Agronomic perspective on the increase of water use efficiency at the field scale in Mediterranean environments

Casa R.

in

Rana G. (ed.), Mastrorilli M. (ed.), Albrizio R. (ed.).
WEMED workshop: how to advance the knowledge on water use efficiency in the Mediterranean region ?

Bari : CIHEAM
Options Méditerranéennes : Série A. Séminaires Méditerranéens; n. 72

2007
pages 83-91

AGRONOMIC PERSPECTIVE ON THE INCREASE OF WATER USE EFFICIENCY AT THE FIELD SCALE IN MEDITERRANEAN ENVIRONMENTS

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SUMMARY - The increase of field scale water use efficiency, commonly defined as the ratio of marketable yield or biomass to crop evapotranspiration, can be obtained from a range of practices that can be categorised into those which convert more of the water resources into transpiration and those that increase the transpiration water use ratio. Relevant agronomic practices are those that can act directly or indirectly to: maximise yield, increase harvest index, increase transpiration vs. soil evaporation, reduce deep percolation, reduce surface runoff. This paper attempts to briefly review some topics that can be expected to stimulate more agronomic research on WUE in Mediterranean environments in the next few years, the discussion being focused to field crops. These topics include: conservation tillage, regulated deficit irrigation and partial root-zone drying, the revision process of the FAO Irrigation and Drainage paper n. 33 and precision irrigation.
The improvement of water use efficiency at the field scale in the next few years is expected to depend equally on the use of the best agronomic practices available for each specific cropping system and on the availability of better varieties. However efficient systems for the transfer and promotion of successful agronomic research results into farming practice, through integrated participatory approaches, should also be in place, if real progress in this strategically important issue for the Mediterranean area is to be made.

INTRODUCTION

In Mediterranean environments, major constraints to crop growth are represented by moderately cool temperatures and low incoming radiation during winter, often with occurrence of late frosts especially in some inland areas, and by high temperatures and lack of rainfall during summer, precluding any significant summer cropping without irrigation (Katerji *et al.*, 2006; Turner, 2004). Both dryland and irrigated farming pose special challenges to Mediterranean farmers, who need to adopt sensible agronomic practices in order to reach the objectives of maximising yields and quality while using efficiently natural resources and artificial inputs. In particular, the efficient use of water resources has become increasingly important in recent times, and presumably will even intensify in the future, given the demographic growth in the Mediterranean and the resulting increased competition between agriculture and other sectors and the possible impacts from climate change (Katerji *et al.*, 2006; Norrant and Douguédroit, 2004; Wallace, 2000). Many studies have pointed out to the wide present occurrence of low efficiencies in water use in Mediterranean farming systems, which represent the major freshwater resource users in this region (Katerji *et al.*, 2006).

Therefore, improvement of the efficiency by which irrigation and rainfall is used in Mediterranean farming systems is an important objective, though it is essential to clearly identify the relevant indicator of water use efficiency we want to increase, so that it is appropriate for the spatial and temporal scale chosen (Steduto, 1996). For example at the overall irrigation system scale, maximising water productivity, i.e. yield obtained for unit water used, may not be the best objective when considering also socio-economic aspects (Zoebl, 2006). Equally, at the farm scale, it is wise to allow for inefficiencies which result in non-consumptive, but reusable (e.g. leaching or runoff), losses (Pereira *et al.*, 2002).

When dealing with the field or canopy scale, i.e. a spatial extent in the order of one to few hectares and time steps in the order of weeks to months, the most widely used indices (incorrectly but commonly called water use efficiency, WUE) are: 1) the ratio between dry biomass and water used by the crop (WUE_b), 2) the ratio between marketable yield and water used by the crop (WUE_y). There are methodological problems in the measurement of terms of these ratios, which complicate the comparison of research results and assessment of the improvement in WUE due to different crop management practices (Katerji *et al.*, 2006). For example in most cases only above-ground dry biomass is measured, though different water and soil management treatments can impact root biomass allocation, thereby potentially impacting WUE_b (Jones, 1992). Water used by the crop can mean very different things, i.e. only transpired water, evapotranspiration (including soil evaporation), or irrigation and/or rainfall amounts (Du *et al.*, 2006; Kang *et al.*, 2000; Steduto, 1996; Steduto and Albrizio, 2005).

