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Optimizing Water Consumption Using Crop Water Production Functions

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1. Introduction

There are two options for increasing crop production: Increasing acreage and improving land utilization. Food supply in the early period of agriculture was obtained only by expanding the physical area of land. Gradually, improving land productivity using different agronomy and management techniques for food production has had a more prominent role than increase in physical land area. As today, the acreage increase does not play key role in the crop production. Historical samples are proof of this claim. Historical trends indicate that, although application of fertilizers, pesticides and plant breeding could improve yield per unit area, but gradually due to improper management of resources, pollution caused by chemical fertilizer and pesticides has led to agricultural sustainability is threatened. While in terms of plant breeding, in many cases the plants have reached their biological production limit. But irrigation management has still key role to increase land productivity and food production. Currently, 2.5 billion people in terms of employment, food and income are dependent on irrigated agriculture. It is estimated that within the next 30 years, 80 percent of the additional food needed for world population is rely on irrigation. Although the increase in irrigated agriculture can play a significant role in providing world food needs, but water resources for such development is limited. Therefore, more effective use of current resources in irrigation is emphasized. Groundwater extraction in the short term is effective in producing food, but its continuance would not be sustainable in the long run.

Agricultural is the largest consumer of water in the world. About 80 to 90 percent of exploited water resources are used in the agricultural section. In this section, it is possible to increase water productivity and use of saved water for the new land could increase crop production. Generally, traditional management to reduce risk from water shortages in the agricultural sector was demand management, mainly to develop water storage using dams or water captivates had been focused. Of course, it is led to various problems of environmental because of changing in water hydrologic cycle. Today, most countries have reached the peak utilization of their water resources, extracting the main accessible water. It is natural that in these circumstances water extraction costs more and more expensive every day, and in practical point of view, agricultural practices will be non-economic. In these conditions, the agricultural sector had to compete with other sectors to use of each unit of

water. In other words, a serious question arises whether in the long term water extraction in large scale to crop production is economy? or use of water in other sectors like industry has a higher comparative advantage? Rapid population growth and the need for more production has caused the agricultural sector would have more demand for water than any other water consuming sectors (industry, domestic, drinking). So, the main challenge of the agricultural sector is to produce more crops from less water. In this context, increasing of water use efficiency is one of the important strategies for more production. One of the important solutions to reduce hunger, poverty and maintaining the previous level of production will be increasing water productivity proportional to increase in demand for food. Increasing water use efficiency while maintaining stable production and reducing water consumption, a significant volume of water can store without a new structure to be constructed. There are two basic solutions for increasing water productivity: These are reducing water consumption with proven production (irrigation management) and increasing production with a fixed amount of water (agronomy management) that eventually will lead to more production with less water.

Reducing water consumption while maintaining the previous production, includes all activities that are leading to improve irrigation management. Ways to increase water productivity from the perspective of improving irrigation management can be summarized as follows:

- improving irrigation efficiency (improving conventional irrigation systems and change to modern irrigation systems)
- optimal allocation of water resources
- deficit or alternate irrigation
- optimize water use by determination of water – yield relations (production functions)
- the use of uncommon water
- reduce evaporation

Increasing production per unit water consumption is achievable by improving the production management. The production management refers to all agricultural activities that are leading to increase production. The following can be cited In this context:

- breading activities to make drought resistant cultivars
- reduce the period of plant growth
- increasing the depth and root density in soils
- change and reform cropping pattern on the basis of the highest plant productivity
- crop rotation
- application of conservation tillage techniques for more efficient use of available moisture in the soil, irrigation water and rain
- controlling pests and diseases
- improving soil fertility

Irrigation strategy management to increase production would not be the same in all areas. In areas where enough water is available, full irrigation strategy could be a suitable option, while in areas where water is limited, deficit irrigation is appropriate strategy and finally in areas where water resources are saline, use of management strategies for achieving sustainable production as well as economic yield is suitable management. However, any optional strategies are needed to specific management, and they are a function of time and space. But in all cases, knowledge of water-yield relation (production function) is necessary in order to achieve optimal amounts of irrigation water and sustainable production. The

purpose of this section is to optimize water consumption using production functions in terms of saline and non-saline water application.

2. Crop production functions

To express the relationship between inputs and crop yield, production functions are used. Crop production functions are mathematical relationship between yield and inputs used in the production process. In other words, the crop production function identifies the conversion rate of input to output. The statistical data obtained from field observations or controlled experimental design can be used to estimate of production functions. Overall form of the crop production function can be written as follows:

$$Y = F(X_1, X_2, \dots X_n) \tag{1}$$

This equation shows the amount of production determined by different amounts of inputs (n). Production factors can be classified in different ways. Some factors are variables and some others are fixed. Some of the factors are very important and some others not significant. The crop production function is usually estimated based on a few variable factors under controlled. Using the estimated production function can be defined different scenarios based on user-defined. The amount of yield in different levels of inputs used to crop production function, marginal production, the final value of each of the factors of production and marginal rate of technical substitution factors could be calculated.

3. Optimizing water consumption

Optimizing water consumption is a type of management options that may establish relationship between land and water under limitation of water/land conditions. So that crop production is economically affordable and technically possible. Generally, Figure 1 shows relationship between the applied water (AW) as a function of gross income and cost (English, 1990). As shown, there is curvilinear relation between gross income and applied water and a linear relation with cost function. In fact, the gross income increases with water and reaches the maximum point, then decreases mainly due to increasing water cost and also decreasing in production. But cost function rises linearly with increasing water amount. Net income is equal to the difference between gross income and cost (distance between two curves in Figure 1).

Selection of appropriate strategy depends on the presence or absence of limiting factors previously mentioned. If land is limiting factor, using the amount of water maximizing net benefit per unit of land, is the best strategy (AW_L in Figure 1). Although with increasing amount of water, gross income could be increased so that maximum crop production is obtained with full irrigation (AW_F on the right AW_L in Figure 1), but net income resulting from application of AW_F is less than AW_L. Reducing the amount of water applied from AW_L and move to the left curve gradually decreases the net income, so that net income in AW_d per unit of land is equal to net income from full irrigation. It is clear that full irrigation needed to achieve maximum production, but to get the highest net profit not need to full irrigation. In practical point of view, in water scarcity areas economic benefit could be achieved using deficit irrigation scheduling. In areas where water is a limiting factor, the costs of supply, transmission and distribution of water are the most serious challenges. In

these areas, due to water shortages a large part of the farms are not cultivated or remained as rainfed. According to presented analysis, in terms of water consumption there is a point that irrigation depth is less than the amount of crop water requirement and full irrigation depth, however its net profit per unit of land is equal to net income from full irrigation (AW_d). So with the saved water for irrigating new lands can produce more revenue achieved without paying additional cost for new water supply. To achieve optimal levels of water consumption and choosing appropriate management options, it is necessary to estimate variable amounts of derived functions such as AW_L, AW_F and AW_d.
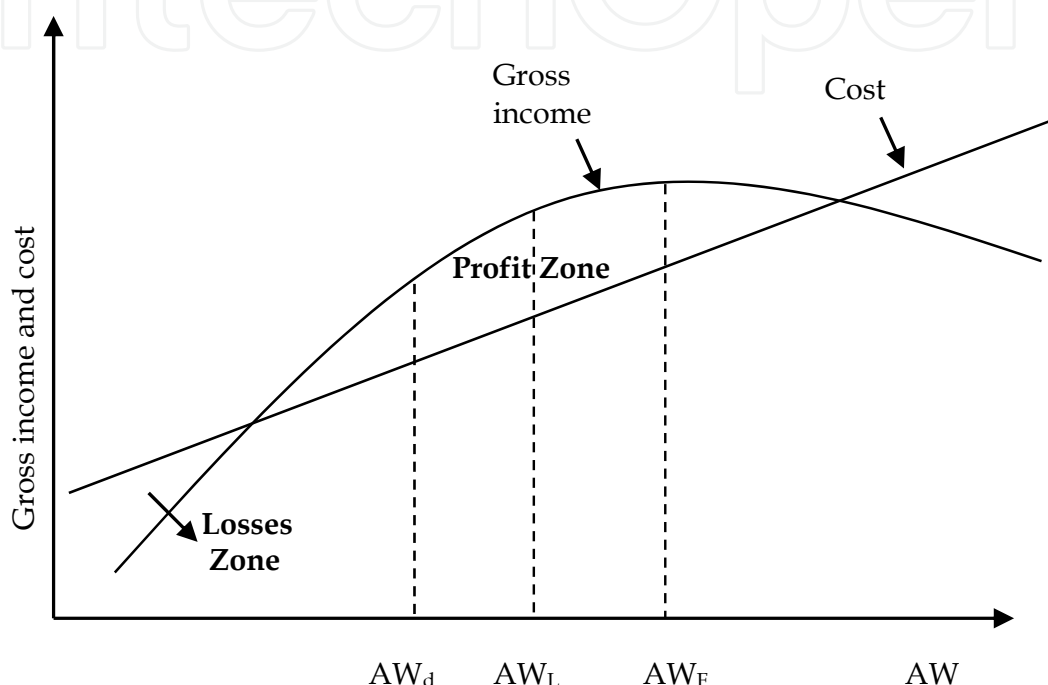

