Improving water productivity of crops in the Mediterranean region: case of cereals

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Abstract

Water scarcity and drought are the main constraints of crop production in the Mediterranean basin. However, the situation is more alarming in the southern and eastern parts of the basin. Although many technologies have been developed by scientists in the region to cope with these environmental problems, the difference between the farmers' and potential achievable yields remain in general highly significant in both rainfed and irrigated areas. A large dissemination of the improved management packages can help close the observed yield gap. Moreover, because water shortage and drought will be more intense in the Mediterranean due to the effects of the global warming, the increase of land productivity should not be anymore the only objective, but more emphasis has to be put also on the improvement of the productivity per unit of water consumed by the crop. This will ensure water saving and higher global production. In this paper, the concepts of water use efficiency will be presented and strategies of water productivity increase will be discussed. In the rainfed areas, these strategies are based on better crop and soil management and the improvement of genetic makeup of the cultivated plants to capture more water for use in transpiration, to use CO_2 more effectively in producing biomass and to convert more of the biomass into grain or other harvestable products. In the irrigated zones, water losses at different steps of water use in crop production should be reduced and water productivity has to be increased by the application of the required amounts of water and nitrogen at critical stages. Moreover, supplemental irrigation and wide spaced furrows and raised-bed planting irrigation technologies should be used to save water and irrigate more area. Finally, varieties with higher water and nitrogen use efficiencies should be developed.

Introduction

Water shortage in the Mediterranean basin is a well-known and alarming problem. Increasing water scarcity is threatening the economic development and the stability of many parts of the region. At present, agriculture accounts for over 75% of the total consumption of water in the southern and Eastern part of the basin. However, with rapidly growing demand it is certain that water will increasingly be reallocated away from agriculture to other sectors. Moreover, opportunities for the significant capture of new water are now limited. Most river systems suitable for large-scale irrigation have already been developed. Only few major resources of renewable groundwater remain untapped and current resources are subject to overexploitation, with extraction exceeding recharge rate in many cases.

Many agricultural areas of the Mediterranean countries are rainfed and a large proportion of the region's agricultural livelihoods are based on dryland farming systems. Rainfed production is dependent on low and extremely variable rainfall and, therefore, productivity is low and unstable. This is further affected by frequent droughts and continuing land degradation.

Nevertheless, despite the problems described above, there is still room for crop production increase in the Mediterranean, and especially in the southern and eastern parts where the gap between the farmers' and the potential achievable yields remains high. As a matter of fact, the comparison between the farmers' yields and those obtained in experiment stations using data from rainfed (Chaoui) and irrigated (Tadla) regions in Morocco (Pala et al., 2009) showed that the gap is high and it amounts 80-98% and 40-50%, respectively. The same result was obtained for semi-arid areas of Morocco by Karrou et al. (2009) who used the approach developed by Sadras and Angus (2006) to evaluate wheat yield gap (Fig. 1). This approach is based on the scatter points of grain yield versus evapotranpiration. In this case, the upper boundary line (intercept = 60 mm and slope = 22 kg ha^{-1} mm^{-1}) was drawn and the vertical distance from each point to the line measures the yield gap.

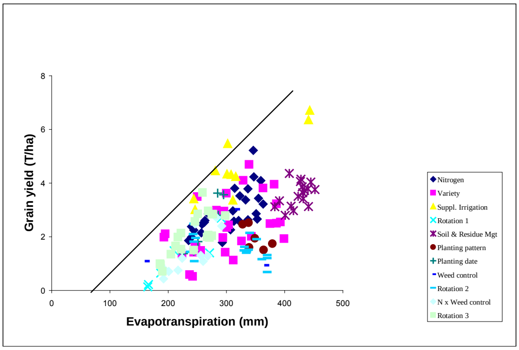

Figure 1. Scatter points of grain yield and seasonal ET in wheat (Karrou et al., 2009)

From these studies it can be concluded that if the yield gap is reduced, more crops and food productions can be achieved.

One of the strategies that can help to cope with the problems of water shortage and drought described above is the dissemination of the existing improved management packages to close the yield gap. However, to face the future challenges of more rainfall reduction and temperature increase, research that aims at the better understanding of the climate change and its effects and at the development of new technologies of water use efficiency improvement needs to be promoted.

In this manuscript, the general concepts and definitions of water use efficiency and the methods of improving water productivity will be presented. Moreover, new areas of research on the mitigation of and adaptation to water scarcity and drought will be addressed

Concepts of water use efficiency and water productivity

Efficiency is defined in general by economists as the ratio of output to input.

In the case of water management in agriculture, the term has been widely used by engineers to design the irrigation systems. In the hydrological approach, the numerator and denominator of the ratio have the same unit (mm/mm or m^3/ m^3 of water). Consequently, the efficiency is unitless and we talk about the «Efficient-water use».

