Water–yield relations and optimal irrigation scheduling of wheat in the Mediterranean region

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Abstract

Crop yield is primarily water-limited in areas of West Asia and North Africa with a Mediterranean climate. Ten years of supplemental irrigation (SI) experiments in northern Syria were conducted to evaluate water–yield relations for bread wheat (Triticum aestivum L.) and durum wheat (Triticum turgidum L.), and optimal irrigation scheduling was proposed for various rainfall conditions. The sensitive growth stages of wheat to water stress were from stem elongation to booting, followed by anthesis, and grain-filling. Water stress to which crop subjected depends on rainfall and its distribution during the growing season; the stress started from early March (stem-elongation stage) or even in seedling stage in a dry year, and from mid-April (anthesis) in an average or wet year. Crop yield linearly increased with increase in evapotranspiration (ET), with an increase of 160 kg for bread wheat and of 116 kg for durum wheat per 10 mm increase of ET above the threshold of 200 mm. Water-use efficiency (WUE) with a yield $\geq 3$ t ha$^{-1}$ was ca. 60% higher than that with yield $<3$ t ha$^{-1}$; this emphasises the importance of that to achieve effective use of water, optimal water supply and relatively high yields need to be ensured. Quadratic crop production functions with the total applied water were developed and used to estimate the levels of irrigation water for maximizing yield, net profit and levels to which the crops could be under-irrigated without reducing income below that which would be earned for full SI under limited water resources. The analysis suggested that irrigation scenarios for maximizing crop yield and/or the net profit under limited land resource conditions should not be recommended. The SI scenarios for maximizing the profit under limited water resource conditions or for a targeted yield of 4–5 t ha$^{-1}$ were recommended for sustainable utilization of water resources and higher WUE. The time of irrigation was also suggested on the basis of crop sensitivity index to water stress taking rainfall probability and available soil water into account. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Water use efficiency; Supplemental irrigation; Irrigation scheduling; Wheat; Crop water stress; Economics; Mediterranean

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1. Introduction

Water shortage is the major constraint to agricultural production in areas of West Asia and North Africa (WANA) with a Mediterranean climate. Supplemental irrigation (SI) is widely practised to stabilize and/or improve crop yield (Perrier and Salkini, 1991; Oweis et al., 1998). The water used for SI is mainly from shallow groundwater aquifers and surface sources. In some part of northern Syria, over-exploitation has resulted in a decline of the groundwater table at a rate of 1 m per year since the 1960s (Ward and Smith, 1994). The excessive use of groundwater for SI seriously threatens the sustainability of groundwater utilization and, consequently, the agricultural systems that rely on it. The declining aquifers require farmers to deepen existing wells or drill new ones at fairly frequent intervals, which increase extraction costs. The needs for improving water-use efficiency (WUE) in crop production and sustainable use of water resources are clearly urgent. The question of water use and improving WUE is complex, embracing not only agronomic issues, but also hydro-geological, human, economic and social issues. Research interest at the International Center for Agricultural Research in the Dry Areas (ICARDA) has been broadened to take this complexity into account. Fully satisfying crop water requirements may be prohibitive in terms of sustainable utilization of limited water resources in WANA. The solution is to limit water application to specific stages, minimizing loss of yield from water stress. We need to know, therefore, at what stages of crop growth a small amount of water application results in optimal WUE and minimum loss of yield.

The relationships between crop growth or crop yield and water use have been a major focus of agricultural research in the arid and semi-arid regions and have been reviewed previously by Hanks (1983); Vaux and Pruitt (1983); Howell (1990). Crop yield relationships with seasonal evapotranspiration (ET) have been reported as linear (Singh et al., 1979; Mogenson et al., 1985; Steiner et al., 1985; Musick et al., 1994). Although yield–seasonal ET relations have been widely used for management purposes in water-deficient areas as a guideline for irrigation, they do not account for the effects of timing of water application. Water stress during certain growth stages may have more effect on grain yield than similar stress at other growth stages. The effect of water stress on crop yield during individual growth stages has been investigated using an additive model (Minhas et al., 1974; Howell and Hiler, 1975) and a multiplicative model (Jensen, 1968; Hanks, 1974). The effects of irrigation on crop production are usually quantified using crop water production functions which relate crop yield to the amount of water applied (Yaron and Bresler, 1983; English, 1990; English and Raja, 1996). These functions are used to optimise on-farm irrigation and economic evaluation of irrigation water application (Yaron and Bresler, 1983; English and Raja, 1996).