Fig. 1. Income and cost curves as a function of applied water (AW)

3.1 Determination of threshold values

For optimum irrigation scheduling, driving water-yield relation (crop water production function) is required for determination of optimum amount of water. Generally, the quadratic form of crop water production is used to describe relationship between irrigation water and crop yield:

$$Y = a_0 + a_1(I) + a_2(I^2) \tag{2}$$

where, Y is crop yield (t ha^{-1}), I is irrigation water (mm) and a_0, a_1 and a_2 are constants.
The cost equation is used as:

$$C = b_0 + b_1(I) \tag{3}$$

where, C is production cost per hectare and b_0 and b_1 are constants.
Constant coefficients in above equations can be derived using various levels of water against their corresponding yields as follows (English, 1990):

$$I_F = -a_1/2a_2 \tag{4}$$

$$I_L = (b_1 - P_C a_1)/(2P_C a_2) \qquad (5)$$

$$I_d = [(P_c \times a_0 - b_0)/(P_c \times a_2)]^{0.5} \qquad (6)$$

where, I_F, I_L and I_d are full irrigation, optimum amount of irrigation where land is limiting and water is limiting, respectively (mm) and Pc is the crop price per kg.

Above equations, were modified by Sepaskha & Akbari (2005) for case having rainfall (P) as follows:

$$I_F = -a_1'/a_2' - P \qquad (7)$$

$$I_L = (b_1 - P_C a_1')/(2P_C a_2') - P \qquad (8)$$

$$I_d = \{[P_c(a_0'P + a_1'P^2 + a_2') - b_0]/P_c a_2'\}^{0.5} \qquad (9)$$

where, , a_0', a_1' and a_2' are the similar constants as equation 2 when total applied water (AW) is replaced with I.

The following sections present how to determine the optimal amount of water consumption by using analysis of production functions in different conditions.

4. Wheat production function under supplementary irrigation

Supplementary irrigation plays a key role in crop production in many countries in the world. In most rainfed areas, the amount of rainfall and its distribution is not suitable throughout growing season of winter crops. Therefore, increasing crop production is necessary to timing irrigation with supplementary irrigation. At present, supplementary irrigation covers 80 percent of cultivated areas over the world, producing 60 percent of the global production (Harris, 1991). Wheat yield under rainfed conditions in arid and semiarid regions of the world, including West Asia and North Africa, varies between 0.6 to 1.5 t/ha. In these areas, supplemental irrigation significantly increases yield and water productivity. The experimental results on wheat show that water productivity is increased with deficit irrigation scheduling (Sun et al., 2006; Zhang et al., 2005; Zhang et al., 2006). Supplemental irrigation potentially increases wheat yield and water productivity. Irrigation water for achieving optimum water productivity is not the same in different areas of the world, mainly due to different climate. For example, the highest water productivity of wheat in northern Syria (Zhang and Oweis, 1999) was corresponded with 440-500 mm of water application (140-180 mm irrigation water), in northern China (Zhang et al., 1999), with 400 mm (120-160 mm irrigation water) and in Oregon America (English and Nakamora, 1989) with 750-850 mm of water applied (350-450 mm irrigation water).

A field study was conducted to compare various genotypes of wheat to water using line source sprinkler irrigation during growing season of wheat (2005-2006). The geographical location of the farm was 36° 54' N, 54° 25' E and 155 m above mean sea level. This area represents medium annual rainfall, mostly falls in winter (November–April). Seasonal rainfall during the wheat growth stages was about 250 mm. Four irrigation treatments were provided by the decline with distance from the line source, during the growing season to meet 100 %(W_1), 76 %(W_2), 52 %(W_3) and 39% (W_4) crop water requirement. Optimal irrigation water application was considered by generated crop water production functions for six cultivars of wheat under supplementary irrigation. The experiment used a strip plot

design to examine the effect of the fixed irrigation rates on six cultivars treatments (C_1=TAJAN, C_2= N-80-6, C_3= N-80-7, C_4= N-80-19, C_5= N-81-18, C_6= Desconcido) with four replications. The soil texture of the experimental plots was silty clay loam in the surface layer (0-30 cm) and silty loam in the deeper layers (30-90 cm), having soil bulk density of 1.3 and 1.4 gr /cm^3, respectively.

Wheat yield variation of different cultivars as a function of applied water (AW) illustrated in figure 1, separately. A quadratic form of production function was used to describe the relationship between applied water and yield. The general trend is similar to all the cultivars, so that with increasing applied water, yield increases and at a certain point that yield reaches the peak value, more increasing water will result in decreasing the yield. Estimated wheat production function for any cultivars showed that they have different constants as well as different response to water. As a result, appropriate cultivar could be selected due to provide different production from a certain amount of water. For example, the cultivars C_1 – C_6 produced 4.2, 4.8, 4.5, 4.4, 4.6 and 4.2 t/ha against 350 mm applied water, respectively (Fig. 2).

Crop water production and cost functions were used to describe optimum scheduling of irrigation water. Due to the presence of effective rainfall in the region, optimum irrigation water under full irrigation (I_f) and deficit irrigation (I_d) were estimated as function of seasonal rainfall (with the assumption that wheat price equal to 1700 Rials/kg and production cost without irrigation costs are 2.5 million Rials/ha, 10000Rials=US\$1). The results revealed that, optimum irrigation water depth will be decreased when seasonal rainfall increased. Required water under full irrigation strategy for maximizing production in cultivars C_1 to C_6 was 362, 370, 335, 342, 340 and 345 mm. Optimum irrigation water under deficit irrigation for all cultivars as a function of seasonal rainfall was presented in Table 1. It is observed that under deficit irrigation, whenever during the wheat growing season 250 mm of rainfall occurs with a similar distribution, all cultivars will not require to irrigate. If rain does not happen (in terms of deficit irrigation) C_2 cultivar will need more water than the others (331 mm). So, if assumes that the average value of 250 mm rainfall occurs during the wheat growing season, in case of full supplemental irrigation two or three irrigation event will be needed to all the cultivars. However, in case of deficit irrigation cultivars will not require irrigation water (Table 2).

