Deficit Irrigation of Cereals and Horticultural Crops: Economic Analysis

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ABSTRACT

Different water management alternatives have been evaluated considering three crops grown in Tunisia under semi-arid conditions: potato, tomato and winter wheat. Irrigation simulations performed with the ISAREG model have demonstrated the interest of using this kind of tool in irrigation management. The economic optimization of different water supply strategies was performed with the help of a linear programming model. Results indicate that, when there is no water restriction, the optimal irrigation strategy is achieved by fulfilling the crop water demand in order to reach the potential yields, whatever the climate conditions are, and considering fixed water prices. When there is limited water availability, each crop reacts differently to the water restriction imposed. Every water supply reduction produces for every crop a decrease in the gross margin per unit surface. Under high and very high demand conditions, the gross margin per unit of water applied decreases for the potato and the tomato crops but increases for the wheat crop. So, considering an average year, the adoption of a deficit irrigation scheme is feasible for the tomato and the potato crops, while for the wheat crop it is not economically advantageous to use reduced irrigation depths, reason why the crop is usually grown in rainfed conditions. When high and very high demand conditions prevail, adopting a strong restriction in water supply is not a viable economic solution for the tomato crop; instead, the option would be to decrease the cultivated surface. For the potato crop, deficit irrigation could be economically justified but there is also a trend to restrict the cultivated surface. When heavy supply restrictions would be considered, the wheat crop presents a different behavior, as the reduction of applied water depths is a viable economic solution, preferred to rainfed cropping. This fact shows that, differently from the other two crops, wheat responds well to deficit irrigation, with a good water valorization, including for high demand conditions. The restriction tends to favor the strategies that guarantee the best water irrigation valorization evaluated by the increase of the gross margin per m^3 of water applied.

Keywords: Irrigation scheduling; optimization, gross margins, drought

1 INTRODUCTION

Despite the fact of being responsible for 33% of the agricultural product, irrigated agriculture represents only 7% of the Tunisian cropped area. The increase in the irrigated area from 176000 ha in 1980 to 334000 ha in 1995, and the related agricultural intensification have contributed to the continuous rising of water demand for irrigation, which represents near 80% of the total water demand in Tunisia (DG/GR, 1996).

Along with the diversity of water sources (e.g. dams, diversions from wadis, groundwater wells), water management is also diverse as it is strongly influenced by the regional climate and socio-economic and cultural conditions. The frequent occurrence of droughts requires a pro-active and rational water management approach, which could be helpful to both managers and farmers. It includes not only the reinforcement of the hydraulic infrastructures, the increase of water reuse, the restriction of volumes supplied for irrigation, and higher water prices, but also a best knowledge of the climatic variability and its impact on crops yield. Related to water restriction, a recent study shows that a decrease of 10% in water supply would result in a reduction of about 2% in net agricultural product, mainly as a consequence of a reduction in the irrigated area (DG/RE, 1997).

The present study aims at testing different deficit irrigation strategies for cereal and horticultural crops when water restrictions have to be imposed, somehow predicting their impacts in terms of water saving, yield reduction and farmers income reduction.

2. MATERIAL AND METHODS

2.1. Case Study Siliana Irrigation Project

The study is applied to the Siliana irrigation project, with a total irrigated area of 1240 ha. This irrigation project is described in a companion paper (Rodrigues *et al.*, 2001). The annual rainfall varies from 200 to 550 mm, and is erratically distributed inter-annually and seasonally. The main crops in this irrigation project are cereals, horticultural crops including tomato and potato, fruit trees including olives, and forage crops.

2.2. Modeling Tools

The ISAREG model (Teixeira and Pereira, 1992) and the KCISA program (Rodrigues *et al.*, 2000) have been used to simulate different irrigation water management strategies as described in the companion paper (Rodrigues *et al.*, 2001).

