Optimal irrigation of cotton in Northern Greece using AquaCrop: A multi-year simulation study
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Abstract
A hybrid approach for optimizing irrigation was developed and tested via simulation of cotton cultivation in Northern Greece. At any given day during the season the remaining cultivation days were conceptually split into two parts: the five coming days and the rest of the season. Accurate weather forecasts were assumed to be available for the first period, during which only one irrigation event could take place. For the second period, average historical weather data were used as long-term forecasts, and rather than optimizing directly the irrigation events, the decision variables corresponded to a number of soil water levels at which irrigation would be triggered and the corresponding irrigation amounts. This hybrid approach ensured that the number of decision variables remained acceptably small so that the procedure can be computed repeatedly in real time during the season.

Introduction
Cotton is considered in Greece as an important national product and great attention has been given to all the stages of its production, starting from cultivation till the final product, i.e., cotton yarns and fabrics. Greece contributes approximately 79\% of the total EU production, while cotton accounts for 9\% of the country’s final agricultural output, with cultivated areas totaling 350,000 hectares, representing approximately 13\% of the total cultivated land in Greece. However, in Greece, as water over-use has no direct impact on cultivation, farmers tend to ‘be on the safe side’ and irrigate beyond crop water needs, especially when the water tariffs are low. It is considered that typically only approximately 55\% of the irrigation water is used by the crop, 12\% is lost through its transfer, 8\% is lost through its application and 25\% is considered as excessive water, lost through evapotranspiration and surface runoff. Unfortunately, such misuse of irrigation water is not restricted to this specific crop or location, but is rather representative of the low efficiency of water use in agriculture in general. This has led the European Union to fund the project FIGARO (Flexible and precise irriGation plAtform to improve faRm scale water prOductivity) as part of its FP7 Programme. The overall project goal is to improve the use of irrigation water via the development and implementation of irrigation strategies that take into account, in real-time, soil water availability, local weather forecasts, crop physiological status and water needs. The present work focused on the development of an efficient procedure for determining the optimal irrigation schedule for a given crop model, soil and environment. One of the main drawbacks of model-based optimization is that this approach is sensitive to the imperfection of the model and the inaccuracy of the weather forecasts. Accordingly, the model should be improved throughout the season using whatever measurements become available, and the
optimization should be repeated when weather forecasts are updated. The first task, so-called data assimilation, has been considered in a number of studies (e.g. Olioso et al., 2005; Thorp et al., 2010; Fang et al., 2011; Ines et al., 2013) but is still a complex issue which requires great care. This issue was not considered in the present work which rather focused on the development of an efficient optimization procedure which could be executed repeatedly during the season. Cotton cultivation in Northern Greece was used as a case study and the proposed procedure was tested via simulation using ten years of weather data.

Materials and methods

Model
The AquaCrop model (Raes et al., 2009a; Steduto et al., 2009) distributed by the Food and Agriculture Organization (FAO) was selected as the benchmark model for the FIGARO project. With respect to the present study, one of the key features of AquaCrop is that it can be used to generate an irrigation schedule that ensures that the soil water content remains above some threshold specified by the user. This threshold does not need to be constant for the whole season and different thresholds can be defined for different contiguous periods. In this mode of operation the user splits the season into a number of periods and must specify two parameters for each period: the soil moisture at which irrigation is triggered (allowable depletion in mm or % readily available water) and the amount of water to be supplied (absolute amount in mm or replenishment to field capacity + X mm). The output of the AquaCrop simulation includes, in addition to all the variables related to crop development and soil water content, the dates and amounts of the required irrigation events. As detailed below, this "irrigation schedule generator" feature of AquaCrop is central to the optimization approach developed in this work.

Cotton cultivation stages
Cotton growth is divided into three main growth phases:
1. Emergence phase, lasting from day 1 (sowing) until day 14, when almost 90% of the cotton seeds have emerged.
2. Rapid growth phase, lasting from day 15 until day 70, when plants grow fast in terms of new stems and rapidly increasing green canopy cover.
3. Yield formation phase starting on day 71. This phase can be further divided into
   a. Lag growth phase, lasting from day 70 to day 113, when plants keep growing but at a lower rate than in the rapid growth phase, until they reach their maximum height at day 113.
   b. Senescence phase, starting from day 123. During this phase, the canopy cover starts to decline slightly.
   c. Harvesting phase, lasting from day 146 until all the cotton is harvested.

Optimization scheme
The cotton growth stages described above can be used for the estimating the irrigation requirements: During the emergence and rapid growth phases, the root zone water content should be maintained above the canopy cover expansion level. Such a policy aims at achieving a canopy cover equal to approximately 90% of the maximum at day 70 (end of the rapid growth period and beginning of the lag growth period), thus improving the harvest index (HI) by 4-5% compared to its no-stress reference value. From day 71 (start
of flowering period) and until the end of the cropping season, the total available water (TAW) in the root zone should be retained roughly 25% above permanent wilting point. This way, the optimum harvest index may be achieved without a failure of pollination or any adverse effects on the green canopy cover.