From an agronomic point of view, the interest is on how to obtain high and good quality yields using as little water as possible. However there is no consistency in results from different years, even for the same location, if we consider the ratio between yield and irrigation and/or rainfall, mainly because of the influence of rainfall pattern and irrigation amounts and timing in relation to crop phenological development. Therefore the most appropriate denominator for WUE ratios, in an agronomic context, seems to be actual crop evapotranspiration (ET), though it needs to be normalised for comparison between different environmental conditions (Steduto and Albrizio, 2005). In some situations the denominator should also include other beneficial depletions, such as leaching of salts (Kijne *et al.*, 2003; Pereira *et al.*, 2002).

By adopting WUE_y with ET as a denominator, we can assess the effects of various agronomic practices on water productivity. These practices, reviewed by Hatfield *et al.*, (2001) and Howell (2001), can be categorised into those which convert more of the water resources into transpiration and those that increase the transpiration water use ratio (Wallace, 2000), the latter mainly domain of plant physiology and genetics. The relevant agronomic practices are those that can act directly or indirectly to: maximise yield, increase harvest index, increase transpiration vs. soil evaporation, reduce deep percolation, reduce surface runoff.

It seems that some of these agronomic practices, especially fertilisation and weed control, have been responsible for most of the recorded past improvements in water use efficiency of crops with a relatively minor contribution of genetics (Passioura, 2006; Turner, 2004). Theoretically increasing the transpiration water use ratio through plant breeding or genomics could contribute less than agronomic measures to the overall field level crop water use efficiency (Wallace, 2000). This could partly explain why the explosive growth of information in genomics over the last decades, had a small impact in the application to problem solving for farming under water limited conditions (Interdrought-II, 2005).

This paper attempts to briefly review some research topics of interest for field-scale agronomic studies on WUE for Mediterranean environments, the discussion being focused on field and vegetable crops.

AGRONOMIC RESEARCH ON WUE AT THE FIELD SCALE

Classical agronomic studies

Classical agronomic research on WUE, recently reviewed by Katerji *et al.* (2006), has been carried out for more than 40 years in several experimental stations in Mediterranean countries. In most of these studies, crop evapotranspiration has been measured by weighting or drainage lysimeters or by using soil moisture measurement and a simplified water balance equation. These studies have delivered most of our current knowledge on the values of WUE for different irrigation methods and timing, species, varieties and phenological stage, mineral nutrition etc…

Given the experimental approach (i.e. mainly the use of lysimeters), there are large gaps in our knowledge, for example concerning tree crops, but also for the assessment of soil management practices such as tillage, given the difficulty of implementing such treatments in lysimeters. Due to the cost of these experimental set-ups, rarely are replicated comparisons between treatments available, moreover whole field effects on WUE, resulting e.g. from soil spatial variability have not been assessed.

However, it is extremely important that classical agronomic research is continued to be carried out, using a systematic and process-oriented approach within an integrated framework (Katerji *et al.*, 2006), in order to complete our knowledge for example on the effects on WUE of salinity, mineral nutrition, new varieties and their interactions with environmental factors and soil properties.

In order to generalise results from specific studies, considerable effort has been devoted in the last decades into the development and validation of explicative models of soil-plant-atmosphere processes (Steduto, 2006). A great usefulness of these modelling research efforts lies in the possibility to condense and integrate current scientific knowledge from different disciplines and hierarchical levels and therefore highlight weak points in our present understanding and prompt for specific research and data collection. It is evident that, due to the crude approximations of real processes as represented even in the most sophisticated models, their predictive ability is often questionable and their use cannot substitute agronomic research in the field.

Additional research focuses

In parallel to classical research, there are some agronomic research topics that have received more attention in recent times or that can be expected to stimulate more research in the next few years. Some of these will be briefly considered in the following sections.

