Analysis and improvement of water use efficiency for crops cultivated in the Mediterranean regions: the state of the art

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ANALYSIS AND IMPROVEMENT OF WATER USE EFFICIENCY FOR CROPS CULTIVATED IN THE MEDITERRANEAN REGIONS: THE STATE OF THE ART

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SUMMARY - The improvement of water use efficiency (WUE) of field crops in the Mediterranean region is an imperative imposed by the critical situation of water resources of the region, as well as by the demographical increment. This review reports the experimental data concerning the WUE of 15 species cultivated in the Region, including cereals, leguminous, horticultural and industrial crops. This review however underlines that WUE data of fruit trees are lacking, despite they represent one of the main productions of the Mediterranean agriculture. The variability of WUE can be ascribed mainly to: (i) mineral and water management (water regime, mineral supply and water quality); (ii) plant factors (growth stage sensitivity, and varietal response to the stress); and (iii) environmental factors (climate, atmospheric pollution, soil texture and climate change). The conclusion highlights the actual gap concerning water use efficiency in the Mediterranean region. This gap will constitute a field of research designated to ameliorate water use efficiency of agriculture in this region.

Key words: Water use efficiency, Mediterranean region, climate, water management, cereals, leguminous, horticultural species, industrial crops, water stress

INTRODUCTION

The Mediterranean region is characterised by a dry season in summer and a mild temperature associated with annual rainfall in winter (Shahin, 1996). Despite the apparent uniformity of the Mediterranean climate, a more detailed analysis shows great differences. The duration of the dry season clearly illustrates that while the south is characterised by a long dry season averaging > 7 months without any precipitation, the dry season is relatively limited and does not exceed 2-3 months in the northern part. In addition, the rainfall and temperature diagrams show great differences between the north (autumn rainfall) and the south (winter rainfall) of the region. During summer, the simultaneous occurrence of high temperatures and low precipitation result in a high water demand by agriculture (Hamdy and Lacirignola, 1999). Finally, the Mediterranean region is characterised by long-term drought sequences that occur in the north as well as in the south (Margat and Vallée, 2000). These sequences are the result of rainfall deficits (Fig. 1) more or less than the means, which increase the severity of summer drought on crops (Ben Mechlia, 2003).

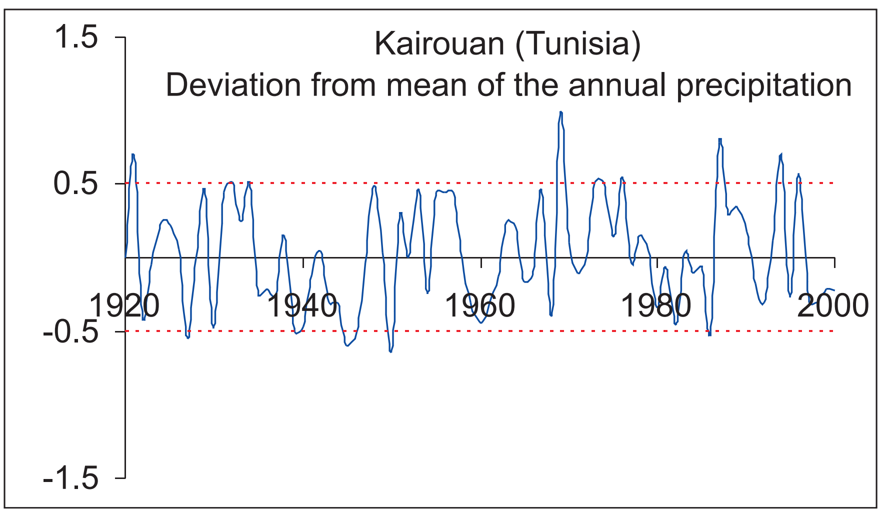

Fig. 1. Deviation from mean of the annual (1920-2000) precipitation typical of the Mediterranean region (after Ben Mechlia, 2003).

Furthermore, the Mediterranean region is characterised by:

- Water scarcity mainly in southern countries (Margat et Vallée, 1997). The threshold of 500 m^3 $capita^{-1}$ $year^{-1}$ that represents absolute water scarcity (Falkenmark and Widstrand, 1992) has been reached in several countries. In other countries, this threshold will be reached in the near future (Tab. 1).
- Water uptake for agricultural use and mainly for irrigation is about 49% in northern countries and 79% in southern ones (Hamdy and Lacirignola, 1997). A population increase (Hamdy and Lacirignola, 1999), mainly in the south (Fig. 2), and chronic deficit in food balance (Med Agri, 2001) resulted in an increase of irrigated areas.

Table 1. Water resources in some Mediterranean countries (after Margat and Vallée, 2000). Information compiled by BLUE PLAN from national and international references.

COUNTRY	year of data	NATURAL RENAWABLE WATER RESOURCES (Km3/yr)				water resources per capita (m3/yr/inhab)	
		total potential resources	national resources	external resources	regular resources	1990	2025
Spain	1993	112.94	111.94	1	13.89	2885	2672
France	1990	185	170	15	86.1	3295	3064
Italy	1990	187	179.4	7.6	30.5	3277	3531
Malta	1990	0.07	0.06	0	0.03	198	180
Albania	1990	50	44.5	5.5	6.5	15408	9978
ex-Yugoslavia	1990	254.2	139.2	115	?	10678	9781
Slovenia			15.9				
Croatia			26.35				
Bosnia		38	38	0			
Montenegro			15.7				
Greece	1980	58.65	45.15	13,5(8,5)	7.7	5838	5818
	1990	53.65					
Cyprus	1989	0.9	0.9	0	0.27	1284	1006
Turkey	1993	235.9	227.4	8.5	N.D	4222	2690
Syria	1989	16.5	8.23	8.26	11	1317	484
Lebanon	1991	4.94	4.94	0	3.2	1829	1050
Israel	1990	1.7	1.23	0.47	1.2	370	246
T. Palestine	1988	0.685	0.65	0.035	0.6	348	c
Gaza	1990	0.065	0.03	0.035	0.05	84	c
Egypt	1990	58.3	1.8	56,5a	55,8b	1112	645
Libya	1990	0.7	0.7	0	0.4	154	55
Tunisia	1990	4.18	3.58	0.6	2.1	511	313
Algeria	1990	14.1	13.9	0.2	2.7	565	271
Morocco	1991	30	30	0	4.2	1197	657

a) Inflow from neighboring countries = 85 km^3/yr. According to agreement Egypt receives 55.5 km^3/yr (measured at Assouan); b) Taking into consideration that Nile is regulated at Assouan; c) Population projection for 2025 not available

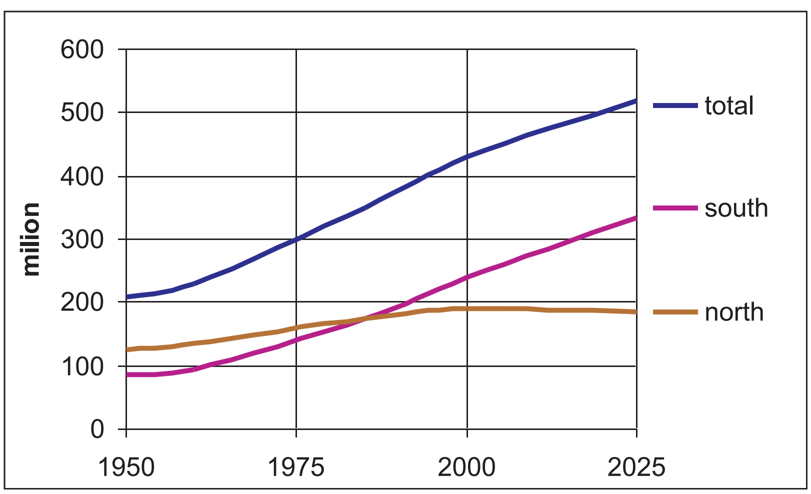

Fig. 2. Evolution of the population in the Mediterranean Region (after Hamdy and Lacirignola, 1999).

- Water loss, even during conditions of water scarcity, is widespread in southern countries. According to recent studies conducted by Shideed *et al.* (2005), in Syria, water use for wheat and cotton (the two main winter and summer crops) exceeded the water requirement by 39% and 24%, respectively. In Jordan, the percentage of over irrigation ranged from a minimum of 23% in the production of citrus crops to a maximum of 70% in the production of wheat. In Iraq, farms over irrigated wheat and potato by 63% and 55%, respectively. Finally in Egypt, farmers allocated a large amount of water, exceeding crop requirements for all winter and summer crops. They over irrigated their crops by 24 to 53%.
- The salinization of irrigated areas is continuously increasing (Tab. 2). It corresponds to the accumulation of soluble salts in the root zone and has two sources (Hamdy *et al.*, 1995): the extension of irrigated areas together with an overestimation of crop water requirements and the use of non-conventional water resources in agriculture. This practice became frequent in southern Mediterranean countries such as Spain, Greece, Portugal, and Italy. Many projects were conducted in Israel (waste water use), in Egypt (use of drainage water), and in North Africa (use of saline water). However, these three types of water have in common a high content of soluble salts.

Table 2. Estimation of the percentage of irrigated soils affected by salinity in a few Mediterranean countries (Hamdy *et al.*, 1995).

	Percentage of irrigated soils affected by salinity
Algeria	10--15
Cyprus	25
Egypt	30--40
Spain	10--15
Israel	13
Greece	7
Jordan	16
Morocco	10--15
Portugal	10--15
Syria	30--35

Agriculture, the main consumer of freshwater in the Mediterranean region, is currently facing with the challenge of new approach to water resource management that insures the protection of water and their integrity. If the use of saline water for agriculture is unavoidable, it would be convenient to manage this practice within a planned framework. This has to be reconciled with two constraints: to provide a sustainable economic yield while minimising the unfavourable effects of salinity on the environment.

New approach to water management depends mainly on three types of strategies, to be considered simultaneously (Katerji, 2003):

- To save water by controlling water supply through:
    a) better determination of crop water requirements (e.g. the review of Rana and Katerji, 2000).
    b) the development of biological and physical criteria (Katerji, 1997) leading to precise determinations of irrigation scheduling.
- \ which ameliorate the water use efficiency of crop species and varieties.

The present study will focus on the latest strategies mentioned above and will cover four main themes:

- To present different steps allowing the analysis of water use efficiency at different spatial and temporal scales,
- To realise a water use efficiency review (at the agronomical scale) of crops cultivated in the Mediterranean basin, and to highlight the actual knowledge in this domain,
- To analyse the actual or future causes susceptible to the production of variability in water use efficiency, and
- To discuss an approach allowing for the integration of water use efficiency in the choice of species and plant variety characterized by high yield as well as high water use efficiency.

A final synthesis will underline the actual gap concerning water use efficiency in the Mediterranean region. This gap will constitute a field of research designated to improve water use efficiency of agriculture in this region.

METHODOLOGY FOR THE DETERMINATION OF WATER USE EFFICIENCY

Two approaches can be considered to determine water use efficiency:

1. the ecophysiological approach, based on the analysis at a given instant of the relationship between photosynthesis and transpiration per leaf unit area, at the leaf scale, crop canopy scale, and territorial scale (Chen and Coughenour, 2004). This approach helps reach the following:
   - To describe the processes determining water use efficiency through theoretical approaches (Jones, 1973; Cowan, 1982; Farquhar and Sharkey, 1982; Hsiao, 1993).
   - To compare leaf photosynthesis and transpiration capacity of a species cultivated under different watering conditions and to analyse the consequences on water use efficiency through theoretical approaches (Morison, 1987; Cheesman, 1991; Leuning, 1995, Katerji and Bethenod, 1997).

   The ecophysiological approach helps in the understanding of global results obtained from the agronomical approach. However, it is not possible to calculate agronomical yield directly from leaf photosynthesis due to the interference of many factors like respiration, leaf growth, transfer of assimilates, flowering, and pod setting (Steduto *et al.*, 1997).

2. the agronomical approach is based on water consumption and yield concept (Feddes, 1985). The time scale considered is the whole vegetative cycle. It is essential data to manage the production of irrigated crops and to point out the sound management method allowing the improvement of yield. However, this approach does not provide the parameters necessary to understand all the obtained results.

In the following paragraph regarding the ecophysiological approach, a comparison between the two approaches will be discussed using some concrete examples; this comparison is necessary to understand the potential production or agronomical yield of studied species under contrasting watering conditions. Moreover, the comparisons will give further insights into the ways which have to be followed for obtaining higher water use efficiency.

Ecophysiological approach

Water use efficiency per leaf unit area (Biehuizen, 1976; Goudriaan, 1982; Pearcy, 1983; Feddes, 1985) WUE_l is the ratio between leaf CO_2 net assimilation rate A_l and leaf transpiration rate E_l :

$$WUE_l = A_l / E_l \qquad (1)$$

A_l and E_l are measured with a photosynthesis chamber.

At the canopy scale, the water use efficiency per unit area WUE_c can be estimated (Baldocchi *et al.*, 1991; Steduto, *et al.*, 1997) as the ratio of carbon flux (A_c) to water flux E_c

$$WUE_c = A_c / E_c \qquad (2)$$

In a study carried out on sweet sorghum cultivated in southern Italy, Steduto *et al.* (1997) observed that WUE_l and WUE_c had a similar kinetics during the day (Fig. 3). The latter value, however, was generally lower because it takes into consideration the lower plant leaves which are characterised by lower photosynthetic activity compared to the upper leaves in the determination of WUE_l.