Since there are several steps in the irrigation chain, four types of efficiency are usually considered. These are 1) the storage efficiency which is the ratio between the volume diverted for irrigation and the volume entering a storage reservoir, 2) the conveyance efficiency which is the ratio between the volume of water received at the farm gate to the quantity of water diverted out of the reservoir for that farm, 3) the farm efficiency which is the ratio of water received at the field edge to water received at the farm gate and, 4) the application efficiency or the ratio of water received at the root zone to water received at the field edge.

To these hydrological efficiencies, we can add also the consumptive efficiency (Evapotranspiration / Water at the root zone) and the transpiration efficiency (Transpiration / Evapotranpiration).

All the above defined efficiencies do not directly take into consideration crop production. Agronomists/crop physiologists use another concept of water use efficiency which refers to the amount of plant material produced per unit of water used taking into consideration the space and time scales. In this case, the input and output have different units and the major types of water use efficiency are «Photosynthetic WUE» (Assmilation/Transpiration), «Biomass WUE» (Biomass/Evapotranspitation) and «Yield or Fruit WUE» (Yield/ET).

To take into consideration all water losses at different steps of water use in crop production, Hsiao et al. (2007) defined the overall efficiency as the product of the eight efficiencies defined above. These authors showed that it is more effective to consider all the chain and make modest improvements in several or more steps than to concentrate efforts to improve one or two steps only.

As shown before, the term «Efficiency» in agricultural water use has different meaning to different people and its use in the literature is confusing and the dialogue among scientists from different disciplines has become difficult. To overcome these problems, the concept of «Water productivity» was introduced recently by Molden (1997) and it is defined (Oweis and Hachum, 2006) in a more general sense as:

WP = Return / Unit of water consumed

Return = biomass, grain, meat, milk, income, environmental benefits, social benefits, energy, nutrition…

Water consumed = evaporation, transpiration, evapotranspiration, water degradation.

In the following sections, only the yield water use efficiency (grain yield/ET) will be discussed and the term «water productivity» will be used instead to avoid the confusion described above.

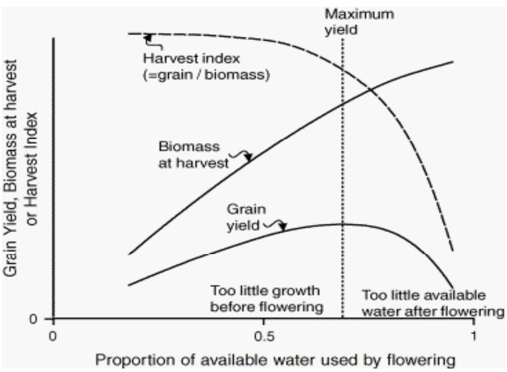

Figure 2. **Schematic graph of grain yield of wheat, Biomass at harvest, and harvest index, in relation to proportion of the available water supply used by flowering (Passioura, 2006).**

How to improve crop water productivity in the rainfed areas of the Mediterranean region?

The main strategy to increase WP in rainfed areas is to better manage crops and natural resources and improve the genetic makeup of cultivated plants to capture more water for use in transpiration, to use CO_2 more effectively in producing biomass and to convert more of the biomass into grain or other harvestable products (Passioura, 2006).

In dry areas, soil water loss by evaporation is the most important source of inefficient use of water (Cooper, 1983, El Mourid, 1988). In irrigated zones, the over- and mis-use of scarce water is the main cause of the reduction of water productivity.

One source of water loss by evaporation in rainfed areas is related to planting periods. As a matter of fact, most of the farmers in the region delay wheat planting until it rains enough, in Autumn, to till and cultivate the soil and hence prepare a good seedbed. This practice is also used to control the early emerging weeds. Nevertheless, this technique involves the disturbance of a wet soil and consequently increases water loss by evaporation. Many experiments conducted on planting date under rainfall conditions in WANA by the NARS and ICARDA have shown that the early planting of cereals is the best strategy because it allows the crop to take advantage from early rains and warm soil and air temperatures required for the seeds germination and seedling growth. It also helps the plants escape terminal drought and heat. However, planting early is not an easy task to achieve by farmers in arid and semi-arid areas of the Mediterranean where the probability of having enough rain to ensure a good seedbed preparation is low. To by-pass this problem and be able to plant early, there is a need for the use of a no-till planter that puts the seeds directly in the soil without any previous cultivation. Although this technique has been proven to reduce evaporation and improve yield under dry conditions, it still has some limits. For example because of soil compaction, roots development and tillering capacity are reduced under this system. Moreover, the increasing of sowing depth in no-till recommended for a rough soil surface of farmers' fields in dry areas may reduce the seedlings emergence and vigor of standard widely used semi-dwarf wheat that have short coleoptiles. The solution in this case can be the development of varieties that contain alternative dwarfing genes (Rht8) that provide the benefits of short stems without restricting the maximum length of the coleoptile (Passioura, 2006).