Clearly, such considerations provide only general guidelines around which adjustments should be made to ensure optimal results. Accordingly, for the initial optimization the season was divided into these five periods, each with two parameters to be optimized: the water content at which the irrigation is triggered and the amount of water provided by irrigation. Mathematically:

\[
\text{Find } (t_1, r_1, t_2, r_2, t_3, r_3, t_4, r_4, t_5, r_5) \text{ such that } Y \to \text{maximum} \quad (1)
\]

where \( t_i \) denotes the soil water content at which irrigation is triggered during period \( i \), \( r_i \) denotes the amount of water provided at each irrigation event during the period \( i \), and \( Y \) denotes the yield. If relevant, inequality constraints corresponding to monthly or seasonal quota can be added to this simple formulation.

The optimization problem can also be formulated as a multi-objective optimization problem which emphasizes the trade-off between two conflicting objectives: maximizing yield and minimizing the use of irrigation water. This formulation has the advantage that it does not yield a single optimal solution but rather a series of solutions which are equally optimal in the mathematical sense but emphasize the trade-off between water use and yield. These solutions can be presented to the farmer who can then decide which one to implement.

Splitting the season into periods during which the soil water depletion at which irrigation is triggered and the irrigation amounts are constant has the advantage that the optimization problem includes only a small number of decision variables (ten in the present case). Unfortunately, this formulation does not provide much flexibility since the strategy remains constant during each period and future rain is not taken into account when triggering irrigation. However, optimizing individually the amount of irrigation water for each day of the season would be prohibitive computation-wise, especially when one considers that the optimization should be repeated numerous times throughout the season.

The proposed approach tackles this problem via a hybrid formulation of the optimization problem. Starting at the current day \( D \) the remaining season is split conceptually into 2 periods:

- **Period A**, from day \( D \) to day \( D + \Delta \), during which it is assumed that there is at the most one irrigation event. There are therefore 2 decision variables associated with this period: The date of the irrigation event \( (\delta, \text{ measured from the current day } D) \) and the amount of water provided, if any, denoted \( I_{\delta} \).

- **Period B**, from day \( D + \Delta + 1 \) to the end of the season, during which the irrigation schedule is generated using the "threshold approach" described above. The number of decision variables associated with this period is \( 2*(N_s + 1) \) where \( N_s \) is the number of switching points between periods \( q \) and \( q + 1 \) remaining until the end of the season. Initially there are 4 switching points (Days 15, 71, 114 and 146).

In terms of the AquaCrop simulation, each simulation requires performing three consecutive runs of the model:
Run #1: From day 1 to day $D - 1$, starting from the initial values of the state variables and simulating the crop development and soil water content with the irrigation implemented up to the present day. The end-result of this simulation provides the initial conditions for Run #2.

Run #2: From day $D$ to day $D + \Delta$, in which the irrigation event $[\delta, I]$ is implemented. The end-result of this simulation provides the initial conditions for Run #3.

Run #3: From day $D + \Delta + 1$ to the end of the season, in which the irrigation events are generated by AquaCrop using the decision vector $[t_1, r_1, \ldots, t_5, r_5]$ supplied by the user.

In the unrealistic case where perfect weather forecasts are assumed to be available for the whole season, the appropriate intervals of these forecasts are used for all three runs. If, more realistically, only imperfect forecasts are available, Run #1 is performed with the actual weather while forecasts must be used for Runs #2 and #3. However, the forecasts need not to be the same for these two runs. If $\Delta$ is in the order of a few days, it is reasonable to assume that much more accurate short-term predictions are available for this period than for rest of the whole season. This is shown schematically in Figure 1. The value for $\Delta$ should be chosen based on hydrological considerations (since only one event is assumed to take place during this period of $\Delta$ days) as well as on weather forecasting considerations.

As emphasized before, this optimization procedure does not produce a single optimal solution but a set of optimal solutions. For the sake of the study, it was assumed that the farmer would implement the solution which predicts a yield closest to his desired target.

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**Figure 1: Hybrid optimization timeline**

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**Experimental data**

Ten years of historic meteorological data (2004-2013) were used for AquaCrop simulation runs in this study. Data were collected from the Democritus University of Thrace meteorological station (Xanthi, Greece. 41.13°N, 24.91°E), which records parameters such as air temperature, barometric pressure, precipitation, wind speed and direction, relative humidity, and incident solar radiation with a 10-minutes time step. From this dataset, the cumulative daily precipitation values were extracted and the daily mean, minimum and maximum values of the remaining parameters were computed. Daily evapotranspiration was calculated through the FAO’s ETo calculator which is based on FAO 56 -Penman-Monteith equation.

The soil profile used in the Aquacrop simulations comprised of two soil horizons and is considered to be representative of the broader Xanthi plain area in Northern Greece. The upper horizon was characterized as a sandy loam layer, extending from the surface down to a depth of 30 cm, and the second horizon as a clay loam, extending from the interface
to 180 cm depth. This characterization was based on soil textural class analysis performed in a pilot cotton field in the area. The hydraulic soil parameters required by the model are presented in Table 1.