P (mm)	Cultivars					
	C_1	C_2	C_3	C_4	C_5	C_6
0	325	331	311	315	315	315
10	314	320	300	305	305	305
20	303	310	290	293	293	293
30	291	297	279	282	282	282
40	280	286	269	270	270	270
50	268	274	257	260	260	260
70	245	250	235	238	238	236
100	208	214	200	202	203	200
150	140	146	139	139	141	135
200	30	43	57	50	59	35

Table 2. Optimum irrigation water as a function of seasonal rainfall in different cultivars of wheat
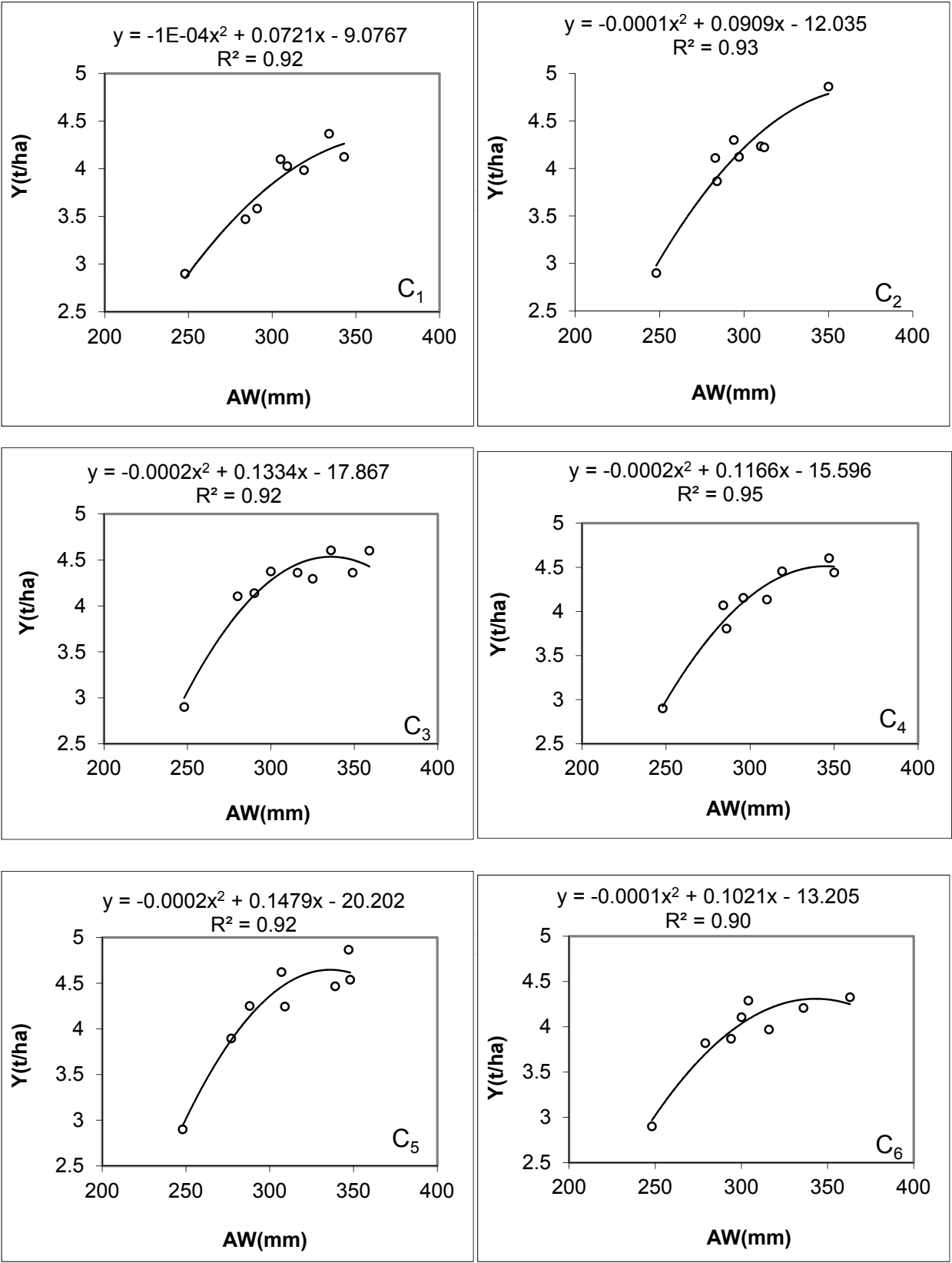
Fig. 2. Wheat grain yield as a function of applied water in different cultivars

4.1 Comparison of deficit and full irrigation strategies

Generally, when farmers face water scarcity, as water resources are not enough to follow the full irrigation, they have two options (Oweis and Hachum, 2003): in the first case may be, they apply the available water for irrigating a part of the farm and leave the rest as rainfed. In the second case may be, they apply less water to irrigate the whole farm (deficit irrigation). The quantitative comparison of deficit and full irrigation strategies are showed in Table 2 that deficit irrigation is more useful strategy for obtaining more production as compared to full irrigation. For example, in C_1 cultivar, if full irrigation (99 mm) is applied to irrigate one hectare and left a 1.54 hectare as a rainfed, totally it can be obtained 7.27 ton grain yield. But, if instead of full irrigation of one hectare, it is applied deficit irrigation (39 mm) for all the 2.54 hectare, totally 9.02 ton grain yield can be obtained. This trend with more appropriate result for other cultivars is presented in Table 2. It is observed that in W_4 treatment total yield in C_1 to C_6 cultivars were increased 24%, 40%, 47%, 40%, 48% and 32%, respectively, when compared to the W_1 treatment. To minimize risk with water stress on crop yield reduction, it is needed to know sensitivity of different growth stages of wheat to water stress.

C_i	IT*	I (mm)	Y (t/ha)	Area (ha)			Y (t/ha)			Increased Yield (%)
				Irrigated	Rainfed	Total	Irrigated	Rainfed	Total	
C_1	W_1	99	4.19	1	1.54	2.54	4.19	3.1	7.27	24
	W_4	39	3.55	2.54	0	2.54	9.02	0	9.02	
C_2	W_1	109	4.74	1	2.11	3.11	4.74	4.22	8.95	40
	W_4	35	4.02	3.11	0	3.11	12.5	0	12.5	
C_3	W_1	111	4.15	1	2.26	3.26	4.51	4.54	9.03	47
	W_4	34	4.06	3.26	0	3.26	13.2	0	13.2	
C_4	W_1	100	4.26	1	1.7	2.7	4.26	3.4	7.66	40
	W_4	37	3.98	2.7	0	2.7	10.8	0	10.8	
C_5	W_1	101	4.52	1	2.37	3.37	4.52	4.74	9.26	48
	W_4	30	4.07	3.37	0	3.37	13.7	0	13.7	
C_6	W_1	100	4.5	1	1.7	2.7	4.5	3.4	7.9	32
	W_4	37	3.86	2.7	0	2.7	10.4	0	10.4	

* Irrigation Treatments

Table 2. Comparison of total production in different cultivars of wheat at full (W_1) and deficit (W_4) irrigation

5. Soybean production function

Soybean is one of the most important crops for oil and protein production in the world. Generally, soybean is planted in warm and semi-warm climate and relatively resistance to low and very high temperatures, but its growth rate is reduced at temperatures higher than 35 ˚C and less than 18 ˚C (FAOSTAT, 2001). Because soybean having a high concentration of

protein (36%), oil (18%) and carbohydrate (20%) planted in almost all parts of the world for human consumption, livestock and plants (Boydak et al., 2002). A field study was conducted to consider water-yield relation in three genotypes of soybeans, optimum irrigation depth, comparison of deficit and full irrigation at Gorgan Research Station in two lasted growing seasons (2005 & 2006). In this experiment, four irrigation treatments (W_1, W_2, W_3 and W_4) were provided by the decline in irrigation with distance from a line source. The experiment was based on a strip plot design to examine the effect of the fixed irrigation rates on three cultivars treatments (SAHAR, G_3 & DPX) with four replications.

