We are IntechOpen,
the world's leading publisher of
Open Access books
Built by scientists, for scientists

6,900
Open access books available

185,000
International authors and editors

200M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

BOOK CITATION INDEX
CLARIVATE ANALYTICS
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Saving Water in Arid and Semi-Arid Countries as a Result of Optimising Crop Evapotranspiration

Salah El-Hendawy[1], Mohamed Alboghdady[1],
Jun-Ichi Sakagami[2] and Urs Schmidhalter[3]
[1]Faculty of Agriculture, Suez Canal University, 41522 Ismailia,
[2]Japan International Research Center for Agricultural Sciences, Tsukuba,
[3]Department of Plant Sciences, Technische Universität München,
[1]Egypt
[2]Japan
[3]Germany

1. Introduction

Although water covers about 71 percent of our planet surface, 98 percent of it has too high salt content to be used for drinking water, for irrigation, or even for most industrial purposes. Fresh water represents one percent of all the water on the earth and is distributed unevenly on the earth surface. As a result of the dramatic increase in population, in economic activities, and a subsequent increase in water usage, the world fresh water resources became scarce during the past decades (Postel et al., 1996; Hoekstra & Chapagain, 2007).

Shortage of water currently plagues almost every country in North Africa and the Middle East (MENA) to the extent that hampers economic growth and threats social stability. Most importantly, the scenarios for global environmental change suggest a future increase in aridity and in the frequency of extreme events in many areas of the earth. Economists believe that water problem cannot be solved until water is considered as economic good. There is an urgent need to develop appropriate concepts and tools to do so.

Evapotranspiration (ET) is defined simply as the sum of the amount of water returned to the atmosphere through the processes of evaporation (moisture loss from the soil) and transpiration (biological use and release of water by vegetation). Crops are different in their response to water stress at a given growth stage. Therefore, estimating ET is an important tool to calculate the actual crop water requirements in given conditions. As a result, optimizing ET may contribute in solving water shortage problems at two levels, the farm level and the national/global level.

Firstly, at the farm level, the process of water irrigation losses has two main components: one due to evapotranspiration losses, and the other including the losses resulting from the percolation of water beneath the root zone in excess of any required leaching for salinity management. Therefore, saving water on the farm level can be achieved by using deficit

irrigation strategy and irrigation scheduling. Deficit irrigation strategy, defined as the application of water below full crop-water requirement (evapotranspiration, ET), is an important tool to achieve the goal of increasing water use efficiency through their affecting on the amount of water losses by evapotranspiration (Fereres & Soriano, 2007). Irrigation scheduling, defined as determining when to irrigate and how much to apply, is another important element in improving water use efficiency through their exerting positive or negative effects on the amount of water percolating under the root zone (Bergez et al., 2002; El-Hendawy & Schmidhalter, 2010).

Full irrigation is the amount needed to achieve maximum yield; however, when irrigation water is insufficient to meet crop demand, limited irrigation management strategies should be considered. Use of limited irrigation strategies could save large amounts of water and might alleviate the issue of increasing food shortages found around the world. However, it is difficult to plan for reducing ET without a penalty in crop production, because evaporation from canopies is tightly coupled with the assimilation of carbon (Monteith, 1990; Steduto et al., 2006). For instance, El-Hendawy et al. (2008) found that average maize yield decreases under drip irrigation for 0.80 and 0.60 ET relative to 1.00 ET were 32 and 63%, respectively. Al-Kaisi & Yin (2003) also reported that average yield decreases for maize under sprinkler irrigation were 43% with 0.60 ET and 25% for 0.80 ET relative to 1.00ET. This indicates that application of water below the ET requirements requires further effective management strategies. These strategies should aim to achieve the highest possible economic return per unit of water applied. Recently, rapid and economically feasible approaches have been proposed to counteract yield losses and water use efficiency (WUE) decreases under deficit irrigation strategies. Several studies have emphasized that osmotic adjustment, which is achieved by exogenous application of osmoprotectants, is a useful approach for improving crop and water productivity under deficit irrigation (Agboma et al., 1997; Hussain et al., 2009). Of the different compatible solutes known, glycinebetaine (GB) is relatively more important as it is capable of promoting yields and WUE under water deficit. The reason for that may lie in the nature of GB as it exerts positive influence on the photosynthetic machinery (Xing & Rajashekar, 1999), and it does not inhibit enzymes even at high concentrations (Ashraf & Foolad, 2007). Therefore, it can be accumulated in the cytoplasm of plant cells to contribute to the osmotic balance between the cytoplasm and vacuole without causing any damages. This unique nature of GB has led to that foliar-applied GB is widely used for crop production throughout the world for different purposes. Exogenous application of GB to non-accumulators of GB has been taken as an alternative to improve the stress tolerance. For example, Ma et al. (2006) reported that GB-treated plants maintained a higher net photosynthetic rate during drought stress than non-GB treated.

Most importantly, foliar application of GB may be a simple and cost effective methodology to increase the net benefit per unit of water applied under limited water application. Brand et al. (2007) reported that foliar application of GB can be adapted as a management strategy to alleviate water deficit at a cost less than a US $ 2.5 per hectare. Under furrow irrigation application, Hussain et al. (2009) also found that foliar application of GB reduced water consumption by 25%, increased cost by 6% and increased net income by about 9% when the sunflower plants were exposed to water stress and treated by exogenous applications of GB simultaneously at vegetative and flowering stages. Therefore, it is important to know the optimum coupling combinations between GB levels and irrigation rate, to seek maximize

yield and IWUE simultaneously under deficit irrigation strategy which is one of the objectives of this chapter.

Drip irrigation is the most effective method in terms of both maximizing yield and water conservation and also providing efficient use of limited water (Cetin & Bilgel, 2002). At the same time, several authors have shown that the water use efficiency and yield of drip-irrigated crops could be improved under limited water applications by decreasing the amount of water that moves beneath the root zone (Bergez et al., 2002; El-Hendawy et al., 2008). Thus, optimizing the coupling between irrigation frequency and water application rate could help to achieve maximum yield and water use efficiency (WUE) by exerting positive or negative effects on the amount of water percolating under the root zone. For instance, coupling very high irrigation frequency and rate will avoid stress situations, but at the cost of reduced drip irrigation efficiency and WUE as a result of the increased amount of water moving beneath the root zone because the amount of water being applied can exceed the amount extracted by roots. Coupling very low irrigation frequency and rate, by contrast, can cause water stress between successive irrigation events (especially in sandy soils) because the amount of water applied at each event is insufficient to meet the water requirement of the plants as time proceeds. Finally, coupling very low irrigation frequency and very high water application rate, particularly in sandy soils, may result in a decreased efficiency of the drip irrigation system and finally water use, because the amount of water applied at each irrigation event may be higher, and possibly excessively so, than the soil–water storage capacity, thereby increasing the amount of water that moves below the root zone so as to reduce their availability to plants as time proceeds. Therefore, it is important to know the optimum coupling combinations between irrigation frequency and water application rate, to seek maximize yield and IWUE simultaneously for drip irrigated crops which is another objective of this chapter.

Secondly, at the national/global level, while trade of real water between water-rich and water-poor regions is generally impossible due to the large distances and associated costs, it is argued that international trade moves "virtual water" from a comparatively more favorable region, where there is a surplus of soil water in soil profiles, to comparatively disadvantaged regions such as the MENA region. The virtual water is defined as the volume of water used in producing a unit of commodity, or service (Allan, 1998). Agricultural trade is by far the largest transporter to move water virtually around the world.

The virtual water concept has two types of practical uses (Hoekstra, 2003). Firstly, virtual water can be seen as an alternative source of water assisting to achieve the regional water security. Secondly, the virtual water content of a product tells something about the environmental impact of consuming this product. Raising the awareness of virtual water content of products thus providing an idea of which goods impact most on the water system and where water savings could be achieved.

