Optimization of Cotton Irrigation using Evolutionary Algorithm and Simulation Model

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ABSTRACT

The optimal management of irrigation is a principal constraint facing agriculture worldwide. The potential number of combinations of irrigation schedules over a growing season is enormous when the variables involved are considered. Theoretically, on any given day during a cropping season, a decision can be made to irrigate or not. This associated with specific irrigation amounts and methods. The outcome of a decision and the nature of future decisions is a function of the status of the crop at any given decision point. Thus, there are an extremely large number of potential irrigation schedules for any given crop season. Evolutionary algorithms are computer based optimization and search techniques that mimic natural selection to efficiently search very large solution spaces. They are based on the biological concepts of evolution through mechanisms such as selection, crossover and mutation. Cotton irrigation scheduling (timing and amount of water) can be approached as an adaptation problem. In this study a cotton simulation model (GOSSYM) was integrated with an evolutionary algorithm to provide irrigation recommendations to farmers. The results show that this approach to irrigation scheduling is an improvement over the expert system currently associated with the model. This evolutionary algorithm consistently derived irrigation itineraries that resulted in higher economic return. More interesting, this new approach is also generic and it is applicable to other cultural practices and to any cropping situation.

Introduction

Quantitative, mathematical computer-based simulation models are common in decision making. The decision-making process relies on using the model as a surrogate for real experimentation. Recently other modes of model-based decision-making have been investigated. Indeed, some of the early leading ideas in modern biology (the mechanisms underlying the processes of evolution, for example) are re-emerging in the bio-sciences and finding innovative applications in agriculture through the discipline of Artificial Intelligence (AI). This is the case of evolutionary algorithms, such as the Genetic Algorithms technique. Genetic Algorithms (GA) are computer based optimization and search techniques that mimic natural selection to efficiently search very large solution spaces. They are based on the biological concepts of evolution through mechanisms such as selection and genetic crossover and mutation. The sequence of farmer practices and the level of the input (e.g., amount of irrigation) can be seen as an adaptation problem. With this approach, it becomes obvious that GAs may have a role in decision-making for farmers. The main objective of this study was to develop a new approach for irrigation optimization, using a crop model and an evolutionary algorithm.

Materials and Methods

One objective of this study was to compare irrigation recommendations made with a strong AI technique, the COMAX expert system, with recommendations made using a weak AI technique, an Evolutionary Algorithms (EA, here a GA with the crossover rate set to zero). Both systems are described.

The GOSSYM-COMAX System. GOSSYM, a well-tested and widely known cotton simulation model, was used in this study for practical reasons. However, the linkage of AI techniques with crop models is applicable to any cropping situation. GOSSYM is a dynamic, daily simulation of the development and growth of the cotton plant. Baker *et al* (1983), Jallas (1991) and Sequeira and Jallas (1995) published the descriptions of the theoretical background and most mathematical functions. GOSSYM output includes graphs of the daily mass accumulation and number of organs produced for different plant parts. Additionally, soil Nitrogen, soil water, stress factors, leaf area index, weather summaries, and other variables are also in the output. COMAX is a decision support system coupled by McKinnion and Lemmon (1985) with GOSSYM. Bridges (personal communication) later re-engineered this expert system and today provides users with expert decision support. GOSSYM, the simulation component in the GOSSYM-COMAX system, simulates the daily behaviour of the crop based on user input. If the user wants the system to provide advice as to irrigation, nitrogen, or plant growth regulator use, he can use the COMAX decision support system. COMAX uses an expert system rule base to determine the optimal actions to perform, given a projected or set of projected weather scenario. If COMAX has been invoked, COMAX monitors the GOSSYM simulation in order to detect stress symptoms. If COMAX detects stresses, it may recommend different practices to solve the problems. COMAX output includes recommendations for irrigation, nitrogen use, and for the application of plant growth regulators. COMAX proposes three kinds of irrigation advisors: a short-term irrigation advisor that informs the user if the crop needs irrigation within the next two weeks, a long-term irrigation advisor that develops an irrigation schedule for all of the growing season, and finally, a water conservation advisor that make its recommendations based on the evaporative demand of the crop. All these advisors derive their recommendations based on multiple GOSSYM simulation runs and use an average value of -0.5 bars for soil water potential as a trigger for the initiation of irrigation. The rule for deciding whether to apply irrigation can be summarized as follows:

If: today the current soil water potential is less than -0.5 bars and,

If: today's date is greater than or equal to the first day to consider irrigation, and today's date is less than or equal to the last day to consider irrigation, and the minimum number of days between irrigations has elapsed since the last irrigation,

Then: make an irrigation application.