Generally, obtained highest soybean yield is consisted with treatment that has received the highest water (W_1). In W_4 treatment, grain yield of soybean were 47% and 40% of the W_1 treatment, for 2005 and 2006, respectively. The average values of 2-years irrigation water in W_2, W_3 and W_4 were 80, 49 and 24% of W_1. Irrigation water application in both years with distance from the line source was reduced for all three cultivars (Fig. 3). The largest amount of irrigation was W_1 treatment being 360 mm in 2005 and 342 mm in 2006. In the first year in terms of irrigation water, W_4 treatment in Sahar, G_3 and DPX has received 17, 19 and 24% as compared with W_1 treatment, respectively (the same trend also observed in the second year).
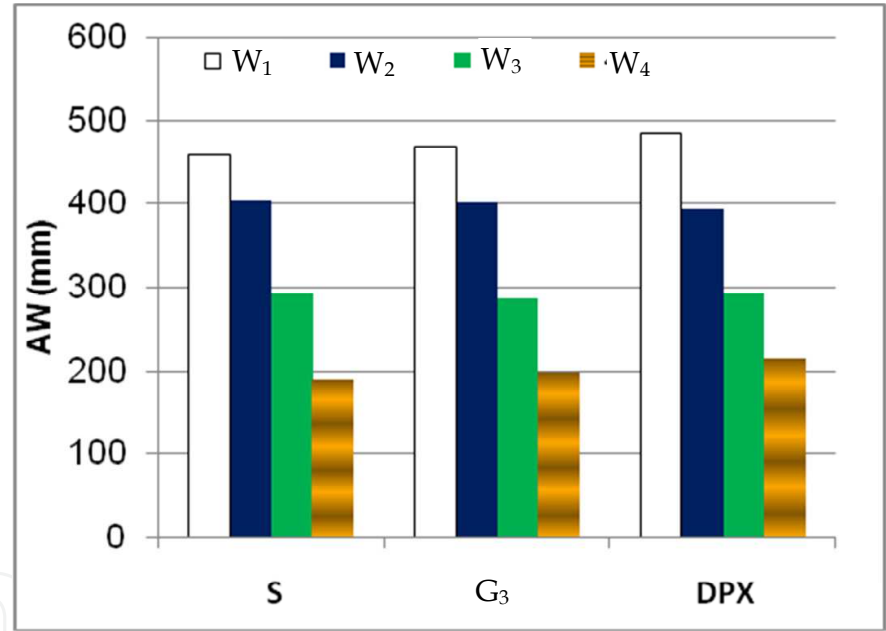

Fig. 3. Applied water (AP) in different treatments (2-year average)

The estimated coefficient using equation 2 and their statistical analysis in different cultivars were presented for 2005, 2006 and average 2-years in Table 3.

As shown in Table 4, the determination of coefficient (R^2) of the quadratic function for all cultivars are more than 84% and it is found that the effects of water levels on soybean grain yield is significant. This indicates that 84% of the yield variability of soybean is explained by the variations of applied water (AW). A quadratic form has been reported between yield and applied water by many researchers (Stewart and Hagan, 1983; Zhang and Oweis, 1999; Sepaskhah and Akbari, 2005). The grain yield of soybean cultivars as a function of AW in 2005, 2006 and 2005-2006 are illustrated in Fig. 4. Figure 4 states that the yield of soybean cultivars is increased as a decline slope with increasing water amount. In other words, for

every certain amount of water increase, soybean yield will not increase proportionally. After a certain level of water, with increasing water, the yield starts to decrease (Fig. 4). The equation coefficients on three cultivars are different. It is found that the yields have a different response to given water. For example, the most productive use of water in the Sahar (2.5 t/ha), G_3 (3 t/ha) and DPX (3.7 t/ha) were reached with about 490, 490 and 510 mm of AW, respectively. For a certain amount of AW, the DPX cultivar produced more grain yield than the 2 other cultivars (Fig. 4).

Factors*	2005			2006		
	S	G_3	DPX	S	G_3	DPX
$a_0^{'}$	-0.487	0.0264	-1.204	-2.502	-3.261	-0.439
$a_1^{'}$	0.0085	0.0041	0.0152	0.022	0.0267	0.0098
$a_2^{'}$	-9.19E-6	-1.39E-6	-1.53E-5	-1.96E-5	-2.26E-5	-5.89E-7
R^2	0.84	0.91	0.91	0.85	0.97	0.98
SE	0.17	0.14	0.20	0.47	0.24	0.16
F	12	26	25	15	92	128
SigF	0.01	0.002	0.002	0.008	0.0001	0.0001
	2-years average					
	S		G_3		DPX	
$a_0^{'}$	-0.242		-1.669		-1.229	
$a_1^{'}$	0.0138		0.0166		0.0151	
$a_2^{'}$	-1.247E-5		-1.424E-5		-1.176E-5	
R^2	0.85		0.99		0.97	
SE	0.31		0.11		0.15	
F	14		184		82	
SigF	0.008		0.000		0.0002	

* R^2 = determination of coefficient; SE= Standard Error; F= Function statistic; SigF= Significant function

Table 3. Equation constants and their statistical analysis in three soybean cultivars

Based on derived equations, irrigation water under deficit irrigation conditions (I_d) as a function of seasonal rainfall are calculated and presented in Table 4. Using rainfall-irrigation water relation can be decided that for a given rainfall how much water is needed to achieve optimal production. Unit price of soybean yield equal to US$35/kg (2-years average) and total production cost for soybean (without irrigation cost) equal to US$350/ha including: land preparation (US$35), planting (US$50), total fertilizer, pesticide, herbicide and thinning (US$75), harvest (US$55) and land rent (US$135) were used to calculate the best amount of irrigation water. Table 4 shows that in deficit irrigation condition with increasing effective rainfall during the soybean growing season amount of optimum irrigation water decreases to achieve optimal production. In full irrigation strategy to obtain maximum grain yield the cultivars Sahar, G_3, and DPX are required to 550, 580 and 640 mm of AW, respectively. Water requirement of soybean is 450-600 mm to produce maximum depending on climatic conditions and variety (FAO, 2002). But, in deficit irrigation strategy, if no rainfall occurs during the growing season, Sahar, G_3 and DPX need 425, 435 and 435 mm of irrigation water, and if 200 mm effective rainfall occurs the cultivars will not need to irrigation water.

Under no irrigation water and with 200 mm effective rainfall the grain yield of Sahar, G_3 and DPX were obtained at 1, 1.2 and 1.5 t/ha, respectively. However, with increasing the amounts of AW from optimal level increasing yield is possible, but this strategy for areas that facing with water shortages are not appropriate.
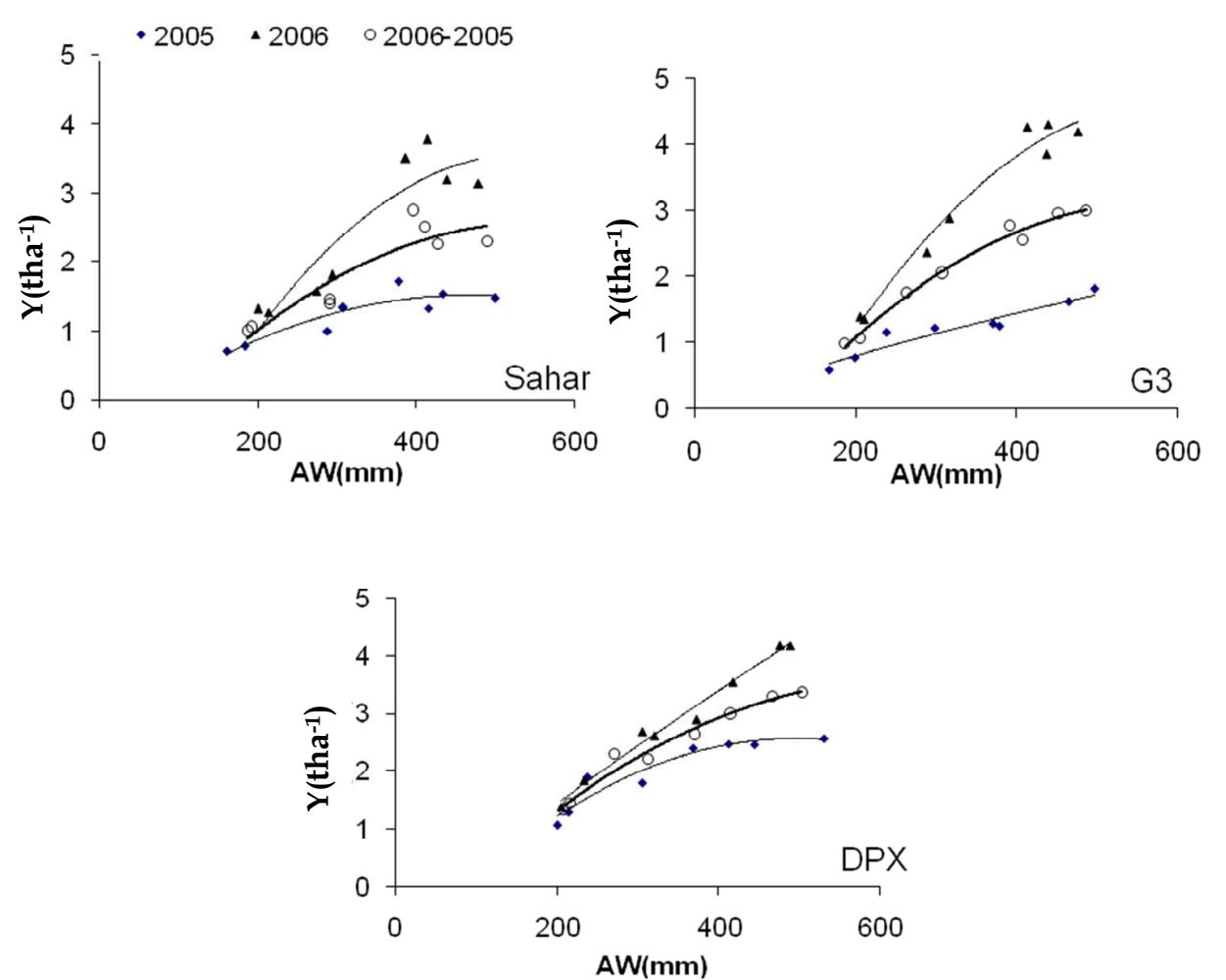

