazione di soccorso. La simulazione ha coperto un intervallo di 30 anni per tre scenari climatici riguardanti una situazione di riferimento (passato) e due scenari futuri caratterizzati ad un incremento di temperatura media globale di 2 e 5 °C.*
In questo articolo i consumi di GW e BW sono stati presentati ed analizzati su scala regionale riguardante la regione Puglia (Sud Italia) caratterizzata da un'alta domanda evaporativa dell'atmosfera. La componente di GW è risultata predominante rispetto al consumo di BW, coprendo quasi il 90% dell'ETc del frumento. Nello scenario di riferimento la BW è stata dell'11% aumentando leggermente negli scenari futuri. GW è apparsa dipendere dalla distribuzione spaziale e temporale delle piogge ma anche dalle caratteristiche idrauliche dei suoli di ogni unità di calcolo. Dopo aver considerato la probabilità che i cambiamenti climatici determinino un aumento dei fabbisogni irrigui del frumento, si è effettuata un'analisi per verificare la convenienza economica dell'irrigazione di soccorso al frumento duro. La probabilità che l'irrigazione abbia una redditività nulla o negativa è risultata compresa fra il 55 e il 60% e i cambiamenti climatici non hanno modificato questo parametro, almeno per le condizioni economiche e agro-pedoclimatiche considerate per la Puglia in questo studio.
Parole chiave: *irrigazione, produttività dell'acqua, modello di simulazione, cambiamenti climatici.*

1. INTRODUCTION

The latest IPCC Assessment Reports (IPCC, 2007 and 2014) showed a likely increase in global temperatures during the 1906-2005 period, and demonstrated that this change is largely due to increased atmospheric concentration of Green House Gases (GHGs). Both observed data and simulations of future climate conditions indicated that the effect of global warming is and will also likely be even more unequally distributed around the globe. As a consequence, some areas are likely to be much more affected by climate change than others, and in view of such proiections special attention should be paid to the Mediterranean region.

In fact, the Mediterranean region has been defined as a possible hotspot for the decades to come, by both increasing temperatures and by relatively large changes in the frequency of extreme climatic events, with relevant impacts on agricultural production (Giorgi, 2006; Saadi *et al.*, 2015). The amount of rainfall per event has been shown to be increasing, and changes in the distribution of seasonal rainfall

* Corresponding author's e-mail: domenico.ventrella@entecra.it
[1] Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria - Unità di ricerca per i sistemi colturali degli ambienti caldo aridi, 70125 Bari.
[2] Università degli Studi Firenze - Dipartimento di Scienze delle Produzioni Agroalimentari e dell'Ambiente, 50144 Firenze.
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have also been recorded (Kharin *et al.*, 2013; Toreti *et al.*, 2013; Paxian *et al.*, 2014).
The impacts of climate change could cause water availability to reach critical limits in many areas of Southern Europe, and exert manifold adverse effects on crops productivity and quality.
Considering the socio-economic importance of agricultural activity, it is fundamental to assess the effects of future climate change on crop yield (Bindi and Olesen, 2011). For this purpose, crop growth simulation models have been widely used (Donatelli *et al.*, 2002) as these tools allow to evaluate the crop responses to climate change by combining different climate conditions, fertilizations, CO_2 physiological effects, and agronomic scenarios as derived from crop experiments (Ainsworth and Long, 2005; Kimball *et al.*, 2002).
Many crop simulation studies have been carried out on major crops (soft wheat, maize, potato, rice, etc.), but only a few studies have focused on typical Mediterranean crops like durum wheat, vegetables, olive, grapevine, etc. (Ventrella *et al.*, 2012; Ferrise *et al.*, 2011; Moriondo *et al.*, 2010, 2011; Guereña *et al.*, 2001; Giannakopoulos *et al.*, 2009; Bindi *et al.*, 1996).
Among crop simulation models used for assessing the impact of climate change on agricultural crops, the DSSAT model (Jones *et al.*, 2003) has been the most successfully used worldwide over the last years (Dettori *et al.*, 2011; Jin and Zhu, 2008; Soltani and Hoogenboom, 2007; Alexandrov and Eitzinger, 2005; among the others).
Globally, crop evapotranspiration has increased with the expansion of agricultural lands, and irrigated areas in particular (Klein Goldewijk and Ramankutty, 2004). According to Siebert and Doll (2010), we define the consumptive blue water (BW) as the amount of crop evapotranspiration stemming from irrigation. This water is withdrawn from surface or subsurface water bodies (e.g. streams, reservoirs, etc.). The green water (GW) use is the crop evapotranspiration stemming from rain infiltrated on soil. So, the total crop water use is the sum of blue and green water use and corresponds to the total actual crop evapotranspiration.
The assessment of GW and BW for a determined cropping system or crop species is a fundamental step in order to define the virtual water flows from the area where the crop is cultivated to the region where the crop is processed or consumed. In fact, due to the increasingly global food trade, growing world population, climate change and increasing water scarcity, virtual water trade provides a renewed water management perspective. In this view, the access to water resources is not limited anymore by the boundaries of the watershed or country in which people are living, but such virtual water flow is likely to increase the dependence on external resources. Moreover some populations may not be able to access this trade for economic reasons.
Another important aspect of the GW/BW approach concerns the planning of a sustainable use of water resources in agriculture, a sector in which water is a fundamental productive factor and is increasingly becoming a limiting resource due to climate change. In this context, the concept of the water footprint (WF) has gained global recognition. The water footprint is an indicator of freshwater use that looks at both direct and indirect water use of a consumer or producer. The water footprint is defined as the total volume of freshwater used to produce the goods and services consumed by the individual or community or produced by the business. Water use is measured in terms of water volumes consumed (evaporated or incorporated into a product) and/or polluted per unit of time (Hoekstra *et al.*, 2011).
The WF of a crop is defined as the ratio between the evapotranspiration (ET) and the crop yield, computed over the cropping period (Hoekstra *et al.*, 2011). The green and blue component in the water footprint of a crop (WFg and WFb, respectively; $m^3\ t^{-1}$) is calculated as the green and blue component in crop water use (CWUg and CWUb, respectively; $m^3\ ha^{-1}$) divided by the crop yield (Y, $t\ ha^{-1}$), according to Hoekstra *et al.*, 2009. The green and blue com-ponents in crop water use are calculated by accumulation of daily evapotranspiration (mm day^{-1}) over the total growing period.
Many studies reported the water footprint of different crop such as rice (Chapagain and Hoekstra, 2010), cotton (Chapagain *et al.*, 2006), tomato (Chapagain and Orr, 2009), tea and coffee (Chapagain and Hoekstra, 2007), wheat (Yang *et al.*, 2011) and energy crops (Dalla Marta *et al.*, 2012); Gerbens-Leenes *et al.*, 2009). Although the number of research activities related to the assessment of food and no-food crop water footprints is steadily increasing, a few of them have addressed the question how it is affected by climate variability and projected future climatic conditions.
The assessment of how much GW the environment can provide to the crop and how much BW is necessary to match the evapotranspiration requirements of a specific crop species to a given environment and period, may be of fundamental

