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WUE AT REGIONAL SCALE WATER SAVING AND GLOBAL BENEFIT

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SUMMARY - Water use efficiency, WUE (yield per unit of water) at crop and farm level, needs to be improved to cope with the increasing water demand forecasted for 2025. At the regional and/or catchment scale a coherent scheme for water resource use and environmental protection must be implemented. Approaching the WUE issue on a large scale opens various opportunities to improve water management (water storage and distribution, irrigation scheduling and technology). We used a crop growth model to compare different scenarios for water saving and irrigation efficiency in maize and wheat production. A simple economic calculation is included to quantify the gross income. The evaluation was performed in two Mediterranean areas with low (500 mm) and medium (750 mm) precipitation. The simulation results show that under reduced availability of irrigation water or increased water cost, non-irrigated crops and supplementary irrigation become more competitive. The break-even point between irrigated and non-irrigated crops emerges at a water price of about 0.35 € m^{-3}, assuming 60% efficiency of water use; however, this value varies widely depending on environment, climate and the price of the grain.

Key words: Irrigation scheduling, crop models, maize, wheat, economical evaluation.

INTRODUCTION

Global market scenarios predict an increasing water demand for food production in the Mediterranean environment (Giorgi, 2002; Giorgi *et al*., 2004). Future climate predictions indicate a reduction of precipitation in winter and an increase of temperatures by the end of the century (Giorgi *et al*., 2004b). Several physiological processes, such as photosynthesis, development and growth dynamics and, eventually, total biomass and yield, are all affected by water availability (Zhang and Oweis, 1999). Therefore, one needs to optimize crop water use to adapt to likely water shortages and increasing costs in the Mediterranean, in view of the competing uses for water (Rosegrant and Ringler, 2000; Cai *et al.*, 2003) and constraints introduced by European law (minimum river flow). An effective knowledge of water requirement and corresponding yields is fundamental to developing an irrigation network for economically efficient water use (Pereira *et al*., 2002; Sepaskhah and Ghahraman, 2004). The improvement of water use through planning and the adoption of technologies for water harvesting and network distribution will not be covered here. This paper will focus on correct decisions at farm level about technology for irrigation, timing and volumes of water delivered to the field.

Common strategies for water saving are based on soil moisture control, irrigating when the percentage of available water content (AWC, the fraction of water between field capacity (FC) and wilting point (WP)) declines below a pre-determined threshold. Typically, when irrigation scheduling avoids any reduction of soil water content (SWC) below 50% of AWC, Durum wheat is considered to be stress-free (Oweis *et al*., 1998). The same threshold is considered to be appropriate for maize to avoid yield loss (Steele *et al*., 2000), confirming earlier work by Stegman (1982 and 1986). Another strategy is based on restoring a fraction of the evapotranspiration (typically between 30 and 70%) computed from a fully-watered crop (e.g. Zhang and Oweis, 1999). Another option, specifically for extreme water limitation, is to deploy a defined amount of water for supplemental irrigation, which is given in the early stages of crop development (Oweis *et al*., 1999).

This paper firstly evaluates the effects of some common strategies for irrigation and water saving (full and deficit irrigation) using a combined water and energy balance crop growth model to estimate yields and their variability. Secondly, we present a simple economic analysis which considers the net amount of water delivered to the field and the efficiency of the irrigation system, excluding any consideration about efficiency of the water distribution at the network and farm level.

MATERIAL AND METHODS

To simulate yields under different irrigation management options, we used the integrated model for water and energy balance and crop growth developed in the Stamina Project (EU-QLK-5-CT-2002-01313). This model was specifically designed to describe physical impacts on crop performance, e.g. effects of climate/weather and terrain. The crop model is based on the principles of the "Sucros Family" models (Van Ittersum *et al.*, 2003), which is linked to a micrometeorological model, predicting plant transpiration and soil evaporation at hourly time steps, taking into consideration the atmosphere stability condition and the effect of topography on the energy balance. More details can be found in the STAMINA report (Richter *et al.*, 2006).

