Automatic programmers for solid set sprinkler irrigation systems.

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Abstract

The application of new technologies to the control and automation of irrigation processes is becoming very important and the automatic generation and execution of irrigation schedules is receiving growing attention. In this paper, a prototype automatic irrigation controller for solid-set systems is presented. The device is composed by software and hardware developments. The software was named Ador-Control, and it integrates five modules: the first four modules simulate drop trajectories, water distribution, crop growth and yield, and the last module ensures bidirectional communication between software and hardware. Decision variables based on soil, crop and irrigation performance indexes were used to make real-time irrigation decisions. A field randomized experimental design was designed to validate the automatic controller over a corn crop during two seasons. Three treatments were analyzed: T0) manual programmer or advanced farmer; T1) automatic scheduling controlled by indexes based on soil simulated water content and irrigation performance; and T2) advanced automatic scheduling controlled by simulated thresholds of crop and irrigation indexes. Experimental results in 2009 and 2010 indicated that automatic irrigation treatments resulted in similar maize yield but using less water than manual irrigation (10% between T0 and T1, and 18% between T0 and T2).

Key words: automatic programmer, sprinkler irrigation,

1. Introduction

The spatial variability of water application in sprinkler irrigation systems is due to technical design problems (spatial variability of pressure and discharge, sprinkler spacing) and to meteorological constrains (mainly wind speed and evaporative demand). Technical design problems have been addressed through engineering approaches, such as head loss analysis, sprinkler overlapping, flow control nozzles or pressure regulators. This approach has improved uniformity in sprinkler irrigated farms, but has not been able to control the effects of adverse meteorology. Low irrigation uniformity results in large variability in water application. As a consequence: crop yield and yield quality can be reduced (Stern and Bresler, 1983; Bruckler et al., 2000; Dechmi et al., 2003), pumping costs escalate as a result of low irrigation efficiency; and environmental problems multiply. On the other hand, agricultural soils are heterogeneous by nature, both chemically and physically. Soil water holding capacity can strongly vary across a cultivated field (Hanks, 1992; Herrero et al., 2007). Even under uniform irrigation applications, soil variability can accentuate the spatial variability of irrigation water and applied agrochemicals. Scheduling irrigation events considering the abovementioned variability and aiming at optimizing water productivity is a major challenge. Solving this problem may involve using automated, real-time technologies.

Coupled solid-set irrigation system and crop models (Dechmi et al., 2004a and 2004b; Playán et al., 2006; Zapata et al., 2009) have been developed to support irrigation decision making. Target variables may involve irrigation performance indexes (optimizing irrigation), crop indexes (yield) or a combination of both (water productivity). This type of solutions addresses the management problems of solid-set irrigated plots, which can be summarized in maximizing irrigation uniformity and efficiency, minimizing sprinkler evaporation losses and energy costs, and maximizing crop productivity. The coupled model presented by Dechmi et al. (2004a and 2004b) was calibrated and validated to adequately simulate the spatial variability of irrigation water in a corn plot accounting for variability in soils, meteorology and operating pressure. The model simulates the trajectory of drops emitted by each sprinkler (Fukui et al., 1980; Dechmi et al., 2004a and 2004b; Playán et al., 2006). Zapata et al. (2009) presented a more advanced coupled simulation model, focusing on collective irrigation systems. This model used a structured, hierarchical description of land use and infrastructure. The tool provided input to the management of a collective irrigation system based on irrigation and crop performance and on network conveyance capacity.

In this paper an automatic irrigation controller prototype for solid-set sprinkler irrigation based in the solution abovementioned is presented. The device includes software and hardware developments. The software evolved from previous works (Dechmi et al., 2004a and 2004b; Playán et al, 2006 and Zapata et al., 2009), while the hardware was a research, non-commercial prototype capable of monitoring the irrigation environment and executing irrigation orders. The main objective of the prototype was to minimize farmer intervention on irrigation activities (reducing human subjectivity, increasing labor productivity), while maintaining an adequate level of irrigation performance and without affecting crop yield (optimizing water productivity). A field experiment was designed to test and validate the prototype in a corn crop during two irrigation seasons.

2. Material and Methods

A field experiment was designed to validate the automatic controller prototype operation and to evaluate its performance in comparison with conventional irrigation scheduling and programming. The experiment was conducted in a 2.0 ha solid-set facility located at the experimental farm of the Aula Dei Agricultural Research Centre in Montañana (Zaragoza, NE Spain). The field was equipped with a solid-set system composed of impact sprinklers with 4.4 and 2.4 mm nozzles, located at an elevation of 2.3 m over the soil surface, using a rectangular 18 x 18 m arrangement, and operating at a nozzle pressure of 300 kPa. The experimental field counted on 64 sprinklers and 12 experimental plots composed by one sprinkler spacing each (Figure 1). The area of each experimental plot was 18 x 18 m^2. Each experimental plot and each irrigation block was controlled by an automatic valve.