Resurgence of conservation tillage

Conservation tillage, defined as a set of tillage systems in which a substantial part (at least 30%) of the soil remains covered by previous crop residues (Unger, 1990), was firstly introduced more than 70 years ago in the US, primarily to contrast soil erosion (Blevins and Frye, 1993). Several studies have shown that in conservation tillage (CT) systems, water stored in the soil profile is generally more as compared to conventional systems, due to reduced soil evaporation, increased infiltration and soil conducibility, reduced runoff and reduced deep percolation also due to the increase in soil organic matter (Unger, 1990; Blevins and Frye, 1993; Hatfield et al , 2001). Additionally it has been shown that in CT, particularly in no-tillage systems (NT), there is usually a larger presence of biopores than in conventional tillage (Lo Cascio and Venezia, 1986). These allow easier penetration by water and roots of following crops, thereby allowing a increased exploration of the soil profile (Venezia *et al.*, 1995; Turner, 2004).

If these effects are accompanied by similar or higher yields than conventional tillage systems, there is a resulting improvement in WUE by adopting CT systems (Moret *et al.*, 2007; De Vita *et al.*, 2007; Hatfield *et al.*, 2001).

Some reports have shown that the classical dryland agronomic practice of leaving the soil fallow for one year, with repeated soil tillage operations to clean the soil from weeds and to promote soil water storage, carried out since thousand of years in the Mediterranean, does not really contribute to an effective increase of WUE, also because usually only 10-20% of the precipitation during fallow is retained in the soil at sowing of the following crop (Turner, 2004; Hatfield *et al.*, 2001).

It has been shown that, in arid environments, conventional tillage during fallow periods offers no advantages as compared to NT (Moret *et al.*, 2007; Aboudrare *et al.*, 2006).

Despite the interesting results and decades of experimentation on CT, there is still a lack of specific research to assess the effect of CT on WUE in Mediterranean environments, perhaps for the methodological reasons mentioned earlier. A methodology available to study WUE in different tillage systems is through measuring ET by micrometeorological techniques (see review by Rana and Katerji in this issue). The use of these techniques has the advantage, as compared to the only available alternative, i.e. water balance methods, to illustrate some of the causes of differences in ET between tillage systems throughout the growing season. It is evident that tillage can aof the energy balance, i.e. net radiation, soil heat flux, sensible and latent heat flux (Hatfield *et al.*, 2001). For example, in a study carried out by using two Bowen ratio systems in adjacent large plots of irrigated soybean (Casa and Lo Cascio, 1997), it appeared that differences between energy balance terms between no-tillage (NT) and conventional tillage (mouldboard ploughing plus harrowing), changed during crop growth phases (Fig. 1).

These differences were due to crop cover canopy development, which was delayed in the no-tillage treatment as compared to the conventional tillage, so that during the initial growth period when LAI was low in NT, ET was often higher in the conventional tillage plot. Subsequently, NT had generally a equal or higher ET as conventional tillage (Fig. 1).

There is some renewed interest in the promotion of CT systems, also `on root expansion in the soil profile, also due to soil pathogens carried in crop residues (Turner, 2004); research on sowing machinery suitable for small Mediterranean farms; crop protection and herbicides solutions through selection of competitive varieties of suitable crops, or herbicide resistance (GMOs or conventional breeding); research on varieties with tolerance to cold, in order to promote early stand establishment, that can be delayed in NT because of lower soil temperatures.