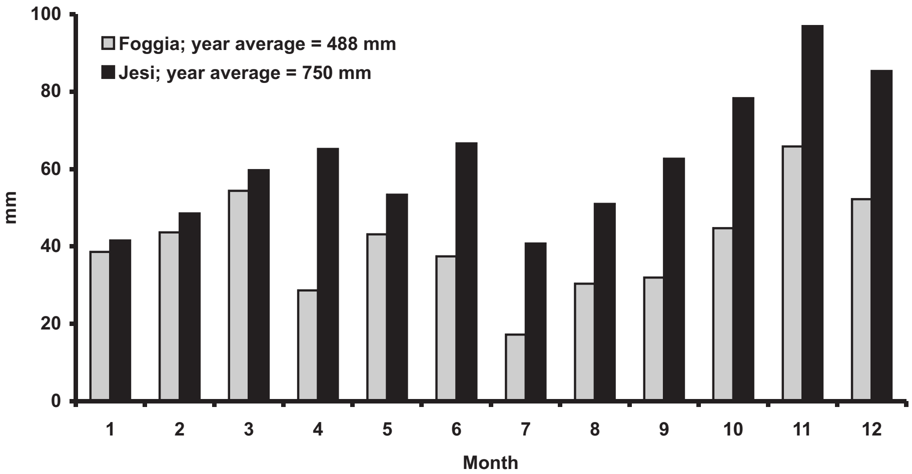

Fig. 1. Monthly average rainfall in Foggia and Jesi, Italy.

We carried out the simulations using 11 years of meteorological data (1980-1990) from Foggia (41° 28′ 0″ N, 15° 34′ 0″ E, 76 m A.S.L.) and 21 years from Jesi (43° 31′ 47″ N, 13° 14′ 28″ E, 97 m A.S.L.). The rainfall in Foggia showed a typical distribution for the semi-arid Mediterranean, with maximum rainfall in spring and autumn and minimum in summer, while in Jesi, more rain was available overall, especially in the summer (Figure 1). In Foggia, non-irrigated spring-sown crops were unable to grow, while in Jesi, sunflower but seldom maize could be cropped without irrigation.

The management scenarios assumed the availability of irrigation water on demand. We considered an unlimited availability of water, and several maxima of irrigation. The following six irrigation strategies for the maize crop were applied using the model: 1) irrigation to reach FC as soon as SWC drops below 50% of AWC (SWC 50%); 2) using a 30% threshold of AWC before irrigation (SWC 30%); 3) maximum irrigation of 150 mm (Limit150); 4) maximum irrigation of 100 mm (Limit100); 5) maximum irrigation of 50 mm (Limit50) to simulate one supplemental irrigation; and 6) no irrigation. For the wheat crop, which is typically never irrigated in either location, we simulated application strategies 5 and 6.

Table 1. Mean water use efficiency (kg m^{-3}) and coefficient of variation (CV %) for maize, based on rain + irrigation for different irrigation management (see text).

	SWC 50%	SWC 30%	Limit150	Limit100	Limit50
Site: Foggia					
Mean WUE	3.66	3.74	3.64	2.81	1.81
CV%	22	23	37	72	112
Site: Jesi					
Mean WUE	3.06	3.17	3.17	3.17	2.97
CV%	26	25	25	25	31

The model estimates of yield were used to evaluate farm profitability under reduced water availability. Economic evaluation simply assumes that water costs are not distinguished between fix and variable costs, and that costs are directly proportional to the amount of water used. We assumed two prices for water (0.15 and 0.30 € m^{-3}) and two levels of irrigation efficiency (80% and 60%), corresponding to the best technologies to deliver water to a maize crop at low pressure (pivot system) or with standard sprinkler (big gun), respectively. A fixed ratio of 1.2 is assumed between prices for wheat and maize grain.

The statistical analysis was carried out, assuming homogeneity of variances between treatments, using specific test for this kind of data: the Welch approach for ANOVA and the Tamhane test for multiple comparison.

RESULTS AND DISCUSSION

The amount of irrigation water for each strategy is reported as the synthesis of all years' results in a boxplot (Figure 2).