Fig. 4. Soybean grain yield as a function of applied water (AW)

	P (mm)							
Cultivars	0	30	60	90	120	150	180	200
S	424	384	342	297	248	191	115	0
G3	433	391	348	301	249	188	101	0
DPX	435	385	331	269	192	58	0	0

Table 4. Optimum irrigation water (I_d, mm) as a function of seasonal rainfall in three soybean cultivars

5.1 Comparison of deficit and full irrigation strategies
Using collected data, W_1 (full irrigation) and W_4 (deficit irrigation) treatments were compared and presented in Table 5. The quantitative comparison of two strategies showed

that for all cultivars total production under deficit irrigation (W_4) was more than full irrigation (W_1) for a given levels of farm. For example, in Sahar cultivar, if full irrigation (345 mm) is applied to irrigate one hectare and left a 3.85 hectare as rainfed, totally 4.5 ton grain yield can be obtained. Instead of full irrigation of one hectare, if deficit irrigation (71mm) is applied for all the 4.85 hectare, totally 5.8 ton grain yield is achievable. This trend with more appropriate results for G_3 and DPX cultivars are presented in Table 5.

Cultivars	irrigation treatment	I (mm)	Y (t/ ha)	Areas (ha)			Y (t/ha)		
				irrigated	rainfall	total	irrigated	rainfall	total
S	W_1	345	2.585	1	3.85	4.85	2.585	1.923	4.508
	W_4	71	1.2	4.85	0	4.85	5.82	0	5.82
G_3	W_1	342	3.349	1	3.22	4.22	3.349	1.61	4.959
	W_4	81	1.389	4.22	0	4.22	5.86	0	5.86
DPX	W_1	367	3.984	1	3.08	4.08	3.984	1.54	5.524
	W_4	90	1.648	4.08	0	4.08	6.724	0	6.724

Table 5. Quantitative comparison of full (W_1) and deficit irrigation (W_4) in three soybean cultivars

Two-year average has shown that there was a tendency for more production in DPX cultivar than other cultivars, mainly due to appropriate response to water. As a result, using deficit irrigation and allocation of saved water to other lands where facing with water scarcity is the optimal strategy to maximize production as well as farmer's income. It is clear that water stress does not have similar effect on the whole crop growth. The advantage of deficit irrigation can be achieved by saving water during those periods when the crop is less sensitive to water stress.

6. Water–salinity production function

Water scarcity and salinity are major problems in reducing crop production in the arid and semi-arid regions of the word. Due to scarcity of fresh water, use of saline water is becoming inevitable to meet agricultural crop water requirement. In some water shortage areas of the world, farmers usually apply saline water especially to winter cereals in the pre-sowing and early stages of the crop growth. Farmers are faced with the challenges of optimal water applications for given saline water and economical effect of using saline water. Therefore, it is necessary to estimate crop yield in response to joint salinity and water stress conditions resulting from the use of any given set of water quantity and quality.

Several studies have explored the response of crops to salinity and water stress, i.e., use of saline water for irrigation purposes (Ayers and Westcot, 1985; Tanji, 1990; Rhoades *et al.*, 1992). Blending non-saline and saline water, or cyclic use of these types of water, have been developed to use saline drainage water for irrigation. Water-salinity production functions are estimated by two different approaches. The first one uses mathematical models to describe the combined effects of the amount of applied water and its salinity on crop yields (Letey *et al.*, 1985; Letey and Dinar, 1986). The second approach experimentally estimates production functions by statistical analysis from a wide range of water qualities and quantities (Dinar *et al.*, 1985; Dinar and Knapp, 1986; Russo and Bakker, 1986; Datta *et al.*, 1998; Datta and Dayal, 2000; Kiani & Abbasi, 2009). The first approach is valuable. Because it

allows exploration of different management strategies by using appropriate water–salinity production functions saving time and costs. But, due to the implicit assumptions, the practical application is restricted. However, several studies have been published where production functions have been verified by field data, or have been used to assess the dual effects of salinity and the amount of applied water on crop yields (Letey *et al.*, 1985; Shani and Dudley, 2001; Oster *et al.*, 2007). An experiment was conducted in the northern region of Golestan province (37°07' N, 54°07' E) in Iran, for two growing seasons (2001–2002 and 2002–2003). The mean annual rainfall in this region is 330 mm of which more than 80% occurs in autumn and winter (November to April). The average annual temperature and relative humidity are 17.8 ˚C and 75%, respectively. The experimental design was a randomised complete block design with split plot layout considering water quantity as the main plot and water quality as subplot with three replications. The treatments consisted of four levels of irrigation water providing 50(W_1), 75(W_2), 100(W_3) and 125(W_4) percent of the crop water requirement and four levels of irrigation water salinity of 1.5(S_1), 8.5(S_2), 11.5(S_3) and 14.2(S_4) dS/m. Saline waters for different irrigation salinity levels were obtained by mixing various ratios of well (1 dS/m) and drainage channel (10-30 dS/m) waters.

In the first year, a pre-sowing of 26 mm non-saline water was applied to all treatments using a sprinkler irrigation system, and three irrigations were subsequently applied using surface irrigation. In the second year, due to suitable rainfall at sowing date, water was applied in four irrigations after the vegetative stage. The amount of irrigation water during the growing season, for W_1, W_2, W_3 and W_4 treatments was equal to 118, 163, 209 and 246 mm in the first year and 104, 160, 212 and 264 mm in the second year, respectively. Effective rainfall in the growing season was 163 and 184 mm in 2001-02 and 2002 - 2003, respectively. Data obtained from the experimental plots were used to investigate crop response to both electrical conductivity of soil water (EC_{sw}) and soil water content (θ), assuming that the crop responded only to these two factors. Other possible factors affecting the yield were assumed to be constant according the following relationship:

$$Y = f(\theta, EC_{sw}, X) \tag{10}$$

Where, *X* is the constant vector for considering other factors affecting the yield.