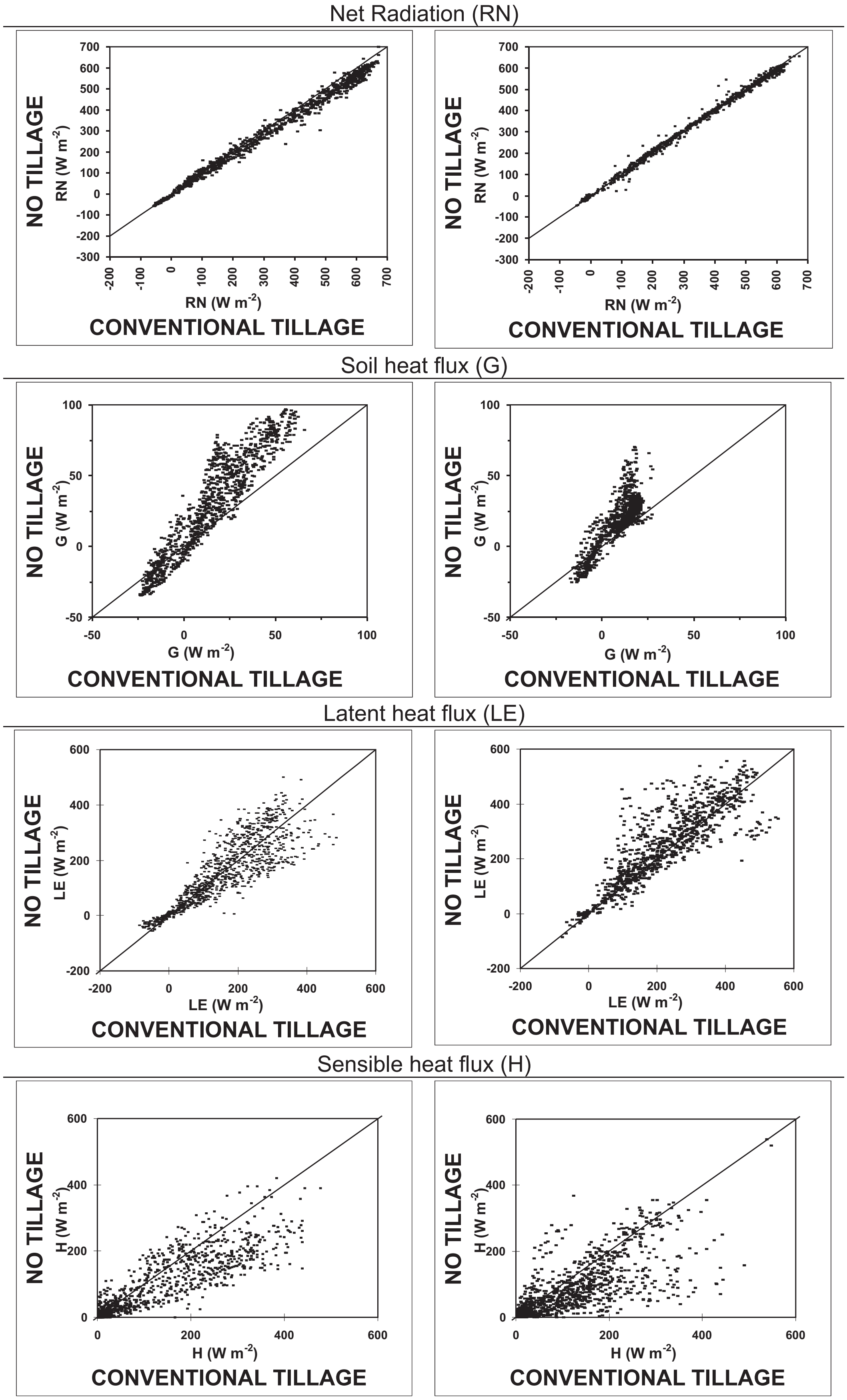

Fig. 1. Intercomparisons between flux densities measured on conventional tillage and on no-tillage respectively before (left) and after (right) canopy closure (LAI<2) on no-tillage. Redrawn from Casa and Lo Cascio (1997).

Regulated deficit irrigation (RDI) and partial root-zone drying (PRD)

Because of decreased water availability for agriculture, it is expected that fully meeting crop water requirements will become increasingly difficult and that deficit irrigation (DI), a strategy under which crops are deliberately allowed to sustain some degree of water stress and yield reduction, will become the major system for field irrigation (Interdrought-II, 2005). Research in the last decades has proposed new deficit irrigation techniques such as regulated deficit irrigation (RDI) and partial root-zone drying (PRD).

