# Deficit Irrigation of Cereals and Horticultural Crops: Simulation of Strategies to Cope with Droughts

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## ABSTRACT

To cope with droughts and water scarcity in semi-arid to sub-humid climates require the development of preparedness measures. For irrigated agriculture these include the identification of irrigation scheduling strategies that minimize the water demand with acceptable impacts on yields Those strategies may be produced by simulation and focus on different levels of water demand, from average to drought conditions. The irrigation scheduling simulation model ISAREG, first calibrated in Portugal and later validated for Tunisia, is used to simulate those strategies. Results for validation in Tunisia are given in this paper. The generated irrigation scheduling strategies to cope with droughts are applied to the deficit irrigation of winter wheat, tomato, and potato crops, both in Tunisia and in Portugal. The alternatives are evaluated through the combined use of indicators relative to the reduction in demand for irrigation water and the consequent yield reduction. An economic analysis applied to the Tunisian case study is presented in a companion paper. Results show the technical feasibility of reducing the water demand for supplemental irrigation of the wheat crop, including when large water deficits are considered. Results show that crop responses are more favorable when the crop season is relatively short. Also shown that center-pivot systems are less appropriate when deficit irrigation aims at large reductions in the water demand. Results for tomato, cropped out of the irrigation season, evidence that only mild deficits are acceptable and it is less appropriate to adopt large water deficits. In case of the potato crop, it was observed that deficit irrigation is easier to be adopted when early planting is practiced; for late planting, this crop behaves like the tomato crop, thus showing large yield losses when heavy deficits are considered.

**Keywords:** water scarcity, irrigation scheduling, modeling

## 1 INTRODUCTION

The arid, semi-arid and sub-humid regions are characterized by an irregular climate, both throughout the years and within the same year. Precipitation is the main factor

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responsible for the high variation on the availability of water and crop irrigation requirements.

*Drought* is a nature produced but temporary imbalance of water availability, consisting of a persistent lower-than-average precipitation, of uncertain frequency, duration and severity, of unpredictable occurrence, resulting in diminished water resources availability, and reduced carrying capacity of the ecosystems (Pereira, 1990). Many other definitions are currently adopted (Tate and Gustard, 2000).

Preparedness measures to cope with droughts are essential given the difficulties to predict droughts and the pervasive characteristics of their occurrence. Among measures, in case of irrigated agriculture, are the identification, evaluation and selection of irrigation scheduling strategies that minimize the water demand with acceptable impacts on yields. This may be achieved using simulation models, duly validated from field experiments. Simulation of strategies needs to be performed taking into account different levels of climatic demand: average, high and very high. The latter correspond to the occurrence of severe droughts.

Droughts affect all water use sectors. However, because the nature of impacts produced by droughts varies according to the nature of the affected activities, a low priority is usually assigned to agriculture for using water under drought conditions. It is therefore required to search which irrigation management strategies may be implemented under drought to minimize water demand but keeping crops production at an acceptable level. Despite abundant literature on the subject (cf. Pereira, 1989, 1990, 1992; de Jager *et al.*, 1997, Maracchi, 2000), it still is required to produce more refined analysis which could be further used by decision makers.

This study aims at improving the use of an irrigation scheduling model, to be incorporated in a decision support system now being developed, to help decision-makers to implement irrigation management strategies to cope with droughts in the Mediterranean climatic region. The application herein concerns two irrigation projects, one in Tunisia and the second in Portugal, which allow comparing approaches and better validating the modeling approaches. An economical analysis of the irrigation strategies relative to Tunisia is presented in a companion paper (El Amami *et al.*, 2001).

## 2 MATERIALS AND METHODS

### *2.1 Case study areas*

The Siliana irrigation project is located in Central Tunisia (35° 58' N, 7° 02' E, 431.0 m a.s.l.) near the Serj Mountains. The irrigated area (1240 ha), sprinkler irrigated, is supplied by the Lakhmès storage dam (7 $Mm^3$/year), diversions from the Oued Ouzafa, and is supplemented by groundwater which potential is evaluated in 3 $Mm^3$/year. The climate is classified as semi-arid superior, with a cold winter and a hot and dry summer. The annual rainfall varies from 200 to 550 mm.

The Vigia irrigation project is located in South East of Portugal, in Alentejo region (36° 31' N, 7° 47' W, 230.0 m a.s.l.). The irrigated area (1505 ha) is supplied by the Vigia dam (16.7 $Mm^3$ storage capacity). The annual precipitation in this region varies from 300 to 900 mm.

The most common soils in Siliana are alluvial silty-clays and brown steppe silty-clays. In average, the textural classes are 10% sand, 45% silt and 45% clay. The average soil water at field capacity and at wilting point are $\theta_{FC}$ = 0.40 $m^3m^{-3}$ and $\theta_{WP}$ = 0.20 $m^3m^{-3}$ respectively. Loamy and sandy-loam soils are the most representative in Vigia. In average, the soil water content characteristics are $\theta_{FC}$ = 0.34 $m^3m^{-3}$ and $\theta_{WP}$ = 0.17 $m^3m^{-3}$. In both cases, soils have a high water holding capacity.

Main climate characteristics of both locations relevant for irrigation requirements are analysed in section 3.1.

### *2.2. Simulation Models*

The irrigation scheduling alternatives have been generated using the irrigation scheduling simulation model ISAREG (Teixeira and Pereira, 1992).

The ISAREG model performs the soil water balance using different options to define and evaluate the irrigation schedules, as described in (Teixeira and Pereira, 1992, and Liu *et al.*, (1998):

a) to schedule irrigation aimed at maximum yields;

b) to simulate an irrigation schedule using selected irrigation thresholds;

c) to evaluate an irrigation schedule when water is applied at given dates;

d) to search an optimal irrigation scheduling under conditions of limited water supply, with constant or variable irrigation depths;

e) to execute the water balance without irrigation; and

f) to compute the net crop water requirements for irrigation.

The model requires the following input data:

(i) *Meteorological data*: effective precipitation, $P_e$ (mm) and reference evapotranspiration, $ET_o$ (mm)., computed with the FAO-Penman-Monteith method (Allen *et al.*, 1998);

(ii) *Crop data*: dates of the crop development stages; crop coefficients, $K_c$; root depths, z (m); the soil water depletion fractions for no stress, p; and the seasonal yield response factors, $K_y$;

(iii) *Soil data* referring to a multi-layered soil: for each layer the respective depth, d (m); and the soil water content at field capacity, $\theta_{FC}$ (mm $mm^{-1}$) and wilting point, $\theta_{WP}$ (mm $mm^{-1}$). A complementary file may be used for the potential ground water contribution, G (mm $day^{-1}$).

The reference evapotranspiration in this application is computed with the FAO-Penman-Monteith method (Allen *et al.*, 1998). The crop data parameters are determined with the KCISA program (Rodrigues and Pereira, 1999; Rodrigues *et al.*, 2000), which computations follow the updated methodology proposed by FAO (Allen *et al.*, 1998). In particular, the crop coefficients have been adjusted to the climate for both locations. Yield losses due to water stress are estimated utilising the yield response factors proposed by Doorenbos and Kassam (1979) and Allen *et al.* (1998).

