Optimal Irrigation Scheduling and Crop Production Functions Development using AquaCrop and TOMLAB

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Abstract: Water stress is one of the most influential factors contributing to crop yield loss. The importance of the irrigation constantly increases because of water scarcity and growing demand for agricultural production worldwide. Previously, an approach using empirical water production functions and analytic optimal control methodology has been developed for optimal irrigation scheduling. Such an approach based on numerical optimal control is an alternative to common irrigation scheduling based on agronomy practice. Nowadays, more complex dynamic crop simulation models, such as the FAO AquaCrop model, predict crop responses to different irrigation strategies and climates. The state variables of the AquaCrop model include crop characteristics, such as biomass, and soil water content in up to 12 soil layers. In this paper the numerical optimal control scheme for irrigation scheduling and crop water production function development is described and demonstrated using this model and the TOMLAB optimization library. Maize crop in Foggia, Italy, for season of the year 2000, is used as an illustrative case study.

1 INTRODUCTION

In order to cope with increased water scarcity and hence limited water supply, the development of methods to produce efficient irrigation scheduling is an important task. Many studies were performed in this area during decades. For instance, the effects of the supplemental irrigation for wheat in the region of Aleppo, North Syria, were investigated in (Oweis et al., 2003) using the simulation model ISAREG. Different water policies to cope with water shortage were studied in (Amir and Fisher, 2000) for the case of Jezreel Valley district, Israel, using linear programming optimization model. Analytical optimal control was used in (Shani et al., 2004), (Shani et al., 2009), (Ioslovich et al., 2012), in conjunction with the simplified STZ model. This model has only two state variables: biomass of the crop and water content of the soil. The harvest index HI (percent of the yield to the biomass) was assumed to be constant. No precipitation was considered and the climate inputs were assumed to remain constant. By comparison, the FAO model AquaCrop described in (Steduto et al., 2009), (Geerts et al., 2009), (Geerts et al., 2010), (Heng et al., 2009), (Xiangxiang et al., 2013) is much more detailed and mimics crop development much more closely. This model has several mechanisms of stresses, up to 12 soil layers and accept time-varying climate inputs. It has been used with averaged statistical measurements for development of crop-water production functions in (Garcia-Villa and Fereres, 2012). However these data concerned the use of the irrigation water were connected only with existing agronomic practice without any prospects on its optimization. Model based optimization of irrigation scheduling with AquaCrop and genetic algorithms has been presented in (Linker et al., 2013) for cotton in the Northern Greece.

Here we consider the optimal control scheme for maximization of the yield within given irrigation water quota and development the crop-water production function based on the set of these optimizations. The example of a maize crop in the Foggia region, Italy, season 2000 is presented.

2 PROBLEM FORMULATION

The considered formulation of the problem of optimal irrigation scheduling is as follows:

$$J = Y(w_1, w_2, \ldots, w_i, \ldots, w_n)\ [t/ha] \to \max$$
$$w_1 + w_2 + \ldots + w_i + \ldots + w_n \leq w\ [mm]. \quad (1)$$

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Here Y is a value of yield, w_i is daily irrigation for day i, and w is a seasonal irrigation water quota. This is a discrete analog of the optimal control problem as follows:

$$\begin{aligned} &J = \int_{t_0}^{t_f} f_0(t, w(t), x(t), t)dt \to \max \\ &\frac{dx}{dt} = f(t, w(t), x(t)), \\ &\int_{t_0}^{t_f} w(t)dt \leq w. \end{aligned} \tag{2}$$

However the functions f_0 and $f(t, w(t), x(t))$ are not known and only the value of the functional J in response to the seasonal sequence of the irrigation events w_i can be obtained from the AquaCrop simulation.

The AquaCrop predicts the seasonal crop development in response to environmental variables and irrigation. By calculating the set of these solutions with gradually decreasing seasonal water quota w we can construct the crop-water production function $y(w)$ which can be used for planning purposes both by farmers and by water authorities.