In RDI, a moderate water stress is imposed to crops in particular development stages when they are less sensitive to water deficits (Pereira *et al.*, 2002). It has been tested with success in several species, obtaining remarkably good results especially for tree crops, in which there is great scope for the optimisation of the allocation of assimilates between vegetative parts and fruits (Behboudian and Mills, 1996). One difficulty of applying RDI is the high buffering capacity of many soils that make it difficult to impose the desired level of stress at the prescribed time.

Partial root-zone drying (PRD) is an irrigation strategy in which half of the root system is always exposed to drying soil while the remaining half is irrigated as in full irrigation (Kang and Zhang, 2004). The wetted and dried sides of the root system are alternated in a frequency according to crops, growing stages and soil water balance. This technique was developed from ecophysiological studies and is based on two theoretical assumptions: (i) fully irrigated plants usually have widely opened stomata. A small narrowing of the stomatal opening may reduce water loss substantially with little effect on photosynthesis (Jones, 1992). (ii) Part of the root system in drying soil can respond to drying by sending a root-sourced signal to the shoots where stomata may be closed to reduce water loss. Application of PRD to several tree crops (grapevine, raspberry, apple, pear, peach) has shown in most cases no yield reduction as compared to full irrigation, with increases in WUE and improvements in quality (Kang and Zhang, 2004). For annual crops, very few studies have been carried out in open field conditions so far, though the results seem very promising (Table 1). It is evident that PRD should be compared to other deficit irrigation techniques, such as RDI, in order to assess its benefits. In principle PRD can reduce soil evaporation as compared to other DI techniques due to reduced wetted soil area, therefore improving WUE.

More research under field conditions is needed in order to confirm the good results obtained by PRD under controlled conditions. Additionally the long term sustainability of DI techniques in general, in Mediterranean environments, should be investigated, in relation to possible problems deriving from gradual depletion of soil water reserves and from salinisation.

Modelling WUE: the revision of FAO33

An important activity undertaken by FAO in the last few years is the revision of the Irrigation and Drainage Paper n. 33 (Doorenbos and Kassam, 1979), which represented an important reference for the estimate of yield response to water of crops for more than twenty years. The consultative revision process lead, for field crops, to the development of a crop model based on a water-driven engine (Steduto and Albrizio, 2005; Steduto, 2006) to be used for planning, management and scenario simulations. Transpiration efficiency (called water productivity, w_p), i.e. the ratio of biomass produced to water transpired, is the core parameter of such a model and it is expected to confer robustness to the approach. In fact, once normalized for different climates, dividing it by reference evapotranspiration, w_p is expected to be constant for broad groups of crop species also under water and salinity stress, and to be only moderately sensitive to nutritional deficits (Steduto, 2006).

It is evident that in order to confirm the robustness and reliability of the proposed approach, or to identify suitable parameter values for different species and environments, extensive research targeted at the calibration and validation of the model will be necessary. For example it will be necessary to evaluate, from comparison with measurements under a range of conditions, the impact of the partitioning ET into transpiration and soil evaporation on w_p determination and modelling.

Separate measurement of canopy transpiration and soil evaporation is not easy. There are difficulties when trying to up-scale leaf level (cuvette) or single plant transpiration measurements, e.g. from sap flow (Smith and Allen, 1996), because of leaves, plants and field spatial variability.

It is however possible to combine ET measurements, e.g. from micrometeorological methods or weighing lysimeters, with measurements of soil evaporation using microlysimeters (Boast and

Robertson, 1982) or evaporation plates (e.g. Sauer *et al.*, 1995) and calculate transpiration as a residual. The limited number of studies carried out using such approaches reveal that soil evaporation represents a non negligible fraction of ET, even under full canopy cover, especially after soil wetting events (e.g. Fig. 2). Obviously soil spatial variability, and the intensive labour required, are major limitations to the use of microlysimeters. Additionally there are now interesting techniques for separating ET components based on the use of stable isotopes, such as deuterium (Williams *et al.*, 2004) and ^{18}O (Braud *et al.*, 2005), though further development and validation of proposed explicative models is needed (Braud *et al.*, 2005).