Three experimental treatments were established:

1. T0, representing manual irrigation scheduling and programming. This represents the operation of an advanced farmer that uses the evapotranspiration information provided by a conventional irrigation advisory service to produce a weekly irrigation schedule. Once scheduled, the irrigation event will proceed without modifications for one week.

2. T1, representing a simplified automatic controller which can run autonomously in the field. T1 does not make use of Ador-Crop for irrigation decision making. This treatment uses a minimum irrigation performance (PAE_{lqMIN}) and a maximum soil water allowable depletion (SWD_{MAX}) as control variables. Definition of PAE_{lqMIN} and SWD_{Max} can be found in Zapata et al. (2009). Minutes before midnight, a simplified water balance is run for each irrigation block. SWD for the previous day is updated with crop evapotranspiration, precipitation and net irrigation depth. When SWD exceeds SWD_{MAX}, irrigation is scheduled for the next day. Meteorological conditions are checked every hour while the irrigation event lasts. If meteorology becomes unsuitable (foreseen $PAE_{lq} < PAE_{lqMIN}$) irrigation stops for an hour. After an hour, meteorological conditions are reassessed and irrigation can be resumed. Thresholds for SWD_{MAX} and PAE_{lqMIN} must be calibrated for the experimental conditions before running the experiment.

3. T2, representing an automatic controller based on the use of Ador-Crop. The intense computational requirements would in practice require either an on-farm PC or a remote PC communicating with the farm every hour. The simulated irrigation depth (Ador-Sprinkler) received at each point within a sprinkler spacing is used as an input to Ador-Crop (Dechmi et al., 2004a and 2004b). This permits to characterize water stress, and to

estimate the average time since stress started in this treatment (ES). Definition of ES can be found in Zapata et al. (2009). Decisions are based on ES and on irrigation performance (PAE_{lqMIN}). The two decision variables are hierarchically used in this treatment. PAE_{lq} can suspend irrigation at any hourly interval. However, once the threshold value of ES (ES_{MAX}) is reached, irrigation is executed independently of the meteorological conditions. This rule allows applying inefficient irrigations to avoid large affections to crop yield. Threshold values of ES and PAE require calibration for the experimental conditions.

In this experiment, the irrigation network was composed by three hydrants, each of them irrigating a plot. Each plot corresponded to one irrigation treatment of the field experiment. Six irrigated blocks (labeled from 0 to 5) were defined in each treatment. The number of blocks, combined with the gross application rate (5.29 mm h-1), the average peak crop water requirements (10.7 mm d-1) and the irrigation time availability (5 days out of 7), resulted in a peak network occupation of 70 %. This represents the minimum time slack to select periods of adequate meteorology for sprinkler irrigation during the peak of the season.

The sequential irrigation of the six blocks of each treatment was arranged by the software. Only irrigated block 0 (IB0) of each treatment was physically represented in the field experiment. The other five sectors of each treatment were virtual: their irrigation time was simulated and allocated by the automatic programmer, but they did not exist in the field. A randomized experimental design containing four replicates of IB0 per treatment was performed. A total of twelve field subplots (three treatments, four replicates) composed the field experiment (Figure 1). Corn (*Zea mays* L.) cv. Pioneer PR34N43 was sown on 20 April in 2009 and on 21 April in 2010, at a density of 85,000 plants ha-1 and at 0.75 m distance between rows. Agronomical practices (fertilization and application of herbicides and insecticides) were the same in all subplots.