The main difference between the long-term advisor and the water conservation advisor is that the long-term irrigation advisor will always apply the maximum application amount of water specified by the user. In contrast, the water conservation advisor will use the evaporative demand simulated from a first run of the model to determine the amount of irrigation that should be used for each application.

The Genetic Algorithms. Briefly described, GAs involve techniques called representation, selection, reproduction (including crossover, mutation, and inversion), and replacement. In GAs, possible solutions to a problem are often represented as bit strings (although many alternative representations are used). The representation of a possible solution is called a "chromosome". The representation of a parameter is called a "gene". Each chromosome represents an approach to solving the problem. Since any proposed solution to a problem may be rated as better or worse than other solutions, each chromosome has a comparative rating. This rating, the value of an individual chromosome relative to others, is often referred to as the "fitness value" of the chromosome. GAs manipulate chromosomes with evolutionary operators (selection, cross-over, mutation, inversion, and replacement) and "evolve", generation after generation, better solutions, tending towards improvement/adaptation as the evolutionary process continues (Goldberg, 1989). In the irrigation optimization problem the methodology was to use the EA to evolve chromosomes which represented irrigation amounts and dates. Each chromosome was constructed with 200 genes that represented the amount of irrigation from day 1 after emergence until day 200. The daily amount irrigation was allowed to vary from 0 to 1.25 inches. This range was divided into 32 increments of 1.25/32. Thus each gene was coded on 5 bits and each chromosome was composed of 1000 bits. These values were passed to the GOSSYM model that returned the projected yield based on the irrigation recommendations. The fitness function was determined by our specific problem, and simply corresponded to the economic value of a given irrigation schedule because the goal for both, the EA and the COMAX expert system, was to adjust irrigation scheduling to optimize profit. This value was the difference between the cost of the irrigation and the direct gain procured by it. The fitness function was:

$$\text{fitness} = \text{yield} \left\{ \text{number\_irrigation} * 3.5 + \sum_{i=i}^{\text{end of season}} H_2O(i) \right\}$$

where fitness is the fitness value, yield is the simulated yield (in pounds of fiber per acre), number irrigation is the number of irrigations scheduled, 3.5 is the cost per acre of one irrigation in pounds of fiber, and $H_2O(i)$, is the amount of water for the i-the day in inches. Technical constraints for irrigation were included as part of the reproduction process through the form of "lethal genes": chromosomes containing impossible irrigation instructions were eliminated and replaced with other chromosomes. When the EA was stopped, the chromosome with the highest fitness value represented the "best" irrigation schedule for the environmental conditions of the experiment. The code used for the EA was a modified version of the GENESIS code, which is a Genetic Algorithm (GENESIS © 1986, 1990 by John J. Grefenstette, in: Davis, 1991).

Experiments. Experiments were made with a weather scenario based on Mississippi conditions, a Commerce type soil (composed of three horizons with no water table) with a common initial soil condition, and a technical itinerary corresponding to the environmental conditions (Jallas, 1998). Table 1 summarizes this technical itinerary for the simulated field. The variety used represented "mid-season" cultivars, that is, cultivars with a season duration of 140 days. The row spacing used was standard for mechanically cultivated cotton (around 120,000.00 plants/ha or 50,000 plants/acre). Fertilizer was broadcast on three different dates using a urea-ammonium nitrate (UAN) formulation because the model simulates only the effect of nitrogen fertilizer.

Results and Discussion

In order to ascertain the complex effects of rain, two kinds of experiments were conducted, one using the observed weather pattern including rain (WR), and the other using the observed weather pattern with the rain events (and any water other than residual in the soil) removed (NR). The best irrigation schedule evolved by the EA was compared to the irrigation schedule obtained from the COMAX system running under the same environmental conditions.