importance both for planning the use of water resources at the local level. Moreover, the repartition of the crop evapotranspiration in a given environment can also be very useful to compare different agriculture management options and to identify those allowing a high utilization of GW, thus maximizing the water use efficiency both in terms of GW and BW.

Building on these premises, this study aims at evaluating the impact of climate change on water use of winter durum wheat cultivated in Southern Italy with particular reference to the consumptive use of green and blue water and to water footprint. Moreover, an example of analysis was carried out to evaluate the economic benefit of supplemental irrigation in winter durum wheat in Puglia Region.

2. MATERIAL AND METHODS

The study focused on Puglia (Southern Italy), a region of approximately 19.000 km^2 and strategically important for agriculture. Winter durum wheat (WW: *Triticum turgidum* L., subs. durum [Desf.]) is one of the most important herbaceous crops cultivated in the Puglia region.

The software AEGIS/WIN, a GIS interface implemented into the model DSSAT v.4.5, was applied in order to simulate the growth and the productivity of WW in the agricultural lands of Puglia potentially cultivated to WW, according to the land use map.

CERES-Wheat is a primary crop model in the DSSAT software package and is one of the most physiologically based agronomic models currently available. It simulates the impacts of weather, soil properties, genotype and management options on daily crop phenological development and growth, as well as on the dynamics of soil water and nitrogen. It calculates potential biomass accumulation as the product of radiation use efficiency and intercepted photosynthetically active radiation (PAR). In this study, the Priestley and Taylor equation to estimate potential evapotranspiration was used.

DSSAT based on the CERES model was calibrated and validated in the test area for winter durum wheat (cv. Simeto; Rinaldi 2001).

The AEGIS/WIN-DSSAT platform was applied to Puglia on 189 calculation units based on the overlay of geographical information on soil (ACLA2, 2001), land use (Sigria, 2002), and climate.

Puglia has a typically Mediterranean climate with temperatures that may fall below 0 °C in winter (in the Northern part or hills) and exceed 40 °C in summer. Annual rainfall ranges between 400 and 550 mm, but it is mostly concentrated during the winter.

For the 1975–2005 time period, observed daily data (Tmin, Tmax, rainfall and global solar radiation) were extracted for six cells (50 x 50 km) from the MARS JRC archive (MARS project http://mars.jrc.ec.europa.eu/). For future climate estimates, time slices were centered over the 2030–2059 (+2 °C) and 2070-2099 (+5 °C) time periods, respectively. Daily data were obtained from HadCM3 experiment for the A2 SRES IPCC (New 2005).

To overcome the problem of the coarse original HadCM3 GCM resolution, a statistical downscaling procedure based on the LARS Weather Generator (Semenov and Barrow 1997; Semenov 2007) was adopted for producing synthetic daily weather data representing the +2 °C (A_2) and +5 °C (A_5) future scenarios. In order to consider the CO_2 fertilization effect, three increasing atmospheric concentrations were selected: 360, 550 and 700 ppm for the 1975-2005 period (Baseline), A_2 and A_5, respectively.