This study also shows that WUE_l and WUE_c hourly measurements are highly correlated with the plant water status characterised by leaf water potential. WUE_l and WUE_c values observed at noon were decreasing with the reduction of leaf water potential (Fig. 3). Under well watering conditions, WUE_l and WUE_c were well correlated with the vapour pressure deficit VPD (Fig. 4).

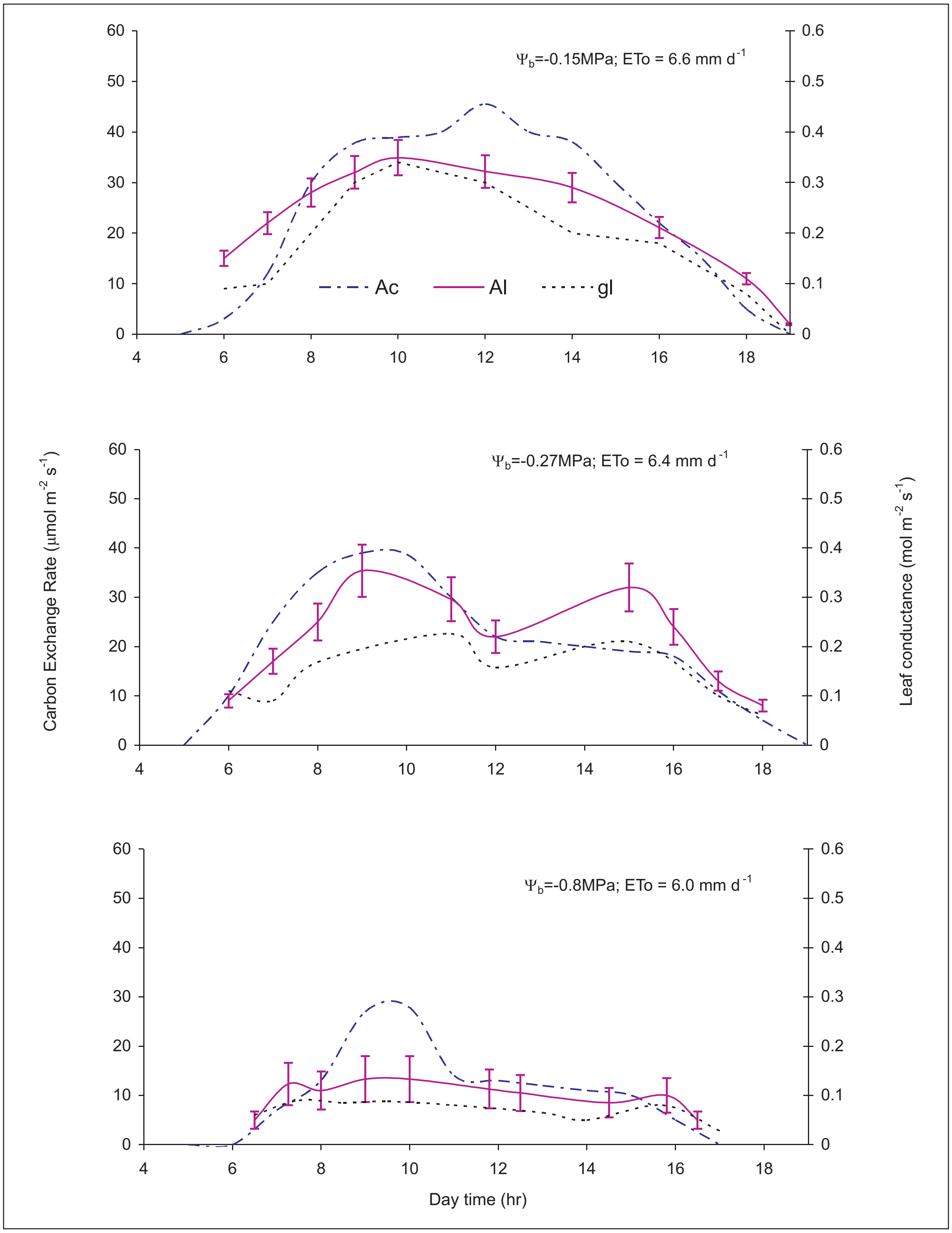

Fig. 3. Diurnal trend of carbon exchange rates at canopy (Ac) and leaf (Al) scales, along with stomatal conductance at leaf scale (gl), of sweet sorghum for well watered, partially stressed and very stressed conditions (after Steduto *et al.*, 1997).

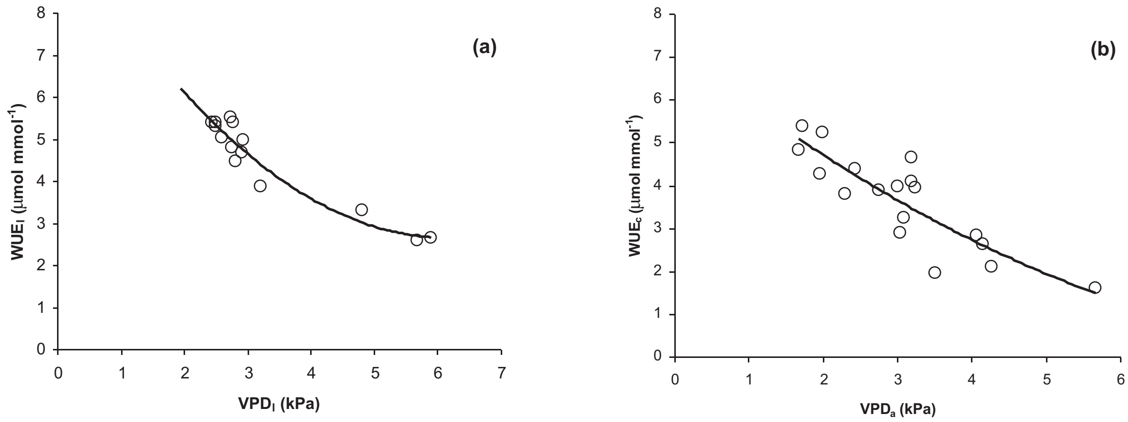

Fig. 4. Relationships (a) between WUE_l and VDP_l at the leaf level, and (b) between WUE_c and VDP_a at the canopy scale (after Steduto *et al.*, 1997).

The previous analysis made by Steduto *et al.* (1997) gave a coherent explanation for the high agronomical water use efficiency observed in sweet sorghum (Mastrorilli el al, 1995a; Gosse, 1996). This high water use efficiency was not due to high photosynthesis capacity per leaf unit area, but rather to low night respiration characteristic of this species.

Katerji and Bethenod (1997) used the ecophysiological approach to compare the water use efficiencies of maize and sunflower. The latter is supposed to be resistant to drought (Puech *et al.*, 1976; Doorenbos and Kassam, 1979) and it is often recommended to replace maize during dry years in southern France. The well founded of this practice has been verified by studying the relationship between leaf photosynthesis and leaf stomatal conductance, according to the theoretical approach proposed by Jones (1973).

In fact, for maize (Fig. 5), according to Jones, a proportionality exists between these two parameters. This proportionality leads to constancy in water use efficiency, especially that each reduction in water supply induces a reduction in photosynthesis.

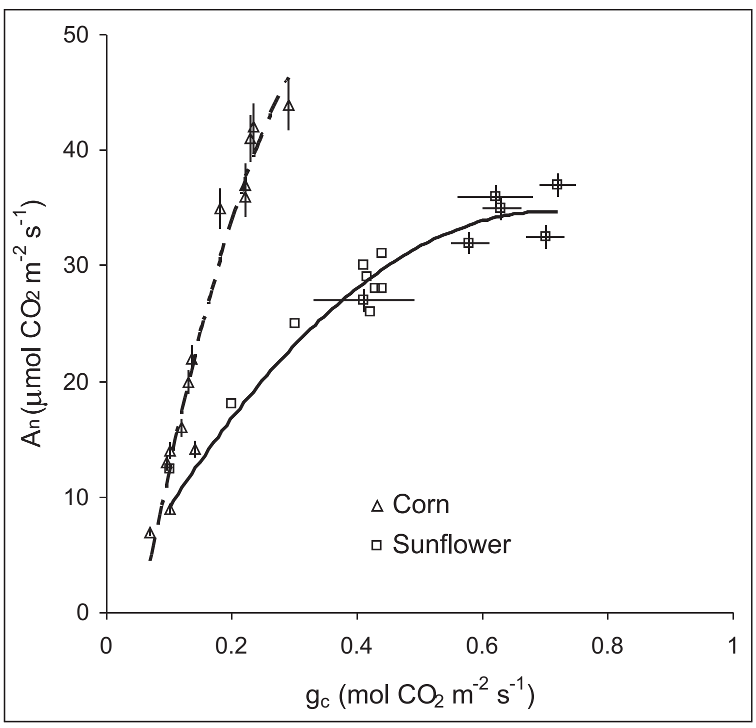

Fig. 5. Relationships at leaf level (a) between CO_2 net assimilation (A_n) and CO_2 stomatal conductance (g_c). (after Katerji and Bethenod, 1997).

Sunflower exhibits two characteristics: stomatal opening is clearly more important for the same value of stomatal conductance and it photosynthesizes less than maize (Fig. 5). A reduction in water availability entails a reduction in stomatal conductance, leading to an amelioration of sunflower water use efficiency because photosynthesis is slightly affected. To observe the proportionality between stomatal conductance and photosynthesis, as is the case for maize, sunflower stomatal conductance has to reach values about 70 % lower than the maximum stomatal conductance. This delay observed between the reduction of photosynthesis and the reduction of stomatal conductance explains why sunflower is retained as a drought tolerant species. Under well water conditions, maize is more economical with water than the sunflower. In addition, during well watered experimental conditions, the sunflower wastes water. This result clarifies the controversy concerning the aptitude of sunflowers for resisting soil water depletion (Robinson, 1978).

Agronomical approach

Since the study of de Wit (1958), different expressions (water use efficiency, crop water productivity) have been proposed and discussed (Rijtema and Endrödi, 1970; Slabbers *et al.*, 1979; Ritchie, 1983; Tanner and Sinclair, 1983; Feddes, 1985; Pereira *et al.*, 2002; Zwart and Bastiaanssen, 2004). In general, water use efficiency can be written as follows:

$$\text{WUE (kg m}^{-3}\text{) = yield / water consumption} \quad (3)$$

Yield in equation 3 can be indicated by two parameters:

- Global dry matter yield expressed in kg m^{-2}
- Marketable crop yield expressed in kg m^{-2}

The marketable crop yield is a criterion more interesting than dry matter for the following two reasons:

- In some species, like durum wheat and those species characterised by similar biomass, yield can vary significantly (Siddique *et al.*, 1990; Katerji *et al.*, 2005b) as a result of genetic improvement. In other species like the chickpea, however, the ratio “grain / biomass” is constant for large ranges of experimental drought (Thomson *et al.*, 1997) and salinity levels (Katerji *et al.*, 2001).
- Marketable yield is more interesting because it represents liable economical value. This value is an important factor in determining irrigation cost (Zairi *et al.*, 2001).

The main drawback related to the use the marketable yield in calculating water use efficiency is the lack of knowledge on yield water content; neglect of this factor by scientists can lead to errors in yield determination.

Of the water used by crops (during the growing season), 99% is released as water vapour into the atmosphere. For this reason, crop water use is considered approximately equal to evapotranspiration (ET) in mm or in m^3. This approximation, discussed by Feddes in 1985, is valid only if the canopy uniformly covers the soil surface, thus when leaf area value is over 2 (Katerji and Perrier, 1985). At this leaf area value, ET is nearly similar to crop water use, because evaporation is very low even when the soil surface is wet (Ritchie, 1983; Saugier et Katerji, 1991). In practice, complicated models are necessary to determine the portion of soil evaporation in ET (Katerji and Perrier, 1985), which is why scientists are content with determining ET in order to evaluate water use efficiency.

On the plot scale, ET can be determined through different approaches:

- Direct ET measurement using weighing or drainage lysimeters or indirectly through micrometeorological methods (Bowen ratio, aerodynamic). The results of these methods are the most precise in determining ET. However, in order to use these methods, precautions are necessary, especially in the Mediterranean region (Rana and Katerji, 2000).
- Through the calculation of soil water balance. This approach, however, is based on some hypotheses: the capillary rise, runoff, and deep percolation are supposedly insignificant and rainfall are all efficient. However, some hypotheses are not valid in Mediterranean climatic conditions (Katerji *et al.*, 1984)
- By calculating ET according to method 56 of FAO (Allen *et al.*, 1998). The recent review by Katerji and Rana (2006) shows that this method used on some species cultivated in Mediterranean climatic conditions can lead to estimates significantly different from the measurements of actual evapotranspiration.
- By calculating ET through different productivity models (CERES, CROP-Syst). The literature shows that the ability of these models to calculate correctly daily evapotranspiration has not been demonstrated (Ben Nouna *et al.*, 2000).

- Finally, in many studies, ET is not measured. It is replaced, however, in equation 3 by the amount of water supplied by irrigation. The overestimation of water supplied to crops is one of the characteristics of irrigation practice in the Mediterranean region, making the understanding of the obtained WUE values difficult (e.g. Shideed *et al.*, 2005).