The idea of actively promoting the import of virtual water in water-scarce countries is based on the idea that a nation can save its domestic water resources by importing a water-intensive product rather than produce it domestically. Import of virtual water therefore leads to a "national water saving" (Hoekstra & Chapagain, 2007). In a widely scope, Oki & Kanae (2004) argued that the virtual water trade produces "global water saving" when the agricultural product a traded from a country in which the unit requirement of water to produce a commodity (UW) is low to the country in which the UW is high. Conversely, the

global water loss occurs when the trade is from a high UW country to a low UW country for a particular crop.

2. Method

2.1 Experimental design, treatments

Two field experiments of drip-irrigated maize were conducted to establish the optimal coupling combinations between ET deficit and irrigation frequency or glycinebetaine concentrations. Each experiment was conducted using a randomized complete block split-plot design with three drip irrigation rates (1.00, 0.80, and 0.60 of the estimated evapotranspiration, ET) as the main plot and four irrigation frequencies (F1, F2, F3 and F4, irrigation events once every 1, 2, 3 or 4 days, respectively) in the first experiment and five exogenous application concentrations of GB (0, 25, 50, 75 and 100 mM) in the second experiment as the split plots. The drip irrigation system was divided into four main sectors in the first experiment and three main sectors in the second experiment with the irrigation frequency treatments and irrigation rates being assigned to the four sectors and three sectors, respectively. The water application rate treatments (1.00 ET, 0.80 ET and 0.60 ET) in the first experiment and GB concentrations (0, 25, 50, 75 and 100 mM) in the second experiment were randomly nested within each main sector as a subplot, with each subplot having three replicates for subplots treatments.

2.2 Calculation of evapotranspiration

The crop evapotranspiration ET_c is given by multiplying the reference crop evapotranspiration ET_0 with the crop coefficient K_c.

$$ET_c = K_c \times ET_0 \tag{1}$$

The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. ET_0 is a climatic parameter and can be computed from weather data. ET_0 expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors (Allen et al., 1998).

With reference to Hoekstra & Hung (2002), crop evapotranspiration is calculated on the basis of the FAO Penman-Monteith equation:

$$ET_0 = \frac{0.408(R_n - G) + \gamma 900/(T + 273)U_2(e_a - e_{d)}}{\Delta + \gamma(1 + 0.34 U_2)} \tag{2}$$

where ET_0 is the reference evapotranspiration (mm day^{-1}), R_n the net radiation at the crop surface (MJ m^{-2} day^{-1}), G the soil heat flux density (MJ m^{-2} day^{-1}), T the mean daily air temperature at 2 m height (°C), u_2 the wind speed at 2 m height (m s^{-1}), e_s the saturation vapor pressure (kPa), e_a the actual vapor pressure (kPa), $e_s - e_a$ the saturation vapor pressure deficit (kPa), D the slope of the saturation vapor pressure curve (kPa °C^{-1}), and g is the psychrometric constant (kPa °C^{-1}).

2.3 Yield response factor (k_y)

Seasonal values of the yield response factor (k_y) for different combinations, which represent the relationship between the relative maize yield reduction $\left(1 - \frac{Y_a}{Y_m}\right)$ and the relative

evapotranspiration deficit $(1 - \frac{ET_a}{ET_m})$, were determined using the formula given by Doorenbos & Kassam (1979):

$$\left(1 - \frac{Y_a}{Y_m}\right) = k_y(1 - \frac{ET_a}{ET_m}) \tag{3}$$

Where ET_a and ET_m are the actual and maximum seasonal crop evapotranspirations (mm), respectively, and Y_a and Y_m are the corresponding actual and maximum yields (kg ha-1).

2.4 Water production function

One of the more useful and widely accepted production function forms is based on the consumptive use, or evapotranspiration (ET). Grimes et al. (1969) and Gulati & Murty (1979) with wheat, barley, and sugarcane reported that the yield-evapotranspiration (Y–ET) relations for these crops were best described by quadratic functions. Many functions were tested to fit the data of the experiment. The quadratic form was the best fitting function.
Y can be described as follows:

$$Y = \alpha + \beta_1 ET + \beta_2 ET^2 \tag{4}$$

As the function is obtained from a given set of yield and ET data, it is only appropriate and reliable for the given range of the observations. In the case of the quadratic function, both α and β_2 have negative signs when the function is derived from regression analysis. The ratio Y to ET reflects the water use efficiency (WUE) for a given amount of seasonal ET. The first derivative of Y, that is, dY/dET, describes the change in Y per unit change in ET that is called marginal product of ET (MP). Corresponding to the microeconomic theory, the Y in Eq. (4) represents the total product, Y/ET the average product of the input, and dY/dET the marginal product of the input (Hexem & Heady, 1978).
The elasticity in the production function (EP) is defined as the percentage changes of Y due to one percent change in ET. Thus,

$$EP = \frac{dY}{Y} \div \frac{dET}{ET} = \frac{dY/dET}{Y/ET} = \frac{MP}{WUE} \tag{5}$$

From equation (5) the EP-ET-MP-WUE relations can be described as follows:
EP=1 if MP = WUE; that occurs at the maximum point of WUE.
EP=0 if MP = 0; that occurs at the maximum point of Y.
EP>1, when the increase in ET leads to increase in WUE.
EP<1 when the increase in ET leads to decrease in WUE.
EP<0 when the increase in ET leads to negative MP or decrease in Y.

2.5 National water saving

The national water saving NWS_{ij} as a result of trade of crop i in country j is:

$$NWS_{ij} = VWM_{ij} - VWX_{ij} \tag{6}$$

where VWX_{ij} and VWM_{ij} are the virtual water exported and imported, respectively, contained in crop i by country j. We can calculate them by multiplying the specific water demand of crop i with exported/imported quantities of the same crop in a given year. Both exported and imported virtual waters are calculated as if the mentioned crop is produced domestically.

$$VWX_{ij} = SWD_{ij} \times X_{ij} \tag{7}$$

$$VWM_{ij} = SWD_{ij} \times M_{ij} \tag{8}$$

where X_{ij} refers to the exported quantities (ton) of crop i in a given year by country j, and M_{ij} is the imported quantities (ton) of crop i by country j. SWD_{ij} refers to the specific water demand (m^3 ton^{-1}) of crop i in country j.

Intuitively, the virtual water exported ($VWX\varphi j$) or imported ($VWM\varphi j$) contained in a group of crops φ by country j is calculated by the summation of multiplying the specific water demand of each crop i in the group φ with the exported/ imported quantities of the same crop in a given year.

$$VWX_{\varphi j} = \sum_{i=1}^{n}(SWD_{ij} \times X_{ij}) \tag{9}$$

$$VWM_{\varphi j} = \sum_{i=1}^{n}(SWD_{ij} \times M_{ij}) \tag{10}$$

For crop i in country j, the specific water demand can be calculated by Hoekstra & Hung (2005)

$$SWD_{ij} = \frac{CWR_{ij}}{CY_{ij}} \tag{11}$$

CY is the crop yield (ton ha^{-1}). Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration under the standard conditions (Allen et al., 1998).

It is sensible to mention that a country may not produce a specific crop and imports all the needed quantities. In this case, we have no data that are required for calculating the specific water demand such as crop yield and some factors required for calculating the crop water requirements. Thus, we compensate the domestic specific water demand of crop j by the weighted average of the regional specific water demand of the same cereal crop.

Crop water requirements are calculated by accumulation of data on daily crop evapotranspiration ETc (mm day^{-1}) over the complete growing period as follows:

$$CWR_{ij} = 10 \sum_{d=1}^{L} ET_{c(ij)} \tag{12}$$

where, the factor 10 is meant to convert (mm ha^{-1}) into (m^3 ha^{-1}). The summation is done over the period from day 1 to the last day of the growing period (L) (Sallam and Abd El Nasser, 2006).

2.6 Global water saving $GWS_{i,ej}$

The global water saving $GWS_{i,ej}$ through trade of crop i from an exporting country e to an importing country j is:

$$GWS_{i,ej} = VWM_{ij} - VWX_{ie} \tag{13}$$

Where, VWM_{ij} and VWX_{ej} are the virtual water content of the importing and exporting quantities of crop i in favor of the actual specific water demand and the actual crop yield of the import and export countries.