In the present paper, 10 years of SI experiments on wheat under different rainfall conditions in northern Syria were examined. Crop yield–water relations were determined, and the sensitivity of crop to water stress at different growth stages was analysed. Using the established crop yield–water relationship functions, the time and quantity of irrigation under different rainfall conditions are proposed with consideration of rainfall probability and the available soil water for efficient management and sustainable utilization of water resources for wheat production. The crop water production functions are also essential for
improving WUE and effective allocation of water resources among crops in a region. In previous two papers, we presented partitioning soil evaporation and crop transpiration and the influence of irrigation and nitrogen on water use, WUE and transpiration efficiency at two levels of nitrogen under rain-fed condition and supplemental irrigation (Zhang et al., 1998) and the interaction between nitrogen and supplemental irrigation and a production function considering water, nitrogen inputs and sowing date from 1992 to 1996 (Oweis et al., 1998).

2. Methods and materials

2.1. Site and experiments

Supplemental irrigation experiments were carried out on ICARDA’s Tel Hadya research farm (36°01′N, 36°56′E) in northern Syria from 1985 to 1996. The soil at Tel Hadya is classified as a Calcixerollic Xerochrept with the clay content over 60%. The soil water content at field capacity and wilting point are ca. 40 and 24% by volume, respectively. The irrigation experiments were coupled with N-fertilizer, wheat variety and sowing date using either split–split–split-plot design or randomized block design, and repeated three to four times (Perrier and Salkini, 1991; Garabet, 1995; Oweis et al., 1998). The plots for individual treatments in the experiments were 140 m² from 1986 to 1989, 20 m² from 1991 to 1993, and 14.2 m² from 1993 to 1996. A weather station at the experimental site recorded temperature, wind speed, solar radiation, class A pan evapotranspiration, and rainfall. Rainfall and its distribution during the crop growing seasons are presented in Table 1.

2.2. Crop and management

The cultivars used for supplemental irrigation experiments were ‘Cham 4’, ‘Gomam’, ‘Mexipak’ and ‘Cham 6’ for bread wheat (*Triticum aestivum* L.), and ‘Cham 1’, ‘Cham

<table>
<thead>
<tr>
<th>Season</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
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<td>75.8</td>
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<td>2.7</td>
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</table>
3’, ‘Omrabi-5’, ‘Sebou’ and ‘Lahn’ for durum wheat (*T. turgidum* L.). Crop was sown between early November and late January. Crops were planted at a row spacing of 17 cm and a sowing rate of 300 seeds m$^{-2}$. Grain yield was harvested in individual plots using a combine harvester. The amount of N application in the experiments ranged from 0 to 150 kg ha$^{-1}$. Nitrogen was applied in split top-dressing applications, half at planting and half at tillering. An adequate amount of phosphorus (40–50 kg P ha$^{-1}$) was applied as a basal dressing each season as triple superphosphate (46% P$_2$O$_5$), and incorporated to 20-cm soil depth during seedbed preparation. In order to avoid the effects on nutrient deficiency and delaying of sowing date to crop yield, the data used for analysis in the present paper were restricted to the treatments without nutrient stress (application of N$\geq$100 kg ha$^{-1}$) and sown before mid-December.

2.3. **Irrigation**

Irrigation water was applied using a line-source sprinkler system from 1985 to 1989 seasons, basin irrigation from 1991 to 1992, and a drip irrigation system from 1992 to 1996. A flow meter was used to measure the amount of irrigation water in all seasons. Different water levels were applied to different treatments. The maximum water applied was estimated to replenish soil water in the root zone to the field capacity, and the minimum was the rain-fed treatments without irrigation. Irrigation was applied when the available soil water in the full supplemental irrigation treatments dropped below 50% of total available water (the difference in soil water storage between field capacity and wilting point in the root zone). The amount of water applied in the different levels of SI treatments was 33%, and 66% of the amounts applied in the full supplemental irrigation treatments in 1985/1986, 1986/1987, 1991/1992, 1992/1993, 1993/1994, 1994/1995 and 1995/1996. Twenty percent, 40%, 60%, and 80% of the full irrigation were applied for the deficit irrigation treatments in 1987/1988 and 1988/1989.

2.4. **Soil water measurements and estimation of evapotranspiration**

A single aluminium access tube was installed at a depth of down to 180 cm in each plot. The soil moisture contents were monitored at $\approx$7–14-day intervals using a neutron probe (MK-II, Didcot Instruments, Abingdon, UK), for each 15 cm layer in the soil profile from a depth of 15–180 cm. The neutron probe was calibrated against soil water content determined gravimetrically at the experimental site. The moisture content at the top 15 cm layer was measured by the gravimetric method.