Values of WUE will be analysed and discussed in the following paragraphs, mainly in those concerning marketable yield and ET determination by lysimeters, microclimatic, or soil water balance methods. This restrictive work method leads to ignore numerous research works. However, it helps reduce the dispersion of observations, and thus makes it possible to analyse WUE with higher data liability.

Territorial scale

To correctly design and manage irrigation and to improve the WUE from the social and political points of view, it is necessary to have an overview of water productivity from a territorial to a regional scale, i.e. of several hundreds km^2 or more. To do this, the input (water) and the output (production) have to be evaluated on a large scale, with all the arising problems due to heterogeneity (Christensen *et al.*, 1996).

Two approaches should be possible: a) one based on physiological climatic estimates, and b) one based on an 'inputoutput' ratio; each of these can be applicable on a large time scale, from the week to the month.

The physiological - climatic approach

The simplest approach to scale the WUE to the regional level is by the analysis of the relationship of photosynthesis to transpiration at larger spatial scales. Theoretically, the process of “up-scaling” is defined as a process in which information taken at smaller spatial and temporal scales are used to derive information for estimating processes at larger spatial and temporal scales (Jarvis and Mc Naughton, 1976). Actually, our knowledge of biological and physiological processes is quite good at the small scale, such as the canopy. At large scales, several problems are introduced, in particular:

- the heterogeneities in the distributions of the processes,
- the nonlinearity in the responses of processes to environmental variables (Nykanen and Foufoula-Georgiou, 2001),
- the difficulty of finding variables which truly represent the “mean” value of a large area, mainly when it is complex (Tunipseed *et al.*, 2003),
- both terms of WUE, water (Bouraoui *et al.*, 1997) and crop production (Wilson *et al.*, 2003), are very difficult to average,
- the response time of the crop to input variation is demanding (Aryal *et al.*, 2005),
- very few data are available, especially in the Mediterranean basin region (Fischer *et al.*, 2002).

One of the possible approaches to tackling the up-scaling of WUE from field to region is that proposed recently by Chen and Coughenour (2004), which was based on previous works, although not conducted in Mediterranean or semi-arid and arid climates. Here, the production data might be obtained directly from the fields and the values of the variables needed for determining water consumption are derived both from surface agrometeorological and soil measurements and from remote sensed data. The satellite method seems to us the best and most reliable method to obtain correct spatial averaged variables. Other methods, based just on surface measurements and estimates should be taken into account in future research.

Following this model, the WUE is defined as

$$WUE_{region} = \frac{NPP}{T_{region}}$$

i.e. the ratio between net primary production (*NPP*) and crop transpiration (T_{region}). The term *NPP* is estimated by the Monteith model (Monteith, 1993, Kumar and Monteith, 1981).

The *NPP* of crops is estimated as a function of intercepted radiation and radiation use efficiency (*RUE*). This model has been improved by detailing process models to take into account the dependence of the RUE on different factors, such as leaf nitrogen, plant type (C_3 or C_4), temperature, and water availability (Chen and Coughenour, 2004). In the estimation of the *NPP*, the variability of intercepted *PAR* must be considered in addition to the *RUE*. The input variables to calculate this term are the incident solar radiation and the fraction of incident *PAR* intercepted by green leaves. The green leaves intercepting *PAR* could be evaluated by the normalized difference vegetation index (*NDVI*) usually available from European satellites. The technique of assimilation should be used to scale transpiration at regional scale. A suitable substitute may be found in another surface variable instead of the *NDVI*: one possibility is the use of surface infrared temperature (T_s) or its derivative (Goodrich *et al.*, 2000; Lhomme *et al.*, 2000; Friedl, 2002).

The T_{region} is estimated by the general energy and mass transfer model (GEMTM) which links leaf level processes, canopy microclimate, soil physical parameters, plant growth, biomass production, and dynamics (Chen and Coughenour, 1994). For this calculation, considering that the method should be applied only to arable crops that do not have nitrogen limitations (conditions very rarely satisfied in the Mediterranean region), only the vapour pressure deficit (*VPD*) on a large spatial scale may be considered (Tanner and Sinclair, 1983; Monteith, 1988).

Attempts to transfer the ecophysiological approach to territorial scales have been few and, before their operative application, deeper studies and field tests are required.

The 'input-output' approach

At the regional scale, the interactions between crop yield and transpiration are complex and unknown, making measures of WUE difficult. The easier and practical way to calculate the regional WUE consists in the 'inputoutput' approach (Zoebl, 2000).

'Input' is the water consumed over the crop growing season and 'output' is the yield. This 'inputoutput' definition takes into account spatial and temporal constructs of regionally available databases. They are commonly established in a geographic information system (GIS).

However, there are at least three weak points of such approach: 1) the regional WUE is referred only to the grain yields (or dry matter yields) and it ignores the fresh crop productions; 2) precipitation that falls on 'bare' soil (areas that are not sown to actively growing crops) is not considered; 3) the surface unit is the field plot, but more frequently the data are referred to the whole farm or to the local administrative area (i.e. county area).

If the base unit of the region is the administrative county, which is the smallest geographic resolution that the available databases covered, many variables influencing WUE are not available (Cao *et al.*, 1995). They include: precipitation patterns, species or crop varieties, soil conditions (comprising soil erosion, sodicity, and salinization), agricultural practices, involving the use of fertilisers (Garabet *et al.* 1998), efficient irrigation management (Zhang and Oweis 1999; Zhang *et al.* 1998), time of planting and crop rotation, planting density (Karrou 1998), and the use of mulch (Tolk *et al.* 1999) or plastic film to reduce soil evaporation.

The spatial analysis of WUE needs to be based on data. It is difficult to infer the causal relationships between WUE and detailed agricultural practices for large areas, because there is currently a mismatch between available and required data. The collection, quality and availability of such data are major issues facing regional agricultural operational and research organisations. These issues need to be addressed by organisations involved in managing agricultural, water and land resources.

WATER USE EFFICIENCY DETERMINED ON THE PLOT SCALE IN THE MEDITERRANEAN REGION: REVIEW AND ANALYSIS

Tables 3a and b present a synthesis of water use efficiency values for different countries and different species of the Mediterranean region. The main crops cultivated in the Mediterranean region are presented in table 4. The agricultural production of the Mediterranean region in comparison with world production is presented in figure 6.

Table 3a. Observed WUE values (kg m^{-3}) for grain crops cultivated in the Mediterranean region: a review.

grain crops			
wheat	Syria	0.5-2.5	*Oweis, 1997*
	Morocco	0.11-1.15	*Corbeels et al., 1998*
	Morocco	0.32-1.06	*Mrabet, 2002*
	Israel	0.6-1.60	*Amir et al., 1991*
	Italy	1.02-1.20	*Van Hoorn et al., 1993*
	Italy	1.08-1.59	*Katerji et al., 2005 b*
	Turkey	1.33-1.45	*Sezen and Yazar, 1996*
corn	Turkey	1.65-2.15	*Dagdelen et al., 2006*
	Turkey	0.22-1.25	*Gencoglan and Yazar, 1999*
	Italy	1.35- 1.80	*Ben Nouna et al., 2000*
	Italy	0.82 -1.17	*Katerji et al., 1996*
	Lebanon	1.36-1.89	*Karam et al., 2003*
	France	1.6	*Marty et al., 1975*
	Spain	1.5-2.16	*Fernandez et al., 1996*
barley	Italy	1.46-2.78	*Katerji et al., 2006*
sunflower	Italy	0.39-0.72	*Katerji et al., 1996*
	France	0.6	*Marty et al., 1975*
soybean	Italy	0.47-0.77	*Katerji et al., 2003*
	France	0.55	*Marty et al., 1975*
	Lebanon	0.39-0.54	*Karam et al., 2005*
sorghum	Italy	0.67-1.59	*Mastrorilli et al., 1995*

Table 3b. Observed WUE values (kg m^{-3}) for species cultivated in the Mediterranean region: a review.

		industrial crops	
cotton	Turkey	0.61-0.72	*Dagdelen et al., 2005*
	Turkey	0.50-0.74	*Yazar et al., 1999*
	Israel	0.22-0.35	*Saranga et al., 1998*
	Lebanon	0.8-1.3	*Karam et al., 2006*
sweet sorghum	Italy	3.69-4.20 (stalk)	*Mastrorilli et al., 1999*
		fresh crops	
potato	Italy	16.2- 18.5	*Katerji et al., 2003*
sugar beet	Italy	6.6- 7.0	*Katerji et al., 2003*
tomato	Italy	4.4-8.3	*Katerji et al., 2003*
	Italy	20 (globe fruit)	*Rana et al., 2001*
	Italy	22.2 (long fruit)	*Rana and Katerji, 2007b*
		fruit trees	
grapes	Italy	16 - 18.1	*Rana and Katerji, 2007a*
clementine	Italy	18.8	*Rana et al., 2005*
		pulse crops	
broad bean	Italy	0.86-1.37	*Katerji et al., 2003*
	Italy	0.45-0.92	*Katerji et al., 2005 a*
	Syria	0.45-0.66	*Oweis et al., 2005*
chickpea	Italy	0.46-0.98	*Katerji et al., 2005 a*
	Syria	0.4- 0.6	*Oweis et al., 2004*
lentil	Italy	0.36- 2.09	*Katerji et al., 2003*
	Syria	0.44-0.58	*Oweis et al.,2004*

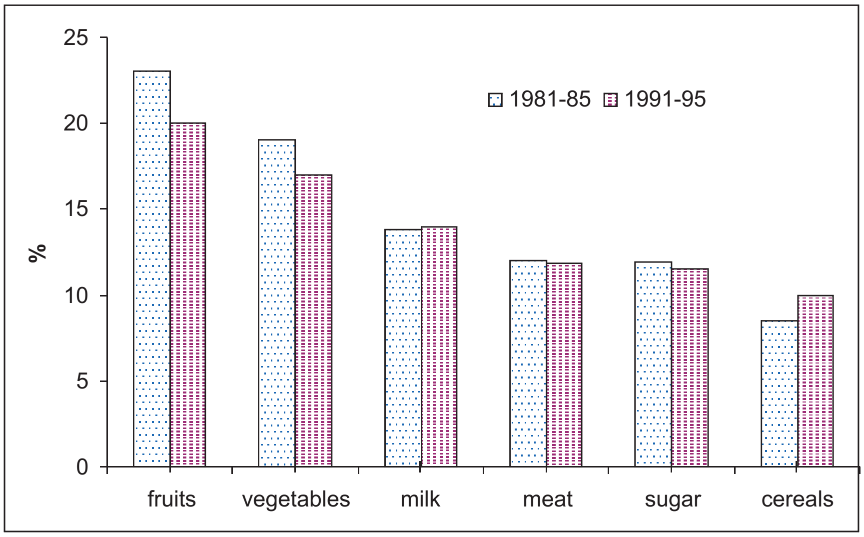

Fig. 6. Mediterranean countries ratio in the world-wide production (after Med Agri., 2001).

Table 4. The most diffuse Mediterranean crops (after Med Agri, 2001).

Cereals	Vegetables	Fruit	other crops
Wheat	Garlic	Apricots	Fibre crops
Maize	Artichokes	Almonds	Tobacco
Barley	Eggplants	Lemons	Centrifugal sugar
Rice and paddy	Cantaloupes	Dates	Sugar beets
Coarse grains	Carrots	Olives	Sugarcane
Pulses	Cabbages	Oranges	
Dry peas	Cucumbers	Grapefruit	
Lentils	Pumpkins and squash	Peaches	
Dry beans	Green beans	Pears	
Chickpeas	Dry onions	Apples	
Olive oil	Watermelons	Grapes	
Roots and tubers	Green peas	Tangerine, mandarin, clementine	
Potatoes	Green peppers		
	Tomatoes		

The main observations of this review can be summarised in the following:

The available data on WUE are made on annual crops, mainly on cereals. However, information on species like rice, characterised by high water consumption and difficulty in analysis, is still lacking. Data on legumes are still limited, while for fruit trees data is lacking completely; these species, however, are the most diffuse irrigated crops. Methodological difficulties in determining ET through the use of lysimeters or soil water balance on multi-annual crops, especially for fruit trees, is at the heart of this lack of information. However, recent measurements for citrus plantations (Rana *et al.*, 2004) and vineyards (Rana and Katerji, 2007a) exist in the Mediterranean region and they give an indication of clementine and grapevine water use efficiency.

WUE of species whose marketable values are related to fresh weight (tomatoes, potatoes) are higher than the values observed for species with dry yield weight like grain crops. For the latter, however, large differences exist between species. C_4 crops like maize are characterised by a WUE higher than that observed for C_3 crops like sunflower. These differences are explained by the relationship between photosynthesis and stomatal conductance realized on the leaf scale, and they are specific for each species. They can also be explained by seed composition; maize contains starch essentially, while sunflower contains 50% oil and 20% protein. The biosynthesis of lipids and protein is more expensive than starch (Pennin de Vries *et al.*, 1974).

Large differences can be observed between the WUE values of the same species. These differences can exist not only in studies made in different countries, but also in studies conducted at the same site. This can be seen for winter crops like wheat, but also for summer crops like maize. The reason for this variability will be analyzed in the following paragraph.