It is evident that the water requirement was lower in Jesi (wetter environment) than in Foggia. In Foggia, for 10 out of 11 years, the limit of 150 mm of irrigation was reached, while in Jesi, 100 mm was usually sufficient to avoid severe water stress. It is important to point out that in Foggia the irrigation at 30% of AWC was met in 9 out of 11 years with an amount between 144 and 148 mm. In Foggia, in 10 out of 11 years, 100 mm of water was fully used, while, in Jesi, there were several years when no extra water was needed, and in 1 out of 21 years, supplemental irrigation was not required.

The yields of maize in both sites show a different response to irrigation (Figure 3). In Foggia, only management with high irrigation resulted in stable high yields. However, a saving of about 25% is possible

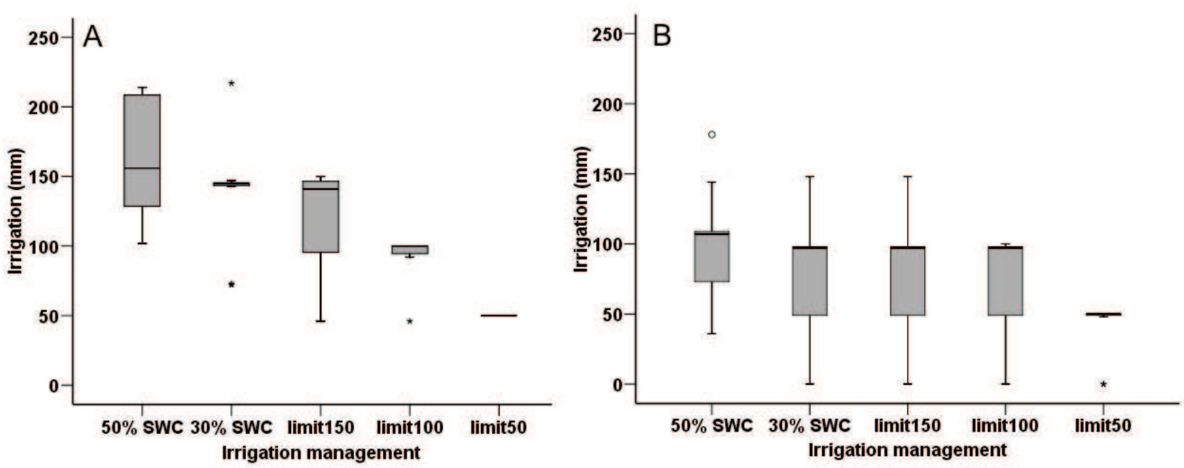

Fig. 2. Box plot representation of the amount of irrigation water in the simulated management for maize (A) 11 year response in Foggia and (B) 20-year response in Jesi

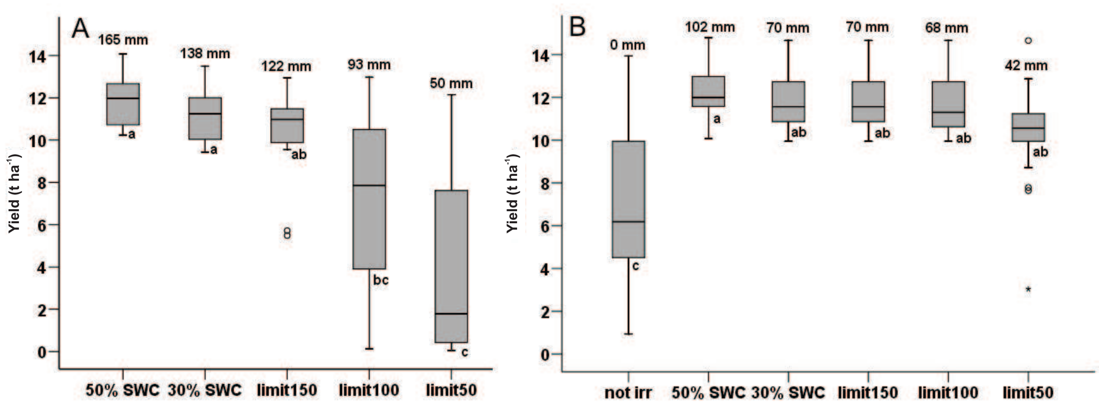

Fig. 3.Maize yields (grain) in Foggia (A) and Jesi (B); different lowercase letters indicate treatments with different means at P=0.05, according to the Tamhane test. Non-irrigated maize in Foggia is not included because yield never reached 1 t ha^{-1}.