Table 1. Published studies on the application of the partial root-zone drying (PRD) irrigation technique to annual crops, carried out under field conditions.

	Location, climate	**Treatments**	**Results**	**Reference**
Maize	Northwest China, arid	AFI[a], FFI[b], CFI[c] at different irrigation amounts	No yield decrease with up to 50% less irrigation, increase in WUE	Kang et al., 2000
Maize	Turkey, Mediterranean	AFI[a], CFI[c] at different irrigation amounts	10-25% yield decrease, but increase in WUE	Kirda et al., 2005
Potato	Denmark, temperate	SDI[d], SPRD[e]	No yield decrease with 30% less irrigation, increase in IWUE	Shahnazari et al., 2007
Bean (*Phaseolus vulgaris*)	Turkey, Mediterranean	SDI[d], SPRD[e] at different irrigation amounts	No yield decrease with 16% less irrigation, increase in WUE	Gençoglan et al., 2006
Bean (*Phaseolus vulgaris*)	Uzbekistan, arid	AFI[a], CFI[c] at different irrigation amounts	0-26% yield decrease, no change in WUE	Webber et al., 2006
Green gram (*Vigna radiata*)	Uzbekistan, arid	AFI[a], CFI[c] at different irrigation amounts	No yield decrease with up to 20% less irrigation, increase in WUE	Webber et al., 2006
Cotton	Northwest China, arid (oasis)	AFI[a], FFI[b], CFI[c] at different irrigation amounts	No yield decrease, no change or small improvement in WUE	Du et al., 2006

[a] AFI = alternate furrow irrigation: irrigation every other furrow, switched at each irrigation date.
[b] FFI= fixed furrow irrigation: irrigation every other furrow, not switched.
[c] CFI =conventional furrow irrigation: irrigation every furrow.
[d] SDI = subsurface drip irrigation.
[e] SPRD = subsurface partial root-zone drying drip irrigation.

Precision irrigation

Because of soil variability in infiltration and water holding capacity and of heterogeneous development of crop stands, water requirements may vary spatially within a field. Therefore irrigation needs may differ between different zones of a particular field and high distribution uniformity across the whole field, commonly indicated as a target for increasing WUE (Pereira *et al.*, 2002), may not always be the ideal objective. Some areas of a field may receive too much water and other areas may not receive enough. Excessive water application could contribute to surface water runoff or deep percolation, while the application of water to non-cropped inclusions within a field is another concern, common for example with current center-pivot systems. All these factors decrease WUE and prompt for research into precision irrigation systems that use variable rate technology to apply water to management zones of a field, applying more or less water where it is needed. Research on this topics is still at its infancy and presently targeted at US and Australian agriculture, especially for center-pivot irrigation (Perry *et al.*, 2003). It is apparent that research, specifically aimed at Mediterranean farming systems and taking into account their structural and social peculiarities, is urgently needed if benefits are to be seized also in this region from information and engineering technologies that are expected to become less expensive and more user-friendly in the future.