According to Siebert and Doll (2010), the consumptive use of GW and BW was obtained from the soil/plant water balance as simulated by DSSAT in two steps considering two cropping systems based on WW cultivated in rainfed and irrigated regimes. As first step we considered the rainfed condition and the GW was set equal to the actual evapotranspiration without irrigation (ETc_{no_irr}):

$$GW = ETc_{no\_irr} \quad \text{(Eq. 1)}$$

The adoption of irrigation was considered in the second simulation, which was equal to first step but including irrigation. In such case, the evapotranspiration (ETc_{irr}) came from rain and irrigation and then we can write the following equation to estimate BW:

$$BW = ETc_{irr} - GW \quad \text{(Eq. 2)}$$

Consequently, the actual evapotranspiration is the sum of GW and BW.

Supplemental irrigation was considered where the irrigation events (IE) were carried out to restore the soil water content to field capacity when the crop available soil water was depleted for 80%. In such way we could simulate irrigation only in dry spring periods (April and May) allowing very few IE per year.

The water footprint (WF) related to rainfed and irrigated WW (WF_{rain} and WF_{irr}, respectively) was expressed in terms of t m^{-3} and calculated with following equations considering the dry matter of WW yield simulated in rainfed and irrigated condition (Y_{rain} and Y_{irr}, respectively):

$$WF_{rain} = WFg = \frac{GW}{Y_{rain}} \quad \text{(Eq. 3)}$$

$$WF_{irr} = WFg + WFb = \frac{GW}{Y_{irr}} + \frac{BW}{Y_{irr}} \quad \text{(Eq. 4)}$$

Finally the water productivity (kg m^{-3}) for BW (WPb) was calculated with:

$$WPb = \frac{Y_{irr} - Y_{rain}}{BW} \quad \text{(Eq. 5)}$$

3. RESULTS AND DISCUSSION

3.1. Green and Blue water

Tab. 1 shows the simulated values of rainfall, irrigation, GW and BW, as key components of the water balance of the soil/plant system under the three climate scenarios considered in this study. The rainfall appears to be underestimated compared to the long-term mean of the Puglia region. Boenzi *et al.*, (2007) reported an average of annual precipitation of about 640 mm for 1951-2003 period in 81 agrometeorological stations homogeneously distributed in the region. Considering the flat area, the long-term annual rainfall is about 550 mm. Such underestimation introduces an element of uncertainty that has to be considered. However, we are primarily interested in the relative variations observed in future scenarios compared to Baseline and less to the absolute values. In fact, starting from about 300 mm of Baseline, the rainfall was reduced by 5 and 12% under A_2 and A_5, respectively. Moreover, Tab. 1 shows a significant reduction in the variability of seasonal rainfall with the standard deviation reduced on average by 18% in the two future scenarios compared to Baseline.

Because of the expected increase in evaporative demand due to higher temperatures and rainfall reduction, the irrigation requirement was expected to increase for both the future scenarios from about 60 mm of Baseline to 76 mm (+30%). This variation has mainly affected the mean irrigation depth while the frequency has been equal to 1-2 irrigations per year regardless of climatic scenario.

As expected, the GW component was larger than the BW, covering almost 90% of the ETc of WW. Under Baseline scenario the weight of BW was 11%, slightly increasing in A_2 (13%) and A_5 (14%) scenarios. Obviously, GW and BW were found to have the same trends as rainfall and irrigation, respectively, and also the variability of GW decreased from Baseline to A_2 and A_5 similar to the rainfall.

Moreover, GW appeared dependent on the spatial and temporal distribution of rainfall during the crop cycle, but also on the hydraulic characteristics of soils corresponding to each calculation unit.

Average annual values of GW and BW simulated under Baseline scenario were grouped into 4 equiprobable classes (0-0.25 (low), 0.25-0.5 (medium-low), 0.5-0.75 (medium-high) and 0.75-1 (high)) and reported on a distribution map (Fig. 1). Under the Baseline scenario, 50% of the areas with the highest consumptive use of GW were concentrated in the areas indicated in Fig. 1 as GW1, GW2 and GW3 in the northern, central and southern part of Puglia, respectively. In the future scenarios, this distribution pattern was the same and the location of these areas almost unchanged.

Scenarios	Rainfall (mm)		Irrigation (mm)		GW (mm)		BW (mm)		Grain yield (t ha^{-1})			
									Rainfed		Irrigated	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Baseline	308.15	118.48	59.46	51.23	231.61	67.44	27.88	27.60	2.02	1.53	2.32	1.54
A_2	291.43	88.00	76.91	53.87	226.59	50.11	35.28	27.56	2.98	1.52	3.42	1.30
A_5	271.76	97.48	75.23	54.40	200.78	46.45	32.36	27.12	3.07	1.36	3.41	1.09

Tab. 1 - Mean (M) and standard deviation (SD) of rainfall occurred during crop cycle, irrigation, consumptive use of Green Water (GW) and Blue Water (BW) and grain yield of winter durum wheat (rainfed and irrigated) under the three scenarios.
Tab. 1 - Media (M) e deviazione standard (SD) della pioggia caduta durante il ciclo colturale, irrigazione, consumo di "Green Water" (GW) e "Blue Water" (BW) e resa in granella del frumento duro nei tre scenari.