(reducing from 165 to 122 mm irrigation) without significant yield penalty. Management according to Limit100 resulted in a significantly lower yield and a much larger variability than management without limitation of irrigation. In Jesi, yields were high and stable for all treatments, with only the non-irrigated maize producing a significantly lower yield. Irrigation management allowing for a limit of 50 mm, showed an insignificant tendency towards lower yields, but with more variability than under the unlimited water management.

In Foggia, the wheat crop required supplemental irrigation in 2 out of 11 years, which resulted in an average yield increase of about 9%, and an average yield of 4.5 t ha^{-1} (CV of 12%). Supplemental irrigation was never required in Jesi, and the average yield was 4.6 t ha^{-1} (CV of 10%).

WUE for maize, based on the sum of rainfall and irrigation water, indicates an optimum for the SWC 30% irrigation management at both sites. In Foggia, WUE decreases and its variability increases sharply when the total amount of water is reduced below 150 mm, which is in contrast to the yield shown in Figure 3. In Jesi, three options for irrigation management (30% SWC, Limit150 and Limit100) used about the same amount of water and produced similar results. Therefore, the WUE is the same for these alternatives, while the management "Limit50" showed a reduced WUE. WUE for wheat is on average 1.32 kg m^{-3} in Foggia (CV = 22%) and 0.96 kg m^{-3} in Jesi (CV = 26%).

Economic evaluation

For Foggia, we consider first the treatments with unlimited water for irrigation (Figure 4A). As expected, assuming a low water price, there are no significant differences (< 50 €) between the two levels of efficiency and the two strategies for irrigation, even if it is slightly more profitable to irrigate according to the SWC 50% strategy. Assuming a high water price, there are significant differences between the two levels of efficiency. These differences are constant across the range of maize grain price considered, (ca 350€ ha^{-1}). Within the same efficiency level, the differences between the SWC50% and SWC30% irrigation strategies are very small (Figure 4 presents their average). In all cases, irrigated Maize is more profitable than non-irrigated wheat with a water price of 0.15 € m^{-3}. If the water price is 0.3 € m^{-3}, there is a break-even point at about 110 € t^{-1}, if irrigation reaches an 80% efficiency. With an efficiency of 60%, the break-even point is at about 145 € t^{-1} of wheat. If water availability is limited, only the strategies of maize irrigation that have a limit of 150 mm of available water allow for an income greater than non-irrigated wheat (Figure 4B), while limiting the irrigation to maintain water at 100 mm or only to supplementary irrigation (limit50) is too severe in this environment. Under a limit of 150 mm and a water price of 0.15 € m^{-3}, both tested efficiencies generate an income greater than that for wheat irrespective of the maize price, and obviously it is more profitable to have a high irrigation efficiency. Under a water price of 0.3 € m^{-3}, only the 80% irrigation efficiency generates an income larger than non-irrigated wheat when the price of maize grain is greater than 115 € t^{-1}. The strategies with water limitation do not respond better than the strategies without water limitation to changes to the maize grain price (the slope of the function price-income is smaller). Under the Limit100 management and a water price of 0.15 € m^{-3}, the threshold to switch to a non-irrigated crop is at a maize price of about 110 € t^{-1}. Such a price is the minimum price recorded in Europe in the period 20052006.

In Jesi, maize is more profitable than wheat under almost all conditions (Figures 4C and 4D). Only in the case of a simultaneously high water price and an exceptionally low grain price for maize does the wheat crop become more competitive, but the income in this case is very low. Maize can grow without irrigation, but irrigation becomes more profitable when the maize price is greater than 120 € t^{-1}. In Jesi, maize is more profitable than in Foggia, due to slightly superior yields and reduced use of irrigation water. As in Foggia, with a low water price (0.15 € m^{-3}), the benefits of different irrigation strategies and efficiencies differ very little (Figure 4C), but income responds more rapidly in Jesi than in Foggia to an increasing maize price. Considering a price of water of 0.35 € m^{-3}, the treatment SWC30% offers an economic advantage independently from irrigation efficiency, compared to the SWC50% strategy.