In order to evaluate the impacts of the deficit irrigation strategies on the farmer's income, a linear programming model was used. It follows the methodology described in Hazel and Norton (1986) and Romero and Rehman (1989). This technique aimed at determining the optimal allocation of water resources that would maximize farmer's income considering the availability of land, labor and water (considering stable water prices).

Economic analysis of farm management and planning activities fit the assumptions of linear programming such as: limited factors of production and farm activities are subjected to constraints that influence the technical performance and, most importantly, all quantities of inputs used and outputs produced, are proportional to the level of the activity. The mathematical optimization model is built to reach the combination of alternative farm activities which will maximize the objective function proposed, and that does not violate any of the fixed constraints or involve any negative activity levels. Mathematically, it can be described by (Hazell and Norton, 1986):

$$\max Z = \sum_{j=1}^{n} c_j X_j$$

subject to: $$\sum_{j=1}^{n} a_{ij} X_j \leq b_i \quad i = 1, \cdots, m$$

and to: $$X_j \geq 0 \quad j = 1, \cdots, n$$

where:

X_j = level of the jth farm activity, within n possible activities,

c_j = calculated gross margin of a unit of the jth activity,

a_{ij} = the quantity of the ith resource necessary to produce one unit of the jth activity, with m being the number of resources,

b_i = the amount of the ith resource available.

In the present study, the activities considered are every one of the irrigation strategies generated for the wheat, potato, and tomato crops, which are characterized by the respective net irrigation and relative yield losses. The objective function is evaluated by the Gross Margin, a linear function obtained by subtracting the variable costs related with the specified activities to the Farm Gross Product. Current prices (in USD) for land, labor and crop products in Tunisia are utilized.

The results are expressed by gross margin per unit surface of land cropped and per unit volume of water applied for the different supply scenarios. So, the main problem is to determine which irrigation strategy is the best in terms of maximization of the farmer's income taking into consideration the above said constraints. The output of the linear problem is shown in terms of percentage of land allocation to each activity after balancing the economic return from water and land.

2.3. Water Supply Strategies

The limitations in water availability oblige to adopt alternative irrigation schedules with different frequencies of irrigation to cope with the water scarcity. These strategies are identified and discussed in the quoted companion paper. Tables 1 and 2 give the main characteristics of the selected strategies which economic analysis is discussed in this paper. Net irrigation depths (NID) for set sprinkle systems are 40 mm and for surface irrigation they are 100 mm.

Table 1 – Deficit irrigation strategies adopted and supply restriction levels for the wheat crop at Siliana, for surface and set sprinkler irrigation

Strategies	*Symbol*	*Supply Conditions*
Sprinkler irrigation		
System constraints	SC	Fixed irrigation depths (40 mm) and variable frequency
Light deficit irrigation	LDI	Seasonal irrigation reduced by 40 mm
Deficit irrigation	DI	Seasonal irrigation reduced by 80 mm
Large irrigation deficit	LID	Seasonal irrigation reduced by 120 mm
Very large irrigation deficit	VLID	Seasonal irrigation reduced by 160 mm
Extreme irrigation deficit	EID	Seasonal irrigation reduced by 200 mm
Surface irrigation		
System constraints	SC	Fixed irrigation depths (100 mm) and variable frequency
Deficit irrigation	DI	Seasonal irrigation reduced by 100 mm
Extreme irrigation deficit	EID	Seasonal irrigation reduced by 200 mm

Table 2 – Deficit irrigation strategies adopted and supply restriction levels for tomato and potato crops at Siliana using set sprinkler irrigation