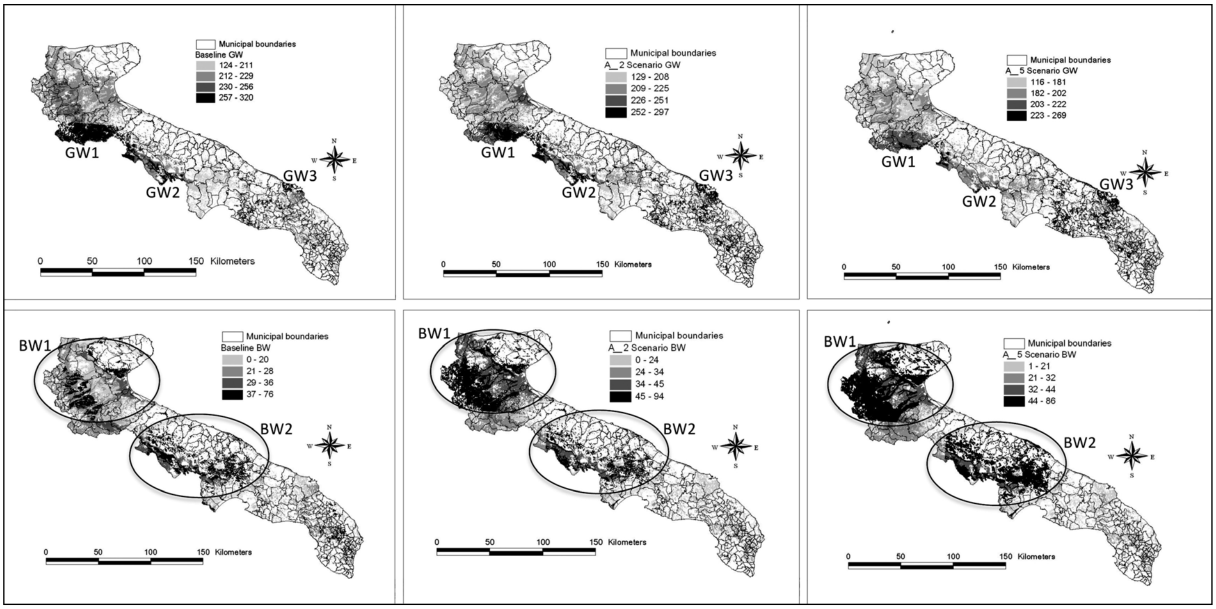

Fig. 1 - Spatial distribution of the simulated consumptive use of GW and BW aggregated into four equiprobable classes under the three climatic scenarios. GW1, GW2, GW3 and BW1, BW2 indicate areas with the highest consumptive use of GW and BW, respectively.
Fig. 1 - Distribuzione spaziale dei consumi di GW e BW aggregati in quattro classi equiprobabili nei tre scenari climatici. GW1, GW2, GW3 e BW1, BW2 indicano aree con consumi più elevate di GW e BW, rispettivamente.

Instead, in areas characterized by low values of GW, our simulations have forecasted higher BW values. The analysis of spatial data allowed us to identify two areas, reported in Fig. 1 as BW1 and BW2 and located in the northern and central part of the region. In these areas the consumptive use of BW was up to 76 and 90 mm under Baseline and future scenarios, respectively. Also for BW the distribution pattern was similar in Baseline, A_2 and A_5. However under future scenarios compared to Baseline, some areas had a higher consumptive use of BW rising from the classes with low or medium-low consumptive use of BW (first two quantiles) to the two upper classes and this spatial concentration was highest under A_5, as indicated by the dark spots in BW1 and BW2.

3.2. Winter Wheat Yield

The average WW simulated yield was very similar to the actual crop production recorded in Puglia region during the last 10 years (about 2.2 ± 0.8 t ha^{-1}) (Istat, 2014). The difference of 0.2 t ha^{-1} between simulated end measured yield was statistically not significant according to "T-Test" applying the "Pooled" and "Satterthwaite" methods (SAS, 2000) with P>|T| equal to 0.4319 and 0.4151, respectively. The supplemental irrigation led to a yield increase of about 15% (under Baseline and A_2) and 11% under A_5 (Tab. 1).

Compared to the Baseline, there was also a significant increase of WW yield under the two future scenarios (Tab. 1). However these results depend on how the simulation model takes into account the effect of increased CO_2 on plant productivity. When such increase was not taken into account, CERES-Wheat simulated a yield decrease of about 5% under A_2 and 20% under A_5 as an effect of climate change (data not shown).

On the contrary, when the model was set to include the CO_2 fertilization, the negative effect on crop yield (about 3 t ha^{-1}, data not shown) due to the forecasted higher temperatures was completely counterbalanced. In other words, this aspect becomes an important element of uncertainty depending on how the models are able to describe the effects of increased CO_2 concentrations on crop growth and yield. Another important aspect is related to the ability of the models to capture the effect of CO_2 on plant physiology and especially on stomata activity. In fact, an increase of CO_2 concentration can affect their conductivity causing evapotranspiration, so that water losses rise.