The following various production functions were explored using the collected experimental data:

Linear:

$$Y = a_0 + a_1\theta + a_2(ECsw) \tag{11}$$

Cobb-Douglas:

$$Y = a_0\theta^{a_1}(ECsw)^{a_2} \Rightarrow Ln(y) = Ln(a_0) + a_1 Ln(\theta) + a_2 Ln(ECsw) \tag{12}$$

Quadratic:

$$Y = a_0 + a_1\theta + a_2\theta^2 + a_3(ECsw) + a_4(ECsw)^2 + a_5\theta(ECsw) \tag{13}$$

Transcendental:

$$Y = a_0\theta^{a_1}(Ecsw)^{a_2}Exp(a_3\theta + a_4(Ecsw) \Rightarrow Ln(y) = \\ Ln(a_0) + a_1 Ln(\theta) + a_2 Ln(ECsw) + a_3\theta + a_4(ECsw) \tag{14}$$

The optimal production function was selected based upon statistical analysis. The coefficients of various production functions were estimated using the Ordinary Least Square (OLS) technique (SPSS, version 11.5). T-statistic of model's coefficients for determination of significantly different, F-value, R^2, Standard Error (SE) and Relative Error (RE) were estimated for comparison of various production functions. The RE was computed by:

$$RE = \frac{(Y_m - Y_p)}{Y_m} \tag{15}$$

where, Y_m and Y_p are measured and predicted yield.

The marginal production of water content (MP_θ) and salinity (MP_{ECsw}), the marginal value product of θ (VMP_θ) and EC_{sw} (VMP_{ECsw}) and the marginal rate of technical substitution of θ and EC_{sw} ($MRTS_{\theta ECsw}$) were determined using the selected production function as:

$$MP_\theta = \frac{\partial Y}{\partial \theta} \tag{16}$$

$$MP_{ECsw} = \frac{\partial Y}{\partial (ECsw)} \tag{17}$$

$$VMP_\theta = P_y . MP_\theta \tag{18}$$

$$VMP_{ECsw} = P_y . MP_{(ECsw)} \tag{19}$$

$$MRTS_{\theta(ECsw)} = \frac{MP_\theta}{MP_{(ECsw)}} \tag{20}$$

where, P_y is wheat price.

Table 6 shows the amount of matric potential (h), osmotic potential (h_o) and wheat grain yield in different treatments. Generally, a rather consistent decrease in yield with increasing salinity application for a given irrigation treatment and a rather constant increase in yield with increasing water application for a given saline water. In the W_1S_1 treatment, the total water potential was -6678 cm, which is somewhat lower than the total potential of –6,403 cm in the W_3S_3 treatment. The yield reduction for the W_1S_1 treatment compared to W_3S_1 was 17%, and for the W_3S_3 treatment it was 7%. For the W_1S_1 treatment, the matric potential contributed 38% of the total water potential as compared to 26% for the W_3S_3 treatment. The results suggest that the reduction of the yield due to joint salinity and water stress are not confirmed by the previously proposed simple linear additive and multiplicative concepts. For example, in the first year, yield reduction for the W_1S_1 and W_3S_4 treatments were, respectively, 0.17 and 0.12 compared to W_3S_1, while the yield reduction for the combined stress W_1S_4 was 0.26. The same results were obtained in the second year. Matric and osmotic potentials were additive in their effect on yield, but the amount of yield reduction due to unit increase of matric potential was more than that due to unit increase of osmotic potential.

Treatments		Matric Potential		Osmotic Potential		Yield	
		h (cm)		h_o (cm)		(kg ha^{-1})	
Irrigation	Salinity	2001-2002	2002-2003	2001-2002	2002-2003	2001-2002	2002-2003
	S1	-2,565	-1,528	-4,113	-3,615	3,213	3,790
W_1	S2	-2,421	-1,489	-4,303	-4,212	3,216	3,663
	S3	-2,595	-1,492	-5,267	-5,111	3,000	3,540
	S4	-3,391	-1,427	-5,922	-5,330	2,862	3,430
	S1	-2,584	-1,420	-3,673	-3,901	3,388	4,439
W_2	S2	-2,519	-1,306	-4,112	-4,478	3,358	4,330
	S3	-2,159	-1,290	-4,666	-4,621	3,325	3,951
	S4	-2,023	-1,227	-5,179	-5,012	3,125	3,938
	S1	-1,527	-1,056	-3,122	-3,804	3,845	4,777
W_3	S2	-1,324	-1,038	-4,227	-4,328	3,605	4,651
	S3	-1,680	-976	-4,723	-4,701	3,578	4,539
	S4	-1,535	-945	-4,732	-5,172	3,400	4,374
W_4	S1	-1,575	-877	-2,555	-2,904	3,825	4,839
	S2	-1,397	-853	-4,248	-3,833	3,783	4,690
	S3	-1,285	-825	-4,531	-4,880	3,773	4,405
	S4	-1,089	-807	-5,383	-5,402	3,467	4,331
LSD(0.05)						510	474

Table 6. Average seasonal matric and osmotic potential and grain yield per treatment combination

The estimated coefficients and the statistical analysis of various production functions are shown in Table 8. The results indicate that transcendental and quadratic production functions provide a better fit to the data. The determination coefficient (R^2) of the transcendental function is about 0.94 (two years average) and larger than the other functional forms. The R^2 values in the transcendental and quadratic production functions suggest that 94% of the yield variability is explained by the variations of EC_{sw} and θ. It is also found that the transcendental model provides a higher F-value and lower standard error (SE) compared to the quadratic model (Table 7). Furthermore, RE of the various production functions suggests that the transcendental model is the best. In addition, the transcendental form of the production function is found useful in describing input-output data including all three stages of the production curve with increasing positive, decreasing positive and negative marginal products (Sankhayan, 1988). As a result, in this study the transcendental model is found as a suitable wheat production function under salinity–water stress conditions.

The isoquant curves of wheat relative yield obtained using the transcendental production function are shown in Figure 5. These curves provide the different combinations of θ and EC_{sw} that result in the same yield. For a given θ, increase of EC_{sw} results in the decrease of relative yield and for a given EC_{sw} relative yield increases with increasing θ. In general, the relative yield is strongly affected by both θ and EC_{sw}. Isoquant curves (Figure 5) indicate that each one of the two factors (EC_{sw} and θ) can be substituted by the other one for a wide range in order to achieve equal amount of yield. The higher level of EC_{sw} can be used with increasing soil water content, without yield reduction. For a given relative yield, results

Variables	Linear		Cobb-Douglas		Quadratic		Transcendental	
	2001-02	2002-03	2001-02	2002-03	2001-02	2002-03	2001-02	2002-03
Constant	618 (1.12)[1]	-2422 (-1.6)	5.01 (8.1)	2.5 (2)	1047 (0.29)	-130925 (-3.4)	-14.3 (-.96)	-123.9 (-2.7)
Θ	147** (7.1) (20)[2]	272** (5.7) (47)	-	-	-188ns (-0.94) (200)	9255** (3.3) (2767)	-0.29ns (-1.2) (0.24)	-1.7* (-2.8) (0.64)
EC_{sw}	-104** (-8.1) (12)	-119** (-3.7) (32)	-	-	630ns (1.5) (429)	-715ns (-0.84) (851)	-0.09** (-4.1) (0.02)	-0.14* (-2.2) (0.06)
$Ln\theta$	-	-	1.16** (6.3) (0.19)	1.93** (5.3) (0.35)	-	-	9ns (1.4) (6.4)	54.1* (2.9) (18.8)
$Ln\ EC_{sw}$	-	-	-0.3** (-6.8) (0.04)	-0.28** (-3.1) (0.09)	-	-	0.829* (2.4) (0.34)	1.2ns (1.8) (0.67)
Θ^2	-	-	-	-	10.2ns (2.2) (4.7)	-158** (-3.2) (48)	-	-
EC_{sw}^2	-	-	-	-	-10.6ns (-2.1) (5.1)	-9.9ns (-0.65) (15.3)	-	-
$\Theta\ EC_{sw}$	-	-	-	-	-18.9ns (-1.5) (13)	-18.9ns (1.3) (27)	-	-
F value	58	24	44	21	33	24	55	27
R^2	0.90	0.78	0.87	0.76	0.94	0.92	0.95	0.92
SE	105	224	0.04	0.06	90	153	0.02	0.04
RE	3.2	4.2	0.33	3.9	1.7	2.3	0.28	0.21

1,2 Values in the parenthesis show t statistic values and standard error (SE), respectively. **significant at level $P < 0.01$ by LSD range. *significant at level $P < 0.05$ by LSD range. ns= not significant

Table 7. Estimated coefficients for each of the examined wheat water-salinity production functions.