Evapotranspiration (ET) for individual plots was determined for seasonal total and between the growing stages using the soil water balance equation as follows:

$$ET = \Delta S + P + I - D_t$$  \hspace{1cm} (1)

where $\Delta S$ is the change of soil water storage (mm) between planting and harvest or between the growth stages, $P$ the precipitation (mm) that was measured from the weather station at the site, $I$ the amount of irrigation (mm) that was measured using a flow meter and $D_t$ the drainage from the bottom of the root zone. On the experimental site, no surface runoff occurred during the study seasons since rainfall intensity is usually low. The
maximum amount of SI water was determined only to fill the deficit in the root zone in the full supplemental irrigation treatments. Also, soil moisture measurements were taken down to 180 cm, which was well below the effective root zone (ca. 120–130 cm). Soil moisture measurements indicate that drainage at the site was negligible, except the 1987/1988 season. Therefore, deep percolation may be negligible and was ignored except for that season.

2.5. Crop sensitivity to water stress

The effect of water deficits during certain growth stages on grain yield was investigated using Jensen’s (1968) model:

$$\frac{Y}{Y_m} = \prod_{i=1}^{n} \left( \frac{ET_i}{ET_m} \right)^{\lambda_i}$$  \hspace{1cm} (2)

where $Y$ is grain yield (t ha$^{-1}$), $Y_m$ the maximum yield from the plot without water stress during the growing season, $ET_i$ the actual evapotranspiration (mm) during the growing stage $i$, $ET_m$ the maximum evapotranspiration corresponding to $Y_m$, $\lambda_i$ the sensitivity index of crop to water stress, and $i$ the growth stage. The growth of wheat was divided into five stages: seedling stage; stem elongation to booting; booting to flowering; flowering to soft dough; and soft dough to maturity. Non-linear regression procedure was used to find $\lambda$ values using SAS software (SAS Institute Inc., 1990). The lowest value of $\lambda$ was set >0.01 to avoid the unrealistic influence of water-stress on crop yield when $\lambda$ is negative.

3. Results and discussion

3.1. Rainfall, soil water dynamics and crop water use

The 10 years of the experiments covered a wide range of climate conditions. The 1988/1989 season was the driest with rainfall of 230 mm, and the 1987/1988 was the wettest with rainfall of 504 mm (Table 1). The rainy season started in October or November and the wettest months were December and January. During March and April, rainfall decreased, temperature and evaporative demand steadily increased. After May, only sporadic rain fell and both temperature and evaporative demand were high.

The seasonal changes of the percentage of plant-extractable water (PEW) (Ritchie, 1981) over the rooting depth (maximum 150 cm) in 1988/1989, 1991/1992 and 1987/1988 were chosen to represent dry, average and wet years, respectively. It is typical of a Mediterranean-type climate, that PEW increases gradually after the break of the season until February–March, then declines to the end of the season (Fig. 1). When PEW is below 55%, plants start to be water-stressed, and below 40% the plants are increasingly water-stressed and all processes are affected (Stapper and Harris, 1989). The actual water stress to which plants subjected depends on the rainfall and its distribution during the growing season; the stress itself starts from early March (stem-elongation stage) or even seedling stage in dry year, and from mid-April (anthesis) in average or wet year.
Regardless of rainfall difference, PEW was depleted to the same level at the end of crop season.

The contrasting effect of SI on the seasonal patterns of daily evapotranspiration for rain-fed and irrigated crops, averaged over five seasons from 1991 to 1996, is illustrated in Fig. 2 for bread and durum wheat. During the cold winter months, when leaf areas were small and soil water was ample, evapotranspiration rates were low, and the dominant moisture loss is via soil evaporation (Zhang et al., 1998). Therefore, there was little difference in water use between rainfed and irrigated crops. However, as leaf area and evaporative demand increase in March, evapotranspiration increases significantly, reaching its maximum values in late March for the rain-fed crop. This is much earlier than in the irrigated crop, because of depletion of plant extractable water in the soil profile (Fig. 1). The rain-fed crop had much lower evapotranspiration rate from the beginning of April onwards (Fig. 2), indicating that it was subjected to water stress. Supplemental irrigation is necessary to reduce water stress in the late stages of crop growth in order to achieve stable yields and to improve WUE.