The calibration and validation of the ISAREG model for Portugal is described in Teixeira and Pereira (1992) and Teixeira *et al.* (1996). For Tunisia, it is described in Teixeira *et al.* (1995) and Zairi *et al.* (1998), partly reproduced in section 3.2.

### *2.3 Supplemental and deficit irrigation strategies*

In the Siliana project, sprinkler (hand moved and semi-permanent set systems) and surface irrigation systems are used. The existing sprinkler systems have been designed to produce application rates close to 6 mm $h^{-1}$ to overcome the low infiltrability of the soils. Farmers adopt a set time of 8 hours, thus net irrigation depths are, approximately, $I_n = 40$ mm (Zairi, *et al.*, 2000) for both wheat and horticultural crops. Surface irrigation is also used for winter wheat, but farmers then adopt large irrigation depths, the net depths being approximately $I_n = 100$ mm (Zairi *et al.*, 1999).

When water availability is non-limiting, the frequency of irrigations is not restricted and varies along the season according to the crop demand. Under limited water availability, the supply is made with restrictions:

- For irrigation of the winter wheat and potato crops, which frequency depends upon rainfall contribution to fill the soil water reserve, the farmers are advised to reduce the number of irrigation events.
- For the tomato crop, farmers are told to adopt large time intervals between successive irrigations. This restriction also reduces the number of irrigation events but it is perceived differently when managing the irrigation systems and when performing the model simulations.

Observations in the practice of irrigation at Siliana allow defining several alternative supplemental irrigation schedules for winter wheat that are summarized in Table 1. The non-restricted schedule is only constrained by the system characteristics and corresponds to the maximal yield strategy. The others are defined by decreasing the number of irrigation events and correspond to deficit irrigation. The deficit irrigation strategies for the horticultural crops are those observed in the Siliana project, and are listed in Table 2. Like for wheat, maximal yields are achievable for the schedule SC.

Table 1 – Supplemental irrigation strategies for winter wheat in Siliana
(set sprinkler and surface irrigation systems)

| ***Strategies*** | ***Symbol*** | ***Supply conditions*** |
|---|---|---|
| ***Sprinkler irrigation ($I_n$ = 40 mm)*** | | |
| ***System constraints*** | SC | Variable frequency and fixed irrigation depths (40mm) |
| ***Light deficit irrigation*** | LDI | Seasonal irrigation reduced by 40 mm |
| ***Deficit irrigation*** | DI | Seasonal irrigation reduced by 80mm |
| ***Large irrigation deficit*** | LID | Seasonal irrigation reduced by 120mm |
| ***Very large irrigation deficit*** | VLID | Seasonal irrigation reduced by 160 mm |
| ***Extreme irrigation deficit*** | EID | Seasonal irrigation reduced by 200 mm |
| ***Surface irrigation ($I_n$ = 100 mm)*** | | |
| ***System constraints*** | SC | Variable frequency and fixed irrigation depths (100 mm) |
| ***Deficit irrigation*** | DI | Seasonal irrigation reduced by 100 mm |
| ***Extreme irrigation deficit*** | EID | Seasonal irrigation reduced by 200 mm |

Table 2 – Deficit irrigation strategies for horticultural crops in Siliana
(set sprinkle systems)

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

In the Vigia irrigation project, center-pivot and semi-permanent set systems are adopted. For the center-pivot systems, the net depths are close to $I_n = 15$ mm, corresponding to a rotation completed every 3 days. However some farmers adopt a higher system speed. For set systems, farmers use a wide ranges of application depths but an average net irrigation depth $I_n = 40$ mm could be considered.

Several irrigation scheduling strategies to cope with drought are adopted in practice. Strategies differ for set and center-pivot sprinkler systems because the latter are used for frequent irrigation. For simulations relative to set sprinkler systems, a management allowed depletion fraction MAD is adopted. MAD is a common criterion for irrigation scheduling (Martin *et al.*, 1990). In this study, MAD are computed as a percentage of the of soil water depletion fraction for non-stress (p), which is a crop and climate dependent factor, as defined by Allen *et al.* (1998). Restrictions were selected by combining different MAD values with limitations on the total available irrigation water for the crop season. The corresponding irrigation strategies are summarized in Table 3 for winter wheat, and in Table 4 for potato and tomato crops.

Table 3 – Supplemental irrigation strategies for winter wheat in Vigia
(set sprinkler and center-pivot irrigation systems)

| ***Irrigation strategies*** | ***Symbol*** | ***Seasonal available water*** |
|---|---|---|
| ***Sprinkler set systems ($I_n$ = 40 mm)*** | | |
| Variable frequency; MAD = p | SC | No restrictions |
| Variable frequency; MAD = 0.9 p | R 200 | 200 mm |
| Variable frequency; MAD = 0.8 p | R 160 | 160 mm |
| Variable frequency; MAD = 0.7 p | R 120 | 120 mm |
| Variable frequency; MAD = 0.6 p | R 80 | 80 mm |
| ***Center-pivot sprinkler systems ($I_n$ = 15 mm)*** | | |
| Variable frequency; MAD = p | SC | No restrictions |
| Variable frequency; MAD = 0.8 p | MAD 80 | No restrictions |
| Variable frequency; MAD = 0.7 p | MAD 70 | No restrictions |
| Variable frequency; MAD = p | SUBOPT | No irrigation after May |
| Variable frequency; MAD = 0.8 p | RMAD 80 | No irrigation after May |
| Variable frequency; MAD = 0.7 p | RMAD 70 | No irrigation after May |

Table 4 - Deficit irrigation strategies for horticultural crops in Vigia
(set sprinkle systems)

| ***Irrigation strategies*** | ***Symbol*** | ***Seasonal available water*** |
|---|---|---|
| ***Potato ($I_n$ = 40 mm)*** | | |
| Variable frequency; MAD = 0.7 p | SC | System constraints |
| Variable frequency; MAD = 0.7 p | DI 400 | 400 mm |
| Variable frequency; MAD = 0.7 p | DI 360 | 360 mm |
| Variable frequency; MAD = 0.7 p | DI 320 | 320 mm |
| Variable frequency; MAD = 0.7 p | DI 280 | 280 mm |
| Variable frequency; MAD = 0.7 p | DI 240 | 240 mm |
| ***Tomato*** ($I_n$ = 40 mm) | | |
| Variable frequency; MAD = 0.9 p | SC | System constraints |
| Variable frequency; MAD = 0.9 p | DI 640 | 640 mm |
| Variable frequency; MAD = 0.9 p | DI 560 | 560 mm |
| Variable frequency; MAD = 0.9 p | DI 480 | 480 mm |
| Variable frequency; MAD = 0.9 p | DI 440 | 440 mm |

## 3 RESULTS

### *3.1 Climate: Rainfall and Evapotranspiration*

For comparing the environmental conditions in both case study areas, average monthly data are selected. Figure 1 shows precipitation and reference evapotranspiration data, together with net solar radiation averages. It shows that rainfall is higher for Vigia than for Siliana. $ET_o$ is also higher at Vigia during the summer months due to differences in solar radiation (computed from observed sunshine hours), (Fig. 1) and wind speed (Fig. 2). However, the minimum relative humidity is higher at Siliana (Fig. 2).