Strategies	*Symbol*	*Supply Conditions*
Potato		
System constraints	SC	Fixed irrigation depths (40 mm) and variable frequency
Light deficit irrigation	LDI	Seasonal irrigation reduced by 40 mm
Deficit irrigation	DI	Seasonal irrigation reduced by 80 mm
Large irrigation deficit	LID	Seasonal irrigation reduced by 120 mm
Very large irrigation deficit	VLID	Seasonal irrigation reduced by 160 mm
Extreme irrigation deficit	EID	Seasonal irrigation reduced by 200 mm
Tomato		
System constraints	SC	Fixed irrigation depths (40 mm) and variable frequency
Restricted frequency	RF	Idem, irrigation frequency > 10 days
Heavy restricted frequency	HRF	Idem, irrigation frequency > 12 days
Extremely restricted frequency	ERF	Idem, irrigation frequency > 15 days

3 RESULTS

3.1. Crop Demand

The annual net irrigation requirements (NIR) for the potato, tomato and wheat crops were computed with ISAREG for the time series 1982-1997 (Zairi *et al.*, 1999, 2000). After a statistical analysis, where a normal distribution was applied to the computed seasonal irrigation depths, the years corresponding to the average (probability $p \approx 50\%$), high ($p \approx 25\%$) and very high ($p \approx 5\%$) demand conditions were selected to perform the simulation analysis. The results are presented in the companion paper.

Analyzing crop responses to different supply strategies, it is possible to detect the relationship between the relative evapotranspiration and the relative yield loss ($RYL = 1-Y_a/Y_m$, with Y_a – actual yield and Y_m - potential yield) for different irrigation depths applied (Teixeira and Pereira, 1992; Rodrigues *et al.*, 2000). When water availability is limited, each crop reacts differently to the water restrictions. Nevertheless, it is notorious that every supply reduction produces a decrease in yield per unit of surface cropped by each one of the three crops, thus also a decrease in the gross margin per unit area.

3.2. Winter Wheat Crop

The irrigated wheat surface (60000 ha) represents less than 5% of the total cereal cropped area in Tunisia but, when drought occurs, the irrigated wheat area contributes with 20% to the total cereal production, while also playing a main role in seed production (El Amami, 1995).

Table 3 summarizes wheat crop responses. Information on the irrigation depths applied, relative evapotranspiration and relative yield losses reproduce that include in the companion paper. The reader is reported to the respective analysis provided in that paper (Rodrigues *et al.*, 2001).

Table 3 – Response of the wheat crop to different deficit irrigation strategies considering sprinkler (NID = 40 mm) and surface irrigation (NID = 100 mm)

Demand conditions	Deficit irrigation strategies	Season irrigation (mm)	Relative ET (%)	Relative yield loss (%)	Gross margin (USD/ha)	Gross margin (USD/m^3)	Percent surface allocated to each irrigation strategy
Sprinkler irrigation							
Average	SC	200	97.1	0.0	1141	0.570	100/SC
	LDI	160	91.0	6.1	1076	0.672	100/LDI
	DI	120	84.0	13.1	993	0.827	100/DI
	LID	80	76.3	20.8	897	1.121	66/DI+33/R
	VLID	40	68.2	28.9	793	1.982	33/DI+66R
	Rainfed	0					100/R
Very High	SC	280	97.1	0.0	1225	0.437	100/SC
	LDI	240	91.4	5.7	1155	0.481	100/LDI
	DI	200	84.1	13.0	1051	0.525	100/DI
	LID	160	76.1	21.0	931	0.581	100/LID
	VLID	120	67.7	29.4	779	0.649	50/LID+50/R
	EID	80	59.1	37.1	669	0.836	100/EID
Surface irrigation							
Average	SC	200	97.1	0.0	1130	0.565	100/SC
	DI	100	80.2	16.9	938	0.938	100/DI
	Rainfed						100/R
Very High	SC	300	99.1	0.0	1221	0.407	100/SC
	DI	200	83.4	13.0	1025	0.513	100/DI
	EID	100	62.7	34.4	713	0.713	100/EID

Observing the results for winter wheat (Table 3), the gross margins per m^3 (GM/m^3) of water vary from 0.407 USD/m^3 for the SC strategy under surface irrigation for very high demand, up to 1.982 USD/m^3, for the VLID strategy under sprinkle irrigation for average conditions. For every case, the GM/m^3 grows from a minimum value when no supply restrictions are applied up to a maximum when more severe water supply restrictions are considered. This fact evidences the particular behavior of the wheat crop relatively to the horticultural crops analyzed below. This positive trend for the gross margin per unit water applied makes it feasible to adopt deficit irrigation, including strong supply restrictions under very high demand, i.e. when severe droughts occur. These results are in agreement with the analysis performed in the companion paper, which indicated the easiness in adopting deficit irrigation to cope with droughts.