3.2. Evapotranspiration–yield relationship

The relationship between grain yield and seasonal evapotranspiration (ET) is presented in Fig. 3. Evapotranspiration depends on the seasonal rainfall under rain-fed conditions and on the combined amount of water (irrigation and rainfall) under SI conditions. Seasonal ET ranged from 200 to 460 mm for both crops under rain-fed conditions, and the corresponding grain yield ranged from 0.35 to 4 t ha$^{-1}$ for bread wheat and 0.6 to 5 t ha$^{-1}$ for durum wheat. Under SI, ET ranged from 300 to 600 mm and grain yield from
2.3 to 7.5 t ha\(^{-1}\) for bread wheat, and ET from 300 to 650 mm and grain yield from 3.6 to 8.4 t ha\(^{-1}\) for durum wheat. Linear regression analysis of grain yield under rain-fed conditions and ET data revealed no significant relationship (\(R^2 = 0.43\) for bread wheat and \(R^2 = 0.37\) for durum wheat). This is mainly attributed to the different rainfall distribution and heat stress between the seasons. The rain-fed data combined with the SI data showed good linear relationship between grain yield and ET (\(R^2 = 0.68\) for both bread and durum wheat). The relationship indicates that for each 10 mm increase in ET, there was a corresponding grain yield increase of ca. 160 kg for bread wheat and 116 kg for durum wheat. Bread wheat seems to have greater response to increase in ET than durum wheat. Similar linear relationships of grain yield to a function of seasonal ET were established for irrigated sorghum (Stewart et al., 1983) and for winter wheat (Musick et al., 1994). Although the threshold for the first gain of grain yield was 156 mm for bread wheat (estimated from the regression equation), the virtual value of ET to achieve initial grain

Fig. 2. Seasonal pattern of daily evapotranspiration of bread and durum wheat averaged over five seasons (1991/1992 to 1995/1996) under rain-fed conditions (dashed line) and supplemental irrigation (solid line).
yield was ca. 200 mm. This value is similar to the threshold for the first gain yield increment for winter wheat in the US Southern Plains (Musick et al., 1994).

There was a considerable scatter between grain yield and ET for rain-fed data and the combined data, probably due to the variation in rainfall distribution within the growing season and temperature differences between the seasons. For example, although the rainfall in the 1985/1986 and 1994/1995 seasons was less than the long-term average, the crops may have benefited from the favourable inter-season distribution of rainfall. Crops may suffer from moisture stress during a long dry spell lasting from mid-March to early May in the 1991/1992 and 1992/1993 seasons (Table 1). However, late rains in the two seasons brought relief of water stress in the grain-filling period. In addition to seasonal crop water use, vapour-pressure deficit (reflecting temperature influence) during the grain-filling stage may play an important role in determining grain yield. Combined
analysis of the 10 years’ data of SI experiments showed that grain yield of bread wheat was negatively \( r = -0.62, P < 0.001, n = 52 \) correlated with vapour-pressure deficit during grain-filling stage. However, this negative effect of vapour pressure deficit did not occur in durum wheat. This could be attributed to greater drought-resistance in durum wheat compared with bread wheat (Simane, 1993).

The sensitivity index \( (\lambda) \) of wheat to water stress at individual growth stages is presented for bread and durum wheat in Table 2. The \( \lambda \) values were small in seedling stage, became larger from stem-elongation to grain-filling stage, and then became small after soft-dough stage. The most sensitive stage to water stress is stem-elongation to booting followed by flowering or grain-filling stage. In a Mediterranean environment where drought stress occurred at stem elongation and ear formation, increased tiller abortion significantly reduced ear number (Blum and Pnuel, 1990). The crop sensitivity index to water stress in this study is in agreement with the results for wheat crop from Utah State (Hill et al., 1984) and from the North China Plain (Li, 1990; Zhang and Liu, 1992). In fact, crop water use was small during seedling stage due to low temperature and small leaf area, and most of ET was via soil evaporation (Zhang et al., 1998). Hence, the crop showed small response to water stress during this stage. From stem-elongation, crop water use significantly increased with increasing temperature and leaf area when plants shifted from vegetative growth to reproductive growth. Therefore, crop response to water stress became more sensitive and \( \lambda \) values increased. The variation of \( \lambda \) values during individual growth stages indicates that crop grain yield not only depends on the total water use during the growing season, but also on water use during individual growth stages.

There is little difference in crop water use before anthesis between rain-fed treatments and irrigation treatments. Correlation analysis at the same N level and sowing date of four seasons (1992/1993 to 1995/1996) showed that grain yield was significantly correlated with post-anthesis water use \( (r = 0.64–0.85, P < 0.001, n = 16 \) for bread wheat; \( r = 0.66–0.89, P < 0.01, n = 16 \) for durum wheat). There was no clear relationship between grain yield and crop pre-anthesis water use. This agrees with the analysis of crop response to water stress using the Jensen’s model. Both analyses highlight the importance of crop water use after anthesis. The degree to which water supply limits yield is indicated by a ratio \((2.1–2.4 : 1)\) of pre- to post-anthesis water use.