Due to the difficulties and complications of calculating specific water demand in each exporting country as each importing country imports from many variable sources over the

Saving Water in Arid and Semi-Arid Countries
as a Result of Optimising Crop Evapotranspiration
231

given period, we compensate each specific water demand of the exporting country by the world average specific water demand for each crop.

2.7 Statistical analysis
Analysis of variance (ANOVA) appropriate for a randomized complete block split plot design was employed to test the overall significance of the data, while the least significant difference test (at P = 0.05) was used to compare the differences among treatment means. Graphical presentation of data was carried out using Microsoft Excel program (Microsoft Corporation, Los Angeles, CA, USA).

3. Results and discussion

3.1 Yield response factor (k_y)
The response of yield to water deficit is quantified through the yield response factor (k_y), which represents the decrease in yield caused by decreases in evapotranspiration (Doorenbos & Kassam, 1979). Generally, higher k_y values indicate that the crop will have a greater yield loss when the crop evapotranspiration is not met. One important finding of this study was the strong response of k_y values to the combination of evapotranspiration deficit with irrigation frequencies or glycinebetaine (GB) concentrations (Table 1). Regarding the combination between ET deficit and irrigation frequency, it is interesting to note that the lowest k_y values were recorded for the combination of 0.80 ET with irrigation frequency once every one day (k_y = 0.12) followed by 0.60 ET with the same irrigation frequency (k_y = 1.15). Both values were lower than those reported by Doorenbos & Kassam (1979; 1.25). The k_y value of 1.25 obtained by Doorenbos & Kassam (1979) represents water deficit's effect on maize crop yield for the total growing period, which means that the reduction in yield for both combinations was proportionately less than the reduction in ET. By contrast, the combination of 1.00 ET with the same irrigation frequency or 1.00, 0.80 and 0.60 ET with the irrigation frequency once every 4 days resulted in significant increases in k_y values (Table 1). These results indicate that optimal coupling combinations of ET deficit with irrigation frequency are useful for maximizing the net income per unit of water applied. Therefore, under the imposed water regime we recommended to switch from irrigation every other day to much smaller irrigations several times. This may be explained by the application of water at low irrigation frequency exceeding the soil–water storage capacity leading to excessive water percolation under the effective root zone. Furthermore, a portion of the water application was not used by the plant and the remaining available water will not meet the long term water requirements of the plants till the next irrigation event.

For the combination of ET deficit with GB concentrations, the maximum maize yield during this study was obtained from a combination between 1.00 ET and 25 mM GB. The value of evapotranspiration at 1.00 ET was assumed as maximum evapotranspiration, and evapotranspiration and grain yield at different combination of 0.80 and 0.60 ET with different GB concentrations were assumed as actual evapotranspiration and actual grain yield. According to the result in Table 1, the k_y value for the combination of 0.80 ET with 25 and 50 mM GB or 0.60 ET with 50 and 75mM GB were less than 1, which means that the reduction in yield for former combinations was proportionately less than the reduction in ET, despite the amount of water applied for 0.80 and 0.60 ET treatments was 20 and 40% lower than those for the 1.00 ET treatment, respectively. These results provided important clues to the physiological role of optimum doses of GB in possibly improving water use

efficiency under ET deficit. The decreases of k_y value under ET deficit with the application of optimum dose of GB indicate that more grain yield was produced from less water use.

Treatments	Evapotranspiration deficit treatments		
	0.60 ET	0.80 ET	1.00 ET
Irrigation frequency treatments (F)			
Once in 1 day (F1)	1.15	0.12	2.34
Once in 2 days (F2)	1.42	1.24	0.00
Once in 3 days (F3)	2.35	2.19	1.50
Once in 4 days (F4)	2.33	3.01	3.74
Glycinebetaine concentration treatments (GB)			
0 mM	1.53	1.53	nd*
25 mM	1.32	0.87	nd
50 mM	0.97	0.51	nd
75 mM	0.93	1.49	nd
100 mM	1.50	2.07	nd

*Not determined

Table 1. Relative yield response factors (k_y) shown as the relationships between the relative yield decrease ($1- Y_a/Y_m$) and the corresponding relative evapotranspiration deficit ($1-ET_a/ET_m$) for combination of evapotranspiration deficit with irrigation frequencies or glycinebetaine concentrations.

This may be due to the effects of GB on transpiration rate. Agboma et al. (1997) reported that the transpiration rate of GB treated plants was decreased to 85% of untreated plants, strongly indicating an anti-transpirant effect of GB treatment. The slower transpiration rate allows the plant to access water for a longer period and exhibit greater photosynthesis, where it would contribute to improved yield and water use efficiency under ET deficit.

3.2 The relation of irrigation water use efficiency with evapotranspiration deficit
In recent years, several researchers have reported about "site specific management", which means applying the right amount of input in the right place at the right time to get maximum profit from per unit input. Based on this basic definition, the profitability of irrigation water applied can be maximized by determining the optimal combination of ET treatments with irrigation frequency or GB concentrations. In this study, the irrigation water use efficiency (IWUE) was significantly affected by the different combination of ET treatments with irrigation frequency or with GB concentrations (Fig. 1). It is interesting to note that the combination of 0.60 ET with irrigation frequency once every one day had IWUE values similar to those obtained for the corresponding 0.80 or 1.00 ET with irrigation

frequency once every two days and was higher to those obtained for the 1.00 ET treatment with either irrigation frequency once every three or four days (Fig. 1). The combined effects of ET treatments and GB concentration on IWUE were also significant. The highest IWUE was obtained under an irrigation rate of 0.80 ET at 50 mM GB, but it was at par with an irrigation rate of 0.60 ET at 75 mM GB. By contrast, the lowest IWUE was recorded for either the combination of 1.00 ET with 75 and 100 mM GB, and 0.80 or 0.60 ET with 100 mM GB. Because of the combination effects between ET treatments and irrigation frequency on the amount of water that is percolated under the root zone or absorbed by the roots (Assouline, 2002; Wang et al., 2006; Uçan et al., 2007) and the combination effects between ET treatments and GB concentration on the amount of water that are transported from canopy (Agboma et al., 1997), the optimal combinations between ET deficit and irrigation frequency or GB concentrations were instead often crucial for maximizing net income per unit water.
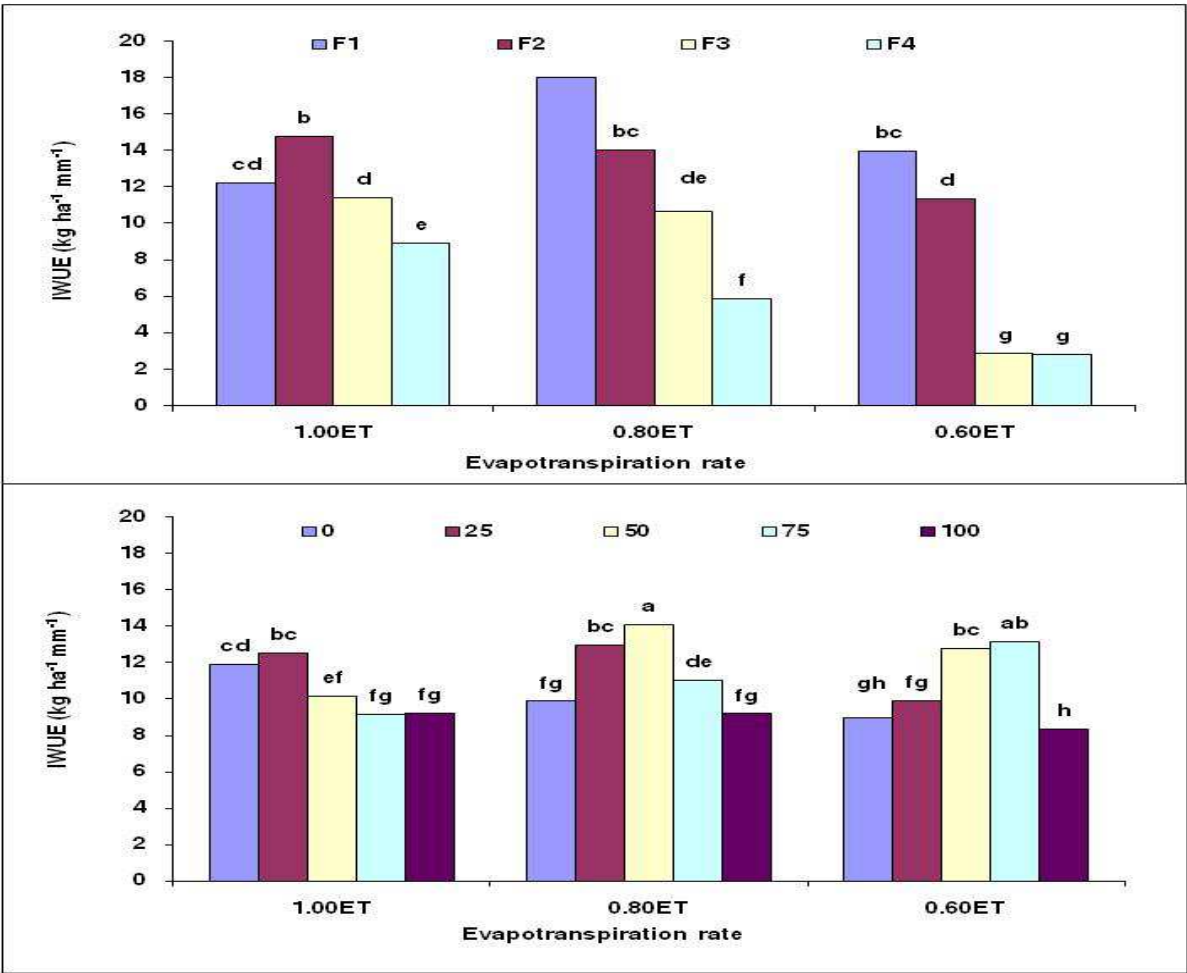