3 CROP MODEL

The FAO Aquacrop model is widely used by many users including farmers, water managers and agricultural consultants. It represents a good balance between accuracy, simplicity and robustness. The AquaCrop model adequately simulates the canopy cover, evapotranspiration, yield, and water content in the soil. It has been successively calibrated and tested for different crops such as cotton, wheat, tomato, potato at different locations. Several algorithms have been included in the AquaCrop that allow the user to generate irrigation scheduling based on triggering irrigation at user-specified soil water contents, which should be linked to crop growth stage via the user agronomic considerations and experience. Many details concerning this model can be found in (Steduto et al., 2009), (Geerts et al., 2009), (Geerts et al., 2010), (Heng et al., 2009), (Mkhabela and Bullock, 2012), (Xiangxiang et al., 2013). Though the underlying principles of the AquaCrop are well described, the source code of the model is not available to users, and thus it can be used only as a sort of black-box model.

4 OPTIMIZATION SOLVER

We are using the TOMLAB optimization library for MATLAB, (Holmstrom et al., 2007), that contains many optimization solvers. The best results were obtained by the use of *OQNLP* solver in combination with the *qlcAssign* procedure for global nonlinear search. A special interface with the AquaCrop model software was designed and used. 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 that we supply the solver with a program that calculates the nonlinear objective function (yield in our case). This function writes the irrigation schedule in the appropriate file, runs the AquaCrop from MATLAB and then reads the output file generated by AquaCrop. The linear constraint which represents the total seasonal irrigation water sum is used. Throughout the optimization search, all intermediate improving and feasible results were recorded and the best result was retrieved after the predefined number of iterations was reached. The *qlcAssign* procedure handles problems of the form

$$\begin{aligned} &c(x) \to \min \\ &b_L \leq Ax \leq b_U, \\ &x_L \leq x \leq x_U. \end{aligned} \tag{3}$$

The constraints b_U are used as an upper limit for daily level of the irrigation. Although AquaCrop requires integer irrigation amounts, the optimization was performed in continuous mode because the mixed-integer option did not yield good results. In order to do this we have used a scaling procedure by multiplying the vector of irrigation values by 1E-6 before transferring it to the solver and then scaling it back before transferring it to AquaCrop. The linear matrix of constraints has to be modified accordingly. The rounding of the variables received from the solver in float format was done with a special stochastic procedure which considers the non-integer part as a value of a probability distribution function (PDF) which generates values in the range $0-1$ from a uniform random numbers generator (MATLAB function rand).

The choice of the initial point for optimization plays an important role. We have used the approach reported in (Linker and Ioslovich, 2015). This approach, which has proved to be very efficient, generates sub-optimal irrigation schedules via optimal levels of soil water depletion at which irrigation is triggered.

5 OPTIMIZATION SCHEME

The optimization scheme for optimal irrigation scheduling with the AquaCrop and *OQNLP* consists of the following steps:

1. The initial point (seasonal irrigation sub-optimal schedule is calculated).
2. The AquaCrop runs the initial irrigation schedule and a special interface transforms the irrigation schedule into initial data for *OQNLP*
3. The *OQNLP* starts and invokes the users non-linear objective function. The objective function writes the AquaCrop irrigation file, invokes the AquaCrop, reads the AquaCrop output file, provides the *OQNLP* with objective function value, and stores the values related to the best record.
4. The *OQNLP* generates the next optimization point and continues until the given number of iterations is exceeded or *OQNLP* ends the execution because the convergence criteria has been met.

6 CROP-WATER PRODUCTION FUNCTION

The constraint related for the seasonal water quota is gradually decreased and a set of optimizations is performed. This way a number of points in the plane w,Y is obtained. The convex hull of the set of these points is constructed up to the point with maximal Y and the points of the vertices of this hull are then used to construct the crop-water production function for this crop. A second-order polynomial is used to fit these vertices. Unlike *e.g.* in (Garcia-Villa and Fereres, 2012) which used so-called "best agronomic practice" this production function represents the optimal irrigation scheduling.