ANALYSIS OF WATER USE EFFICIENCY AT PLOT SCALE

The analysis of water use efficiency at the plot scale consists of finding correlations between the observed values and a number of susceptible parameters to explain the origin of the WUE variability, which is experimentally determined. These analyses do not take into consideration the processes like in the ecophysiological approach, but they take into consideration the correlation with hydric, biological, and environmental parameters that are susceptible to creating variability.

Excluding experimental errors related to the determination of yield and ET, the variability in determining WUE can have mainly three causes:

- Water and mineral regimes applied to crops and analysed in terms of quantity and quality,
- Factors related to plants (differences between species, variety effects, phenological stage sensitivity to water constraints),

- Environmental factors related to soil and climate. These factors include atmospheric pollution and climatic changes.

In reality, the different causes act together and independently. For example, sunny days are favourable for, at the same time, soil and atmospheric drought as well as an increase in air pollution. However, each identified cause will be discussed separately, in order to provide evidence for its role in and contribution to the variability of WUE values. The realised analysis will neglect, however, a certain number of factors capable of modifying WUE, and for which data are not available in the literature. They are cases of biotic stress like diseases, insects, and weeds (Bethenod *et al.*, 2001a and b, and 2005). A number of cultural practices like the date of sowing of winter crops (Oweis, 1997), crop density (Asrar *et al.*, 1984), the possibility of realizing several cycles of the same crop *per* year (Mastrorilli *et al.*, 2002), and the use of mulching (Deng *et al.*, 2006), mainly for summer legumes like tomato (Amayreh and Al Abed, 2005), can also modify water use efficiency. However, taking into consideration the analysis presented in the following paragraph, it seems that a demonstration of well founded management methods represents a second step that will lead to a liable determination of water use efficiency realized in the Mediterranean region under the appropriate conditions.

The role of mineral and water supply

Water regime

Oweis (1997) analyzed the values of water use efficiency for wheat cultivated under irrigated and non-irrigated experimental conditions in Syria. This author noticed that the average WUE of rain in producing wheat in Syria is 0.5 kg m^{-3} (Fig. 7), although with good management and favourable rainfall amounts and distribution, this average could be increased to 1 kg m^{-3}. In fully irrigated areas with good management, the WUE was about 0.75 kg m^{-3}. However, water used in supplemental irrigation can be much more efficient (WUE = 2.5 kg m^{-3}). This extremely high WUE is mainly attributed to the effectiveness of a small amount of water in alleviating severe moisture stress during the most sensitive stage of crop growth. The previous analysis underlines two important facts:

- The limits between WUE measured on irrigated and non-irrigated winter crops are not clear.

- The WUE of irrigated crops can present a large range of values. The generic term "irrigated crops" can include, in reality, extremely different situations of plant water supply.

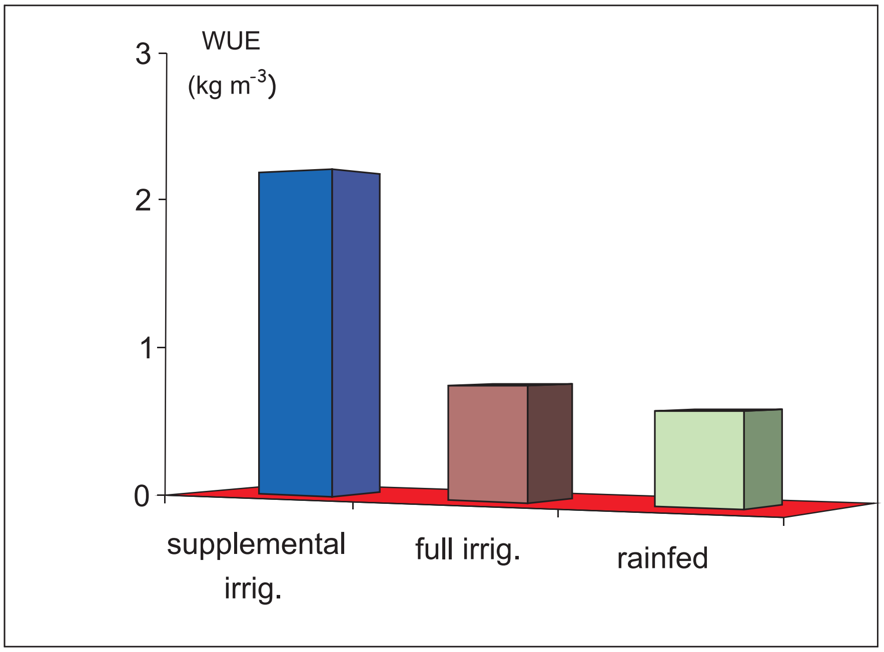

Fig. 7. Potential WUE of supplemental irrigation, rainfall and water applied in fully irrigated areas in Syria (after Oweis, 1997).

Katerji and Hallaire (1984), in their synthesis on indicators of crop water status, demonstrated that soil water status assessed through criteria like soil water content, volume of water supply, humidity, or soil water potential constitute an imperfect parameter to characterise real plant water status, and it leads consequently to variability in WUE. They recommend the use of leaf water potential or pre-dawn leaf water potential in order to identify the actual crop water scheduling and to guide water supply. Under these conditions, yield, crop water use and, in consequence, WUE should present more stable values.

Ben Nouna *et al.* (2000) applied the previous approach to guide maize irrigation in southern Italy during two successive years, mainly through pre-dawn leaf water potential measurements. Three treatments, corresponding to 3 conditions of plant water status, monitored by pre-dawn leaf water potential measurements were identified (Fig.8):

- IRRI treatment irrigated when pre-dawn leaf water potential reached – 0.3 MPa. This irrigation threshold identified by Katerji and Bethenod (1997) corresponds to the level at which maize leaf gas exchanges are affected by water constraints.

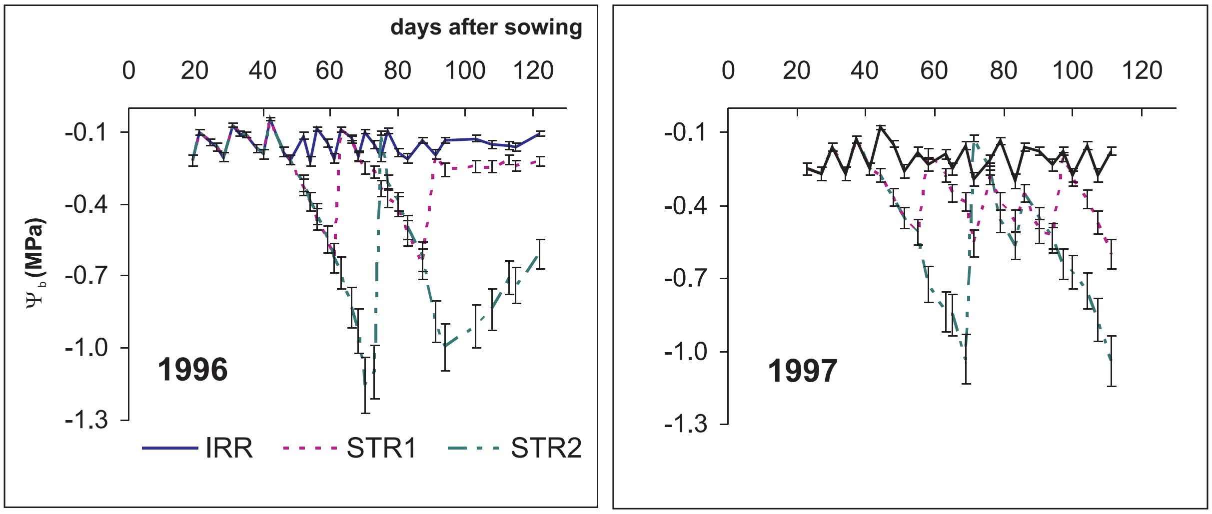

Fig. 8 Daily evolution of predawn leaf water potential measured on corn under well watered conditions (IRR), and moderate (STR1) and severe (STR2) stress in two years (after Ben Nouna *et al.*, 2000).

- STR1 treatment irrigated when pre-dawn leaf water potential reached 0.6 MPa. This treatment corresponded to moderate stress.
- STR2 treatment irrigated when pre-dawn leaf water potential reached 1.2 MPa. This treatment corresponded to severe stress.

These authors noticed that WUE, during the two successive years, was 1.82 and 1.74 kg m^{-3} under IRRI treatment, 1.61 and 1.63 kg m^{-3} for STR1 treatment, and 1.35 and 1.53 for STR2 treatment. The WUE for maize decreased gradually with the reduction of water supply; however, it remained stable from one year to the next for the same water supply level.

The previous example provides evidence for the necessity of reviewing studies on the relationship of water supply to water use efficiency, previously made by Oweis in 1997, using a criterion appropriate to plant water status (Katerji, 1997). This step helps to distinguish the limits between the different water regimes and, consequently, reduces the actual variability in WUE values observed in the Mediterranean region.

Mineral supply

The action of mineral supply on water use efficiency seems often to be strictly related to water supply regime (Oweis, 1997; Oweis *et al.*, 2000; Sadras, 2002 and 2004, Zwart and Bastiaanssen, 2004).

In 1997, Oweis analysed the relationship between water regime and nitrate supply on wheat cultivation in Syria. This author noticed that under rain-fed conditions, the rate of nitrogen fertilizer needed is not high, and that 50 kg ha^{-1} is sufficient. However, with higher water supply, the crop responds to nitrogen up to 100 N kg ha^{-1}, after which no benefit is obtained (Fig. 9). This rate of N greatly improves WUE. It is also important to maintain available phosphorus in the soil so that the response to N and applied irrigation is not constrained.

Fertilization practices in Mediterranean agriculture vary among countries (Tab. 5). Here, due to high temperature, the mineralization of organic matter in the soil is so quick, to reduce natural fertility (Février, 1993). In Algeria, the amount of fertilizer applied per hectare during the year is 29 times lower than the amount applied in Egypt. It is clear, however, that all cultivated areas in Egypt are irrigated and that agriculture is intense (2 to 3 yields per year). However, data in Tab. 5 show important differences between the countries; these concern the amounts of applied fertilizers, with the lowest levels in southern countries. This leads to variability in the comparison of water use efficiency values observed in the Mediterranean region.

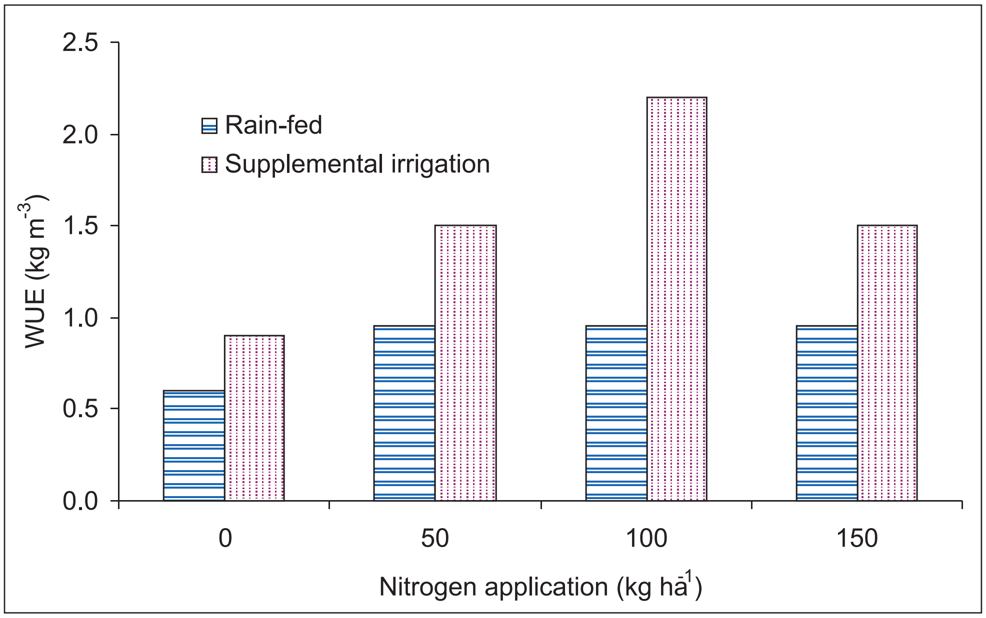

Fig. 9. WUE for rainfed and supplementally irrigated bread wheat as affected by nitrogen (after Oweis, 1997).

Table 5. Mineral fertilizers (kg ha^{-1}) used annually in different countries of the Mediterranean region (after Med Agri, 2001).

	kg ha^{-1} of fertilizers (average 1992-1998)
France	248
Spain	99
Italy	166
Greece	134
Turkey	65
Syria	65
Lebanon	145
Israel	248
Egypt	319
Tunisia	19
Algeria	11
Morocco	30

Water quality

Salinity corresponds to salt accumulation in the root zone, leading to damage of cultivated plants (Katerji, 1995). It occurs through irrigation practices used to face drought. The main causes are: the bad management of irrigation and the use of nonconventional water resources for irrigation (Hamdy *et al.*, 1995).

Soil salinity and drought often have similar effects on plants. In fact, as salinity and drought increase, soil water availability decreases, and this modifies plant water status and gas exchange in the short-term, and growth and yield in the long-term (Katerji, 1995). However, studies on water use efficiency in relation to water quality are few in the Mediterranean region (e.g. Tab. 2), while a significant part of the irrigated area is already affected by salinity.