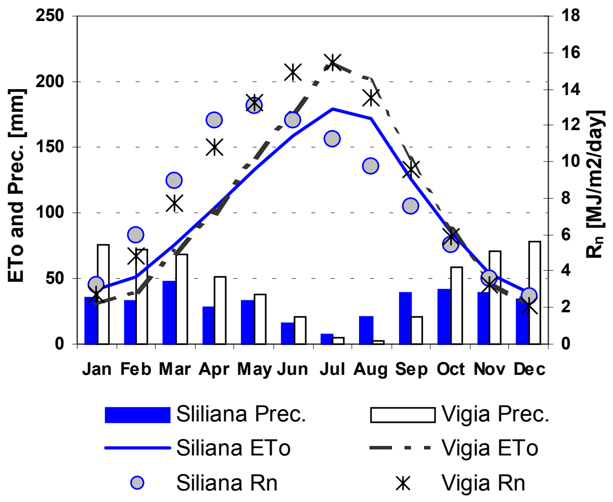

Figure 1 – Average monthly precipitation, reference evapotranspiration and net radiation for Siliana (1982-1996) and Vigia (1941-1991).

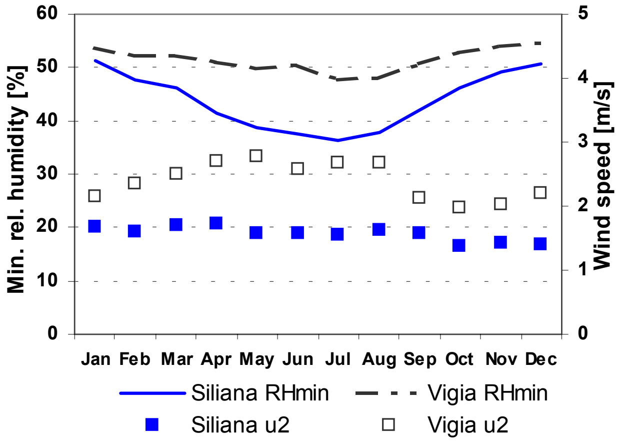

Figure 2 – Average monthly minimum relative humidity and wind speed for Siliana (1982-1996) and Vigia (1941-1991).

Differences in $ET_o$ cause also differences in crop ET and crop irrigation requirements as analysed further in this paper.

### *3.2 Model Validation in Tunisia*

The ISAREG model was validated for winter wheat at an experimental station located at Hendi Zitoun, Central Tunisia, which environmental conditions are close to those of Siliana, including soils and wheat varieties. Data of two irrigation seasons were used (Zairi *et al.,* 1998):

- 1992/93 – field trials with sprinkler set systems, using net irrigation depths $I_n$ = 40 mm, for three treatments with irrigation thresholds MAD = 0.3, 0.6 and 0.9 p;
- 1997/98 – field trials with surface irrigation ($I_n$ = 100 mm) using two treatments with irrigation thresholds MAD = 0.6 and 0.9 p.

The ISAREG model validation is performed comparing the soil water content observed in field experiments throughout the crop season with those simulated by the model. Figure 3 shows the results of the model simulation for winter wheat at Hendi Zitoun in 1992/93 for the treatment where MAD = 0.9 p. It shows that the model appropriately describes the soil water content, expressed in % in volume, along the entire crop season.

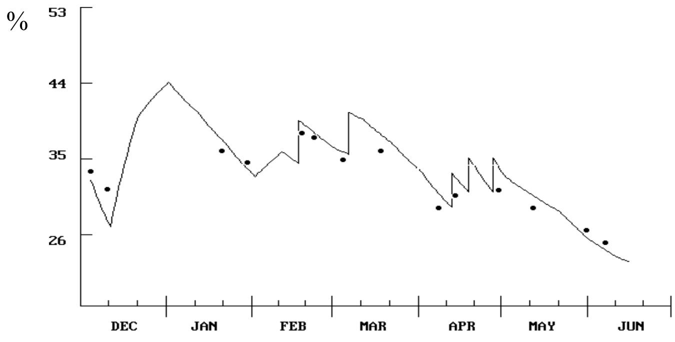

Figure 3 – Simulated (—) and observed (•) soil water content (expressed in % in volume) for a treatment with MAD = 0.9 p at Hendi Zitoun in 1992/93 (from Zairi *et al.*, 1998)

Results in Figure and 4 concern the surface irrigation experiment for 1997-98. It shows that the regression line relative to the simulated vs. observed soil water content is close to 1:1 and that the dispersion of deviations of estimates is the same for high and low values of the soil water content. The Figure 4 also contains the confidence interval relative to the 95% probability. Both figures indicate that the model is able to predict with acceptable errors the soil water content for well irrigated and deficit irrigated crops. More recent observations with summer crops (results not yet published) confirm that assumption. The validation for yield loss predictions is in open literature (Teixeira *et al.*, 1995) and, therefore, is not reproduced in this paper.

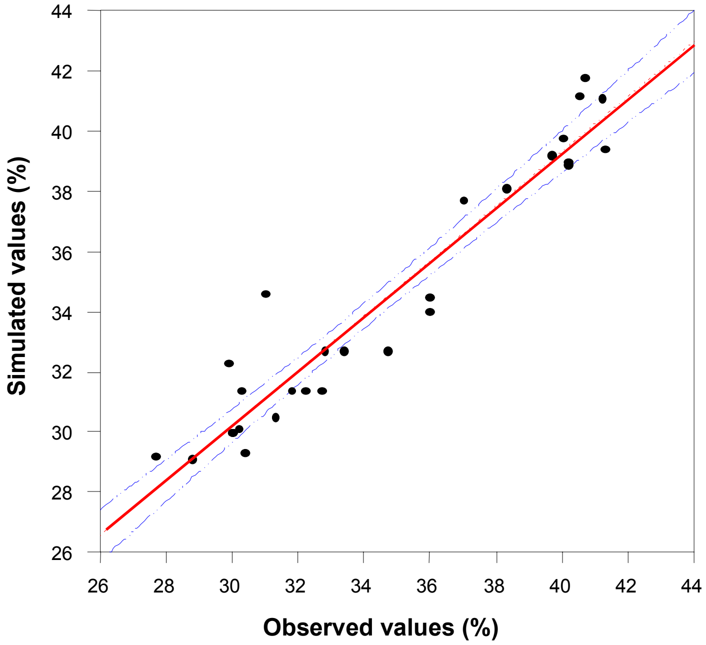

Figure 4 – Comparison between simulated and observed soil water content, expressed in % in volume, for all field trials performed in 1997/98 at Hendi Zitoun (from Zairi *et al.*, 1998)

### *3.3 Net Irrigation Requirements*

To help interpretation of differences between both locations, crop coefficients ($K_c$) and soil water depletion fractions for no stress (p) computed with KCISA program (Rodrigues *et al.*, 2000) for the three crops are presented in Figure 5. Differences observed on $K_c$ are mainly due to differences in planting dates and lengths of crop growth stages for the two locations, which are related to climate and to crop varieties. For the fraction p, differences between locations mainly relate with dates of crop stages.