The latest IPCC reports (2007 and 2014) indicated how +2 °C should be considered a threshold level beyond which the impacts of climate change will remain minimal in many areas of the globe for many agricultural crops. Attri and Rathore (2003) reported different wheat genotype responses under climate change in rainfed and irrigated conditions, while Ferrise *et al.*, (2011) found that for the entire Mediterranean basin, the projected warmer and drier climate is predicted to increase the risk of yield losses especially for temperature increases exceeding 2 °C. However, these studies were focused on the effect of climate change on wheat yields without considering the interactions with adaptation strategies, such as irrigation, that can modify the crop response.

For the middle Egypt area under A2 and B2 climate change scenarios, El Afandi *et al.*, (2010) reported that the adoption of correct irrigation scheduling might be used to reduce the negative impact on wheat yields due to higher temperature and lower rainfall.

The range of crop yield in which the irrigation exerted its positive effect can be described by yield probability functions (Fig. 2). Under Baseline scenario the irrigation was effective to increase the WW yield in a fairly uniform way up to about 4 t ha^{-1}. Instead, under A_2 and A_5 scenarios, the irrigation significantly contributed to increasing the WW yield in low productivity situations and this effect held out to decline to productive levels of 2 t ha^{-1}, confirming the usefulness of supplemental irrigation that could help to recover the WW yield in dry years of future scenarios.

3.3. Water Footprint

The impacts of future climate on water footprint, considering the GW and BW and the agronomic options to cultivate the WW in rainfed and irrigated regimes, were also investigated (Tab. 2 and Fig. 3).

In general, water footprint values obtained under Baseline scenario were rather high compared to literature. In fact, green and blue WFs were almost doubled compared to global averages (1277 and 342 m^3 t^{-1}, respectively) reported by Mekonnen and Hoekstra (2011) and to values for Mediterranean environment indicated by Ruini *et al.*, (2013).

Under irrigated conditions, the obtained higher yields led to a decrease of the total WF of about 20% under Baseline and A_2 and 13% under A_5. Despite this effect, the values remained fairly high.

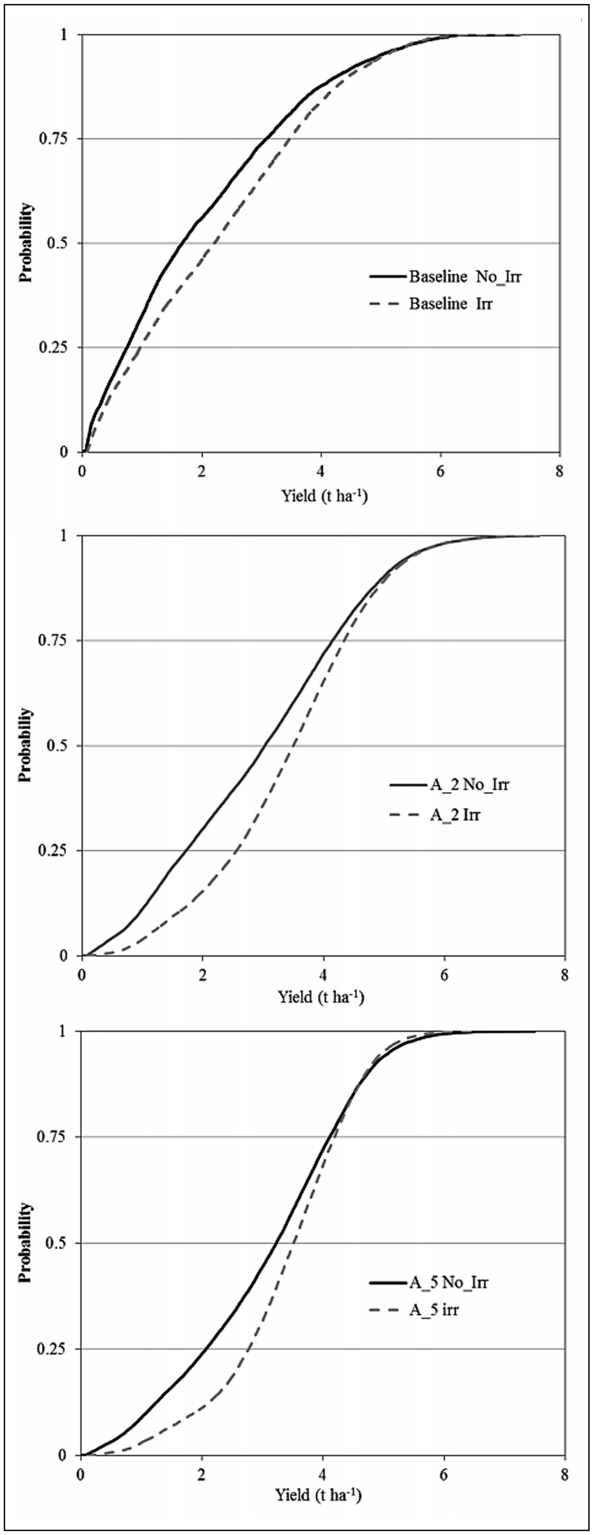

Fig. 2 - Cumulated probability function of winter wheat yield simulated in rainfed (No_Irr) and irrigated conditions (Irr) under the three scenarios.
Fig. 2 - Funzioni di probabilità cumulate delle rese di frumento duro in regime non-irriguo (No_Irr) ed irriguo (Irr) nei tre scenari.