As expected, the gross margin per hectare cropped (GM/ha) decreases when allowed water deficits increase due to the consequent yield losses and the respective decrease in the gross product of the activities. However, the GM/ha are always positive.

Considering surface irrigation for both demand conditions and analyzing the percentage surface allocated by the model to each strategy (Table 3), it is evidenced that the model selects the alternative that best valorizes the water rarity (highest gross margin/m^3). The rainfed option is also accepted when water is not available, but only for average demand conditions. For sprinkler irrigation and average demand conditions, the strategies SC, LDI and DI are accepted by the model, which selects then 100% of the surface. However, when less than 120 mm are available, the solutions permitting to obtain the higher gross margin/ha and gross margin/m^3 are not LID nor VLID but a combination of rainfed with DI, the share of surface under both strategies depending on the available water. The differences in behavior for the surface and sprinkler irrigation are evidenced in Figure 1.

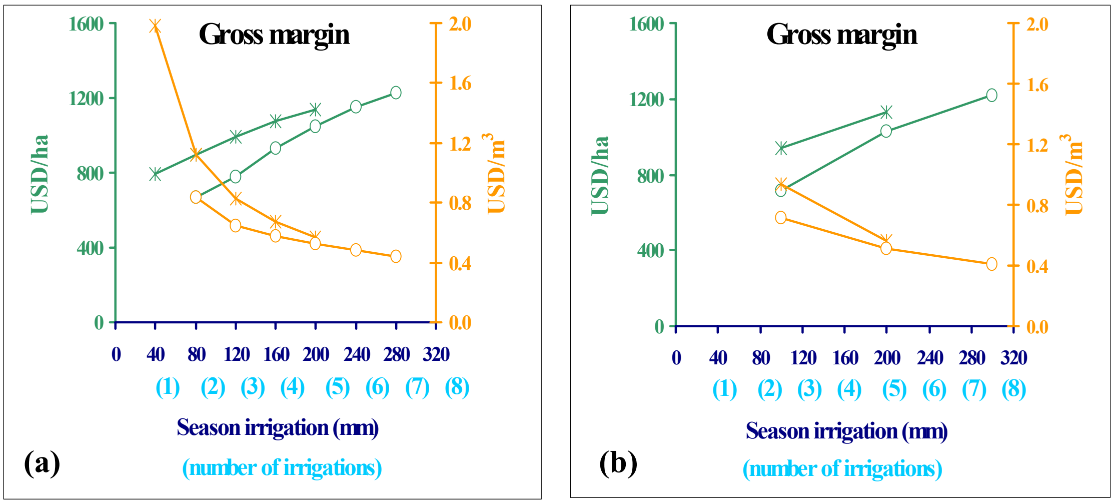

Figure 1 - Gross margins per unit surface and per unit volume of water applied for alternative deficit irrigation strategies of winter wheat under sprinkler (a) and surface (b) irrigation for average (—✳—) and very high (—○—) demand conditions.

To be noted that for equal applied water depths, the gross margins associated with sprinkler irrigation are higher than those relative to surface irrigation because labor costs are higher under surface irrigation. It is also observed that the gross margin/ha for very high demand conditions are higher than those for the average despite the significant difference between water volumes applied. This is explained by the fact that sub-products, mainly straw, have then much higher prices because when drought occurs they become rare and have a high demand as fodder for sheep and cows.