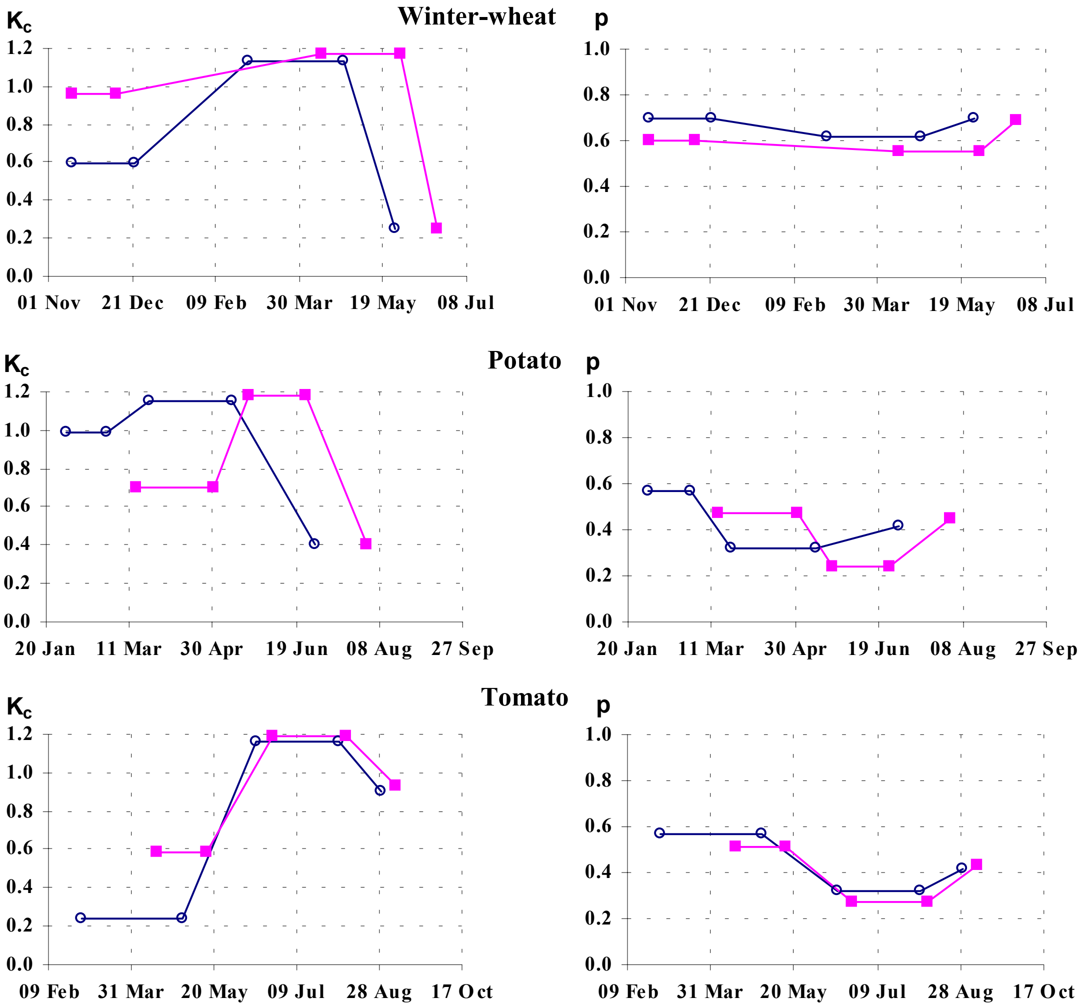

Figure 5 – The $K_C$ and p curves for Siliana (–○–) and Vigia (–■–) for the winter wheat, potato and tomato crops.

The annual net irrigation requirements (NIR) for the winter wheat, potato and tomato crops were computed with ISAREG for the time series 1982-1996 and 1941-1991, respectively for Siliana and Vigia. Adopting a normal distribution for the computed NIR, it were computed the crop irrigation requirements for the average, high and very high demand conditions, which correspond to the probability for being exceeded of 50, 20 and 5%. Results are presented in Tables 5 and 6. For winter wheat in Siliana, because the time series is not enough long, results for the 20 and 5% probabilities are similar, so computations were performed only for the very high demand conditions. In Tables, are also given the seasonal rainfall and crop evapotranspiration used in the NIR computations, and the total available soil water at planting. These depths were computed with ISAREG in a sequential soil water balance starting at the end of the summer of the first year, when soil water depletion is maximal in the environmental conditions of both locations.

The NIR are higher for Vigia than for Siliana. This is justified by the higher $ET_O$ observed in Vigia for the summer months (Fig. 1), and is also due to the fact that the crop seasons are longer in Vigia than in Siliana.

Table 5 - Demand conditions for winter wheat, potato and tomato crops for Siliana project

| Crop | Demand condition | Total available soil water at planting (mm) | Season rainfall (mm) | Season $ET_c$ (mm) | Season irrigation requirement (mm) |
|---|---|---|---|---|---|
| **Winter wheat** | Average | 76 | 229 | 473 | 230 |
| | Very high | 42 | 145 | 445 | 325 |
| **Potato** | Average | 66 | 150 | 347 | 196 |
| | High | 96 | 98 | 364 | 226 |
| | Very high | 80 | 70 | 365 | 265 |
| **Tomato** | Average | 81 | 171 | 653 | 550 |
| | High | 59 | 111 | 609 | 559 |
| | Very high | 36 | 31 | 629 | 651 |

Table 6 - Demand conditions for winter wheat, potato and tomato crops for Vigia project

| Crop | Demand condition | Total available soil water at planting (mm) | Season rainfall (mm) | Season $ET_c$ (mm) | Season irrigation requirement (mm) |
|---|---|---|---|---|---|
| **Winter wheat** | Average | 41 | 336 | 538 | 222 |
| | High | 92 | 241 | 592 | 318 |
| | Very high | 83 | 154 | 533 | 354 |
| **Potato** | Average | 41 | 141 | 610 | 480 |
| | High | 85 | 152 | 664 | 541 |
| | Very high | 16 | 62 | 587 | 561 |
| **Tomato** | Average | 122 | 39 | 778 | 718 |
| | High | 113 | 62 | 832 | 825 |
| | Very high | 89 | 50 | 922 | 884 |

### *3.4 Wheat Crop Responses to Deficit Irrigation Strategies*

The alternative irrigation schedules are evaluated by:

- the reductions in season irrigation depths,
- the corresponding crop ET ($ET_c$) decreases, measured by the relative ET, ratio between actual crop ET and potential crop ET, and
- the relative yield losses (RYL), given by RYL = $1 – Y_a / Y_c$, expressed in %, where $Y_a$ and $Y_c$ are the crop yields that correspond to actual and potential crop ET, respectively.