Non-irrigated maize seems to offer more income than wheat, but the great variability of yields (and incomes) over the years and the presence of several years with very low yields, makes this alternative non-sustainable in practice. Under the treatments with a fixed maximum amount of water, in Jesi, limit150 is never limiting to maximum yields. With the price of water of 0.15 € m^{-3}, best economical results are obtained with the limit100 treatment; irrigation efficiency affects incomes only slightly. All the remaining treatments show little differences among themselves, but are more profitable than the non-irrigated wheat.

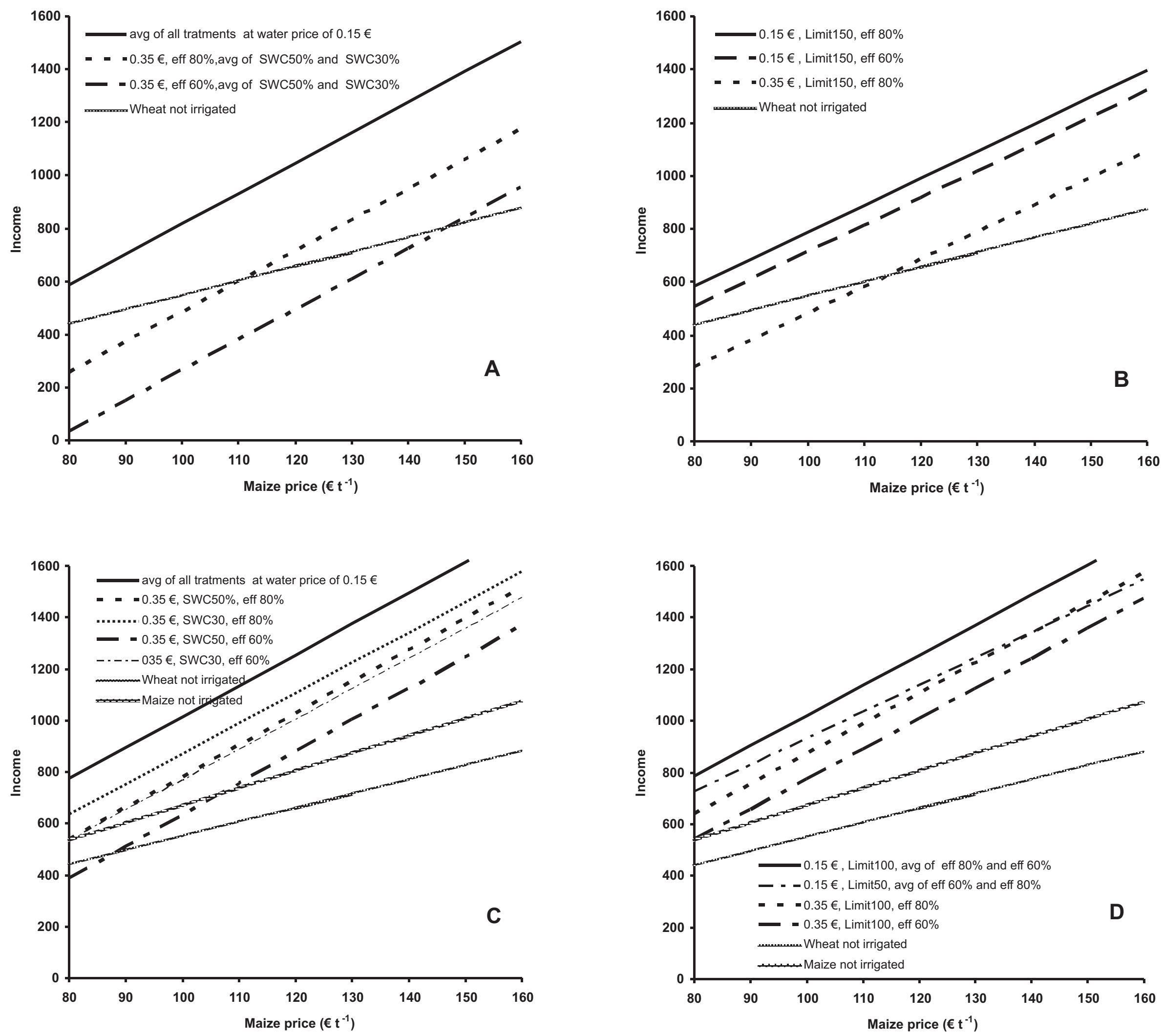

Fig. 4. Gross income under different irrigation management in Foggia (A and B) and Jesi (C and D). Figures in left column (A and C) refer to irrigation management without water limitation, and figures in right column (B and D) refer to irrigation management with a fixed maximum of available water. Only selected irrigation management or averaged results are shown. In B only treatments with income superior to not irrigated wheat are reported. In D at 0.35 €, the treatments with a limit of 50 mm and efficiency of 80%and 60% are included within the treatments wit limit 100 mm and efficiency 80% and limit 100 with efficiency 60%. Results for not irrigated crops are reported in each graph as a reference.

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These results confirm that there is a well-founded strong interest for irrigated agriculture in the Mediterranean area. Therefore, it becomes important to achieve a high efficiency of water application at the field level and of water distribution in the network. At field level, it is particularly important to choose the correct timing and volumes of irrigation and to put in practice the best water-saving strategy, without risking crop productivity. Today, several software programs can help the farmer and the extension services to attain a correct irrigation scheduling. Examples of this software are Moderato (Bergez *et al.*, 2001) and Irriguida (Acutis *et al.*, 2003). Any software must consider the points indicated in Table 2 to be useful in irrigation management.

When volumes and timing of irrigation are established, high irrigation efficiency is obtained by improving the technology for water distribution. Today, most efficient technologies are pivot and linear irrigation, coupled with low energy precision application (LEPA) nozzles (Boldt *et al*., 1999). This equipment offers economical energy use, due to low application pressure, high efficiency, uniformity of distribution, easy adaptation to different crops and soil type under the same pivot. We must also consider that in many countries, with traditionally small farms or strong urbanization pressure (e.g. Italy), it is difficult to irrigate small irregular areas efficiently.