Planting pattern is another important factor in wheat production. The reduction of row spacing can allow an early shading of the soil and hence reduces evaporation from wet soil and increases land and water productivity (Karrou, 1998). Early soil shading by plants cover can be also achieved if varieties that produce large leaves early (large and fast leaf area) with a high specific leaf area index are used.

Nutritional status of the young crop, especially nitrogen, can markedly affect the rate of plant growth and leaf area and hence water use and water loss by evaporation. Early application of high N levels can stimulate growth and high tillering. Too much biomass can involve the rapid depletion of soil water and «hay-off» of the plants if early wet conditions are followed by a long period of drought. That is why many farmers avoid applying N fertilizer in rainfed areas where rainfall amount is usually low. Nevertheless, the supply of an adequate amount of N early in the growing season has also a positive effect. It can induce the rapid covering (shading) of the soil surface and hence reduce evaporation. An alternative to the application of nitrogen in dry areas where soil moisture is frequently low is to develop varieties that have the capacity of using nitrogen more efficiently and cover the soil more rapidly. This type of varieties is even more needed for barley that usually does not receive any inputs.

In addition to soil evaporation, water wastage can be enhanced by weeds infestation. In fact, many farmers, especially the small ones, delay weeding of the crop until the weeds produce sufficient biomass and then they harvest them manually to feed their livestock. However, under this type of management, weeds compete very strongly with the crop for a limited amount of soil moisture and nutrients especially during the sensitive stages. The result is that the yield and water productivity of the cultivated plants are negatively affected. Tanji and Karrou (1992) showed that weed control early in the season (at 3-4 leaf stage of the crop) increased grain yield and water productivity, especially under relatively wetter conditions. Under this situation, WP increase was more than 3-fold as compared to a weedy plot. However, under too dry conditions, the yields were too low and the difference between weed-free and weedy treatments was not significant because drought hindered growth of both weeds and cultivated plants. Data also showed that weedy treatment used more water because weeds tend to explore more soil volume because of their deeper root system.

The balance between the source and sink is also important for land and water productivity improvement. The date of flowering of the crop plays a main role in these processes under water-limited conditions. Too early flowering means insufficient source (biomass) to set and fill the large number of seeds. Too late flowering can involve the production of a high number of seeds. In this case, the seed weight may be negatively affected because the kernels have too little water left in the soil during their maturation (Richards, 1991). El Mourid (1988) determined the optimal dry matter required at anthesis in wheat to assure a good yield under rainfed conditions in semi-arid Morocco (1988). Under these situations, there is a need to identify an optimal flowering time at which there is an appropriate balance between water used during canopy development (source) and during grain filling (Figure 2). However, it was shown that the source is not a major limiting factor for grain filling and grain yield and water productivity can be significantly increased if the number of seeds is increased. This can be achieved through breeding the lengthening of stem elongation phase at the expense of the pre-anthesis period (Otegui and Slafer, 2004 and Araus et al., 2002) and/or by applying nitrogen tactically at the beginning of stem elongation to enhance spike growth and fertility.

How to improve crop water productivity in the irrigated areas of the Mediterranean region?

In irrigated areas of the Mediterranean basin, there is a need to better manage and use water more efficiently not only because of its scarcity but also to preserve the environment. Traditionally, the objective of irrigation is to maximize the yield by unit of land considering water as a non limiting factor. Now, with the increasing of the shortage of the water resources, maximizing the return by unit of water or water productivity should be a priority. So, some trade-off between land and water productivities should be accepted. As a matter of fact, Oweis et al. (1998a) showed that under water scarcity conditions, maximum WP of wheat occurs at sub-optimal crop yield per unit area (Fig. 3); but, water saved by maximizing WP can be used to irrigate more land in dry areas of the Mediterranean and hence increase the total production.

In addition to irrigation water management, improved crop management and varieties can help plants take more advantage from the limited amounts of available water. We will limit our discussion here to only three major issues because of their relevance to the Mediterranean environments. These issues are supplemental and raised bed planting irrigation systems and nitrogen management.

Supplemental irrigation is defined as the addition, to essentially rain-fed crops, of small amounts of water in order to provide sufficient moisture for normal plant growth. The concept of supplemental irrigation is based on two aspects which are: 1) water is applied to rain-fed crops that would normally produce without irrigation and 2) water is applied to supplement the precipitation and to ensure a minimum amount of moisture during the critical stages of crop growth that would permit optimal rather than maximal yield.