Recently, in his review, Katerji *et al.* (2003) analysed the consequences of using water of different salinity levels on the water use efficiency of 10 species cultivated in the Mediterranean basin. The study shows a good correlation between species tolerance to salinity and their aptitude to maintain or to improve WUE when irrigated with saline waters (Fig. 10). This classification, done through the CWSI concept (Crop Water Stress Index) based on the pre-dawn leaf water potential (Katerji *et al.*, 2000), helps identify two groups of species:

- The first includes wheat, sunflower, potato, maize, and sugar beet (Tab. 6). These species are salt tolerant that maintain, or slightly ameliorate, their water use efficiency with an increase in salinity.
- The second group includes tomato, lentil, broad bean, and chickpea. These species are salt sensitive, and their water use efficiency is reduced with the reduction of water quality.

The previous observations are important for the choice of species that are the most appropriate for saline soils or for irrigation with saline water. Also, it underlines that soil salinity, more and more expanded over the Mediterranean region, constitutes a source of variability in the determination of water use efficiency values.

Scientific literature aimed at the study of WUE in the Mediterranean often does not stress adequately the soil and water salinity observed during the studies.

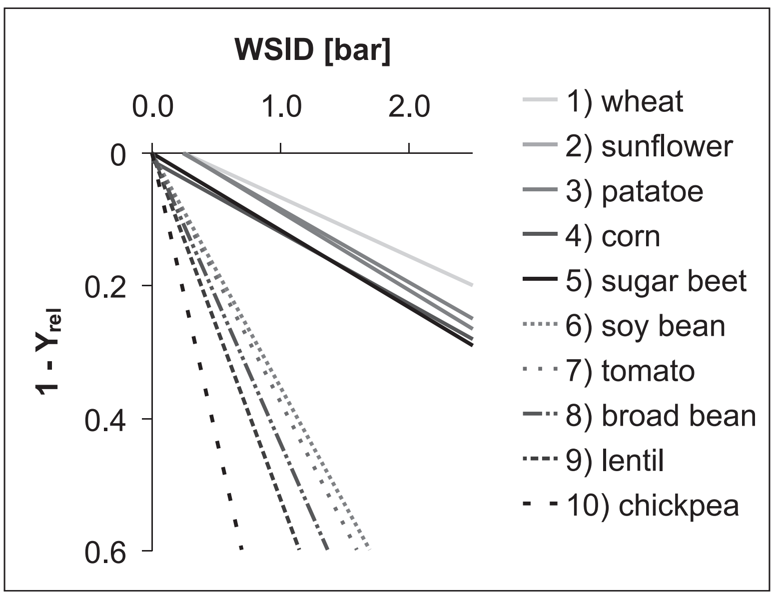

Fig. 10. Relative yield decrease vs. water stress day index (after Katerji *et al.*, 2003).

Table 6. EC_e, relative yield, relative evapotranspiration and water use efficiency of different crops (after Katerji *et al.*, 2003).

Crop	ECe (dS/m)	Yield (%)	ET (%)	WUE (%)
Durun wheat	0.8	100	100	100
	2.3	95	90	106
	4.6	86	80	107
Potato	0.8	100	100	100
	2.6	81	91	88
	4.7	73	81	88
Maize	0.8	100	100	100
	1.9	94	90	105
	3.4	77	80	97
Sunflower	0.8	100	100	100
	2.4	86	88	97
	3.9	73	81	91
Sugar beet	0.8	100	100	100
	3.5	85	89	96
	6.1	83	89	94
Tomato	0.8	100	100	100
	4.3	73	91	80
	5.9	41	77	53
Soybean	0.8	100	100	100
	4.0	80	88	91
	6.7	44	78	61
Broadbean	0.8	100	100	100
	4.6	77	88	88
	6.1	49	78	63
Lentil	0.7	100	100	100
	2.0	81	91	85
	3.2	6	81	17
Chickpea Variety 87-59 C	0.8	100	100	100
	2.4	57	64	90
	3.8	31	46	67

Plant factors

In the previous paragraph, we analysed a group of parameters that allow for explanations of the differences in water use efficiency values observed for different species (relationship of photosynthesis / transpiration at the leaf scale, production type). In this paragraph, the processes associated with plant water supply responses will be discussed.

Drought sensitivity at different crop growth stages

Plant reactions to drought during the growth cycle have been studied deeply in the past. In 1923, this subject was taken up by Heller and Duly (Robelin, 1963). Since that date, many studies aiming to identify stress-sensitive phenological stages were conducted on several species: maize (Robins and Domingo, 1953; Robelin, 1963), soybean (Mingeau, 1975), sunflower (Robelin, 1967), pepper (Katerji *et al.*, 1991), sorghum (Mastrorilli *et al.*, 1995), and sweet sorghum (Mastrorilli *et al.*, 1999). These critical stages correspond to important ones (for example flowering stage, fruit setting, or assimilate transfer) in the elaboration of crop yield. In practice, this knowledge leads to the identification of the conditions necessary for high profit of water supply in relation to crop phenological stage sensitivity.

The method consists of determining sensitive stages by introducing soil water stress at a single phenological phase (Stanhill, 1957; Singh and Alderfer, 1966). Often, it is conducted on plants cultivated in containers. The theoretical analysis made by Katerji *et al.* (1991) shows that this method does not lead to similar drought intensities during different phenological stages, and this is due to many parameters (climatic conditions, leaf surface) intervening in the determination of the observed drought level. These authors proposed a field method, which consisted of reducing the pre-dawn leaf water potential or the leaf water potential (through water rationing) of plants at different phenological stages, then comparing the yield and WUE of treated plants with controls characterised by high and constant pre-dawn leaf water potential.

An example of this method observed in the Mediterranean region is presented in Figure 11, according to a study made on grain sorghum production by Mastrorilli *et al.* (1995). When water stress was applied during the flowering stage, the water use efficiency value was one third of that observed in control and other treatments (Tab. 7). This reduction in water use efficiency is the result of the reduction in yield and not in water consumption. As an example, T1 and T2 (stressed at flowering and seed-setting stage, respectively) treatments used almost the same amount of water (seasonal ET were 369 and 360, respectively), but grain yields were different: 2.5 t ha^{-1} for T1 and 5.7 for T2. Consequently, the WUE value was 0.67 kg m^{-3} for T1 compared to 1.59 kg m^{-3} for T2.

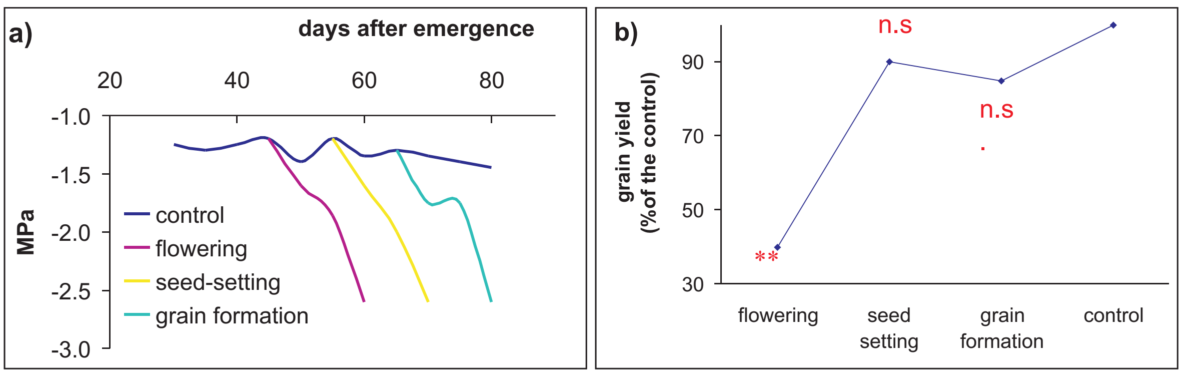

Fig. 11. Grain sorghum: evolution in time of midday leaf water potential during the reproductive phase for the control and the temporary stressed treatments (a); grain yield variations (b) as percentage of the control treatment (after Mastrorilli *et al.*, 1995).

The previous example clearly indicates that the irrigation calendar, corresponding or not to sensitive phenological stages, has an important effect on yield, and consequently, it can be a source of variability observed in WUE values.

Table 7. Biomass (WUE_b) and agronomic (WUE_a) water use efficiencies in relation to temporary soil water stress applied at three phenological stages during the reproductive phase of grain sorghum (after Mastrorilli *et al.*, 1995).

Stress at	WUE_b	WUE_g
flowering (T1)	2.64	0.67
seed-setting (T2)	4.01	1.59
seed ripening (T3)	4.51	1.41
Control	4.85	1.51

Variety response to water stress

Most studies on water regime have been dedicated to the analysis of crop response in the Mediterranean region to water stress caused by drought or soil salinity in order to identify factors associated with plant tolerance (Clarke, 1987; Acevedo, 1987; Araus *et al.*, 1998; Munns 2002) that may be taken into consideration for the creation of new resistant varieties (Ceccarelli *et al.*, 2004).

Genetic improvements affecting the drought resistance of cultivated species has made important progress in the last 20 years. This progress, however, has not involved salinity (Sharma and Goyal, 2003).

A significant number of recent studies have provided elements on the relationship between WUE and plant variety in the presence and absence of saline water stress for many Mediterranean species. These studies concerned chickpea, faba bean, and durum wheat (Katerji *et al.*, 2005 a and b). The study on durum wheat included the analysis of the behaviour of 7 varieties with different genetic origins.

The authors used experimental studies in greenhouses to analyse yield and water efficiency of 7 durum wheat varieties irrigated with 3 different water qualities: fresh water, 4 dS m^{-1}, and 8 dS m^{-1}. Irrigation was performed whenever soil water content reached 30% of maximum water content value. In this study, the experimental protocol avoided the exposure of plants to soil drought.

The 7 studied varieties exhibited (Tab. 8) a large range of WUE, depending on saline water stress. The realised functional classification at each water salinity allowed for the identification of 2 varieties, exhibiting the extreme behaviours at different saline conditions; these varieties are Haurani and Cham1.

Table 8. Classification of seven durum wheat varieties (V1 Om Rabi-5; V2 Hagla; V3 Haurani; V4 Gidara-2; V5 Waha; V6 Jennah Khetifa; V7 Belikh-2) at three salinity levels according to water use efficiency (after Katerji et al., 2006). Numbers followeed by different letters are significantly different at the 5% level according to the student-Neuman-Keuls test.

ECiw = 0.9 dS/m			ECiw =4.0 dS/m			ECiw = 8.0 dS/m		
V6	1.61	a	V5	1.68	a	V7	1.75	a
V7	1.59	a	V7	1.61	a	V5	1.69	a
V5	1.45	ab	V6	1.49	a	V6	1.41	b
V4	1.35	ab	V4	1.26	b	V4	1.40	b
V1	1.24	ab	V2	1.21	b	V2	1.04	c
V2	1.21	ab	V3	1.09	bc	V1	0.83	c
V3	1.16	b	V1	0.93	c	V3	0.78	c

The difference in WUE of these two varieties observed in the previous study was confirmed:

- Under drought conditions, according to studies conducted in the field (Ali Dib *et al.*, 1992; Annicchiarico and Pecetti, 2003).
- Through irrigation with different water qualities measured in lysimeters (Katerji *et al.*, 2005b).

The WUE values obtained in this study are presented in Table 9. The Cham 1 variety had a higher WUE in comparison with Haurani when irrigated with fresh water, and it ameliorated its water use efficiency when irrigated with saline water. Under these conditions, both varieties presented WUE differences that reached about 40%.

Table 9. Cumulative evapotranspiration, grain yield and water use efficiency for three soil salinity levels of the salt sensitive (S) and salt tolerant (T) varieties of durum wheat (after Katerji et al., 2005b).

	Haurani (S)			Cham-1 (T)		
soil salinity, ECe (dS m^{-1})	0.9	4.8	7	0.9	4.2	6.9
ΣET ($m^3 m^{-2}$)	0.72	0.64	0.60	0.68	0.60	0.55
yield (kg m^{-2})	0.83	0.69	0.66	0.97	0.96	0.87
WUE(kg m^{-3})	1.15	1.08	1.10	1.43	1.58	1.59

The previous example on wheat underlines 2 aspects:

1. the importance of the choice of salt resistant or drought resistant variety in order to ameliorate WUE.
2. the large variability in WUE observed within a species can be attributed to the response of different varieties to water stress caused by drought or salinity.

Environmental factors

Climate

The effect of climate, especially air water deficit, on the WUE of a determined species has been the subject of analysis of many studies (Tanner and Sinclair, 1983; Howel and Musik, 1985; Angus and Herwaarden, 2001). A recent review conducted by Zwart and Bastiaanssen (2004) on WUE values observed for a winter crop (wheat) and three summer crops (maize, rice, and cotton), cultivated under similar experimental conditions between 10 and 40 degrees latitude (north and south of the equator), is of considerable interest. These authors noticed that the vapour pressure deficit generally decreases when moving away from the equator and WUE is expected to increase with increasing latitude. For example, the highest WUE values occur between 30 and 40 degrees latitude where a 2- to 3-fold difference in WUE of wheat, rice, and maize was detected when compared to areas between 10 and 20 degrees latitude.

