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Optimal model-based deficit irrigation scheduling using AquaCrop: A simulation study with cotton, potato and tomato

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ABSTRACT

Water shortage is the main limiting factor for agricultural productivity in many countries and improving water use efficiency in agriculture has been the focus of numerous studies. The usual approach to limit water consumption in agriculture is to apply water quotas and in such a situation farmers should use an irrigation schedule that maximizes the yield and abides to the quota constraints. In contrast to the widespread use of irrigation scheduling based on agronomy practices, irrigation scheduling may be considered as a constrained optimization problem. When drip irrigation is used, the decision variables are the irrigation amounts for each day of the season. The objective function is the expected yield calculated with the use of a model. In the present work we solved this optimization problem for three crops modeled by the model AquaCrop. This optimization problem is non-trivial due to the non-smooth behavior of the objective function and the fact that it involves multiple integer variables. We developed an optimization scheme for generating sub-optimal irrigation schedules that take implicitly into account the response of the crop to water stress, and used these as initial guesses for a full optimization of daily irrigation. Performing this optimization with various values of water quotas produced the function that expresses the relationship between water quota and yield.

1. Introduction

Water resources are over-exploited in most European countries and agriculture has often been singled-out as one of the sectors most wasteful water-wise. It is well established that timely irrigation can substantially increase irrigation efficiency and water productivity (Molden, 2003; Zwart and Bastiaanssen, 2004; Fereres and Soriano, 2007; Battilani et al., 2004, 2015; Ahmadi et al., 2010; Jensen et al., 2014), and many studies have considered the development of decision support systems (DSS) which could help farmers use irrigation water more efficiently (e.g. Lee et al., 1991; Epperson et al., 1993; Plauborg et al., 1996; Battilani and Ferreres, 1999; Shani et al., 2004; McClendon et al., 1996; Ioslovich et al., 2012). Although the earliest studies relied on so-called water production functions, these static empirical functions could be replaced advantageously by dynamic models which simulate crop development and production under a wide range of environmental conditions. If such a crop model is available, constrained non-linear optimization can be used to derive the irrigation schedule which is optimal in some sense for a given environment.

The crop model is a key component for such an approach, as it must obviously describe the crop development and production sufficiently well but it should not be too complex or involve lengthy computations. With this respect the model AquaCrop (Steduto et al., 2009; Raes et al., 2009) distributed by FAO offers a good compromise between accuracy and simplicity. Furthermore, this model has been parametrized for over 15 crops at different locations. A number of studies have shown that AquaCrop is an effective tool that can predict with reasonable accuracy both total biomass and final yield in response to various irrigation strategies - from no water stress to mild (or in some cases severe) water stress (Battilani, 2006; Garcia-Vila et al., 2009; Mkhabela and Bullock, 2012; de la Casa et al., 2013; Katerji et al., 2013; Wellens et al., 2013; Rankine et al., 2015). The model includes the soil, with its water balance, the crop, with its growth, development and yield, and the atmosphere, with its thermal regime, rainfall, evapotranspiration, and carbon dioxide concentration. The model does not include underlying

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hierarchical processes simulating the intermediary steps leading to biomass accumulation, and as a result the model structure is simple and it includes relatively few crop-specific parameters.

Having recognized the advantages of AquaCrop, a number of researchers have investigated the use of this model for developing irrigation strategies. For instance, in a study related to quinoa in Bolivia, Geerts et al. (2010) used historical climate data to derive optimal frequencies of irrigation (time interval of a fixed net application depth) to avoid drought stress and guarantee maximum water productivity. They summarized their results in simple charts appropriate for policy makers, extension specialists or farmers. Garcia-Vila et al. (2009) and Garcia-Vila and Fereres (2012) combined AquaCrop with an economic model to investigate the impact that could be expected from measures such as imposing water quotas or increasing water prices. A key element in these studies was the relationship between the applied irrigation water (AIW) and yield. These relationships were obtained by trial and errors (Garcia-Vila et al., 2009) or based on expert knowledge (Garcia-Vila and Fereres, 2012). In the present work we show how nonlinear constrained optimization can be used to derive these functions automatically in a rigorous manner.