SCENARIO	WF_{rain}		WF_{irr}		WFg		WFb		WPb	
	M	SD	M	SD	M	SD	M	SD	M	SD
Baseline	2718	3695	2193	2597	2019	2530	174	550	0.94	4.73
A_2	1136	1306	905	590	781	554	124	135	0.95	4.23
A_5	884	907	767	380	658	373	109	124	0.53	5.22

Tab. 2 - Water footprint (m^3 t^{-1}) of winter durum wheat cultivated in rainfed (WF_{rain}) and irrigated (WF_{irr}) regime and water productivity of blue water component (WPb: kg m^{-3}). WFirr is divided into green (WFg) and blue (WFb) components.
Tab. 2 - Water footprint (m^3 t^{-1}) del frumento duro coltivato in regime non-irriguo (WF_{rain}) ed irriguo (WF_{irr}) e produttività della "blue water" (WPb: kg m^{-3}). WFirr è ripartito nelle componenti relative alla "green water" (WFg) e "blue water" (WFb).

As expected, the green WF decreased in favor of the blue component. It has to be pointed out that the obtained WFs were affected by a certain level of uncertainty, as demonstrated by the high values of standard deviations.
On the other hand, both green and blue WFs under A_2 scenario seem to align towards global and national averages reported in literature. Compared to Baseline scenario, the reduction of WF_{irr} is 59 and 65% under A_2 and A_5, respectively. The lowest values of 660 and 110 m^3 t^{-1} (WFg and WFb, respectively) were obtained under A_5 scenario. This contraction was mainly due to the significant increase of crop yield simulated under climate change scenarios considered. Nevertheless, as demonstrated by the marginal productivity of blue water, the efficiency of the applied water decreased dramatically (- 43%) going from Baseline to A_5, while no contraction was detected under A_2. This should be carefully

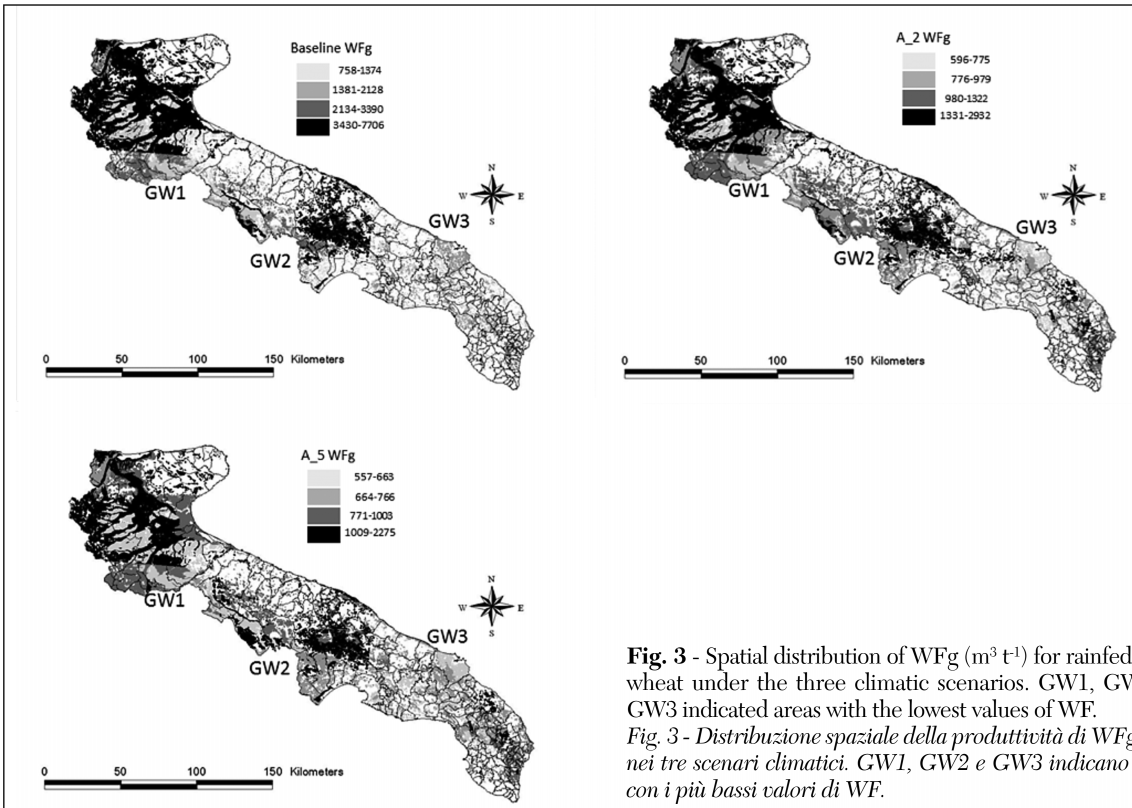

Fig. 3 - Spatial distribution of WFg (m^3 t^{-1}) for rainfed winter wheat under the three climatic scenarios. GW1, GW2 and GW3 indicated areas with the lowest values of WF.
Fig. 3 - Distribuzione spaziale della produttività di WFg(m^3 t^{-1}) nei tre scenari climatici. GW1, GW2 e GW3 indicano le aree con i più bassi valori di WF.