The previous results could not be demonstrated for crops cultivated in the Mediterranean region, due to the large range of WUE values obtained for each species and each experimental site. However, the range of air water deficit observed during winter and summer in the Mediterranean region is smaller in comparison with that observed by Zwart and Bastiaanssen. Taking into consideration the factors interfering with the determination of WUE values, the analysis of climate effects on WUE requires experimental studies at sites of similar characteristics (same variety, same water and mineral regime). This kind of data is not actually available for the Mediterranean region.

Atmospheric pollution

The Mediterranean region is an area prone to the development of photochemical oxidants (Bussotti and Ferretti, 1998; Alonso *et al.*, 2001). The typical climatic conditions of this region (high temperatures and solar levels combined with stable air masses and high emission of air pollutants) favour the formation of secondary pollutants such as ozone (O_3). Ozone content in the atmosphere is evaluated through indices as AOT40. This is the accumulated ozone over a threshold of 40 ppb during an hour (Fuhrer at al., 1997). When cumulated AOT40 during the growing season surpasses a certain threshold, plant functions, mainly gas exchange (Darral, 1989; Heath, 1996), leaf growth (Mortensen, 1994; Long and Naidu, 2002), flower and pod setting, yield, and water use efficiency are affected. However, annual species (Mills *et al.*, 2003) show a large variability in responses to ozone (Tab. 10).

Table 10. Ozone sensitivity classification of cultivated species (after Mills et al., 2003).

Sensitive	Semi-sensitive	Semi-resistant	Resistant
< 5 ppm h	5 10 ppm h	10 20 ppm h	> 20 ppm h
melon	sugar-beet	rice	fruit trees
wheat	potato	corn	barley
leguminous	colza	vineyard	
cotton	tobacco	broccoli	
rape			
tomato			
onion			
soybean			
lettuce			

The AOT40 values observed during the growing seasons of winter and summer crops are not well known in the region, and this demonstrates the lack of information concerning the effect of ozone on WUE in the Mediterranean region. The first study on this subject (Bou Jaoudé, 2006) was conducted in southern Italy on soybean, which was classified as sensitive (Tab. 10) to ozone by Mills et al (2003). This study, conducted over 3 successive years, shows the presence of an important interannual variability of cumulated AOT40 during the soybean crop cycle (Fig. 12). These values varied between 3400 and 10000 ppb, thus at a ratio of 1 to 3.

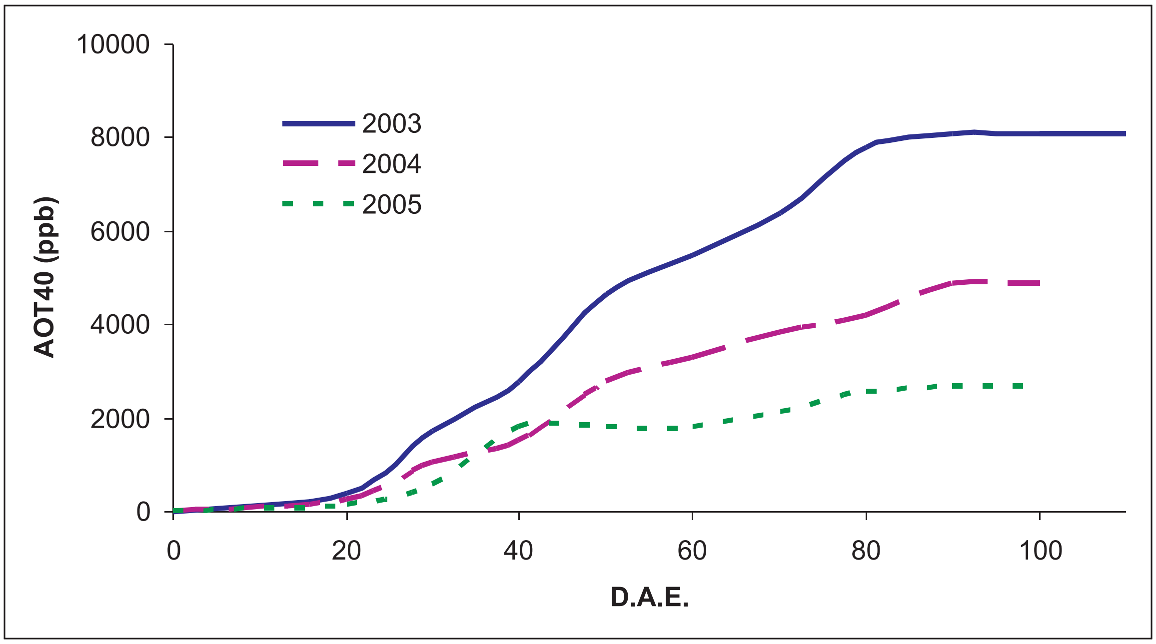

Fig. 12 Accumulated O_3 over a threshold of 40 ppb (AOT40) monitored at Rutigliano (Bari) during three soy bean crop seasons (after Bou Jaude, 2006).

The reaction of soybean to ozone in comparison with a control where ozone was filtered is well correlated with measured AOT40 values and with the water regime applied during the cropping season:

- When AOT 40 was about 3400 ppb, ozone had a slight effect on WUE of irrigated soybean (under optimal watering conditions) and on water stressed soybean (by water rationing),
- Whereas, when AOT 40 was about 10000 ppb, ozone reduced the WUE of irrigated soybean about 30% (Tab. 11), while it had no significant effect on water stressed plants.

Tab. 11. Cumulative evapotranspiration, grain yield and water use efficiency for soy bean growing at Rutigliano (Bari) under two soil water regimes (well watered and stressed) and two ozone levels: AOT = 0, and AOT = 9000 (after Bou Jaude, 2006).

	well watered		stressed	
	AOT = 0	AOT = 9000	AOT = 9000	AOT = 0
ET (m^3 m^{-2})	0.38	0.28	0.27	0.28
Grain yield (kg m^{-2})	0.28	0.15	0.18	0.19
WUE (kg m^{-3})	0.74	0.53	0.68	0.67

The study by Bou Jaoudé (2006) analysed the physiological and agronomical mechanisms modifying WUE of irrigated crops. This study shows however, that the absence of effect on water stressed plants is due to stomatal closure, which reduces ozone flux towards leaves, and thus its action on plant functions.

The ozone level in the atmosphere is often a neglected parameter in studies; however, it is susceptible to creating variability in irrigated crops in the Mediterranean region. The literature shows that few studies have been conducted on this subject, which is why the effect of ozone on plants needs to be analysed deeply in the future.

Soil texture

The effect of soil texture as a factor susceptible to modifying WUE has not been studied yet.

A recent study (Katerji et al 2007) in the Mediterranean region on 8 species cultivated on clay and silt soils shows the presence of a correlation between soil texture and WUE. Studied species included winter crops (wheat, potato, and sugar-beet) and summer crops (maize, sunflower, tomato, and soybean). These crops were irrigated under optimal watering conditions as shown by pre-dawn leaf water potential values obtained during the crop cycle.

The main conclusions of this study are summarised as follows:

- The WUE of some species are reduced significantly when cultivated on clay soil in comparison with silt soil. This is the case for sugar-beet, potato, and sunflower (Tab.12),
- As for other species, WUE did not vary with soil texture. This is the case for tomato, wheat, corn, soybean.

Table 12. Water use efficiency (kg of marketable yield per m^3 of evapotranspired water) of different crops growing on two different soil types.

	loam		clay	
sugar-beet	7.80	a	6.10	b
wheat	1.02	a	1.05	a
broad-bean	1.14	b	1.58	a
corn	1.12	a	0.85	a
potato	20.80	a	16.00	b
tomato	8.65	a	7.96	a
soy-bean	0.81	a	0.72	a
sunflower	0.24	a	0.18	b

Katerji *et al.* (2007) analysed the mechanism of this behaviour. They noticed that, in comparison to cultivation in silt soil, sugar beet and potato showed lower gas exchange, leaf growth, and dry matter accumulation when they are cultivated in clay soil. The physiological mechanisms regulating gas exchange and growth in clay soil probably originate from root signals (Davies and Zhang, 1991; Tardieu *et al.*, 1991) transmitted to the aerial plant part to reduce leaf growth and stomatal conductance. These signals, indeed, represent the reaction to mechanical (Masle and Passioura, 1987) or water (Tardieu *et al.*, 1992) constraints exerted by soil on the roots.

The relations between the WUE of Mediterranean crops and soil texture deserve more scientific attention, especially since they may provide explanations for the variability observed for WUE.

Climatic changes

Climatic change is due to the continuous rise of green house gases, primarily in the form of CO_2 (IPPC, 2001). According to recent scientific reports, the effect of these variations on mean earth temperature levels are not yet known, especially when they are evaluated through general circulation models (Mitchel *et al.*, 1995; Manabe and Stoufer, 1997; Carnel and Senior, 1998; Reader and Boer, 1998). These models were developed to take into consideration many processes essential in determining future climate (Radiation, convection, air mass circulation, turbulence exchange with the surface) and they are susceptible, consequently, to important variability (Mégie and Jouzel, 2003).

The effect of CO_2 increases is better evaluated on air temperature than on rainfall. However, the different models agree on a forecast of increased temperature and reduced rainfall in the Mediterranean basin (Laval and Polcher, 1999; Ragab, 2003). Observations on rainfall analysed in Foggia (Southern Italy) using long-term data seem to agree with this hypothesis (Fig. 13). Thus, it is necessary at the moment to examine the consequences of these changes on agriculture in general and on WUE in particular.

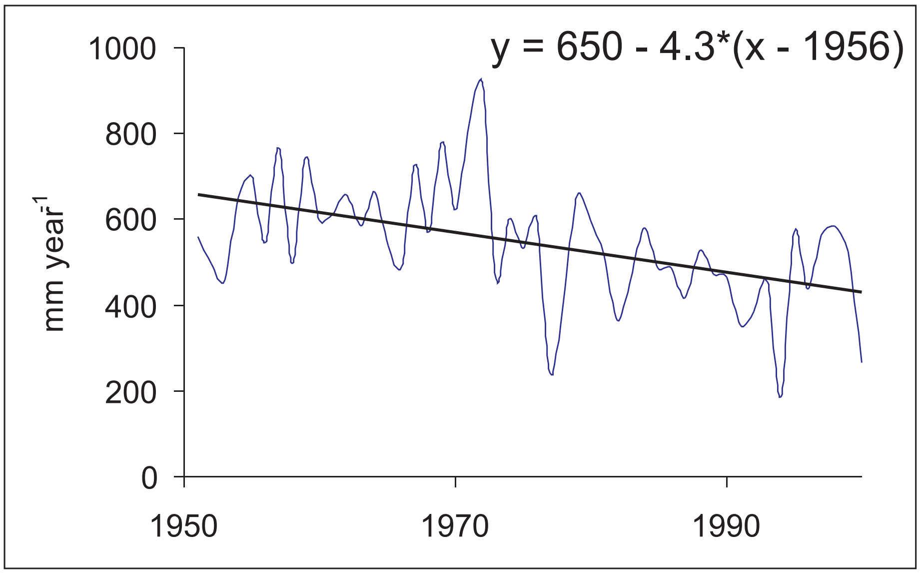

Fig. 13. Annual rainfall measured in Foggia (Southern Italy) from 1950 until 2000.

In the analysis of the effect of environmental modification on WUE, it is necessary to distinguish the effects related to CO_2 increase, to temperature, and to water resources used in agriculture and their interaction.

The rise in CO_2 levels increases WUE for the following two reasons:

- The increase in photosynthesis and consequently an increase in yield. For C_3 plants (wheat, rice, potato), yield increases up to 30% when CO_2 values double (Lawlor and Mitchell, 1991; Kimball *et al.*,1993). Whereas for C_4 plants (maize, sorghum), the effect of CO_2 levels on photosynthesis is lower and final yield is not significantly affected (Morison and Gifford, 1984, Hocking and Meyer, 1991, Ruget *et al.*, 1996).
- The reduction of stomatal conductance (Woodward, 1987) and, as a consequence, the reduction of transpiration of C_3 and C_4 plants (Emus and Jarvis, 1989). For maize, transpiration is reduced 15 - 17% (Fig. 16) with the doubling of CO_2 level and this leads to a significant increase in WUE (Bethenod *et al.*, 2001a).

Temperature increases modify WUE for 2 reasons:

- The reduction of crop cycle, which reduces water consumption (Perarnaud *et al.*, 2002),
- The increase of daily evapotranspiration due to the increase of vapour pressure deficit, as a result of the increase in temperature (Chosinel, 1999; Ragab, 2003).

The analysis of the interaction between temperature and CO_2, associated with more or less important modifications on water resources, is possible nowadays through the use of crop simulating models, that incorporate climatic scenarios expected to occur in the future (Delécolle *et al.*, 1999, Gervois *et al.*, 2004). Thus, these models give predictions in relation to crop type, water amount, fertilizer uptake, and they test the strategies of water need and adaptation to climatic change (Gervois *et al.*, 2004). Combined with geographical information systems, they help generate predictions on the adaptation of different crops.

Results expected from models will be different from previous ones according to the crop considered: annual crops (seed crops, tuber crops, gramineous or legumes), perennial herbaceous crops (forage crop, prairie), or ligneous crops (vine, fruit trees).