### 3.3. Water-use efficiency–grain yield relationship

The relationships between WUE and grain yield are presented for bread wheat and durum wheat in Fig. 4. The relationships suggest the importance of attaining relatively

<table>
<thead>
<tr>
<th>Crop</th>
<th>Seedling</th>
<th>Stem elongation–booting</th>
<th>Booting–anthesis</th>
<th>Anthesis–soft dough</th>
<th>Soft dough–maturity</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bread wheat ( a )</td>
<td>0.01</td>
<td>0.31</td>
<td>0.28</td>
<td>0.21</td>
<td>0.10</td>
<td>0.67</td>
</tr>
<tr>
<td>Durum wheat ( b )</td>
<td>0.15</td>
<td>0.31</td>
<td>0.17</td>
<td>0.26</td>
<td>0.07</td>
<td>0.69</td>
</tr>
</tbody>
</table>

\( a \) The bread wheat cultivar was Gomam.

\( b \) The durum wheat cultivar was Omrabi-5.
high yield for attaining high WUE. For example, WUE of bread wheat was 6.8±0.31 kg ha⁻¹ mm⁻¹ for grain yield <3 t ha⁻¹ (the yield level at an average rainfall of 330 mm at the experimental site), and 10.8±0.28 kg ha⁻¹ mm⁻¹ for grain yield >3 t ha⁻¹. Water-use efficiency of durum wheat was 7.4±0.96 kg ha⁻¹ mm⁻¹ for grain yield <3 t ha⁻¹, and 11.9±0.20 kg ha⁻¹ mm⁻¹ for grain yield >3 t ha⁻¹. Water-use efficiency was 59 to 61% higher for grain yield >3 t ha⁻¹ compared with that of grain yield <3 t ha⁻¹. The maximum WUE is transpiration efficiency when there was no water loss from the soil surface, and was estimated at ca. 15 kg ha⁻¹ mm⁻¹ for wheat in the Mediterranean region (Siddique et al., 1990; Zhang et al., 1998). The combined rain-fed and irrigated WUE data showed a curvilinear relationship with increase of grain yield. The plateau of the WUE relation with grain yield with a maximum value of ca. 15 kg ha⁻¹ mm⁻¹, indicates an offset of WUE at higher grain yields. The association of

Fig. 4. Relationship between water-use efficiency (WUE) and crop yield for bread and durum wheat over five seasons, 1991/1992 to 1995/1996.
high WUE values with high yields has important implications for the crop management for achieving efficient use of water resources in WANA. It emphasizes the importance of supplemental irrigation to limit duration and severity of plant water stress for attaining relative high yields.

3.4. Yield relation with total applied water

In the Mediterranean region, the stored soil water at planting has been considered unimportant for wheat production after a dry and hot summer, as the water used by crop from soil was negligible compared with precipitation (Cooper et al., 1987; Zhang et al., 1998). Hence, the following analysis takes the sum of precipitation and irrigation water as the total water applied to the crop. The relationship between grain yield of wheat and the sum of precipitation ($P$) and irrigation water ($W$) is presented in Fig. 5 using the data from 1985 to 1996. Cham 4 was chosen to represent bread wheat and Cham 1 durum wheat, because the two cultivars were used continuously in the 10 years experiments, and are the most popular wheat cultivars in the region. Grain yield linearly increased with increasing $P+W$ up to 450 mm during the growing season. When the total applied water ($P+W$) was above 600 mm, grain yield showed a plateau. Grain yield finally approached the maximum because either rain or irrigation water was left in the soil profile or percolated into deeper layers at high levels of water application. The increase in grain yield per unit of $P+W$ gradually decreased when $P+W$ was above 450 mm. This response of yield to $P+W$ can be described using a quadratic equation as follows:

$$Y(W) = b_0 + b_1(P + W) + b_2(P + W)^2 \tag{3}$$

where $Y$ is grain yield (t ha$^{-1}$), $W$ the irrigation water (mm), $P$ the precipitation (mm) during the growing season, and $b_0$, $b_1$ and $b_2$ the regression coefficients. A highly significant polynomial relationship existed between grain yield and the total applied water ($R^2=0.84$ for bread wheat and $R^2=0.87$ for durum wheat), with a minimum requirement of 203 mm water for initial grain yield for both crops. This minimum water requirement was similar to the virtual value of ET estimated from yield–ET relationships (Fig. 3), and close to the 206 mm ET for irrigated and dry-land wheat in the US Southern Plains (Musick et al., 1994). The highest grain yield required 680 mm water for bread wheat, and 750 mm water for durum wheat, with corresponding yields of 6.42 and 6.65 t ha$^{-1}$.