Table 2. Requirement of a software to help farmers in irrigation scheduling

Functional requirement	User requirement	Operational requirements
Able to connect automatically to a meteorological field station network	Cheaper or free	Suitable for several crops
With very low requirements in terms of farm data (e.g. soil data)	Easy to use	Take in account the irrigation method adopted, considering their efficiency
Useful to collect technical data for local extension service	Running on older PCs (or directly from the web)	Offer the option to manually insert meteorological data
	With very low crash rate	Offer the possibility to delay a scheduled irrigation date
	With technical support	Do a forecast of the next irrigation (date and amount)
	In the farmer's language	

CONCLUSIONS

The analysis carried out in this paper has showed the following major points:

- Simulation scenarios for two different regions demonstrate that irrigation management can be optimized site-specifically for a spring-sown crop, identifying minimum water requirements and possible savings.
- Maize yields clearly increased under irrigation in southern Italy (e.g. Apulia region), setting a threshold of 120 mm and thus saving 25% water.
- Maize yields in central Italy only require a supplemental irrigation of 50 mm to save 34 to 60 % water.
- Economic analysis identified benefits of improved irrigation technology and the impacts of price structure (water costs and grain prices) on decision-making and also allows quantifying the switch to rain-fed crops (wheat)

In general, simulation models proved to be a useful tool to estimate yields and yield uncertainty for different management scenarios. This basically confirms that current practice allows prediction of the response to climate change.

Today, environmental concerns are usually considered the most significant problem for irrigated agriculture. These problems not only include excessive water depletion, but also water quality reduction, waterlogging, and salinization of soils. Progress in specific technical areas, such as irrigation systems, is very important but not sufficient on its own (Cai *et al*., 2003). Future utilization of water resources will require a multi-disciplinary approach to fully integrate different expertise, such as agronomy, geology, hydraulic engineering, and environmental protection to solve the problems of water scarcity, cope with increasing food demand and maintain environmental quality and biodiversity.

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