2. Materials and methods

2.1. Problem formulation

The problem of optimal deficit irrigation is formulated as follows:

$$\begin{aligned} J \;=\; & Y(w_{1,1},\ldots,w_{m_1,1},w_{1,2},\ldots,w_{m_2,2}\ldots,\\ & w_{1,p},\ldots,w_{m_p,p}) \quad [t/ha] \rightarrow \max \end{aligned}$$

subject to

$$w_{1,k}+w_{2,k}+\cdots+w_{m_k,k} \le W_k \quad [mm],$$

$$\sum_{k=1}^{p}\sum_{i=1}^{m_k} w_{i,k} \le W \quad [mm].$$

Here Y denotes the yield, k is the month index, $w_{i,k}$ is ith irrigation for month k, m_k is the number of irrigation events in month k, W_k is a monthly quota for month k, and W is a seasonal quota. If p months are included in the season, the linear matrix of inequality constraints consists of $p+1$ rows: one row for each month and one row for the whole season.

The maximum yield that can be achieved with a given seasonal quota W is determined by running a simulation model which predicts the crop development in response to environmental variables (AquaCrop in the present case). After obtaining these solutions for a set of values of W, the maximum yield can be plotted as a function of W and this function can be used for planning purposes both by farmers and water authorities.

Note that in addition to the seasonal optimization presented above, it is possible to formulate a very similar optimization problem for a specific month when the water demand of a crop is maximal and thus quota constraint is often violated. In this case the decision variables are the values of daily irrigation for this month while the irrigation schedule for the rest of the season remains unchanged. The results of this problem can be used for irrigation management or for investigating reallocation of water quotas between different months. More details about this particular application can be found in Ioslovich et al. (2014).

2.2. Optimization

Given environmental conditions and initial conditions for soil moisture and crop size, the AquaCrop model predicts yield in response to irrigation. This function is non-convex and even non-monotonous and non-continuous, which makes it far from ideal for optimization purposes. In addition, irrigation in AquaCrop is represented by integer variables, which restrict the choice of potential solvers. We have chosen to use the TOMLAB optimization library for MATLAB and tested different solvers (see http://tomopt.com/tomlab/). The best results were obtained by the use of the OQNLP solver in combination with the qlcAssign procedure for global nonlinear search. The OQNLP solver realizes a smart multistart heuristic algorithm in conjunction with smooth optimization to search for a global optimum of nonlinear constrained optimization. This approach requires supplying the solver with a program that calculates the nonlinear objective function (yield in the present case). This program writes the irrigation schedule in the appropriate file, invokes AquaCrop from within MATLAB and then reads the output file generated by AquaCrop. Different linear constraints such as total seasonal irrigation water or monthly quotas for all or chosen months can be readily implemented. Throughout the optimization search, all intermediate improving and feasible results were recorded and the best result was retrieved after the predefined number of iterations. As mentioned above the procedure was executed a number of times with different values of W.

Although AquaCrop requires integer irrigation amounts, the optimization was performed in continuous mode because the mixed-integer option did not yield good results. This was done using a custom scaling procedure in which the vector of irrigation values was multiplied by 10^{-6} before transferring it to the solver and then scaled back before being transferring it to AquaCrop. The linear matrix of constraints was modified accordingly. The rounding of the variables received from the solver in float format was done with a special stochastic procedure which considered the non-integer part as a value of a probability distribution function generating 0–1 values from a random numbers generator.

2.2.1. Initial guesses

In most optimization problems, the starting points for the optimization procedure must be chosen with care, especially if, as in the present case, the model is highly non-linear. Therefore, we developed a generic method for obtaining 'good' sub-optimal points from which the optimization was started. This method was based on two features of AquaCrop:

1. Yield formation is controlled via the 'Harvest Index (HI)', which determines the partition between biomass and harvestable material (Raes et al., 2009). Each crop is characterized by a reference (no-stress) HI which is adjusted (upward or downward) in response to various stresses. The relationship between HI and stresses is crop-dependent and varies with crop development stage. More specifically, with respect to water stress, before flowering or yield/tuber formation stage, HI may be affected positively by reduced vegetative growth. During flowering and yield/tuber formation, HI may be affected positively by reduced leaf expansion and negatively by stomatal closure. The time-varying soil water contents corresponding to the onset of these stresses are calculated during the AquaCrop simulation and are available in the output file generated by AquaCrop.
2. AquaCrop can be used to generate an irrigation schedule by specifying the (time-varying) allowed water depletion level (at which irrigation is triggered) and the replenishment level (or the irrigation amounts). In this mode, AquaCrop generates an irrigation file which contains the irrigation dates and the corresponding irrigation amounts.

Based on the above, the season was split into five (or in some cases four) periods during which the irrigation amounts and the soil water contents at which irrigation was triggered remained constant