The relationship between grain yield and the total applied water is useful for optimizing irrigation strategy. In order to derive the amount of water required under different rainfall conditions, one can fix the precipitation in Eq. (3) and the response of yield to irrigation water can be found. The response of grain yield to irrigation water ($W$) can be described using the equation:

$$Y(W) = c_0 + c_1W + c_2W^2 \tag{4}$$

where $c_0=b_0+b_1P+b_2P^2$, $c_1=b_1+2b_2P$ and $c_2=b_2$. Under rain-fed conditions ($W=0$), grain yield of both bread and durum wheat increased from ca. 1.2 to 4–5 t ha$^{-1}$ when rainfall increased from 250 to 450 mm. The response of grain yield to water applied decreased as rainfall increased, with the highest response for lowest rainfall.
In order to develop optimal irrigation management, it is necessary to develop a cost function in addition to the crop water production function. A linear cost function with increasing SI was derived as follows:

\[ c(W) = a_1 + a_2 W \]  

where \( c(W) \) is the cost in Syrian pound (SP), \( W \) the water in mm, \( a_1 \) and \( a_2 \) the fixed and variable costs of production, respectively. The values of \( a_1 \) and \( a_2 \) were estimated from the Syrian statistical book (1995) and are 13 377 and 25.9 SP, respectively (Table 3).
The net profit per hectare is a function of applied water:

\[ R_n(W) = P_y Y(W) - c(W) \]  \hfill (6)

where \( R_n(W) \) is the net profit, \( Y(W) \) the crop production function and \( P_y \) the price per unit of grain of wheat. The level of water use for maximizing yield can be determined by taking the derivative of Eq. (4). The level of water use for maximizing the net profit under different constrained conditions can be determined by taking a partial derivative of Eq. (6) with respect to \( W \). The various levels of water use for different interests are as follows:

(a) for maximizing yield, the amount of irrigation water \( (W_m) \) is:

\[ W_m = c_1/(-2c_2) \]  \hfill (7)

(b) for maximizing the net profit under limited land resources, the amount of irrigation water \( (W_l) \) is:

\[ W_1 = (c_1 - a_2/P_y)/(-2c_2) \]  \hfill (8)

(c) for maximizing the net profit under limited water resources conditions (English, 1990), the amount of irrigation water \( (W_w) \) is:

\[ W_w = [(P_y b_0 - a_1)/(P_y b_2)]^{1/2} - P \]  \hfill (9)

where \( P \) is precipitation (mm) during the crop growing season.

(d) the amount of irrigation water at which net income will equal that at full irrigation under limited water resources conditions \( (W_{ew}) \) (English, 1990):

---

Table 3

<table>
<thead>
<tr>
<th>Cost category</th>
<th>Costs a (SP ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed costs (field machinery, tillage, planting and irrigation equipment, etc.)</td>
<td>4841</td>
</tr>
<tr>
<td>Variable costs: rain-fed</td>
<td></td>
</tr>
<tr>
<td>Fertilizer (N : 75 kg ha(^{-1}), P(_2)O(_3) : 50 kg ha(^{-1}))</td>
<td>2646</td>
</tr>
<tr>
<td>Seeds</td>
<td>2941</td>
</tr>
<tr>
<td>Harvest</td>
<td>2949</td>
</tr>
<tr>
<td>Variable costs: irrigated at 250 mm</td>
<td></td>
</tr>
<tr>
<td>Irrigation</td>
<td>2997</td>
</tr>
<tr>
<td>Fertilizer (N : 140 kg ha(^{-1}), P(_2)O(_3) : 90 kg ha(^{-1}))</td>
<td>4800</td>
</tr>
<tr>
<td>Seeds</td>
<td>3950</td>
</tr>
<tr>
<td>Harvest</td>
<td>3360</td>
</tr>
<tr>
<td>Total costs</td>
<td></td>
</tr>
<tr>
<td>Non-irrigated</td>
<td>13377</td>
</tr>
<tr>
<td>Irrigated</td>
<td>19858</td>
</tr>
<tr>
<td>Cost function</td>
<td>( c(W)=13377+25.9W )</td>
</tr>
</tbody>
</table>

a Data are from Syrian annual statistical book in 1995. The official rate in 1995 was 43.5 SP for 1 US dollar.
\[ W_{ew} = \left( -Z_2 + \left| Z_2^2 - 4P_y b_2(P_y b_0 - a_1) \right|^{1/2} \right) / 2P_y b_2 - P \]  
\[ \text{(10)} \]

where 
\[ Z_2 = (P_y b_1^2 - 4a_1 b_2 + 4P_y b_0 b_2) / 2b_2. \]