A case study on climatic changes in the Mediterranean region

Research to analyse the effect of climatic change on Mediterranean crops could produce a sound tool to manage water use in the future. A recent example of such studies was performed on corn grown under not limiting soil water conditions in Southern Italy (Ayoub, 2006). This study simulated the yield and water use of corn through the Stics model (Brisson et al, 2003) using two climatic scenarios. Both scenarios foresee, in the years from 2070 to 2099, the increase of CO_2: A (severe), the CO_2 content air of is about 700 ppm; B (mild), the CO_2 content of air ranges from 500 to 550 ppm.

In comparison with the 1984-2004 period, the corn simulation in the 2070-2099 period under both scenarios shows:

- Slight above-ground biomass reduction (fig. 15) and high reduction in grain yield (fig. 16) which is due to lower grain weight (fig. 17). The yield component is reduced as a consequence of the shorter duration of the flowering-maturity phase.

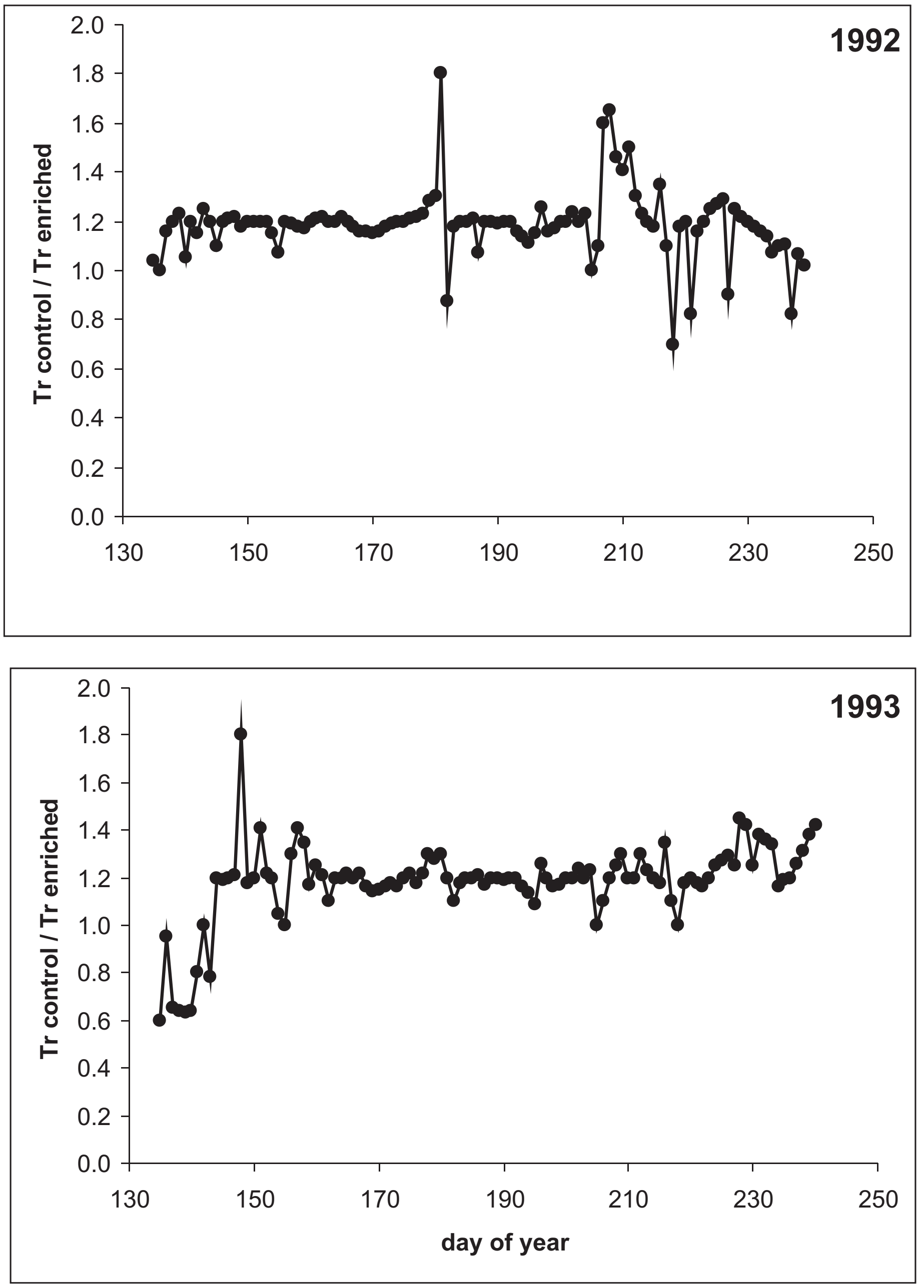

Fig. 14. Daily ratio of the transpiration of the control treatment and the transpiration of the elevated (750 ppm) CO_2 treatment for maize plants during two growing seasons (after Bethenod *et al.*, 2001a).

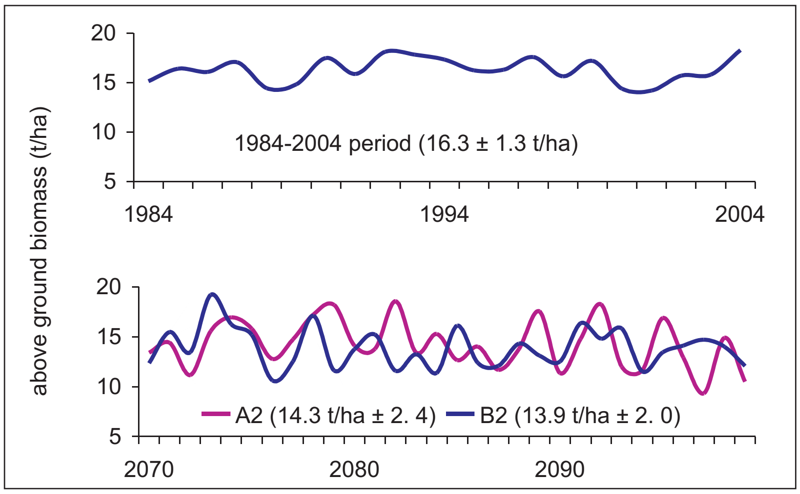

Fig. 15. Above-ground biomass (t/ha of dry matter) simulated by STICS model under non limiting soil water conditions using the agrometeorological data measured at Rutigliano (Southern Italy) from 1984 until 2004, and the data derived by A2 and B2 scenarios (2070-2099 period).

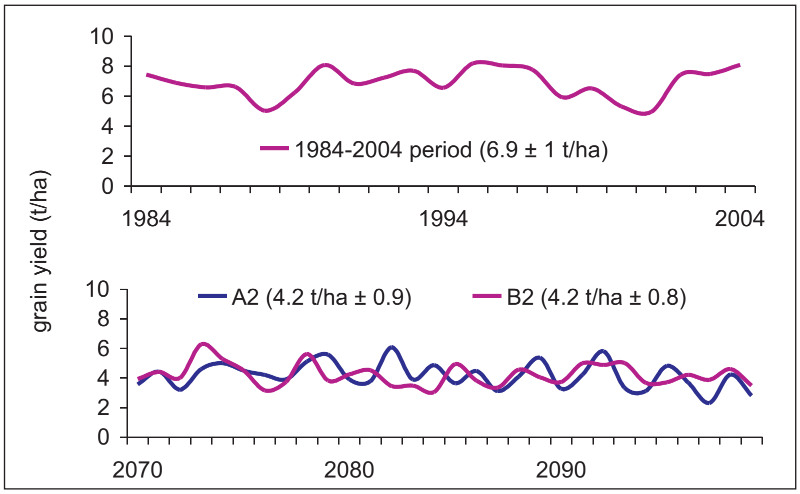

Fig. 16. Grain yield (t/ha, at 0 % of moisture) simulated by STICS model under non limiting soil water conditions using the agrometeorological data measured at Rutigliano (Southern Italy) from 1984 until 2004, and the data derived by A2 and B2 scenarios (2070-2099 period).

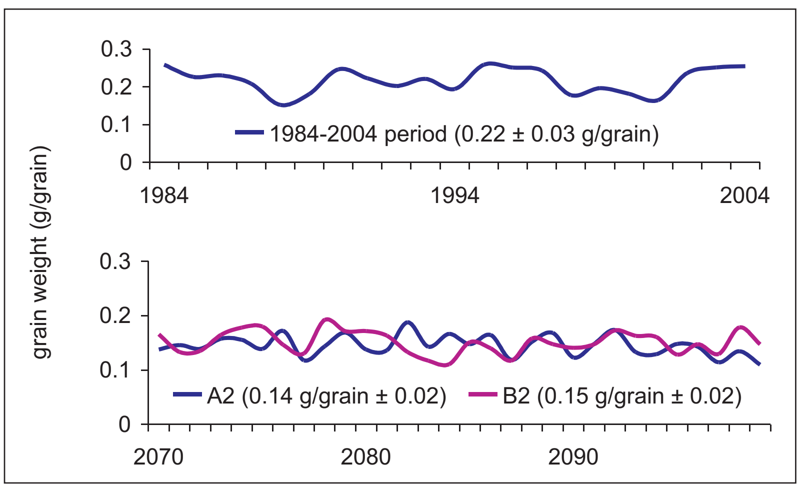

Fig. 17. One grain weight (g at 0% moisture) simulated by STICS model under non limiting soil water conditions using the agrometeorological data measured at Rutigliano (Southern Italy) from 1984 until 2004, and the data derived by A2 and B2 scenarios (2070-2099 period).

- Reduction in seasonal evapotranspiration (fig. 18) and in WUE (fig. 19). The latter reduction is not statistically significant because of the imprecision which affects the realized simulations.

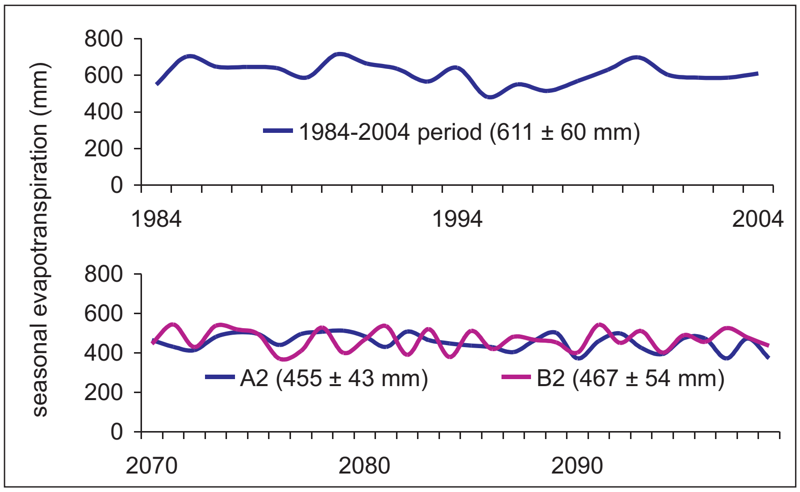

Fig. 18. Cumulated evapotranspiration (mm) simulated by STICS model under non limiting soil water conditions using the agrometeorological data measured at Rutigliano (Southern Italy) from 1984 until 2004, and the data derived by A2 and B2 scenarios (2070-2099 period).

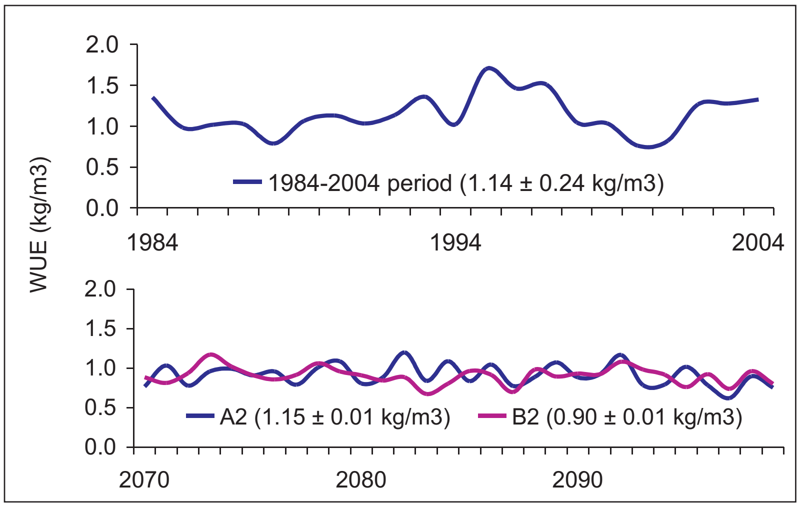

Fig. 19. Water use efficiency (kg/m3) calculated on the basis of the STICS model outputs, using the agrometeorological data measured at Rutigliano (Southern Italy) from 1984 until 2004, and the data derived by A2 and B2 scenarios (2070-2099 period).

A NEW APPROACH TAKING INTO CONSIDERATION WUE IN ORDER TO SELECT PLANT VARIETIES AND SPECIES APPROPRIATE TO THE SITE

For the agronomist mainly interested in final yield, the choice of the appropriate species or variety consists of identifying the one exhibiting yield superiority over all environments (Reitz, 1974).

Irrigation specialists, however, do not consider yield as an important indicator (see review by Pereira et al., 2002). To identify the best irrigation scheduling strategies (Shideed et al., 2005) and to analyse the water saving performance of irrigation systems (Ayars et al., 1999), they use the water use efficiency (WUE) as an indicator. This choice is justified by the increase in water value through the reduction of water supply. It also helps to protect the environment through the reduction of salt accumulation in the soil profile (Burt et al., 1997).