show that the optimal combination of EC_{sw} and θ is located where the slope of the isoquant lines is parallel to the θ axis. From this point forward, an increase of θ will not result in increasing the yield. For example, a relative yield of 85% can be obtained with water content of 25% and EC_{sw} of 8 dS/m. If EC_{sw} increases to 12.2 dS/m, previous relative yield (85%) can be achieved, but the water content must be increased to 27%. The direction of the isoquant

curves changes for EC_{sw} less than 6.5 dS/m. The slope of the isoquant curves becomes parallel to EC_{sw} axis. This means that by increasing EC_{sw} from 0 to 6.5 dS/m the relative yield will increase slightly with low water contents, but sharply with relatively high water contents.
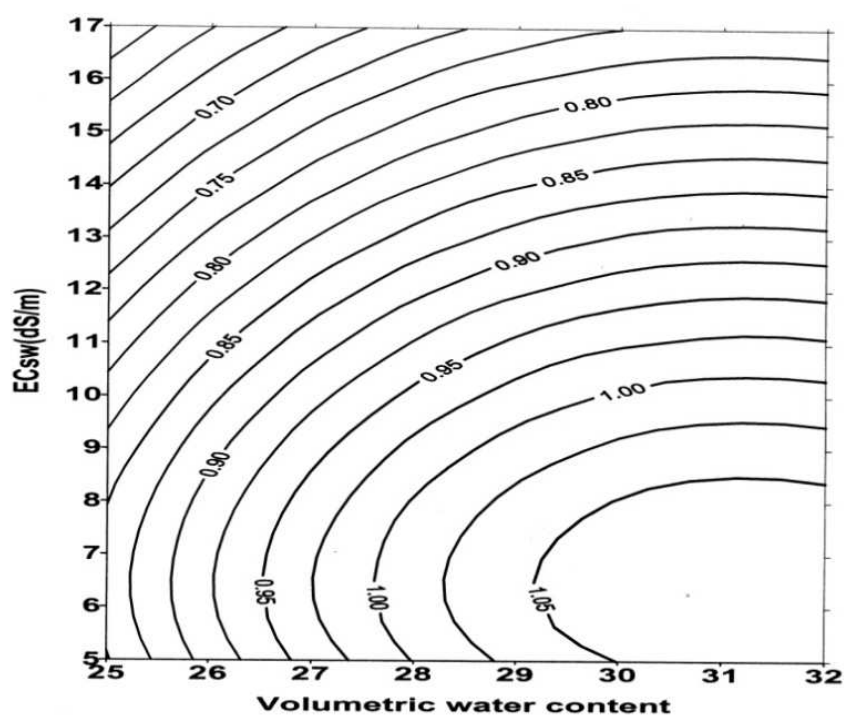

Fig. 5. Calculated isoquant curves of wheat relative yield (Yr) as a function of the 2001-2002 seasonal average θ and ECsw

Maas and Hoffman (1977) did not consider soil water contents. They obtained and reported yield as a function of the ECe. In fact, soil water content was not a limiting factor in their study. Consequently, their function applies only to well watered conditions and inherently cannot be construed to have implications to situations where soil water content is limiting. Letey *et al.* (1985) assumed that the relative yield becomes maximal at EC_{sw} equal to zero. However, it is clear that the relative yield does not become maximal at EC_{sw} equal to zero because $EC_{sw} = 0$ implies that there is not any mass (i.e., fertilizer) in the soil, which it can provide minimum relative yield. Of course, Letey *et al.* (1985) did not intend an extrapolation to a situation where all nutrients are removed from the soil.

The $MRTS_{\theta EC_{sw}}$ for the two growing seasons were 0.96 and 0.67, respectively. This means that one unit increase in EC_{sw} requires the soil water content to be increased by a factor of 0.96 and 0.67 to prevent the yield reduction in two studied years. The marginal production of θ (MP_θ) and EC_{sw} ($MP_{EC_{sw}}$) were 125 and -121 kg/ha, respectively in the first year, and 232 and -158 kg/ha, respectively in the second year. It means that the marginal value of income per hectare due to one unit increase in water content is US$50 (two years average) and the marginal value of damage per hectare due to an increase in EC_{sw} is US$38 ($P_y$ = US$0.28). Using the Cobb-Douglas model, Datta and Dayal (2000) reported that the marginal value product of water quantity of irrigation water and the marginal value of damage of water quality were US$1.2/ha and US$4.2/ha, respectively.

The iso-($\partial Y/\partial \theta$) and iso-($\partial Y/\partial ECsw$) lines determined using the transcendental model are shown in Figs. 6a and 6b, respectively. In the dry soil (for θ less than 21%), the rate of change of the yield with θ ($\partial Y/\partial \theta$) increase as θ increase and EC_{sw} decrease. On the contrary, in the wet soil (for θ more than 22%) $\partial Y/\partial \theta$ decreases as both θ and EC_{sw} increase (Figure 6a). The rate of change of yield with θ becomes negative at water content of over 32% (data was not showed in Figure 6a). Figure 5a revealed that $\partial Y/\partial \theta$ is influenced by θ changes, but slightly changes with EC_{sw} variations. Findings of Letey *et al.* (1985) for a given EC_e showed that $\partial Y/\partial W$ was affected by applied water. The decreasing yield per unit increase in soil water content is consistent with the findings of Letey *et al.* (1985). The $\partial Y/\partial ECsw$ increases (with negative slope) as both θ and EC_{sw} increase (Figure 6b). In the dry soil, the EC_{sw} variation has a little effect on $\partial Y/\partial ECsw$ and θ variation has a more effect on $\partial Y/\partial ECsw$. In contrary, in the wet soil, the EC_{sw} variation has a more effect on $\partial Y/\partial ECsw$ and θ variation has a little effect on $\partial Y/\partial ECsw$.
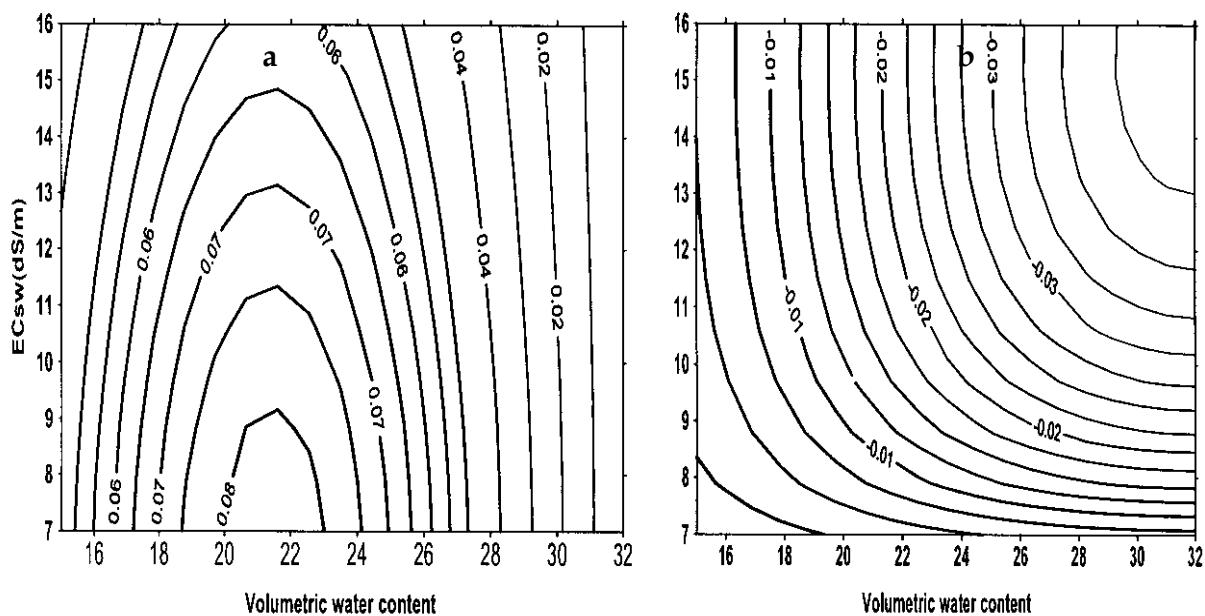
Fig. 6. Calculated isoquant curves representing the variation of $\delta Y/\delta \theta$ (a) and $\delta Y/\delta EC_{sw}$ as a function of the 2001-02 seasonal average θ and EC_{sw}