Results for alternative supplemental irrigation of the wheat crop are given in Tables 7 and 8 for Siliana and Vigia. Results for sprinkle and the average year at Siliana show that when irrigation demand is reduced by 60%, from 200 to 80 mm, a RYL close to 20% (Table 7) is induced. However, under severe drought conditions (very high demand), a reduction of 57% of the seasonal irrigation, from 280 to 120 mm, induces relative yield losses close to 30% (Table 7). Differences are due to the fact that for the average year the crop uses more rainfall and soil water, which are less available in drought years. This indicates that reducing the seasonal irrigation during drought years to the deficit irrigation depths that are acceptable for average conditions is difficult to achieve in the practice because yield losses are then very.

Table 7 - Response of the wheat crop to different supplemental deficit irrigation strategies in Siliana (set sprinkler and surface irrigation systems).

| *Demand condition* | *Supply strategies* | *Season $ET_c$ (mm)* | *Number irrigation events* | *Season irrigation (mm)* | *Relative ET (%)* | *Relative yield loss (%)* |
|---|---|---|---|---|---|---|
| ***Sprinkler irrigation*** | | | | | | |
| ***Average*** | SC | 456 | 5 | 200 | 97.1 | 0.0 |
| | LDI | 431 | 4 | 160 | 91.0 | 6.1 |
| | DI | 398 | 3 | 120 | 84.0 | 13.1 |
| | LID | 362 | 2 | 80 | 76.3 | 20.8 |
| | VLID | 323 | 1 | 40 | 68.2 | 28.9 |
| ***Very high*** | SC | 432 | 7 | 280 | 97.1 | 0.0 |
| | LDI | 407 | 6 | 240 | 91.4 | 5.7 |
| | DI | 374 | 5 | 200 | 84.1 | 13.0 |
| | LID | 339 | 4 | 160 | 76.1 | 21.0 |
| | VLID | 302 | 3 | 120 | 67.7 | 29.4 |
| | EID | 263 | 2 | 80 | 59.1 | 37.1 |
| ***Surface irrigation*** | | | | | | |
| ***Average*** | SC | 460 | 2 | 200 | 97.1 | 0.0 |
| | DI | 380 | 1 | 100 | 80.2 | 16.9 |
| ***Very high*** | SC | 441 | 3 | 300 | 99.1 | 0.0 |
| | DI | 372 | 2 | 200 | 83.4 | 13.0 |
| | EID | 279 | 1 | 100 | 62.7 | 34.4 |

Considering stronger water restrictions under severe drought conditions, i.e. only one sprinkle irrigation applying 40 mm, the $ET_c$ would be 220 mm, resulting RYL = 50 %. This condition would be out of the limit of the model applicability because validation experiments did not included water deficits larger than 50%. Other studies using the same wheat variety concluded that grain production is only viable when $ET_c$ is above 200 mm (Zairi *et al.*, 1996). So, it is not appropriate to apply less than 80 mm in two irrigation events, one at planting and the second by the beginning of February. The rainfed crop is not feasible for very high demand (very severe drought).

Results for surface irrigation show differences relative to sprinkle irrigation as shown in Figure 5. These differences are due to the fact that larger application depths are used

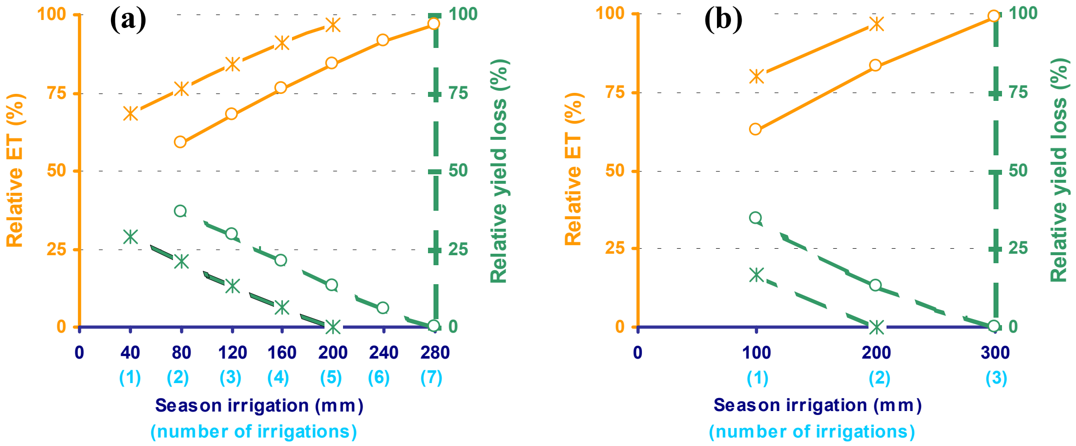

Figure 5 – Response of the wheat crop to different supplemental irrigation strategies in Siliana using sprinkler (a) and surface (b) irrigation for average (—✳—) and very high (—○—) demand conditions.

with surface irrigation, which favor deeper crop roots and the use of soil water in deeper soil layers. For surface irrigation, one irrigation at seedling constitutes the minimum under very high demand conditions.

Table 8 - Response of the wheat crop to deficit irrigation strategies in Vigia (set and center-pivot systems)