Results from the COMAX Expert System. Two water management strategies were selected to initialize COMAX: long term (LT) and water conservation (WC). As expected, when the maximum possible amount of irrigation increased, the total number of irrigations decreased from 19 to 6 using the LT strategy and from 19 to 16 using the WC strategy. The maximum yield was obtained with about the same maximum amount of irrigation (between 50 and 63 mm) in both “cases”, without water and with rain. The maximum yield was a higher (1944 versus 1703 kg/ha) in the case without rain than in the case with rain. This result is linked to the indeterminate nature of the cotton plant: in the case “with rain” the plant continue its vegetative development and all the fruits could not arrive to maturity before the end of the cropping season. In the case of the WC strategy, the reduction in number of irrigations is clearly not a linear function of the amount of irrigation applied each time.

EA Results. EA experiments were run using input weather files with rain (WR) and without rain (NR), as described for the COMAX experiments. The schedules evolved by the EA are described herein, after a description of the EA performance. In the following discussion, the behaviour of the algorithm will be examined via the performance of the best chromosome for each generation. Yields follow the same patterns as fitness for both experiments NR and WR, this suggests that yields are the main driving factor for the EA. However it was interesting to notice that high rates of increase in yield are always higher than corresponding rates of increase in fitness. This behaviour seems to indicate that abrupt yield increases are always associated with water application. The difference between better gains from yield and more costs from irrigation explains differences in rates of increase. Nevertheless, the best yielding chromosomes (irrigation itineraries) do not show a monotonic increase for any of the experiments. Indeed, yield decreases (relative to previous performance) are noted during the plateau periods. Another interesting feature is the fact that yield drives the system at the beginning of the process but rapidly stops being so important (between generation 100 and 400). The maximum value for yield was obtained after about 935 generations for the WR experiment, at which time it was 1717.67 kg of lint/ha, and after about 6454 generations for the NR experiment, at which time it was 1939.69 kg of lint/ha. Table 2 shows that compared to the COMAX expert system, the evolved irrigation is better both in terms of total yield and in terms of optimality. That is, the schedule evolved resulted in reduced costs while manipulating the timing of irrigation such that the yield was not only maintained, but also increased.

Conclusions

The EA showed its overall better value for decision support compared to the COMAX expert system. Unlike COMAX, the EA proposed an irrigation schedule with large variations in amount of irrigation, number of irrigations, and timing. The irrigation schedule planned important irrigations during critical growth stages; the blooming and boll filling periods. Like COMAX, it doesn’t recommend irrigation at the beginning of the cropping season because there is enough residual water in the soil during this period of the crop. In the experiments, the EA found a better solution than the expert system. This solution is not necessary the best solution in the space of all the possible solutions. Although it is a good enough solution, a human can still produce an even better solution once the EA results are obtained. Then, the integration of a crop model with an evolutionary algorithm could be see as a good approach for irrigation optimization. And more interesting, this new approach is also generic and it is applicable to other cultural practices and to any cropping situation.

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Table 1. Technical itinerary and simulation conditions.

Simulation Conditions				
Start Simulation			05/09/92	
Stop Simulation			12/20/92	
General Crop Conditions				
Emergence			05/13/92	
Season Length			226	
Variety			Mid season	
Latitude			34°	
Density Conditions				
Row Spacing (cm)			96.00	
Plant Spacing (cm)			3.50	
Plants per Ha			118700	
Fertilization Conditions				
Date	Description	Rate	Units	Method
05/10	UAN	447.7	Kg/ha	Broadcast
06/15	UAN	6.7	Kg/ha	Broadcast
06/30	UAN	167.9	Kg/ha	Broadcast

Table 2. Comparison of "best" schedules proposed by COMAX and the EA, for a maximum amount of irrigation of 31.7 mm (1.25 inches).

Treatment		Number of Irrigation	Amount of Irrigation	Yield	Fitness
Without rain	COMAX	18	510.54	1737.53	1466.90
	EA	18	441.43	1939.69	1649.96
With rain	COMAX	9	285.75	1687.09	1462.25
	EA	13	354.37	1714.70	1470.19