Fig. 1. Irrigation water use efficiency (IWUE) for the combination of evapotranspiration deficit (ET) with irrigation frequency (F) or with glycinebetaine concentration.

3.3 Yield-seasonal crop evapotranspiration relationship

A linear relationship has been reported between maize grain yield and seasonal crop ET (Payero et al., 2006) and was also indicated here for the combination of ET treatment with irrigation frequency or GB concentration (Fig. 2 A and B). However, when broken down
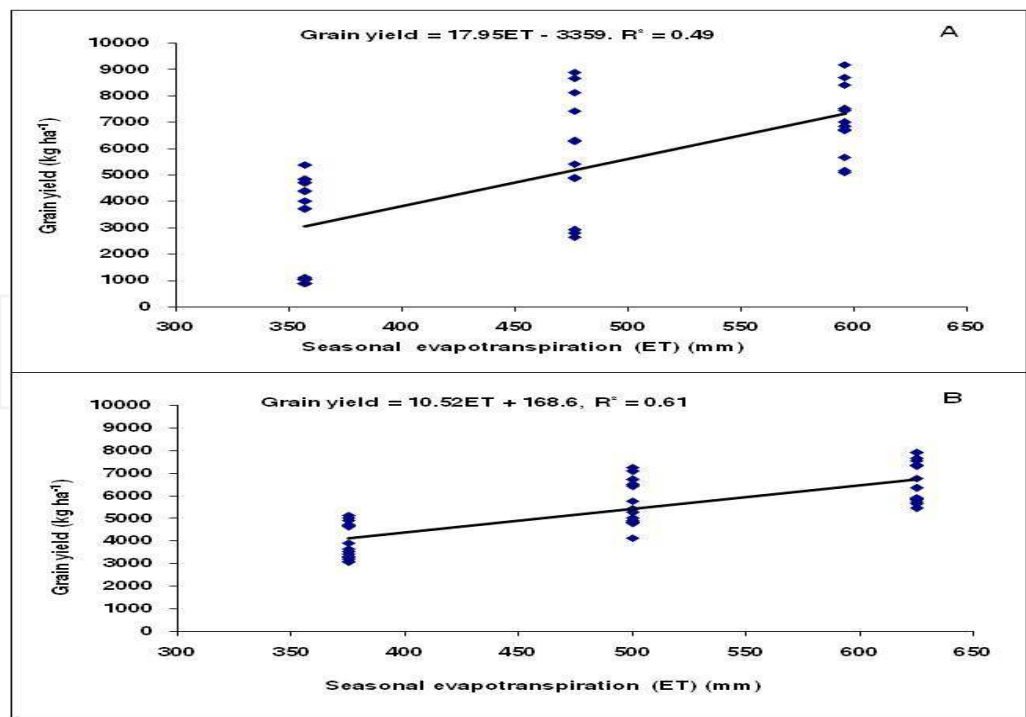
Fig. 2. Relationship between seasonal crop evapotranspiration (ET) and grain yield for the combination of ET treatment with irrigation frequency (A) or with GB concentration (B).
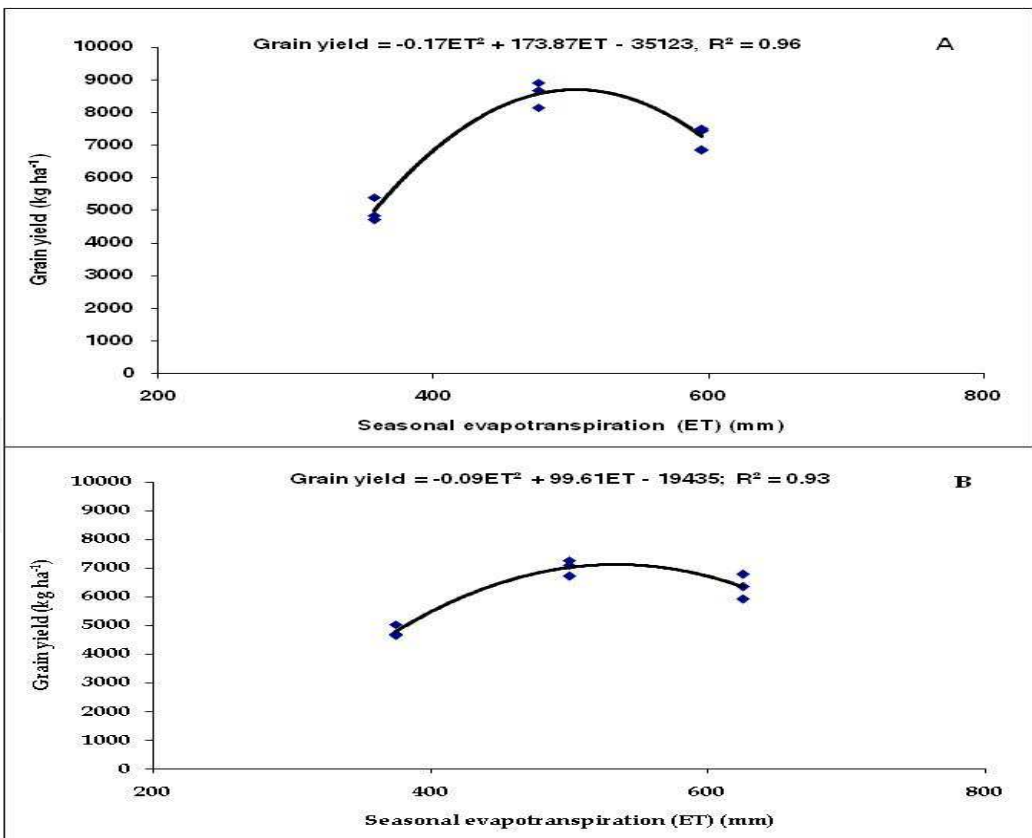

Fig. 3. Relationship between seasonal crop evapotranspiration (ET) and grain yield for irrigation frequency once every one day (A) and for 50 mM GB concentration (B).