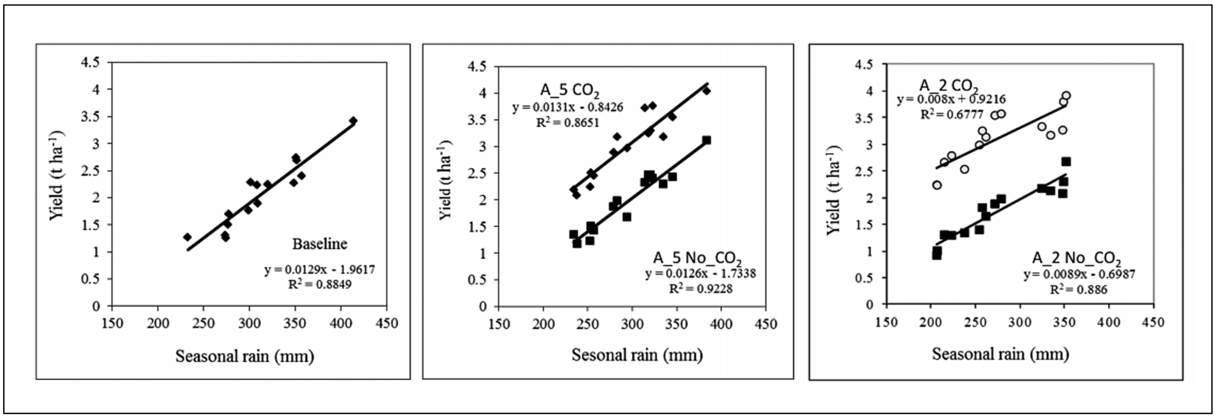

Fig. 4 - Relationship between yield and seasonal rainfall under Baseline, A_2 and A_5 scenario (with and without the fertilization effect of CO_2).
Fig. 4 - Relazione tra resa e pioggia nello scenario di riferimento (Baseline), A_2 e A_5 (con e senza l'effetto fertilizzante della CO_2).

considered when planning supplemental irrigation. The supplemental irrigation and climate change resulted also in a significant reduction of the variability of WF. In average, the variation coefficients were 118% and 77% under rainfed and irrigated regimes. Considering the effect of climate change on WF variability, Tab. 2 shows that such contraction was higher for WFg than WFb. Indeed, the correspondent variation coefficients for GW decreased going from Baseline (125%) to A_2 (70%) and A_5 (56%).
The three areas characterized by high consumptive use of GW (Fig. 1) are also highlighted in Fig. 3 because of their lowest WFg with their values included in the first two quartiles.
The importance of GW, and consequently of rainfall, is also demonstrated by the relationship between yield and seasonal precipitation (with and without CO_2 effect under A_2 and A_5) as simulated in rainfed regime (Fig. 4). The relationships are always linear showing that the main limiting factor for WW yield in Puglia remains the rainfall. In fact, high and sustainable yield would be possible when seasonal rainfall catch up 350 mm, regardless of climate scenarios considered.

3.4. Irrigation and income

The histogram of Fig. 5 shows how the irrigation practice adopted for WW in Southern Italy could be expected to intensify with climate change. Under Baseline, the probability not to carry out irrigation was higher than 20%. Moreover, in the 40% of cases the irrigation was between 50 and 150 mm. However, under A_2 and A_5 the no irrigation probability decreased to 13% in average,

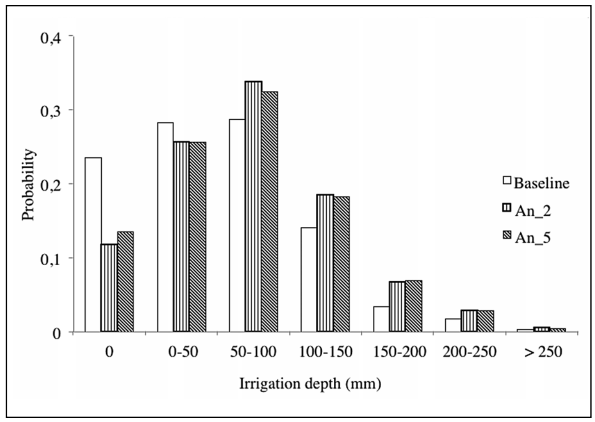

Fig. 5 - Probability distribution of annual irrigation depths aggregated in seven frequency classes under the three climatic scenarios.
Fig. 5 - Distribuzione di probabilità dell'altezza annuale di irrigazione aggregata in sette classi di frequenza nei tre scenari climatici.