The crop file used for the simulations was a modified version of the cotton model included in the AquaCrop package. The modifications (the plant density, the minimum effective rooting depth ($Z_{n}$) and the number of days required for maximum rooting depth ($Z_{\text{max}}$)) were based on measurements and observations at a pilot cotton field in the area and are summarized in Table 2.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Saturation (%)</th>
<th>Field Capacity (%)</th>
<th>Permanent Wilting Point (%)</th>
<th>Saturated Hydraulic Conductivity $K_{\text{sat}}$ (mm/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>43</td>
<td>22</td>
<td>10</td>
<td>93.1</td>
</tr>
<tr>
<td>30-200</td>
<td>50</td>
<td>42</td>
<td>27</td>
<td>239.2</td>
</tr>
</tbody>
</table>

Table 2. Modified crop model parameters

<table>
<thead>
<tr>
<th>Plant Density (plants/m$^2$)</th>
<th>$Z_{n}$ (cm)</th>
<th>$Z_{\text{max}}$ (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>12</td>
<td>0.3</td>
</tr>
<tr>
<td>Modified</td>
<td>20</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Results

The weather conditions of the last ten years were used to investigate three scenarios differing in terms of the weather data used in the optimization procedure:

- Scenario #1: perfect weather forecasts available for the whole season
- Scenario #2: perfect weather forecasts available daily for the five coming days (Run #2) and historical weather data available for the rest of the season (Run #3).
- Scenario #3: only historical weather data available for future (Runs #2 and #3).

In all three cases, the optimization was repeated every four days, using the algorithm described in Herrero et al. (2007). The historical weather data consisted of the average of the daily values recorded during the 2004-2013 period. From a practical point of view, Scenario #1 is unrealistic but it provides the best achievable solutions to which the results of the other two scenarios can be compared. Scenario #2 corresponds to the case in which very reliable short-term forecasts are available. Scenario #3 corresponds to the extreme case in which no reliable short-term weather forecasts are available and one has to rely on historical data. Scenarios #2 and #3 correspond to the extreme cases which can be encountered in real-world applications. The constant improvements of short-term forecasting tools, together with the fact that the availability of these forecasts on the internet is rapidly expanding, is likely to make Scenario #2 increasingly relevant in the future.

The analysis was conducted assuming that the farmer wishes to achieve a yield of 4.50 t/ha. The results are summarized in Figure 2. For comparison, the boundary of the optimal solutions obtained by full optimization of the daily irrigation amounts (Ioslovich, private communication) is also shown in Figure 2. When perfect forecasts were assumed to be available for the whole season, recalculating the hybrid optimal solution every four days produced a final [irrigation, yield] combination which was very close to the one obtained
by full optimization of daily irrigation amounts (empty symbols and solid lines, respectively). Assuming perfect 5-day forecasts led to results which remained close to the optimality boundary (shaded symbols): in most years, the irrigation was within 30 mm of the "true" optimal irrigation, and yield was decreased slightly or increased sometimes appreciably. As expected, worse results were obtained when historical weather was used for the whole future (filled symbols). The largest deviations were observed for 2012 and these poorest results can be explained by the rain pattern in that year. Figure 3 shows that 2012 precipitations were very low during the first 85 days but strong rain events between days 88-92 brought the cumulative precipitations to within 40 mm of the multi-year average. In Scenario #1 (perfect forecasts), the irrigation planning took into account this abundant rain late in the season and minimized irrigation during the first 80 days. On the other hand, in Scenarios #2 and #3, the almost total lack of rain during the first 2.5 months led to an expected deficit of up to 100 mm which was compensated by significant irrigation (all irrigation took place within the first 80 days).

Conclusion

An efficient hybrid approach for optimizing irrigation has been developed and tested via simulation. The rationale for the proposed approach is that since the long-term weather forecasts are inaccurate, one doesn't need to perform a detailed optimization of all future irrigation events but can rather optimize only the next event together with soil water content levels at which irrigation would be triggered in the future. In this fashion, the number of decision variables that need to be optimized remains acceptably small and the irrigation schedule can be computed repeatedly during the season using updated weather forecasts. The approach was tested for cotton cultivation in Northern Greece using ten years of weather data and in most cases this approach yielded a final [irrigation, yield] result which was close to the "true" optimal result obtained assuming perfect weather forecasts and optimizing all daily irrigation events.

The present study did not consider infield spatial variability, which would occur for instance due to soil inhomogeneity. The simplest way to address this issue would be to consider that the field has been divided a priori into management zones which are assumed to be homogeneous and managed independently from each other. In this case the proposed approach could be applied to each zone. A more complex but probably more realistic assumption would be that the different zones can not be management completely independently of each other, or the delineation of management zones could be made in integral part of the optimization. Both approaches should be investigated in future work.

Acknowledgements

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Figure 2: Optimal [irrigation, yield] combination assuming perfect weather forecasts (empty symbols), 5-day perfect forecasts (shaded symbols) and using only historical weather (filled symbols). The solid line corresponds to the optimal front calculated by optimizing daily irrigation events (Iosovich, private communication).
Figure 3: Cumulative rain during the simulation period (starting April 15)

References