according to the irrigation frequency treatments or GB concentration treatments, the relationships between grain yield and seasonal ET deviated from linear relationships to second order relationship for irrigation frequency once every one day or 50 mM GB concentrations (Fig. 3 A and B). Therefore, the regression of Fig. 2A and B shows that about 51 and 39% of the grain yield variation is not explained by seasonal ET under the combinations of ET treatment with irrigation frequency or with GB concentrations, respectively. The second order relationship also indicates that the increase in maize grain yield was not proportional with the increment in the amount of irrigation water. This phenomenon was especially obvious when irrigation frequency once every one day or 50 mM GB was combined with 1.00 ET because a portion of the water applied does not contribute to ET. At the same time, both former combinations resulted in significant reductions in grain yield due to the combination of 1.00 ET with the irrigation frequency once every one day resulting in a very humid region in the root zone and the combination of 1.00 ET with 50 mM GB effects on stomatal conductance and transpiration rates, which in turn both affects the crop photosynthesis. Therefore, it is suggested that the ET treatments should be matched well with other variables which directly or indirectly affects on grain yield (Paolo & Rinaldi, 2008; Farré & Faci, 2009).
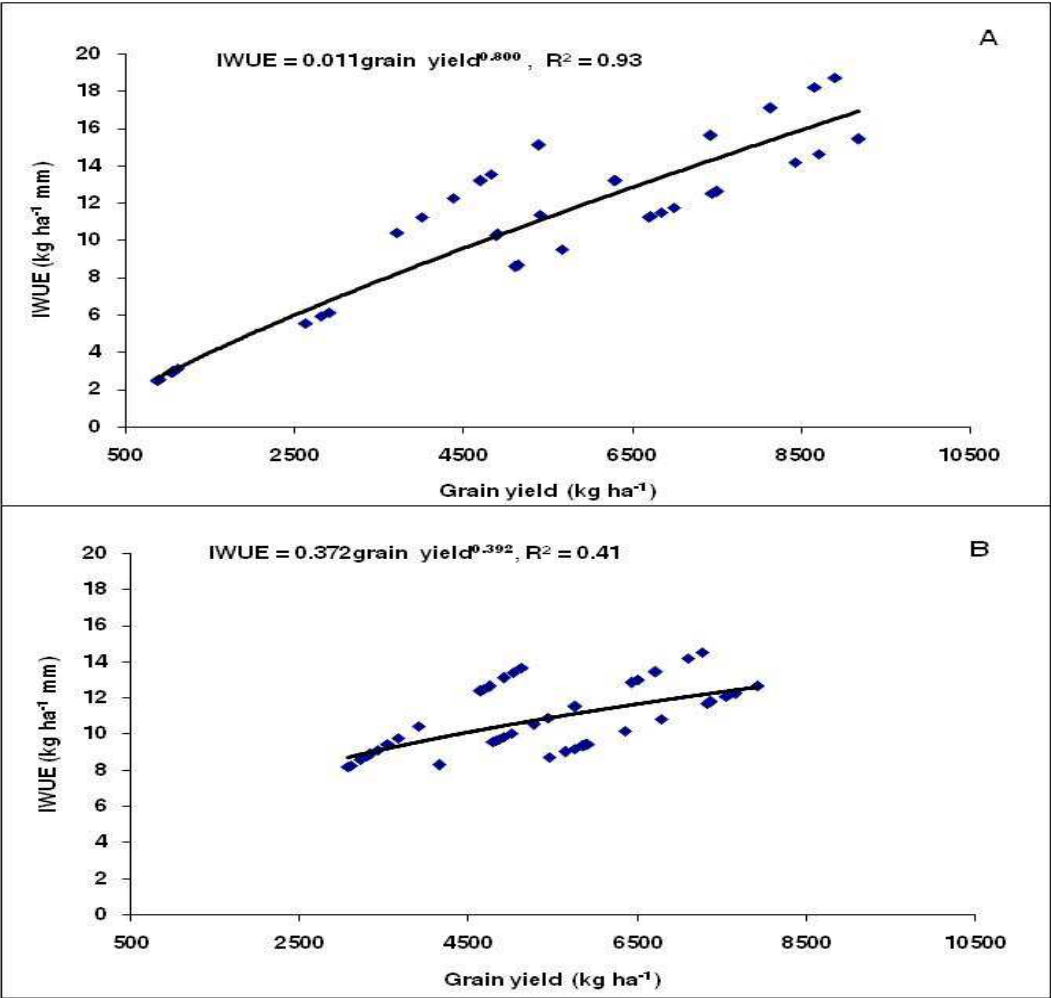

Fig. 4. Relationship between grain yield and irrigation water use efficiency (IWUE). Power regression equations; ***, * indicate significances at 0.001 and 0.05 P level, respectively.

3.4 The relation of irrigation water use efficiency with grain yield

Chen et al. (2003) mentioned that the relationship between WUE and grain yield is often used for determining the optimal irrigation strategy for arid and semiarid regions. Based on R^2 values, the power model was found to be the best fit model to describe the IWUE-yield relationship of our data, with a coefficient of determination value of 0.93 and 0.41 for the combination of ET treatments with irrigation frequency or GB concentrations, respectively (Fig. 4). In the power model, the elasticity of y with respect to x is the percentage change in y for each percentage change in x. Based on this definition, when grain yield is increased by 10%, the IWUE was increased by 8.0 and 3.9% in the combination of ET with irrigation frequency or with GB concentrations, respectively (equations in Fig 4). These equations indicated that high irrigation water use efficiency is obtained for high yield values. Therefore, it is important to know the optimum coupling combinations between ET and irrigation frequency or GB to seek maximize yield and IWUE simultaneously with saving water on the farm level.

3.5 Marginal analysis of water production function

The Y-ET function in a quadratic form is described as:

$$Y = -5921.93 + 38.6ET - 0.028ET^2 \quad R^2 = 0.78 \tag{14}$$

The relationships for EP, WUE, MP, Y, and ET based on the function of Eq. (5) are shown in Fig. 5 under a limited water supply. One of two goals can be achieved by ET applications. The first goal is maximizing the WUE, point A. Such goal can be achieved, in terms of the economic sight of the production function, at the point of which the first derivative of WUE is equal to zero, MP is equal to WUE, and EP is equal to one. The maximum WUE of 12.9 kg mm can be attained when ET was equal to 459.9 mm. The second goal is maximizing crop production, point B. At this point, the MP and EP are equal to zero as the first derivative of Y is equal to zero. ET maximizing yield is 689.3 mm at which the total yield is 7381.3 kg. Consequently, the WUE is with 1.07 kgm^{-3} less than the maximum WUE by 17.1%. It is sensible to mention that the EP is a reliable indication to recognize the range of desirable or economic production stages which fall in the range $1 \geq EP \geq 0$. With other words, the rational economic productivity must fall between the maximum WUE and maximum yield.

3.6 Virtual water as instrument to achieve water security in North Africa

The aim of this section is to analyze the consequences of North African international virtual water flows associated with cereals trade on national and global water budgets. With this aim, it quantifies and assesses national and global water savings and losses per cereal crop in the North Africa region.

Virtual water trade has a positive direct effect on water saving for the importing countries. This effect has been intensively discussed in virtual water studies since the concept of virtual water raised by Allan in the nineties. In this study, we examine the water saving at two levels. Firstly, national water saving that concentrates on the benefit gained by importing countries. Secondly the global water saving, the global net effect of virtual water trade between two nations will depend on the actual water volume that would have been required to produce a commodity in the importing and exporting countries. (Chapagain et al., 2006).