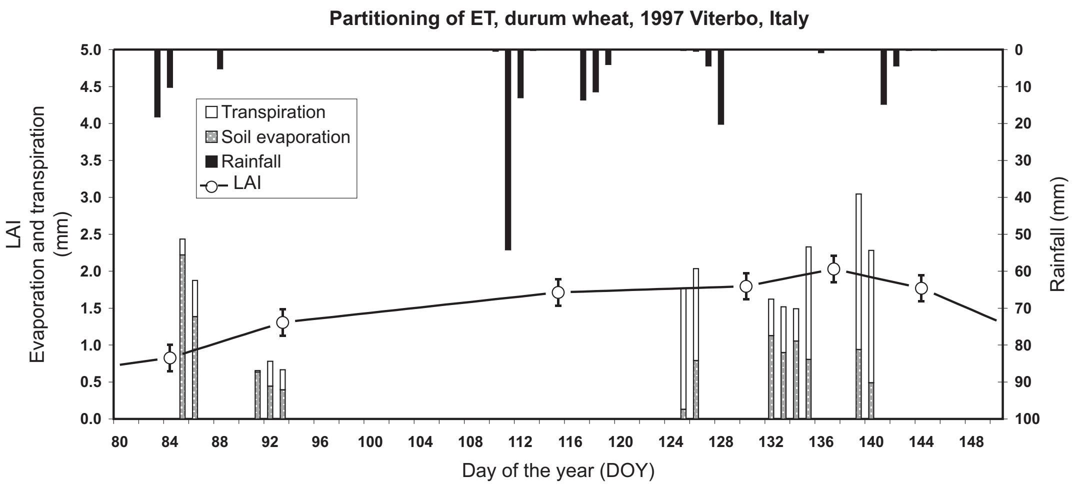

Fig. 2. Soil evaporation and canopy transpiration of durum wheat, from micrometeorological (Bowen ratio) ET and microlysimeter (10 replicates) measurements (Casa, unpublished data).

CONCLUSIONS

There is a wide range of agronomic options available in Mediterranean cropping systems for increasing water use efficiency (WUE) at the field scale, defined as the ratio of biomass or yield to crop evapotranspiration. This stems from the variation in climatic, soil and technological (agricultural development) conditions existing in the countries of the Mediterranean basin. Some possibilities for increasing field scale WUE and their applicability to Mediterranean conditions might be encouraged by specifically targeted agronomic research that will take into account this variability.

Classical agronomic research should not be considered out of date and should be carried out, using a process-oriented approach, as an important activity capable of delivering essential results specifically targeted at the different cropping systems of the Mediterranean.

The effect of soil management practices, such as the use of conservation tillage systems, should be further investigated, in order to allow a clear assessment of the potential of such systems for bringing improvements in water use efficiency.

Deficit irrigation methods, such as partial root-zone drying, are still largely to be tested in open field conditions and their suitability and feasibility to Mediterranean farming systems needs to be evaluated.

Additional research on WUE is likely to be prompted by the forthcoming release by FAO of a model resulting from the revision of Irrigation and Drainage paper n. 33 (Doorenbos and Kassam, 1979). The model, acting as formalised compendium of much of the current understanding on yield response to water and WUE (Steduto, 2006), will be able to pinpoint specific gaps in our knowledge and drive specific research, during calibration and validation activities, targeted to fill these gaps.

Large improvements in WUE are also possible if soil and crops spatial variability within fields is taken into account, leading to variable irrigation rates or "precision irrigation". Research on these aspects is just beginning and is currently limited to technologically advanced agricultural systems, though the potential is high for better agronomic management also in Mediterranean environments. In fact, the basic principles of precision agriculture is to take into account spatial and temporal variability and manage fields site-specifically. This will undoubtedly bring to more efficient use of inputs such as seeds and fertilisers, or water, and is not in contrast with the flexibility required by cropping systems in uncertain and drought-prone Mediterranean climates (InterDrought II, 2005), given the a number of real-time crop monitoring tools becoming available (Jones, 2004).

The improvement of water use efficiency at the field scale in the next few years is expected to depend equally on the use of the best agronomic practices available for each specific cropping system and on the development of varieties with a higher transpiration efficiency (Passioura, 2006). However efficient systems for the transfer and promotion of successful research results into farming practice should also be in place, if real progress in this strategically important issue for the Mediterranean area is to be made. Successful outcomes can be obtained in an integrated participatory approach, but where each component of the system focuses on the role for which it has the highest competences and skills. In this contest the role of researchers should be that of developing a wide range of agronomic innovations and communicate them properly to society, but should not be confused with, nor could it substitute for, the role of well organised extension services or well informed policy makers, equally important though unfortunately often inadequate in Mediterranean countries.

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