while that related to irrigation of 50-150 mm increased to 50%.
After evaluating the effects of CC on WW irrigation requirement from a climatic point of view, the economic impact of supplemental irrigation was also investigated. We considered a selling price of WW grain (P_{WW}) of 250 Euro t^{-1} and a water cost (C_{WI}) of 0.15 Euro m^{-3}. The benefit of irrigation (Euro $year^{-1}$ ha^{-1}) was calculated as:

$$In = P_{WW}\,(Y_{irr} - Y_{rain}) - C_{WI}Irr \quad \text{(Eq. 5)}$$

Where Irr is the annual irrigation volume (m^3) as simulated by CERES-Wheat for each calculation unit under the three climatic scenarios.
The probability that irrigation generates a negative

or null income ranged between 55 and 60%. Almost 40% of cases fell into an income class of less than 250 Euro per ha, and only the 5% of all considered cases was included in the three highest profitable classes. The future scenarios considered did not affect the results but it can be said that climate change did not impact the profitability of irrigation for WW as simulated for the agro-pedoclimatic conditions of Puglia region (Fig. 6). Our results are not in agreement with those obtained by El Afandi *et al.*, (2010) for Egyptian conditions, because of the more extreme impact of climate change forecasted for that area compared to Southern Italy.

The expected income due to supplemental irrigation projected for A_2 was reported in the distribution map of Fig. 7. For this analysis, and considering only the cases for which the model simulated irrigation events, we could identify three areas located in the northern, central and southern part of Puglia, in which the supplemental irrigation was expected to result in an economic gain ranging from 76 to 151 Euro ha^{-1} year^{-1}.

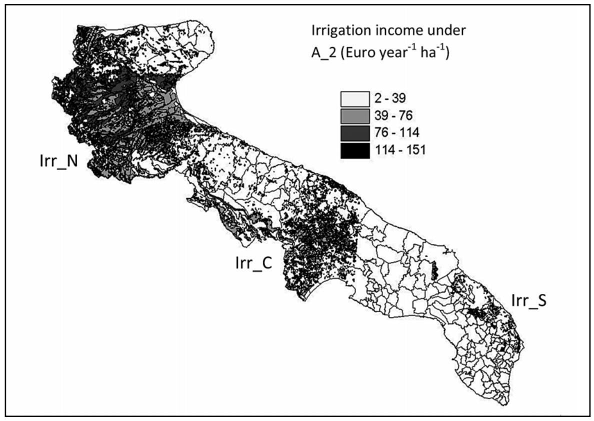

Fig. 7 - Spatial distribution of irrigation income for 4 equiprobable classes under A_2 scenario. Irr_N, Irr_C and Irr_S indicate the areas with the highest irrigation income in the northern, central and southern part of Puglia, respectively.

Fig. 7 - Distribuzione spaziale del guadagno dovuto all'irrigazione per 4 classi equiprobabili nello scenario A_2. Irr_N, Irr_C e Irr_S indicano le aree con il guadagno più elevato nella parte settentrionale, centrale e meridionale della Puglia, rispettivamente.

4. CONCLUSIONS

This simulation study has provided details on the responses of winter durum wheat to climate change, on how the water resources could be managed in order to optimize the crop yield, and on the economic benefit of supplemental irrigation. The approach based on estimating the consumptive use of green and blue water has proved to be a useful tool to evaluate the sustainability of cropping systems based on rainfed or irrigated regimes for the agro-pedoclimatic conditions of Puglia region. In this framework, the consumptive use of green and blue water and their productivity were estimated at the regional scale. Their regional distribution pattern can support the territorial water resource management planning.

The supplemental irrigation of winter durum wheat cultivated in Puglia could be considered as a strategy of adaptation to climate change, especially for several soils of the northern part of the region. However, the economic benefit of such agronomical practice does not seem sufficient to justify a systematic use of irrigation for winter wheat.

For the agro-pedoclimatic conditions considered in this work, it appears more convenient to apply systematic irrigation to crops that allow higher profitability than autumn cereals (e.g. horticultural crops) and to cultivate winter durum wheat under rainfed conditions taking advantage of rainfall that occurs during the winter and autumn periods.

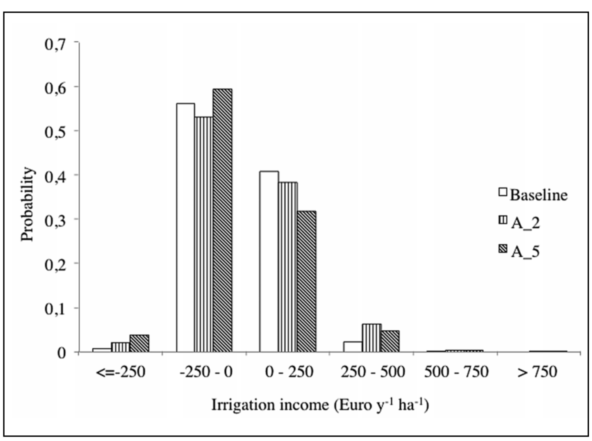

Fig. 6 - Probability distribution of irrigation incomes aggregated into six frequency classes under three climatic scenarios.

Fig. 6 - Distribuzione di probabilità del guadagno dovuto all'irrigazione aggregato in sei classi di frequenza nei tre scenari climatici.

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