Saving Water in Arid and Semi-Arid Countries
as a Result of Optimising Crop Evapotranspiration
237

Figure 6 shows the notable variations among the specific water demand for the cereal crops production in North Africa countries and on the world average. Such highly significant variations derive mainly from two reasons. One reason is that in the North Africa region the evaporative demand is relatively high. The second reason is the low yield of the cereal crops in most NA countries. The water requirements to produce one ton of cereals in NA are equal to five times those in the world average. Highest differences were witnessed in maize and sorghum crops.
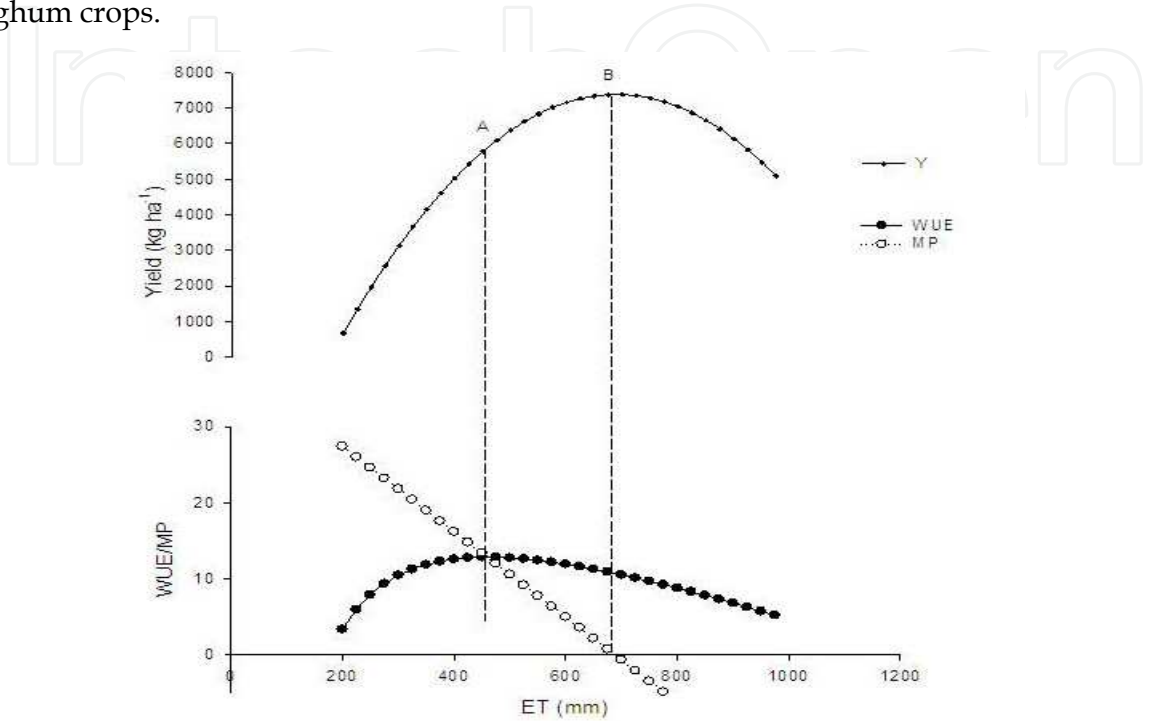

Fig. 5. Relations of EP, WUE, MP, Y, and ET for a quadratic production function for maize during 2007 -2008 in Egypt.
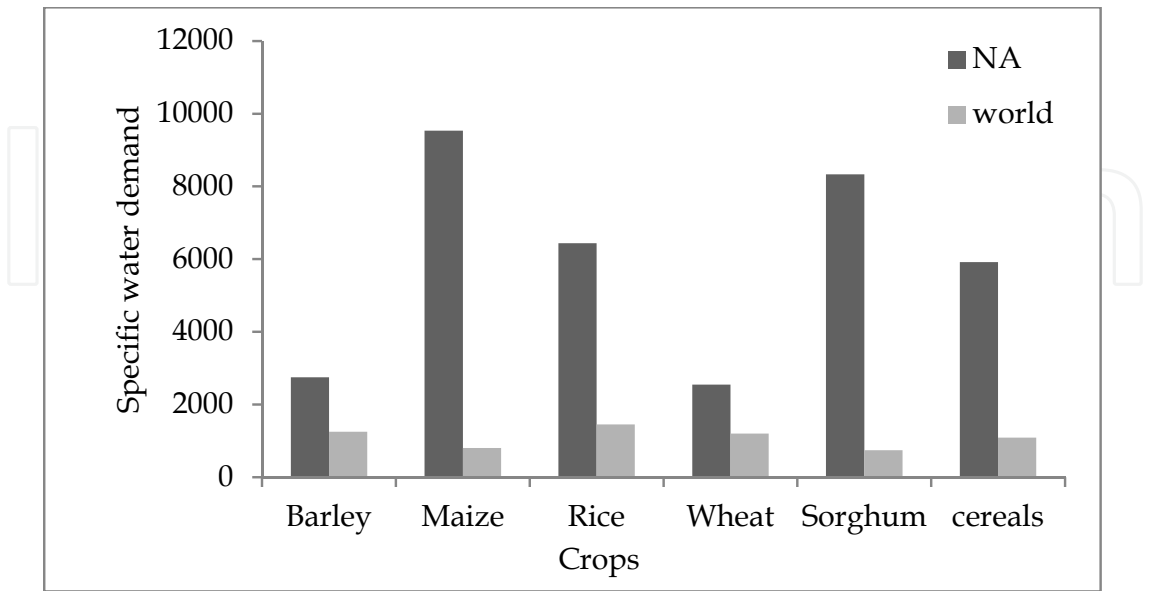

Fig. 6. Specific water demand for cereal crops in the North African and world (m³/ton) 2003-2007

3.6.1 National water saving in NA countries through cereals trade

Table 2 gives estimates of the national water saving of the North Africa countries expressed in volumes of virtual water embedded in net cereals trade. Seeing that the cereals trade is varying significantly from year to year, the figure presents the annual average for 2003-2007.

Furthermore all respective countries are net virtual water importers, there is a wide range of national water saving from 4.93 billion m³ in Egypt to 44.23 billion m³ in Algeria. The percentages of the national water saving through cereals net trade, to the total fresh water resources availability in each NA countries do extremely vary from around 9 in Egypt to 2136 in Libya. One can intuitively explain such a wide span in these percentages due to the fact that Egypt and Sudan are mainly representing irrigated agriculture countries while the rest countries are mainly rain fed agricultures. In addition, Libya is one of the driest countries in the world. The annual rainfall is very low with more than 95% of the country receiving less than 100 mm y^{-1} (Wheida & Verhoeven, 2007).

	Barley	Wheat	Maize	Rice	Sorghum	Others	Total	%
Algeria	134.5	24205.7	19489.6	370.4	2.3	32.5	44234.9	378.1
Egypt	1.5	2755.5	3465.0	-1307.0	NR	15.0	4930.0	8.6
Libya	921.7	5787.0	3668.0	912.9	NR	1524.6	12814.1	2135.7
Morocco	1361.4	5597.5	17375.9	5.5	NR	101.2	24441.4	84.3
Sudan	NR	4557.4	520.6	334.4	2160.1	15.5	7588.1	11.8
Tunisia	1581.5	2506.6	6368.4	30.2	326.9	7.3	10820.7	235.2
Region	4000.5	45409.6	50887.4	346.4	2489.3	1696.0	104829.2	62.5

% is the percentage national water saving achieved by each country to the total water resources in the same country.

Table 2. National water saving (10⁶ m³) achieved by the North Africa net trade of cereals crops, average 2003-2007