7. Conclusion

Knowledge of water-yield relation (production function) is necessary in order to achieve optimal amounts of irrigation water and sustainable production. Optimizing water use is a type of management options that may establish relationship between land and water under limitation of water/ land conditions so that the crop production is economically affordable and technically also be possible. Optimal irrigation water application was considered by generated crop water production functions for some cultivars of wheat and soybean in different amount of water under non–saline and also combined salinity and water stress conditions. Estimated water production function for any cultivars showed that they have different constants as well as different response to water, resulting the appropriate varieties for higher productivity of water can be selected. Quantitative comparison of two strategies

of full irrigation and deficit irrigation has shown that if producers instead of full irrigation the part of farm, use deficit irrigation to increase irrigated area, total production and total revenue will increase. To minimize risk with water stress on crop yield reduction, it is needed to know sensitivity of different growth stages of crop to water stress. Considering the trend of crop yield under different amounts of irrigation water (steep slope in the deficit irrigation and less slope in full irrigation) priority allocation water resource to little water areas is a very effective strategy for optimal use of water resources, increasing production and farmers income. The reduction in yield due to joint salinity and water stress was not confirmed by the simple linear additive and multiplicative concepts. It was found that transcendental and quadratic production functions reasonably well predicted the yield under salinity and water stress conditions. The results revealed that yield reduction due to a unit increase of matric potential (i.e., water content) was not the same as that due to a unit increase of osmotic potential (i.e., salinity). The effect of soil water content on the rate of change of wheat yield was more pronounced than the effect of salinity. Iso-quant curves indicated that soil water content and salinity can be substituted by one another for a wide range to achieve equal amount of yield. Crop-water productions derived with the experimental approaches are site– and year–specific. Therefore, generalization of the production functions would not be so easy.

8. References

Ayers RS, Westcot DW. 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper, No. 29, Rev.1.

Boydak, E., Alpaslan, M., Hayta, M., Gercek, S. and Simsek, M. 2002. Seed composition of soybeans grown in the Harran region of Turkey as affected by row spacing and irrigation. J. Agric. Food Chem. 50: 4718–4720.

Datta KK, Dayal B. 2000. Irrigation with poor quality water: An empirical study of input use economic loss and coping strategies. Ind. J. Agric. Econ. 55: 26-37.

Datta KK, Sharma VP, Sharma DP. 1998. Estimation of a production functions for wheat under saline conditions. Agric. Water Manag. 36: 85-94. Agric. Econ. 11 (1): 58-66.

Dinar R, Letey J, Vaux HJJr. 1985. Optimal rates of saline and non-saline irrigation waters for crop production. Soil Sci. Soc. Am. J. 50: 440-443.

Dinar A, Knapp KC. 1986. A dynamic analysis of optimal water use under saline conditions. Western J. Soil Sci. Soc. Am. J., 49: 1005-1009.

English, M.J. 1990. Deficit irrigation-I: analytical framework. Journal of Irrigation and Drainage Engineering, 116: 399-412.

English, M.J., and Nakamura, B.C. 1989. Effects of deficit irrigation and irrigation frequency on wheat yields. Journal of Irrigation and Drainage Engineering, 115(2), 172-184.

FAOSTAT 2001. *FAOSTAT* statistical database. Food and Agriculture Organization http://www.fao.org/

Harris, H.C. 1991. Implications of climate variability. In: Harris, H.C., Cooper, P.J.M. and Pala, M. (eds) Soil and Crop Management for Improved Water Use Efficiency in rain-fed areas. Proceedings of an international workshop 1989, Ankara, Turkey. ICARDA, Alepo, Syria, P. 352.

Kiani, A.R. & Abbasi, F. 2009. Assessment of the water-salinity crop production function of wheat using experimental data of the Golestan Province, Iran. Irrigation and Drainage. (ICID), 58: 445-455.

Letey J, Dinar A. 1986. Simulated crop production functions for several crops when irrigated with saline waters. Hilgardia, 54: 1-32.

Letey J, Dinar A, Knapp KC. 1985. Crop-water production function model for saline irrigation waters.

Maas EV. Hoffman GJ. 1977. Crop salt tolerance current assessment. Journal of Irrigation and Drainage Engineering, 103 (2): 115-134.

Oster JD, Stottlmyer DE, Arpaia ML. 2007. Salinity and water effects on 'Hass' Avacado yields. J. Am. Soc. Hort. Sci. 132(2): 253-261.

Oweis, T.Y. and Hachum, A.Y. 2003. Improving water productivity in the dry areas of west Asia and north Africa. CAB International, water productivity in agriculture: Limits and Opportunities for improvement (eds J.W. Kijne, R. Barker and D. Molden).

Rhoades JD, Kandidah A, Mashali AM. 1992. The use of saline waters for crop production . FAO Irrigation and Drainage Paper, No. 48.

Russo D, Bakker D. 1986. Crop water production functions for sweet corn and cotton irrigated with saline waters. Soil Sci. Soc. Am. J., 51: 1554-1562.

Sankhayan PL. 1988. Introduction to the Economics of Agricultural Production. Prentice-Hall of India, Private Limited New Delhi, pp. 131.

Sepaskhah, A. R. and Akbari, D. 2005. Deficit irrigation planning under variable seasonal rainfall. Biosystem Engineering, 92(1): 97-106.

Shani U, Dudley LM. 2001. Field studies of crop response to drought and salt stress. Soil Sci. Soc. Am. J., 65:1522-1528.

Stewart, J.I. and Hagan, R.M., 1973. Functions to predict effects of crop water deficits. J. of Irrigation and Drainage. 99(4):421-439.

Tanji KK. (editor). 1990. Agricultural salinity assessment and management. ASCE Monograph, No 71.

Zhang, H. and Oweis, T., 1999. Water- yield relations and optimal irrigation scheduling of wheat in the Mediterranea region. Agric. Water Manage. 38, 195-211.

Zhang, H., Wang, X., You, M., Liu, C. 1999. Water-yield relations and water – use efficiency of winter wheat in the North China plain. Irrg. Sci. 19, 37-45.
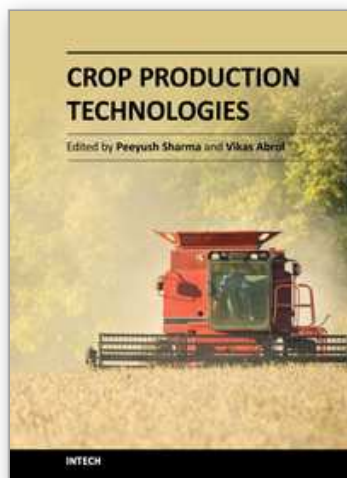
Crop Production Technologies

Edited by Dr. Peeyush Sharma

Crop production depends on the successful implementation of the soil, water, and nutrient management technologies. Food production by the year 2020 needs to be increased by 50 percent more than the present levels to satisfy the needs of around 8 billion people. Much of the increase would have to come from intensification of agricultural production. Importance of wise usage of water, nutrient management, and tillage in the agricultural sector for sustaining agricultural growth and slowing down environmental degradation calls for urgent attention of researchers, planners, and policy makers. Crop models enable researchers to promptly speculate on the long-term consequences of changes in agricultural practices. In addition, cropping systems, under different conditions, are making it possible to identify the adaptations required to respond to changes. This book adopts an interdisciplinary approach and contributes to this new vision. Leading authors analyze topics related to crop production technologies. The efforts have been made to keep the language as simple as possible, keeping in mind the readers of different language origins. The emphasis has been on general descriptions and principles of each topic, technical details, original research work, and modeling aspects. However, the comprehensive journal references in each area should enable the reader to pursue further studies of special interest. The subject has been presented through fifteen chapters to clearly specify different topics for convenience of the readers.

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