7 RESULTS FOR MAIZE IN FOGGIA

The results for maize crop in Foggia region, Italy, season 2000, are shown in Fig. 1 and Fig.2. The simulated period is 138 days long started on 22 of March 2000. Fig 1. represents the optimal irrigation schedule for the water quota 120 [mm]. There are 5 irrigation events throughout the season. The Fig. 2 shows the crop-water production function together with the convex hull vertices marked by '*', the approximated points marked by 'o', and suboptimal points marked by '+'. One can see that the mean increase in yield gives about 10 [kg/ha] of yield per 1 [mm] of irrigation. The table 1 shows the data corresponding to the basic points.

Table 1: Basic points of the crop-water production function for seasonal irrigation. Maize irrigation in Foggia, 2000.

Basic point	Quota [mm]	Yield [t/ha]	HI
1	11	11,506	48,3
2	27	11,821	48,3
3	44	12,095	48,3
4	59	12,266	48,4
5	89	12,483	48,3
6	120	12,588	48,3

One can notice that the harvest index *HI* is rather the same for all the basic points, which indicates that while the biomass is limited by the water quota, the value of the yield for the optimal irrigation takes rather the same part of the total biomass for different quotas.

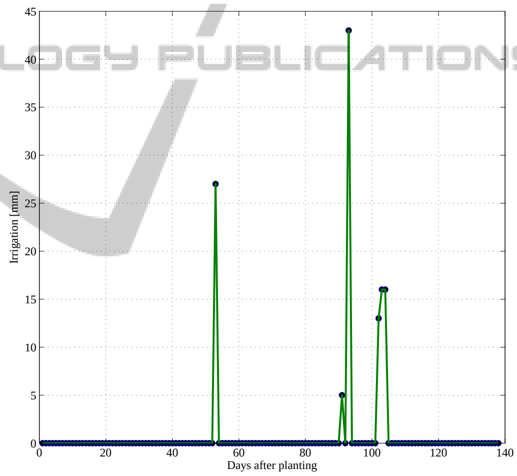

Figure 1: Optimal irrigation scheduling for seasonal irrigation quota 120 [mm]. Maize in Foggia, Italy, year 2000. Irrigation levels marked as 'o'.

8 CONCLUSIONS

The optimization of the irrigation scheduling may be performed using the optimal control scheme and the Aquacrop model as demonstrated in this paper. The agronomic knowledge is already incorporated in the model and can be used in a limited way by supplying of the reasonable initial point for these calculations. The crop-water production functions can be developed based on the optimal irrigation scheduling for different water quotas. This approach has been demonstrated for a maize crop in the Foggia region, Southern Italy, season 2000.

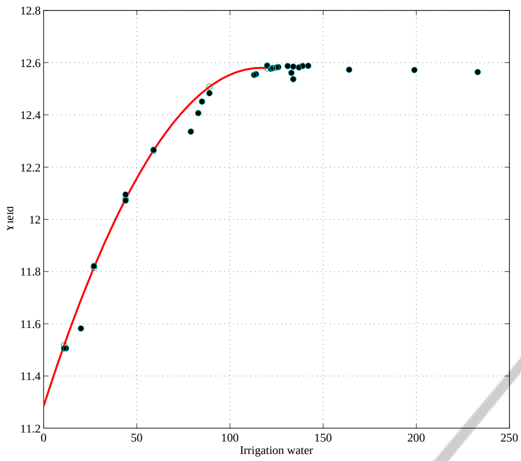

Figure 2: Crop-water production function. Yield [t/ha] vs. irrigation water [mm]. Maize in Foggia, Italy, year 2000. Suboptimal points marked as black 'o', basic points of the convex hull marked as '*', points from quadratic approximation marked as 'o'.

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