Figure 7 show that maize and wheat are the prominent cereal crops in terms of net virtual water imports. Wheat representations vary from around 23% in Tunisia to around 60% in Sudan. In summation, wheat represents about 44% of the national water saving in cereal net trade in NA region. On the other hand, maize representations vary from 7% in Sudan to 71% in Morocco. On the region level, maize is the highest cereal crop in terms of virtual water imports by around 50%. From what has been said, one can conclude that maize and wheat are representing around 91% of the national water saving in the North Africa region. In addition, all crops in the region and in each individual country attain national water saving except rice in Egypt. That because Egypt is a rice net exporter.
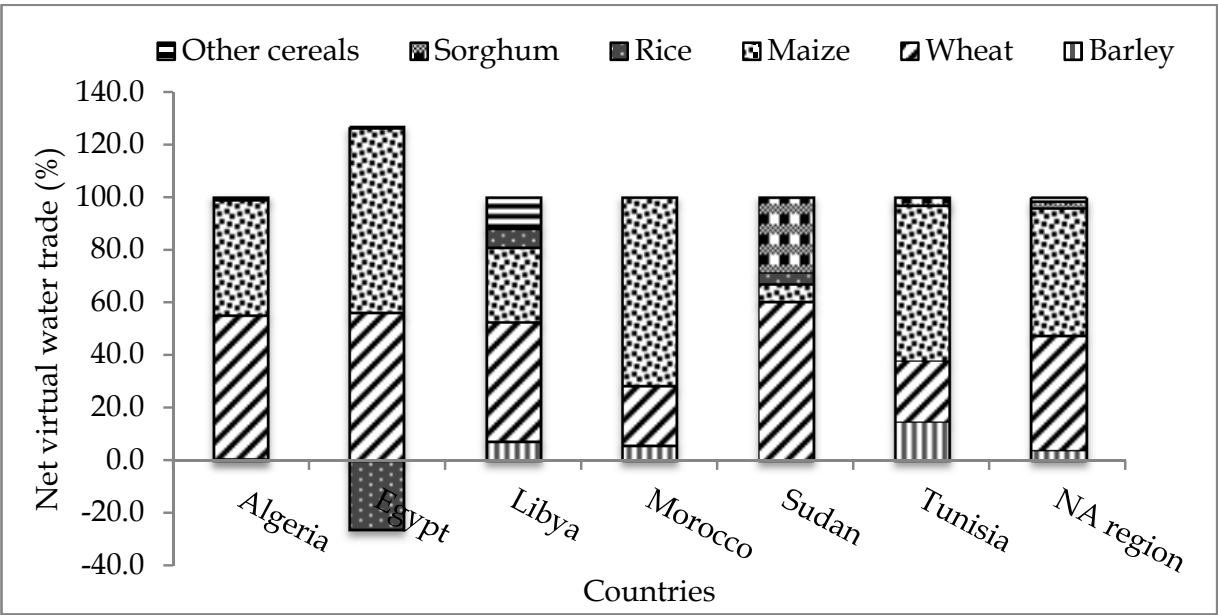
Fig. 7. Percentages of net virtual water trade embedded in each cereal crop, in the North African countries, average 2003-2007

3.6.2 Global water saving through North Africa cereals trade.

The international trade theory confirms that the global food import is approximately equal to the global food exports to achieve the global food market equilibrium over a given period. On the other hand, such equilibrium does not take place in the global virtual water trade associated with global food trade system. This imbalance is a result of the inequality of water used for producing a given amount of food between importing and exporting countries (Yang et al., 2006). Seeing that the global saving is obtained as the difference between the water productivities of the trading partners (Hoekstra & Chapagain, 2007), the positive sign on the difference, in the direction of exporting to importing countries, intuitively indicates global water saving. In contrast, the negative sign refers to global water loss.

Table 3 shows that the global saving resulting from international cereals trade between NA and the world countries is 77.2 billion cubic meter per year as on average of the period 2003 – 2007 . Approximately half of the amount of saved water originated only from Algeria. In addition, more than one quarter of the referred global water saving originated from Morocco. Thus, about 75% of the global water saving through the international trade of cereals crops in NA is derived only from Algeria and Morocco. One can see that there is notable global water saving achieved by cereal trade in all NA countries except in Egypt. The global water losing achieved by Egypt reflects a relatively high water productivity of cereal crops (Table 4). Furthermore, Egypt is the only country in the NA region with complete irrigation coverage. Consequently, the 100% irrigation coverage, adopting modern technology, and agricultural policy reforms explain its stable and significant increase of cereals production (Yang & Zehnder, 2002; El-Sadek, 2009). Considering the crop water requirements and yield, it has been noted that Egypt showed the highest cereal yield (7.5 ton ha^{-1}) among the NA countries. This yield is more than two times of the world average yield. On the other hand, the crop water requirements for

cereal production in Egypt is more than the cereals water requirements of Libya, Morocco, and the world average (Table 4).

	Barley	Wheat	Maize	Rice	Sorghum	Others	Total	%
Algeria	24.1	18016.2	17853.8	286.9	2.1	16.7	36223.7	47.4
Egypt	-0.8	-3461.7	296.5	29.4	NR	26.5	-4003.8	-5.2
Libya			3360.1	707.2	NR	1251.5	10537.5	13.8
Morocco	897.3	2597.5	16206.0	-0.9	NR	85.7	19706.3	25.8
Sudan	NR	2990.0	485.3	239.3	2033.8	12.9	5859.1	7.7
Tunisia	913.4	975.9	5857.7	22.1	292.6	40.0	8133.2	10.6
Region	2554.3	25520.3	44059.5	1284.0	2328.5	1433.3	76455.9	

% is the percentage of global water saving achieved by each country to this achieved by the NA region

Table 3. Global water saving (10^6 m^3) achieved by North Africa net trade of cereals crops, average 2003-2007

	Crop water requirement (m^3/ha)	Yield (ton/ha)	Specific water demand (m^3/ton)
Algeria	8498	1.4	6007
Egypt	4495	7.5	598
Libya	3808	0.6	6123
Morocco	6617	1.2	5611
Sudan	3036	0.6	4775
Tunisia	6034	1.5	4094
World	3574	3.3	1088

Table 4. Crop water requirements, crop yields and the specific water demand of cereals in North Africa countries and in the world. Period 2003-2007.

Saving Water in Arid and Semi-Arid Countries
as a Result of Optimising Crop Evapotranspiration
241

With respect to the global water saving achieved by individual cereal crop trade in NA, it is obvious that maize trading produces 44.1 billion $m^3 y^{-1}$ representing about 57.2% of the global water saving achieved by the region cereals trade. In the same context, wheat trading achieves 25.5 billion $m^3 y^{-1}$ representing about 33.1%. Therefore, only maize and wheat trading are representing 90.18% of all total global water saving.

Although water scarcity is not the main driver of cereals trade on the global level, it plays an essential role in cereal trade between North Africa and the other trade partner countries in the world. At the national level, all North Africa countries achieve water saving to the extent that exceed the total fresh water resources in some cases. Trading of maize and wheat is the most important player of the national water saving among the cereal crops trade.

At the global level, reductions in global water use occur if production by the exporter is more water efficient than by the importer. All countries in the North Africa region achieve global water saving except Egypt. The global water losing achieved by Egypt reveals a relatively high water productivity of cereal crops.

4. Conclusion

The results of this chapter contribute to a better understanding of the role of evapotranspiration in saving water on the farm level and on the national and global levels through their different applications. On the farm level, the optimal coupling combinations of water application rate as ET deficit with irrigation frequency or with GB concentrations play important roles to seek maximum yield and efficient irrigation water used simultaneously under deficit irrigation conditions. At the national level, all North Africa countries achieve water savings to the extent that exceed the total fresh water resources in some cases. Trading of maize and wheat is the most important player of the national water saving among the cereal crops trade. At the global level, reductions in global water use occur if production by the exporter is more water efficient than by the importer. All countries in the North Africa region achieve a global water saving except Egypt. The global water losing achieved by Egypt reveals a relatively high water productivity of cereal crops.

5. References

Agboma, P. C., Sinclair, T. R., Jokinen, K., Peltonen-Sainio, P. & Pehu, E., (1997). An evaluation of the effect of exogenous glycinebetaine on the growth and yield of soybean: timing of application, watering regimes and cultivars. Field Crops Res. 54, 51-64.

Al-Kaisi, M.M. & Yin, X., (2003). Effects of nitrogen rate, irrigation rate, and plant population on corn yield and water use efficiency. Agron. J. 95, 1475–1482.

Allan, J.A. (1998) Virtual water: A strategic resource global solutions to regional deficits. Ground Water 36:545-546.

Allen, R.G., Pereira L.S., Raes D. & Smith M. (1998) Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56.
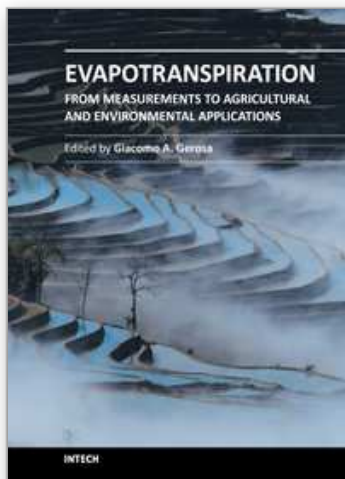
Ashraf, M., & O'Leary, J.W., (1996). Effect of drought stress on growth, water relations and gas exchange of two lines of sunflower differing in degree of salt tolerance. Int. J. Plant Sci. 157, 729–732.