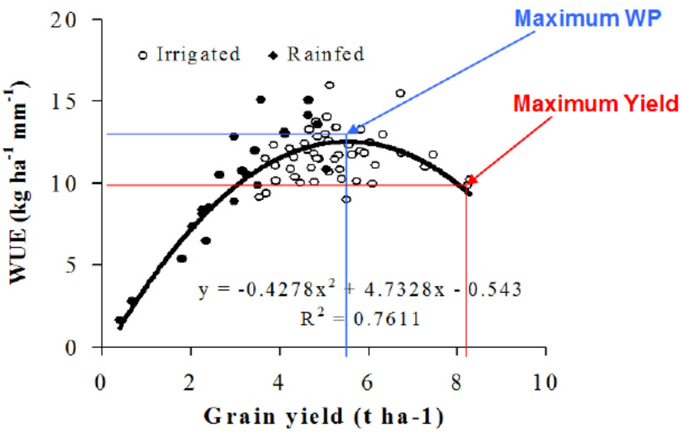

Figure 3. Relationship between water productivity (WP) and grain yield of durum wheat under supplemental irrigation (Oweis et al., 1998a)

Research conducted in dry areas (Oweis and Hachum, 2006); Karrou and Boutfirass, 2007) showed that supplemental irrigation is a technology that can improve significantly water productivity and save the resource without reducing land productivity. In fact, it was shown in demonstration trials conducted in Tadla Morocco (RBM, 2008) by INRA-Morocco in collaboration with ICARDA that supplemental irrigation increased wheat grain yield and water productivity, respectively, by 20% and 22% for the first cropping season (Table 1); 31% and 12.5% for the second year (Table 2); and 20% and 35% in the third year (Table 3) when the crop is sown in early November as compared to late planting of December.

The principle of bed planting consist basically of sowing crops on ridges or beds instead of the flat surface of farmers' fields and applying irrigation water (and other inputs) via surrounding furrows. Research conducted in Egypt (IBM, 2008) by ARC-Egypt in collaboration with ICARDA where improved technologies of irrigation were compared to the conventional system (basin flooding) showed that by using the wide spacing furrow and bed planting technique, water consumption by crops fell by 30%, with correspondingly lower pumping costs. Labor costs for land preparation, irrigation and weed control were also reduced by 35%. However, yields were the same or higher and farmers' net incomes increased by 15%. With less water used, crop water productivity increased by over 30% and the net return per unit of water was 20% higher compared to conventional furrow irrigation.

Another factor that is important in crop production in irrigated areas is nitrogen (N). This nutrient is globally considered to be the second most limiting factor for plant growth after water and hence N fertilization has been a powerful tool for increasing the yields of wheat in many regions of the world. However, the management of N remains difficult. Under soil N deficiency conditions at critical stages of the crop, productivity is usually low. If high rates of N are applied, especially early in the growing season, nitrates may be lost through leaching under high moisture situations. Consequently, in addition to being an extra expense to the farmers, N that is lost has also an environmental cost (pollution of the aquifer). Among the strategies that can increase yield and water productivity is to apply the right amounts of the inputs (water and N) at the right time. This requires the monitoring of soil moisture and N at the main critical stages of the plant growth. Another strategy is the development of varieties that have higher nitrogen use efficiency.

Table 1. Grain yield and water productivity in 2005-06 (RBM, 2008)

Farm	Grain Yield t/ha		GWP kg/ m³	
	Early	Late	Early	Late
Zoubdi	3.9	3.0	0.7	0.5
Erraji	5.5	4.7	0.8	0.7
Ferrari	8.1	6.1	1.4	0.9
Mean	5.8	4.6	0.9	0.7
CV	18.5			
LSD	1.0			

Table 2. Grain yield and water productivity in 2006-07 (RBM, 2008)

Farm	Grain Yield T/ha		GWP kg/ m³	
	Early	Late	Early	Late
Ferrari	5.6	4.3	0.8	0.7
Hettat	3.7	2.3	0.7	0.5
Erraji	6.8	3.9	0.9	0.6
Bennaceur	6.1	4.5	1.0	0.8
Mean	5.5	3.8	0.8	0.7
CV	17.7			
LSD	0.7			

Table 3. Grain yield and water productivity in 2007-08 (RBM, 2008)

Farm	Grain Yield t/ha		GWP kg/ m³	
	Early	Late	Early	Late
Zoubdi	8.8	8.1	1.1	0.9
Erraji	7.3	4.9	0.9	0.5
Nadi	5.4	4.0	0.7	0.4
Ferrari	8.1	6.1	1.4	0.9
Sefrioui	8.2	5.5	1.5	0.7
Hettat	7.0	5.6	1.2	0.8
Mokhtari	8.1	7.4	1.5	1.3
Mean	7.8	6.2	1.2	0.8
CV	15.2			
LSD	0.7			

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