(e) the amount of irrigation water for a targeted yield \((Y_t)\), \(W_t\):
\[ W_t = \left[ -(c_1 + (c_1^2 - 4c_2(c_0 - Y_t))^{1/2}) / (-2c_1) \right] \]  
\[ \text{(11)} \]

The values of \(W_m, W_1, W_w, W_{ew}\) and \(W_t\) were determined for each crop using Eqs. (7)–(11) and the results are summarized in Table 4. To achieve the maximum grain yield for bread and durum wheat, the amount of water required \((W_m)\) ranged from ca. 230 to 310 mm in a wet year with rainfall of 450 to 430–510 mm in a dry year with rainfall of 250 mm. Water resources in WANA are scarce and therefore the strategy for maximizing grain yield is inappropriate because a large amount of water is needed. The operational cost per cubic meter of water in northern Syria plus corresponding increase resulting from additional investment (e.g. fertilizer, harvest, seeds) is ca. 25.9 SP per mm water per hectare (Table 3). The price of 1 kg wheat \((P_y)\) is 10 to 11.5 SP. The ratio of \(a_2/P_y\) in Eq. (8) is <3. This resulted in that the \(W_t\) for maximizing the profit under limited land resources conditions was 100 mm less water than \(W_m\). The \(W_t\) strategy can be applied to the areas without water resource shortage (Yaron and Bresler, 1983; English and Raja, 1996), and hence the amount of irrigation is not recommended for sustainable use of water resources in the water-scarce dry areas. The \(W_w\) strategy for maximizing net profit under limited water resources conditions can save irrigation water by 40–73% with a grain yield loss of only 13% for bread wheat, and by 36–54% with a grain yield loss of only 12% for durum wheat. Hence the \(W_w\) strategy requires much less water with a considerable small loss of grain yield; and thus, it is more suitable for

Table 4
Estimated amount (mm) and timing of supplemental irrigation for maximizing yield, maximizing the net profit and a targeted yield under different rainfall conditions

<table>
<thead>
<tr>
<th>Rainfall</th>
<th>(W_m)</th>
<th>(W_1)</th>
<th>(W_w)</th>
<th>(W_{ew})</th>
<th>(W_t)</th>
<th>Time of irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bread wheat</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>430</td>
<td>336</td>
<td>260</td>
<td>161</td>
<td>158–254</td>
<td>Stem elongation, booting, flowering and grain filling</td>
</tr>
<tr>
<td>300</td>
<td>380</td>
<td>286</td>
<td>210</td>
<td>111</td>
<td>108–204</td>
<td>Stem elongation, flowering and/or grain filling</td>
</tr>
<tr>
<td>350</td>
<td>330</td>
<td>236</td>
<td>160</td>
<td>61</td>
<td>58–155</td>
<td>Flowering and/or grain filling</td>
</tr>
<tr>
<td>400</td>
<td>280</td>
<td>186</td>
<td>110</td>
<td>11</td>
<td>0–144</td>
<td>Grain filling</td>
</tr>
<tr>
<td>450</td>
<td>230</td>
<td>136</td>
<td>60</td>
<td>0</td>
<td>0–55</td>
<td>Grain filling</td>
</tr>
<tr>
<td><strong>Durum wheat</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>510</td>
<td>454</td>
<td>314</td>
<td>180</td>
<td>144–207</td>
<td>Stem elongation, booting, flowering and grain filling</td>
</tr>
<tr>
<td>300</td>
<td>460</td>
<td>404</td>
<td>294</td>
<td>130</td>
<td>94–157</td>
<td>Stem elongation, flowering and/or grain filling</td>
</tr>
<tr>
<td>350</td>
<td>410</td>
<td>354</td>
<td>244</td>
<td>80</td>
<td>44–107</td>
<td>Flowering and/or grain filling</td>
</tr>
<tr>
<td>400</td>
<td>360</td>
<td>304</td>
<td>194</td>
<td>30</td>
<td>0–57</td>
<td>Grain filling</td>
</tr>
<tr>
<td>450</td>
<td>310</td>
<td>254</td>
<td>144</td>
<td>0</td>
<td>0</td>
<td>—</td>
</tr>
</tbody>
</table>