3.3. Potato Crop

The results relative to the potato crop are shown in Table 4. The analysis on water deficit and consequent yield reductions is given in the companion paper (Rodrigues *et al*., 2001).

Under average demand conditions, all deficit strategies are economically acceptable, with 100% of the surface allocated to every optional strategy (Table 4). This means that yield products can remunerate both the land and the water under such conditions. This is evidenced by the fact that the GM/m^3 grows from 1.46 to 1.76 USD/m^3 from the well irrigated to the high deficit irrigation strategy, while the GM/ha decreases from 2331 to 701 USD/ha for the same alternative schedules. The increase in GM/m^3 compensates for the decrease in GM/ha.

Under strong demand conditions, every water supply restriction results in a decrease of the gross margin per hectare, which is not compensated by an increase to the gross margin per m^3 of water supplied. In fact, the GM/m^3 do not increase like for average demand conditions but tend to decrease for the larger irrigation deficits.

Table 4 – Response of the potato crop to different deficit irrigation strategies for set sprinkle systems (NID = 40 mm)

Demand conditions	Deficit irrigation strategies	Season irrigation (mm)	Relative ET (%)	Relative Yield Loss (%)	Gross margin (USD/ha)	Gross margin (USD/m^3)	Percentage surface allocated for each irrigation strategy
Average	SC	160	94.0	0.0	2331	1.46	100/SC
	LDI	120	84.6	10.4	1790	1.49	100/LDI
	DI	80	76.1	19.7	1311	1.64	100/DI
	LID	40	65.5	31.3	701	1.75	100/LID
High	SC	200	96.1	0.0	2400	1.20	100/SC
	LDI	160	84.2	13.1	1710	1.07	33/SC + 50/DI
	DI	120	79.3	18.5	1456	1.21	100/DI
	LID	80	69.7	29.0	908	1.14	67/DI
	VLID	40	59.3	40.5	305	0.76	33/DI
Very high	SC	240	96.0	0.0	2343	0.98	100/SC
	LDI	200	89.1	7.7	1959	0.98	100/LDI
	DI	160	76.5	21.5	1227	0.77	80/LDI
	LID	120	71.8	26.7	985	0.82	60/LDI
	VLID	80	61.7	37.8	402	0.50	40/LDI
	EID	40	51.0	49.6	-219	-0.55	20/LDI

The results in Figure 2 help understanding the differences in behavior of the gross margins variation under average and high and very high demand conditions. Reducing the irrigation depths implies a reduction in GM/ha. The rate of decrease in GM/ha is much higher than for wheat, as it can be observed comparing the respective slopes in Figures 1 and 2. Analyzing the results in GM/m^3, shown in Figure 2, two different trends can be detected. For average demand conditions, the GM/m^3 steadily increases when stronger deficit irrigation are considered, thus indicating the feasibility in adopting deficit irrigation strategies under average demand conditions, similar to the behavior detected for wheat (Fig. 1).