| ***Demand condition*** | ***Supply strategies*** | ***Season $ET_c$ (mm)*** | ***Number irrigation events*** | ***Season irrigation (mm)*** | ***Relative ET (%)*** | ***Relative yield loss (%)*** |
|---|---|---|---|---|---|---|
| ***Set systems*** | | | | | | |
| Average | SC | 527 | 5 | 200 | 98.0 | 0.0 |
| | R 200 | 522 | 5 | 200 | 97.0 | 1.1 |
| | R 160 | 504 | 4 | 160 | 93.6 | 4.6 |
| | R 120 | 473 | 3 | 120 | 88.0 | 10.5 |
| | R 80 | 439 | 2 | 80 | 81.6 | 17.2 |
| High | SC | 592 | 8 | 320 | 100.0 | 0.0 |
| | R 200 | 507 | 5 | 200 | 85.7 | 15.0 |
| | R 160 | 470 | 4 | 160 | 79.3 | 21.7 |
| | R 120 | 431 | 3 | 120 | 72.8 | 28.6 |
| | R 80 | 392 | 2 | 80 | 66.2 | 35.5 |
| Very High | SC | 512 | 8 | 320 | 96.1 | 0.0 |
| | R 200 | 424 | 4 | 200 | 79.5 | 17.0 |
| | R 160 | 386 | 4 | 160 | 72.5 | 24.8 |
| | R 120 | 347 | 3 | 120 | 65.2 | 32.4 |
| | R 80 | 308 | 2 | 80 | 57.9 | 40.1 |
| ***Center-pivot systems*** | | | | | | |
| Average | SC | 526 | 13 | 195 | 97.8 | 0.0 |
| | MAD 80 | 491 | 10 | 150 | 91.3 | 6.8 |
| | MAD 70 | 467 | 7 | 105 | 86.8 | 11.5 |
| | SUBOPT | 511 | 11 | 165 | 95.0 | 2.9 |
| | RMAD 80 | 483 | 9 | 135 | 89.8 | 8.4 |
| | RMAD 70 | 558 | 7 | 105 | 85.1 | 13.4 |
| High | SC | 592 | 21 | 315 | 100.0 | 0.0 |
| | MAD 80 | 533 | 16 | 240 | 90.0 | 10.5 |
| | MAD 70 | 491 | 13 | 195 | 82.9 | 18.0 |
| | SUBOPT | 589 | 20 | 300 | 99.4 | 0.6 |
| | RMAD 80 | 533 | 16 | 240 | 90.0 | 10.5 |
| | RMAD 70 | 491 | 13 | 195 | 82.9 | 18.0 |
| Very high | SC | 509 | 21 | 315 | 95.5 | 0.0 |
| | MAD 80 | 462 | 15 | 255 | 86.6 | 9.3 |
| | MAD 70 | 422 | 14 | 210 | 79.1 | 17.2 |
| | SUBOPT | 492 | 19 | 285 | 92.3 | 3.3 |
| | RMAD 80 | 440 | 15 | 225 | 82.6 | 13.6 |
| | RMAD 70 | 411 | 13 | 195 | 77.1 | 19.3 |

For the average year in Vigia, the adoption of deficit supplemental irrigation for wheat is easily achievable (Table 8). Reductions of the seasonal irrigation depths from 200 to 80 mm with set systems or from 195 to 105 mm with center-pivot systems induce RYL smaller than 17.5%. This happens because available rainfall is abundant, so limiting the yield losses due to the adoption of deficit irrigation. In fact, farmers generally do not irrigate under such climatic demand conditions since the rainfed crop is

Rodrigues, P.N., L.S. Pereira, A. Zairi, H. El Amami, H.A Slatni, J.L. Teixeira, and T. Machado. March 2001. "Deficit Irrigation of Cereals and Horticultural Crops: Simulation of Strategies to Cope with Droughts". Agricultural Engineering International: the CIGR Journal of Scientific Research and Development. Manuscript LW 00 007a.Vol. III.

economically viable. The few farmers that irrigate wheat under average conditions use center-pivot systems, which show to respond well under those conditions. For better illustration of difference in behavior of set and center pivot irrigation, the Figure 6 is presented.

For high and very high demand conditions it becomes more difficult to adopt deficit irrigation strategies that produce high water savings. For set systems, reducing from 320 to 80 mm induces RYL = 35.5% and RYL = 40% respectively under high and very high demand conditions respectively. Such levels of water savings are not achievable with center-pivot systems (see Fig. 6) because a very low MAD should then be adopted. However, a low MAD is associated with high risk for the crop failure because, in case the system would break down for some days, the soil water reserve would be very quickly depleted, thus insufficient to sustain crop growth. Therefore, when supplemental irrigation is practiced for wheat with center-pivot systems only limited water savings can be expected, from 315 to 195 mm, i.e. near 38%, with limited yield losses, close to 18%. Higher water saving scenarios may be considered when based on appropriate economic analysis. An alternative, which is not favored by the farmers, is the adoption of wheat varieties having a shorter cycle but also have lower yields.

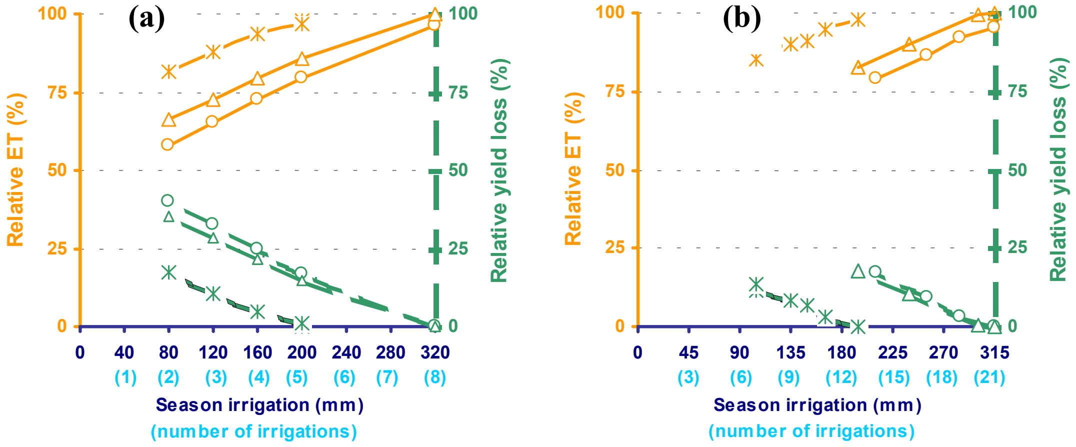

Figure 6 – Response of the wheat crop to different supplemental irrigation strategies in Vigia using set sprinkler (a) and center-pivot (b) systems for average (—✳—), high (—△—) and very high (—○—) demand conditions.

### 3.5. *Responses of the potato crop to deficit irrigation*

Results for potato in Siliana (Table 9) show a much lower demand than for Vigia (Table 10) because the potato growth season is anticipated there relatively to Vigia (see $K_C$ curves in Fig. 3). Potato is somewhat marginal in Vigia area comparatively to other regions in Portugal and the high demand for water is one among other reasons.

In Siliana, for average demand conditions, significant water savings (from 160 to 80 mm) produce yield losses not exceeding 20%, so easy to be practiced. For high and very high demand, reducing the season irrigation from 200 or 240 mm to 80 mm induce RYL near 29% and 38% respectively (Table 9). However, if deficit irrigation aims at reducing to 120 mm, then the yield losses reduce to 18.5 and 26.7% respectively for high and very high demand conditions.