Sinclair and Muchow (2001) underline the importance of both indicators and suggest selecting varieties according to yield and high water use efficiency. In fact "high water use efficiency" in itself is of little interest when it is not associated with high yields. Economic benefits from increased water use efficiency are usually achieved only if yield is maximized for the available water.

Searching for a relationship between yield and water use efficiency constitutes a new approach, not explored sufficiently, in studies concerning variety selection under drought and saline conditions.

The first encouraging studies concern the relationship of yield to water use efficiency realised according to soil water availability. For bread wheat, this relation (Fig 20) is curvilinear ascendant showing a high correlation between yield and WUE (Zhang and Oweis, 1999), whereas for durum wheat, the same relation (Fig 20) is curvilinear that reaches a maximum, indicating a reduction of WUE with an increase in yield (Oweis and Zhang, 1998).

Katerji et al. (2006) compared the relationships of variety yield to WUE of 3 cereals irrigated with different water qualities in a greenhouse experiment. They noticed (Fig 21) that barley increases water use efficiency for all observed yield ranges. For wheat, bread wheat increases water use efficiency in comparison with durum wheat and this is in agreement with the observations made by selectors (Nachit et al., 1998). The curve observed for durum wheat has a plateau form when yield is over 1 Kg/m2, showing stability in WUE at high yield values.

The curvilinear ascendant curves of yield and WUE observed for barley by Katerji et al. (2006) is similar to the one observed for bread wheat (Zhang and Oweis, 1999), lentil and chickpea, (Zhang et al., 2000), and faba bean (Oweis, 2005) cultivated in fields under irrigated and non-irrigated conditions. However, differences exist between our observations and the one made by Zhang and Oweis on durum wheat. These authors found a high correlation between WUE and yield; however, this was true for yields lower than 0.6 Kg m^{-2}. Over this yield value, WUE was reduced significantly, while Katerji et al. found stability in the relationship between yield and WUE.

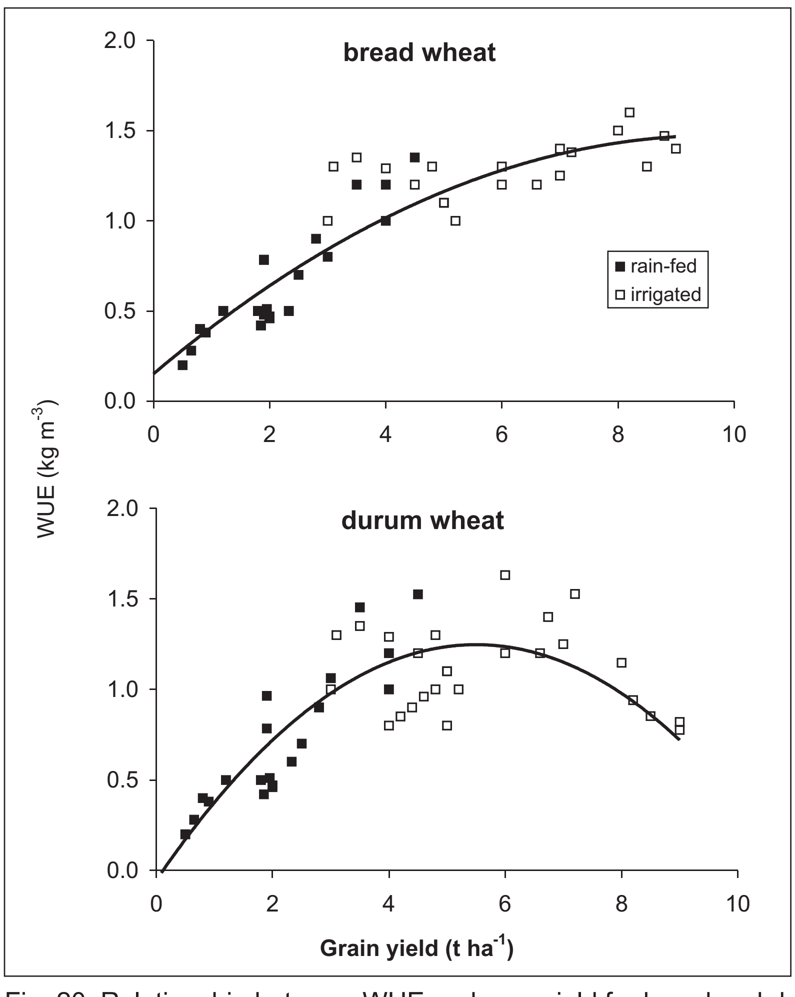

Fig. 20. Relationship between WUE and crop yield for bread and durum wheat over five seasons (after Zhang and Oweis, 1999).

The reduction of WUE found in the study of Zhang and Oweis (1999) could be due to the evapotranspiration estimated through a simplified water balance equation, which was not measured directly as in the study by Katerji et al. (2006). In the simplified water balance equation, runoff and drainage are supposedly negligible. This hypothesis is not valid (e.g. Katerji et al., 1984) for conditions of rainfall and high irrigation. Thus, the calculation of soil water balance leads to an overestimation of evapotranspiration (Rana and Katerji, 2000) and, in consequence, to an underestimation of WUE. As we could notice, the method used to determine ET leads to a different interpretation of obtained WUE values.

The previous observations realised under drought and saline conditions are considered conclusive by Katerji et al. (2006); they lead to the proposal for a methodology to select plant variety based on yield and WUE. This method was applied to barley, bread, and durum wheat. To test this method, the classification already conducted on durum wheat in relation to WUE (table 8) was compared with the classification of relation to yield for the same variety (tab. 13).

The classification of yield and WUE were similar under the different salinity conditions; salinity has a slight effect on the classification of control treatment (fresh water).

Classification of yield and WUE are practically similar, and this results from the positive correlation between the two parameters (Fig. 21).

Table 13. Classification of yield (kg m^{-2}) obtained by two durum wheat varieties growing on three soil salinity levels.

	variety S		variety T	
S1	0.83	a	0.97	a
S2	0.69	b	0.96	a
S3	0.66	b	0.87	b

The agreement between the classification of yield and WUE was also verified on bread wheat and barley (Katerji et al., 2006). Thus, the proposed methodology constitutes a field of research that deserves to be explored in the future.

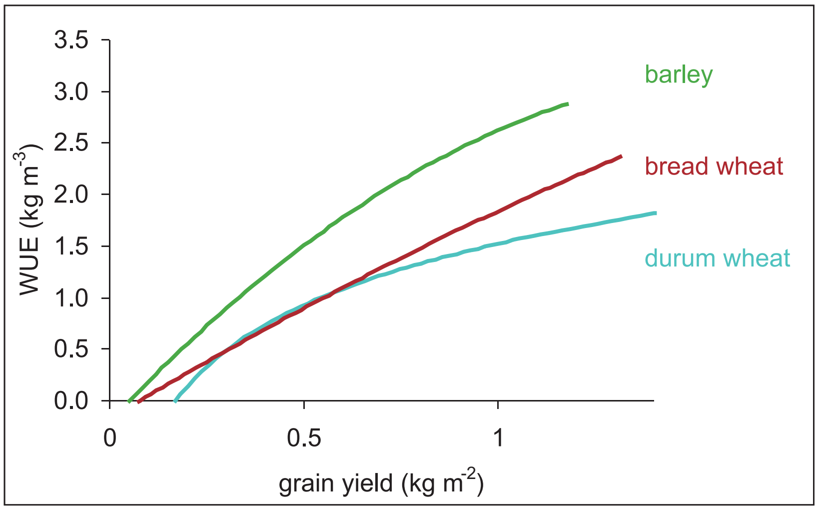

Fig. 21. Relationship between WUE and crop yield for barley, bread and durum wheat (after Katerji et al., 2006).

CONCLUSIONS AND RECOMMENDATIONS

The analysis described in this report and summarized in figure 22 underlines and describes the parameters susceptible to interference in the determination of WUE measured at different temporal and spatial scales:

- From leaf to plot
- From plot to regional scale
- From minute to crop cycle

It is necessary at the moment to mention the lack of the current knowledge in order to identify the promising future of this field of study.

Schematically, these fields can be considered through 2 angles: methodology and research.

Methodology level

- Particular attention should be dedicated to the methods of ET determination at natural sites, and their application to the climate of the Mediterranean region especially that, in the absence of a correct estimation of this parameter, there should be lack of liable WUE analysis.
- The complementarities between the ecophysiological and agronomical approaches are necessary to analyse and understand the WUE data obtained through each approach. The examples reported in this paper clarify the differences between the two approaches.
- The methodology that associates an indicator of plant water status to soil water status criterion in WUE analysis permits a reduction in the variability observed for WUE values through standard experimental conditions. This is a primary condition for a deep WUE analysis. It is the case for the designated research to examine the well-founded management methods in order to ameliorate WUE (modification of sowing date, mulching…)
- The identification of the phenological stages quantitatively and qualitatively sensitive to water constraint under field conditions is preliminary for a rational complementary irrigation practice. The methodology proposed in this study constitutes an easy way to reach this objective.
- The realisation of plant variety selection taking into consideration both yield and WUE as an approach to be developed in the future.

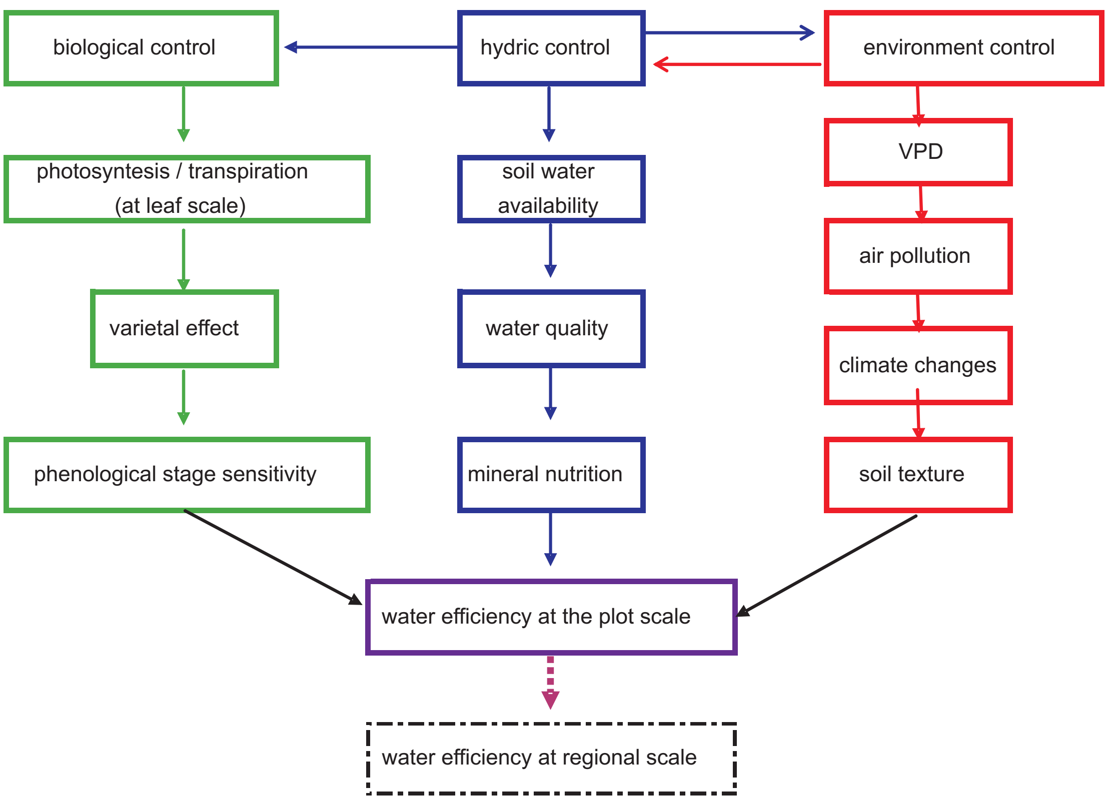

Fig. 22. Parameters involved in the determination of WUE measured at different spatial scales.

Research level

- Research on WUE of multi-annual crops (mainly fruit trees) has not been conducted due to the lack of methods in determining water consumption. They should be developed in the future in order to provide information on these crops, especially since they are major crops in the Mediterranean region.
- Actual research on water use efficiency is carried out with high water quality. The increase of saline soils due to the increase of nonconventional water use for irrigation makes the study of WUE in relation to water quality necessary.
- The research relating WUE to mineral supply is limited in the Mediterranean region. Such research is necessary to demonstrate to farmers the importance of well-founded fertilizing practices on WUE.
- Plant amelioration has made important progress through the creation of varieties with higher drought and salinity resistance. So it is necessary, nowadays, to analyse the WUE of Mediterranean crop varieties in order to show the benefit obtained through these creations.
- The analysis of the relationship between WUE of irrigated crops and ozone air pollution is still at the embryonic stage. This is a new field of research that deserves to be explored in the future.
- According to our current knowledge, climate change could lead to important modifications of agricultural practices in the future (species and variety choice, sowing and yielding date, irrigation practice, WUE...). From here comes the necessity to prepare agriculture to face these future changes

The improvement of WUE in the Mediterranean region is an imperative imposed by the critical situation of water resources present in the region as well as by the demographical increment. This objective can be reached only through high quality research.

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