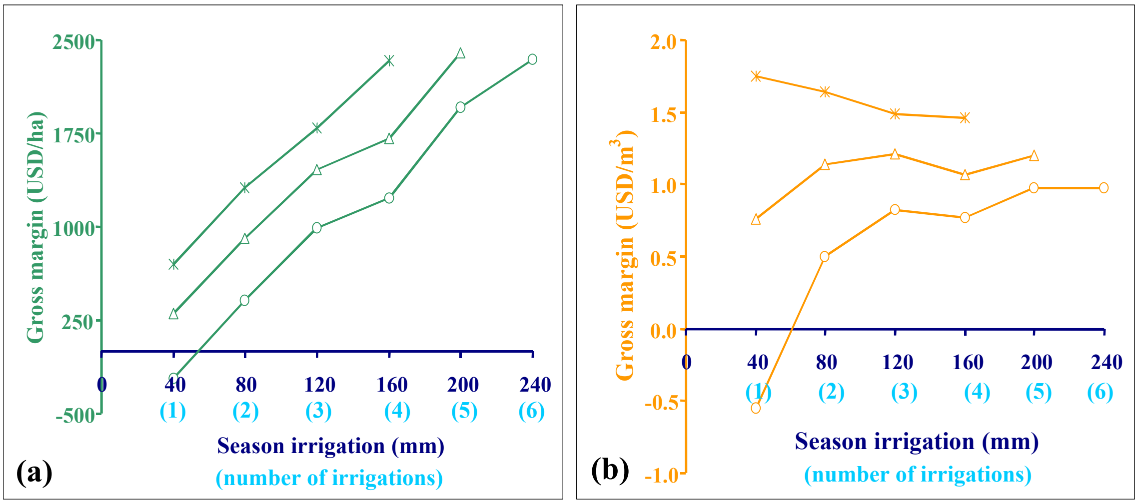

Figure 2 - Gross margins per unit surface (a) and per unit volume of water applied (b) for alternative deficit irrigation strategies of potato crop in Siliana for average (—✳—), high (—△—) and very high (—○—) demand conditions.

Relatively to high and very high demand conditions, results show that, after a given threshold, stronger deficit irrigation are not feasible because the GM/m^3 decrease with GM/ha, down to negative values. This trend is contrary to that of the wheat crop (cf. Fig. 1 and 2). Thresholds near 1.20 USD/m^3 and 0.95 USD/m^3 can be observed for the potato crop, respectively under high and very high demand conditions. Below these threshold values, the best return from the limited water available is obtained by reducing the cropped area and applying there moderate deficit irrigation schedules.

3.4. Tomato Crop

For the tomato crop, the economic evaluation of alternative irrigation schedules produces results similar to those observed for the potato crop (see Table 5).

Table 5 – Response of the tomato crop to different deficit irrigation strategies for set sprinkle systems (NID = 40 mm)

Demand conditions	Deficit irrigation strategies	Season irrigation (mm)	Relative ET (%)	Relative Yield Loss (%)	Gross margin (USD/ha)	Gross margin (USD/m^3)	Percentage surface allocated for each irrigation strategy
Average	SC	440	92.0	0.0	4543	1.03	100/SC
	RF	320	77.0	16.1	3426	1.07	100/RF
	HRF	280	69.0	23.9	2857	1.02	100/HRF
	ERF	200	61.0	32.8	2261	1.13	100/ERF
High	SC	480	91.0	0.0	4372	0.91	100/SC
	RF	400	79.0	12.2	3512	0.88	50/SC + 33/RF
	HRF	320	68.0	23.6	2714	0.85	100/HRF
	ERF	280	62.0	30.8	2195	0.78	87/HRF
Very High	SC	600	92.0	0.0	4307	0.72	100/SC
	RF	440	72.0	21.2	2839	0.65	67/SC
	HRF	360	61.0	32.3	2063	0.57	55/SC
	ERF	280	51.0	43.2	1307	0.47	43/SC

The information in Table 5 indicates that deficit irrigation strategies are accepted for average demand conditions while for high and very high demand conditions, the best solution is to well irrigate a reduced cropped area.

The tomato crop shows a similar behavior to the potato crop. So, for average demand conditions, a reduction in irrigation water depths produces a slight increase in GM/m^3 but smaller than for the potato crop (cf. Fig 2 and 3). Under high and very high demand conditions, introducing severe water constraints in water application induces a decrease in GM/m^3 (Fig. 3). Nevertheless, this reduction is not as large as the one observed in the potato crop (Fig. 2), indicating that the tomato crop valorizes best the water applied.