Table 9 - Response of the potato crop to deficit irrigation strategies in Siliana (set sprinkle systems)

| *Demand condition* | *Supply strategies* | *Season $ET_c$ (mm)* | *Number irrigation events* | *Season irrigation (mm)* | *Relative ET (%)* | *Relative yield loss (%)* |
|---|---|---|---|---|---|---|
| Average | SC | 327 | 4 | 160 | 94.0 | 0.0 |
| | LDI | 299 | 3 | 120 | 84.6 | 10.4 |
| | DI | 265 | 2 | 80 | 76.1 | 19.7 |
| | LID | 228 | 1 | 40 | 65.5 | 31.3 |
| High | SC | 350 | 5 | 200 | 96.1 | 0.0 |
| | LDI | 306 | 4 | 160 | 84.2 | 13.1 |
| | DI | 288 | 3 | 120 | 79.3 | 18.5 |
| | LID | 254 | 2 | 80 | 69.7 | 29.0 |
| | VLID | 216 | 1 | 40 | 59.3 | 40.5 |
| Very high | SC | 350 | 6 | 240 | 96.0 | 0.0 |
| | LDI | 325 | 5 | 200 | 89.1 | 7.7 |
| | DI | 279 | 4 | 160 | 76.5 | 21.5 |
| | LID | 262 | 3 | 120 | 71.8 | 26.7 |
| | VLID | 225 | 2 | 80 | 61.7 | 37.8 |
| | EID | 186 | 1 | 40 | 51.0 | 49.6 |

For Vigia responses follow the same trend as for Siliana (Table 10). For average conditions it is possible to reduce the seasonal irrigation from 400 to 240 mm with RYL = 23.2%. However, for high and very high conditions, the application of 240 mm only would cause relative yield losses of 30.1 and 40.4%, respectively. Because the net irrigation requirements are high, the demand for irrigation would remain quite large, so making less effective the adoption of strong deficits in irrigation when water availability is scarce.

Table 10 - Response of the potato crop to deficit irrigation strategies in Vigia (set sprinkle systems)

| *Demand condition* | *Supply strategies* | *Season $ET_c$ (mm)* | *Number irrigation events* | *Season irrigation (mm)* | *Relative ET (%)* | *Relative yield loss (%)* |
|---|---|---|---|---|---|---|
| **Average** | SC | 546 | 10 | 400 | 89.6 | 0.0 |
| | DI 400 | 546 | 10 | 400 | 89.6 | 0.0 |
| | DI 360 | 527 | 9 | 360 | 86.4 | 3.5 |
| | DI 320 | 493 | 8 | 320 | 80.8 | 9.7 |
| | DI 280 | 457 | 7 | 280 | 75.0 | 16.1 |
| | DI 240 | 418 | 6 | 240 | 68.6 | 23.2 |
| **High** | SC | 596 | 11 | 440 | 89.8 | 0.O |
| | DI 400 | 567 | 10 | 400 | 85.4 | 4.7 |
| | DI 360 | 531 | 9 | 360 | 79.9 | 10.8 |
| | DI 320 | 492 | 8 | 320 | 74.1 | 17.2 |
| | DI 280 | 453 | 7 | 280 | 68.2 | 23.7 |
| | DI 240 | 414 | 6 | 240 | 62.4 | 30.1 |
| **Very high** | SC | 534 | 12 | 480 | 91.0 | 0.0 |
| | DI 400 | 471 | 10 | 400 | 80.3 | 11.8 |
| | DI 360 | 431 | 9 | 360 | 73.4 | 19.4 |
| | DI 320 | 393 | 8 | 320 | 66.9 | 26.5 |
| | DI 280 | 353 | 7 | 280 | 60.2 | 33.9 |
| | DI 240 | 316 | 6 | 240 | 53.8 | 40.4 |

Comparing the results for both locations (see Tables 9 and 10, and Fig. 7), it can be concluded that deficit irrigation is more likely feasible for the potato crop when early planting is performed, so increasing the chances for using winter rains and higher soil water content at planting.

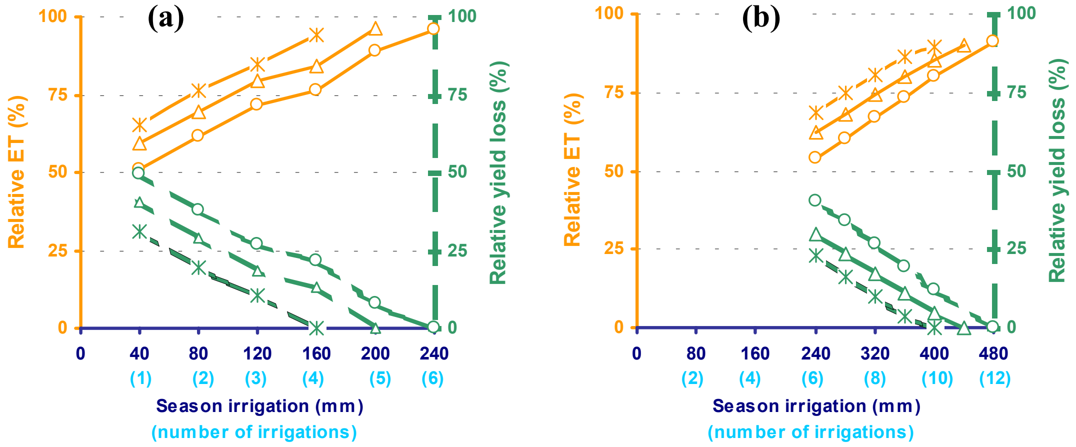

Figure 7 – Response of the potato crop to different supplemental irrigation strategies in Siliana (a) and in Vigia (b) for average (—✳—), high (—△—) and very high (—○—) demand conditions.

### 3.6 *Response of the tomato crop to deficit irrigation strategies*

Results for tomato are not very different from those for potato. However, results for Siliana and Vigia (Tables 11 and 12, and Fig. 8) show smaller differences among them because in both cases the crop develops out of the rain season. For Siliana (Table 11), it can be seen that reducing the season irrigation to 280 mm produces RYL equal to 23.8% for average demand, 30.8% for high demand, and 43.2% for very high demand conditions. For the latter, corresponding to severe drought conditions, maintaining RYL

Table 11 - Response of the tomato crop to deficit irrigation strategies in Siliana (set sprinkle systems)

| *Demand condition* | *Supply strategies* | *Season $ET_c$ (mm)* | *Number irrigation events* | *Season irrigation (mm)* | *Relative ET (%)* | *Relative yield loss (%)* |
|---|---|---|---|---|---|---|
| **Average** | SC | 602 | 11 | 440 | 92.0 | 0.0 |
| | RF | 502 | 8 | 320 | 77.0 | 16.1 |
| | HRF | 454 | 7 | 280 | 69.0 | 23.9 |
| | ERF | 398 | 5 | 200 | 61.0 | 32.8 |
| **High** | SC | 554 | 12 | 480 | 91.0 | 0.0 |
| | RF | 483 | 10 | 400 | 79.0 | 12.2 |
| | HRF | 417 | 8 | 320 | 68.0 | 23.6 |
| | ERF | 375 | 7 | 280 | 62.0 | 30.8 |
| **Very high** | SC | 583 | 15 | 600 | 92.0 | 0.0 |
| | RF | 455 | 11 | 440 | 72.0 | 21.2 |
| | HRF | 388 | 9 | 360 | 61.0 | 32.3 |
| | ERF | 322 | 7 | 280 | 51.0 | 43.2 |

similar to that referred for average demand would require a season net application equal to 440 mm, i.e. the same irrigation depth required for no stress under average demand conditions. This indicates that the adoption of deficit irrigation for summer crops is difficult and does not produce the high demand reduction that is desired to cope with droughts. The economic feasibility analysis in the companion paper (El Amami *et al.*, 2001) confirms these difficulties, which generally lead farmers to reduce the irrigation area and apply there a near to optimal irrigation scheduling.