\(^a\) Amount of water required for maximizing grain yield.
\(^b\) Amount of water required for maximizing the net profit under limited land resources.
\(^c\) Amount of water required for maximizing the net profit under limited water resources.
\(^d\) Amount of water required for deficit irrigation at which the net profit equals that at full irrigation under limited water resources.
\(^e\) Amount of water required for targeted yield of 4–5 t ha\(^{-1}\).
the water-scarce dry areas (Table 4). The amount of $W_{ew}$ was considerably lower than $W_{w}$. Compared with the scenario for the maximizing yield, $W_{ew}$ scenario saved 62–100% of water with a yield reduction of 31% for bread wheat, and 65–100% of water with a yield reduction of 35% for durum wheat. The SI amount $W_{t}$ to achieve a targeted yield (4–5 t ha$^{-1}$) under different rainfall regimes was close to $W_{ew}$ and $W_{w}$ for bread wheat, and lower than $W_{w}$ for durum wheat. The $W_{t}$ for achieving targeted 4–5 t ha$^{-1}$ grain yield ranged from no irrigation in a wet year to 250 mm in a dry year (rainfall 250 mm). Compared with the irrigation scenario of maximizing grain yield, the $W_{t}$ scenario, on average, saved 63% of water with a yield reduction of only 31% for bread wheat, and 84% of water with a yield reduction of 35% for durum wheat. On the other hand, the water saved from the $W_{t}$ scenario can be applied to more than double the areas of the $W_{m}$ scenario for maximizing yield. The overall production of the $W_{t}$ scenario for the targeted yield can be more than double that for the $W_{m}$ scenario for maximizing yield.

Increasing irrigation cost may discourage farmers to use excessive water than crop requires. An increase of $a_2$ from 25.9 SP (the price used in this paper) to 68.3 SP (a price anticipated without subside from the government) reduced the total water applied from 633 to 532 mm. The latter value is still greater than those of the irrigation scenarios we suggested under limited water resource conditions (Table 4). This indicates that an increase in irrigation cost may not result in efficient use of water resources, especially in the areas with scarce water resources. However, an increase in $a_2$ does not affect the values of $W_{ew}$ and $W_{w}$ because $a_2$ was not included in Eqs. (9) and (10). Change of $a_1$ has little effect on the values of $W_{ew}$ and $W_{w}$ (data not shown) although it was included in Eqs. (9) and (10).

The analysis of crop sensitivity to water stress suggests the best time to apply irrigation water. However, the rainfall probability and the available soil moisture in the root zone need to be considered during the crop growing seasons. Although the wheat crops in this study showed that the most sensitive stage to water stress is stem-elongation to booting, the rainfall probability was much higher (Dennett et al., 1984) during this period except in dry years. There is also more available water in the root zone as a result of rainfall and less evapotranspiration (Fig. 1) during winter. The amount of water recommended in Table 4 may be scheduled at booting to flowering stage and grain-filling stage. In a dry year, irrigation may be needed as early as at stem-elongation stage. When rainfall is <300 mm, two to four irrigations and total 108–250 mm water are needed, and irrigation might be applied at stem-elongation, booting, flowering and/or grain-filling stages. When rainfall is above 400 mm, only one or even no irrigation is needed; if irrigation is applied, the best time to apply it is at grain-filling stage. In a year with average rainfall of 330 mm in northern Syria, one to two irrigations are sufficient to stabilize crop yield. In addition, since the response of drought-resistant durum wheat to irrigation is much less than that of bread wheat, irrigation priority may be given to bread wheat in the areas where both bread and durum wheat are cropped.

4. Conclusions

Crop yield in the Mediterranean region depends not only on the total water use during the growing season, but also on water use during individual growth stages. Wheat
response to water stress is more sensitive from stem-elongation to grain-filling stage than at other stages. The linear relation of yield to seasonal ET and curvilinear WUE–yield relationship emphasises the importance of that to achieve effective use of water, optimal water supply and relatively high yields need to be ensured. The curvilinear relationships of yield with the total applied water as well as irrigation water suggest that a policy for maximizing yield and/or the net profit under limited land resources conditions should be avoided in this region. Maximizing the net profit under limited water resources conditions or achieving a targeted yield of 4–5 t ha\(^{-1}\) is recommended for sustainable use of water resources, and these two scenarios can save 36–100% of water required for maximizing grain yield with a limited loss of yield. We suggest that scarce water should be applied at crop-growth stages that are more sensitive to water stress. Irrigation during booting to grain-filling would be preferable for improving water-use efficiency when the available soil water and probability of rainfall are low in this environment.

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**References**