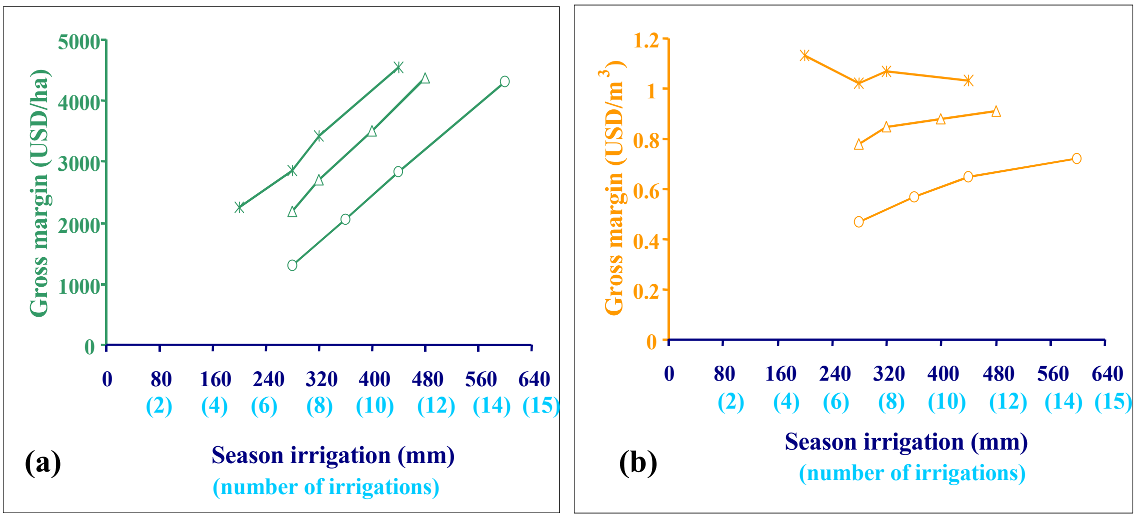

Figure 3 - Gross margins per unit surface (a) and per unit volume of water applied (b) for alternative deficit irrigation strategies of tomato crop in Siliana for average (—✳—), high (—△—) and very high (—○—) demand conditions.

The threshold values for the gross margin per unit water applied are 0.90 USD/m^3 and 0.70 USD/m^3 under high and very high demand conditions, respectively (Fig. 3). These thresholds are lower for the tomato than for the potato crop. The differences for the thresholds between the two horticultural crops relate to the costs of production and yield values, which are higher for tomato. Threshold differences between high and very high demand refer to yields achieved for each supply strategy; i.e. thresholds are higher when the yield reductions are smaller.

4 CONCLUSIONS

The study shows that the adoption of deficit irrigation strategies is generally difficult and requires not only good irrigation scheduling decisions but also appropriate evaluation of the economic impacts at farm level. However, a further sensitivity analysis relative to the price of water and the price of the crop products may be helpful to better understanding how the feasibility of deficit irrigation is affected.

The methodology utilized confirms that combining the use of an irrigation scheduling simulation model to generate alternative deficit irrigation strategies and an economic evaluation model applied to those strategies is helpful to support the selection of the best irrigation schedules to apply when water availability is limited.

Results for the wheat crop show that when surface irrigation is considered, every deficit supplemental irrigation strategy is feasible. However, when sprinkler irrigation is applied not all deficit irrigation schedules are acceptable; instead the best economic returns may be obtained when part of the cropped surface is rainfed.

In what concerns horticultural crops, potato and tomato, it can be concluded that when water availability is limited and average demand conditions prevail, the adoption of deficit irrigation strategies is feasible since reducing water application depths leads to increase the gross margin per m^3 of water. However, when high and very high demand conditions prevail, the best solution is often to apply moderate deficit irrigation and reducing the cropped surface rather than adopting heavy water restrictions.

Despite differences in production costs and yield values for the potato and tomato crops, both have similar behavior but the tomato crop shows higher gross margins per unit surface and lower ones per unit volume of water applied. This indicates that the application of deficit irrigation to the tomato crop is more difficult given its higher demand for irrigation.

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