For Vigia (Table 12) results are similar to those for Siliana but problems are more evident because net irrigation requirements are larger than for Siliana (see Fig. 8 where results for Siliana and Vigia are compared). For average demand conditions, reducing the seasonal irrigation depth from 680 to 440 mm would induce RYL = 23%, which may not be economically feasible.

Table 12 - Response of the tomato crop to deficit irrigation strategies in Vigia (set sprinkle systems)

| ***Demand condition*** | ***Supply strategies*** | ***Season ET$_c$ (mm)*** | ***Number irrigation events*** | ***Season irrigation (mm)*** | ***Relative ET (%)*** | ***Relative yield loss (%)*** |
|---|---|---|---|---|---|---|
| **Average** | SC | 758 | 17 | 680 | 97.3 | 0.0 |
| | DI 640 | 745 | 16 | 640 | 95.6 | 1.8 |
| | DI 560 | 691 | 14 | 560 | 88.7 | 9.0 |
| | DI 480 | 624 | 12 | 480 | 80.1 | 18.1 |
| | DI 440 | 588 | 11 | 440 | 75.5 | 23.0 |
| **High** | SC | 812 | 19 | 760 | 97.5 | 0.0 |
| | DI 640 | 768 | 16 | 640 | 92.3 | 5.5 |
| | DI 560 | 702 | 14 | 560 | 84.4 | 13.8 |
| | DI 480 | 630 | 12 | 480 | 75.7 | 23.0 |
| | DI 440 | 592 | 11 | 440 | 71.1 | 27.7 |
| **Very high** | SC | 899 | 21 | 840 | 97.4 | 0.0 |
| | DI 640 | 762 | 16 | 640 | 82.5 | 15.7 |
| | DI 560 | 686 | 14 | 560 | 74.3 | 24.3 |
| | DI 480 | 610 | 12 | 480 | 66.0 | 33.0 |
| | DI 440 | 571 | 11 | 440 | 61.8 | 37.4 |

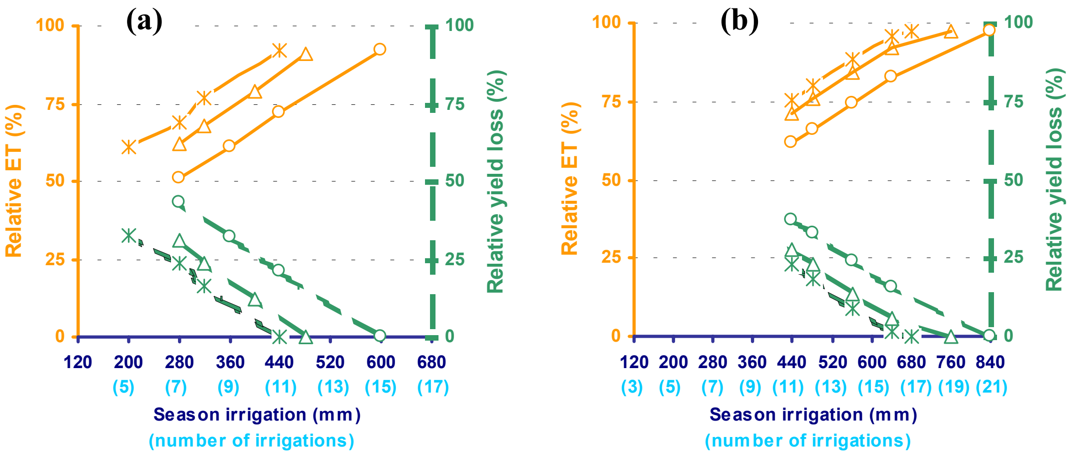

Figure 8 – Response of the tomato crop to different supplemental irrigation strategies in Siliana (a) and in Vigia (b) considering the average (—✳—), high (—△—) and very high (—○—) demand conditions.

Under drought conditions (very high demand) the net irrigation requirements are very high (840 mm), so any reduction in the irrigation amounts that would represent a substantial cut in the crop irrigation demand would lead to a very high yield loss: to reduce from 840 mm to 440 mm induces RYL = 37.4%. Therefore, to adopt deficit irrigation to strongly reduce the crop demand in drought years is difficult and likely is not economically feasible. The option of the farmers is to reduce the cropped area and well irrigate these fields.

## 4 CONCLUSIONS

The analysis above shows that the use of simulation models can be useful to establish and evaluate strategies for supplemental irrigation of cereals or deficit irrigation of horticultural field crops to cope with drought water scarcity. However, these models alone do not provide all the information required for decision making, but are adequate to be coupled or incorporated in a DSS where results of the generated simulation scenarios could be economically evaluated.

Results of this analysis show important differences in responses of crops and respective climatic demand conditions to deficit irrigation. For the wheat crop, which growth season develops during the rainy season, because irrigation is supplemental to rainfall, adopting deficit irrigation is generally feasible, including under high demand conditions. However, deficit irrigation is more easily successful when the crop season is shorter, as it was the case for Siliana comparatively to Vigia.

Irrigation methods also influence the applicability of deficit supplemental irrigation of wheat. For Siliana, results of the water balance simulations show that large reductions in the irrigation amount may impact less the crop yields when surface irrigation is applied than set sprinkle irrigation because surface irrigation uses much larger application depths which favor deep crop rooting and a better use of available soil water. Comparing set sprinkle systems with center-pivot irrigation at Vigia, it was observed that the latter are very appropriate for deficit irrigation when the climatic demand is not high, but not under very high demand. This is justified by the fact that center-pivot systems apply very light and frequent irrigation, thus wetting only a shallow soil surface layer and not favoring deep rooting. Adopting deficit irrigation, that soil layer is quickly depleted and risks for crop failure increase.

The simulated responses of the potato crop to deficit irrigation show that they are very dependent of the crop growth dates. When the crop is planted early, then the crop may use better the winter rains and the soil water at planting may be larger. Then relatively important crop water demand reductions may be achievable without heavy yield losses. On the contrary, if a late crop season is considered, high deficit irrigation strategies produce heavy yield losses, as for the Vigia case study. However, under severe drought conditions when the climatic demand is very high, the benefits of early planting disappear and only mild deficit irrigation looks to be feasible.

For tomato, cropped during the summer, out of the rainy season, every deficit strategy aiming at large reductions in the irrigation amount produces large yield losses, so making it difficult to adopt such water saving strategies. Simulations for both locations produce similar results, indicating that only mild deficit irrigation is feasible for the tomato crop. This is confirmed by the farmers practice, which consists in reducing the cropped area but irrigating well those fields.

## ACKNOWLODEGEMENTS

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