Assouline, S., (2002). The effects of micro drip and conventional drip irrigation on water distribution and uptake. Soil Sci. Soc. Am. J. 66,1630 –1636.

Bergez, J.E., Deumier, J.M., Lacroix, B., Leroy, P. & Wallach, D., (2002). Improving irrigation schedules by using a biophysical and a decisional model. Eur. J. Agron. 16, 123– 135.

Brand, D., Koti, S., & Reddy, K.R., (2007). Application of glycinebetaine to alleviate drought and low temperature stress for soybean production system in Mississippi. Tri-State Soybean Forum. 5 January 2007. Vicksburg, MS, USA

Cetin, O. & Bilgel, L., (2002). Effects of irrigation methods on shedding and yield of cotton. Agric.Water Manage. 54, 1–15.

Chapagain A.K, Hoekstra A.Y. & Savenije H.H.G. (2006) Water saving through international trade of agricultural products. Hydrology and Earth System Sciences 10:455- 468.

Chen, C, Payne, W.A., Smiley, R.W. & Stoltz, M.A., (2003). Yield and water-use efficiency of eight wheat cultivars planted on seven dates in northeastern Oregon. Agron J. 95,836–843.

Doorenbos, J. & Kassam, A.H., (1979). Yield response to water. FAO Irrigation and Drainage Paper 33. Rome, Italy: UN-FAO.

El-Hendawy, S.E., Hokam, E.M. & Schmidhalter, U., (2008). Drip irrigation frequency: the effects and their interaction with nitrogen fertilization on sandy soil water distribution, maize yield and water use efficiency under Egyptian conditions. J.Agron. Crop Sci. 194, 180-192.

El-Hendawy, S.E. & Schmidhalter, U., (2010). Optimal coupling combinations between irrigation frequency and rate for drip-irrigated maize grown on sandy soil. Agric. Water Manage. 97, 439– 448.

El-Sadek A. (2009) Virtual Water Trade as a Solution for Water Scarcity in Egypt. Water Resources Management.

Farré´, I.& Faci, J. M., (2009). Deficit irrigation in maize for reducing agricultural water use in a Mediterrranean environment. Agric. Water Manage. 96, 383–394.

Fereres, E. & Soriano, M.A., (2007). Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58, 147–159.

Grimes, D.W.; Yamada, H. & Dickens, W.L., (1969). Functions for cotton production from irrigation and nitrogen fertilizer variables. I. Yield and evapotranspiration. Agron. J. 61 (5), 769–773.

Gulati, H.S. & Murty, V.V.N., (1979). A model for optimal allocations of canal water based on crop production functions. Agric. Water Manage. 2 (1), 79–91.

Hexem, R.W. & Heady, E.O., (1978). Water Production Functions for Irrigated Agriculture. Iowa State University Press, Ames, IA, 215 pp.

Hoekstra, A.Y. (2003) Virtual water: An introduction. In Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade, in: A. Y. Hoekstra (Ed.),

Value of Water Research Report Series, UNESCO-IHE, Delft, The Netherlands. pp. 13-23.

Hoekstra, A.Y. & Chapagain A.K. (2007). The water footprints of Morocco and the Netherlands: Global water use as a result of domestic consumption of agricultural commodities Ecological Economics 64:143-151. DOI: 10.1016/j.ecolecon.2007.02.023.

Hoekstra, A.Y. & Hung P.Q. (2002) Virtual water Trade: A quantification of virtual water flows between nations in relation to international crop trade, UNESCO-IHE, DELFT, Netherlands.

Hoekstra, A.Y. & Hung P.Q. (2005) Globalisation of water resources: international virtual water flows in relation to crop trade. Global Environmental Change:45-56.

Hussain, M.; Malik, M. A., Farooq, M., Khan, M. B., Akram, M. & Salee, M. F. (2009). Exogenous glycinebetaine and salicylic acid application improves water relations, allometry and quality of hybrid sunflower under water deficit conditions. J.Agron. Crop Sci. 195, 98-109.

Ma, Q.Q., Wang, W.; Li, Y. H.; Li, D.Q. & Zou, Q., (2006). Alleviation of photoinhibition in drought-stressed wheat (*Triticum aestivum*) by foliar-applied glycinebetaine. J. Plant Physiol. 163, 165–175.

Monteith, J. L & Unsworth MH. (1990). Principles of environmental physics, 2nd edn. London: Edward Arnold

Oki T. & Kanae S. (2004) Virtual water trade and world water resources. Water Science and Technology 49:203-209.

Paolo, E.D. & Rinaldi, M., (2008). Yield response of corn to irrigation and nitrogen fertilization in a Mediterranean environment. Field Crop Res. 105, 202-210.

Postel, S.L., Daily G.C. & Ehrlich P.R. (1996) Human appropriation of renewable fresh water. Science 271:785-788.

Payero, J.O., Melvin, S.R., Irmak, S., & Tarkalson, D., (2006). Yield response of corn to deficit irrigation in a semiarid climate. Agric. Water. Manage. 84,101–112.

Sallam, G.A. & Abd El Nasser G. (2006) Implications of Virtual Water Concept on Water Demand Management, Riyadh- Kingdom of Saudi Arabia.

Uçan, K., Kıllı, F., Gençoğlan, H & Merdun, H., (2007). Effect of irrigation frequency and amount on water use efficiency and yield of sesame (Sesamum indicum L.) under field conditions. Field Crop Res. 101, 249-258.

Wang, F.X.; Kang, Y. & Liu, S.P., (2006). Effects of drip irrigation frequency on soil wetting pattern and potato growth in North China Plain. Agric. Water Manage. 79, 248-264.

Wheida, E. & Verhoeven R. (2007) The role of "virtual water" in the water resources management of the Libyan Jamahiriya. Desalination 205:312-316.

Xing, W., & Rajashekar, C.B. (1999). Alleviation of water stress in beans by exogenous glycinebetaine. Plant Sci. 148, 185–195.

Yang, H.; Wang L., Abbaspour K.C. & Zehnder A.J.B. (2006). Virtual water trade: an assessment of water use efficiency in the international food trade. Hydrology and Earth System Sciences 10:443-454.

Yang, H. & Zehnder, A.J.B. (2002) Water scarcity and food import: A case study for southern Mediterranean countries. World Development 30:1413-1430.

Evapotranspiration - From Measurements to Agricultural and Environmental Applications
Edited by Dr. Giacomo Gerosa

ISBN 978-953-307-512-9
Hard cover, 410 pages
Publisher InTech
Published online 09, November, 2011
Published in print edition November, 2011

This book represents an overview of the direct measurement techniques of evapotranspiration with related applications to the water use optimization in the agricultural practice and to the ecosystems study. Different measuring techniques at leaf level (porometry), plant-level (sap-flow, lysimetry) and agro-ecosystem level (Surface Renewal, Eddy Covariance, Multi layer BREB), are presented with detailed explanations and examples. For the optimization of the water use in agriculture, detailed measurements on transpiration demands of crops and different cultivars, as well as results of different irrigation schemes and techniques (i.e. subsurface drip) in semi-arid areas for open-field, greenhouse and potted grown plants are presented. Aspects on ET of crops in saline environments, effects of ET on groundwater quality in xeric environments as well as the application of ET to climatic classification are also depicted. The book provides an excellent overview for both, researchers and student,s who intend to address these issues.

How to reference
In order to correctly reference this scholarly work, feel free to copy and paste the following:

Salah El-Hendawy, Mohamed Alboghdady, Jun-Ichi Sakagami and Urs Schmidhalter (2011). Saving Water in Arid and Semi-Arid Countries as a Result of Optimising Crop Evapotranspiration, Evapotranspiration - From Measurements to Agricultural and Environmental Applications, Dr. Giacomo Gerosa (Ed.), ISBN: 978-953-307-512-9, InTech, Available from: http://www.intechopen.com/books/evapotranspiration-from-measurements-to-agricultural-and-environmental-applications/saving-water-in-arid-and-semi-arid-countries-as-a-result-of-optimising-crop-evapotranspiration

INTECH
open science | open minds