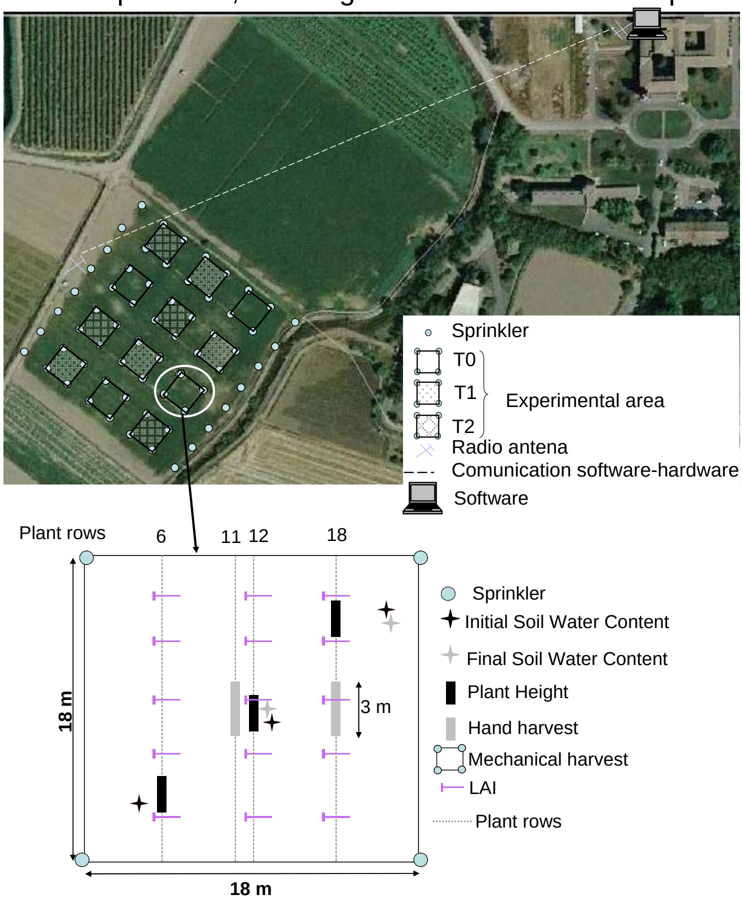

Figure 1. *Aerial photograph of the field experiment, detailing the location the software application, the hardware and the radio antenna. The experimental design (three treatments, four replicates) is presented. The location of the measurement points within an experimental plot is also presented*

Figure 1 presents an aerial picture of the field experiment, including the location of the experimental hardware and software. The software PC was located in an office of the principal building of the Research Centre, around 500 m far away from the field experiment. The experimental design of the irrigation treatments (the IB0 of each treatment) and its four replicates are also presented in Figure 2. A detailed sketch of the elemental experimental area with the location of the measurement points of all soil and crop monitored variables is also presented in Figure 1

In T0, T1 and T2, once the decision to irrigate the plot is made, all its blocks were sequentially irrigated. The irrigation sequence can be established by the user based on a user-planned sequence or on a random sequence. In all software executions reported in this paper, the first sector to be irrigated in each irrigation event was randomly determined. Irrigation proceeded sequentially till all blocks were irrigated. The user can also determine the irrigation time per block. An irrigation time of 4 h was used in all simulations and experiments, as a common practice in the area. Given the characteristics of the experimental solid-set, this irrigation time was equivalent to a gross irrigation depth of 21.2 mm.

At harvest (20 October 2009, 18 Oct. 2010), the corn plants located in a 3-m-long section of two different rows (4.5 m2) in each subplot were hand harvested by cutting them at the soil surface. The grain was separated from the cob and stalks, and both parts were dried at 65ºC. Total biomass and harvest index (HI) were determined. The subplots (18m × 18 m) were machine harvested with a combine, and the grain was weighed with a 1-kg-precision scale. A subsample of grain was collected from each subplot to measure the grain moisture, a measurement used to adjust the grain yield to standard 140 g kg-1 moisture content.

3. Results and Discussion

Table 1 presents simulated crop evapotranspiration and measured precipitation during the crop cycle for 2009 and 2010. The average and coefficient of variation of wind speed and relative humidity during the irrigation events are presented for each treatment. Finally, the seasonal irrigation depth, the seasonal coefficient of uniformity and the simulated irrigation efficiency are presented. Meteorological conditions in the 2009 irrigation season were far from average, particularly for wind speed and for the maximum temperatures. The 2010 irrigation season resulted in wind speeds similar to an average season. Consequently, the average wind speed during irrigation in 2009 was lower than in 2010. Wind variability in T0 was larger than in T1 and T2. On the average, the manual treatment applied 10% more water than T1 and 18% more water than T2. Differences between treatments on simulated seasonal CU resulted very low because of the compensatory effect on the CU of the different irrigation events along the season (Dechmi et al., 2003). Differences between treatments in simulated seasonal irrigation efficiency were very important: the automatic treatments showed higher irrigation performance than the manual treatment. Average differences respect to T0 amounted to 6 and 7 percentual points for T1 and T2, respectively. Most of these differences were due to reductions in wind drift and evaporation losses.

Table 1. *Simulated crop evapotranspiration (ETc), measured seasonal precipitation (P), measured average and coefficient of variation (between brackets) of wind speed and relative humidity, measured irrigation depth applied, and simulated seasonal CU and IE for each irrigation treatment during the two experimental years*

Season	Treatment	*ETc* (mm)	*P* (mm)	*WS* ($m\ s^{-1}$)	*RH* (%)	Irrigation depth (mm)	Seasonal *CU* (%)	*IE* (%)
2009	T0	695	69	1.1 (64)	60 (37)	862.3	89.9	76.3
	T1			0.9 (56)	62 (31)	740.6	89.3	81.3
	T2			1.0 (40)	61 (30)	703.6	88.6	84.7
2010	T0	698	134	1.4 (86)	68 (32)	714.2	90.5	81.4
	T1			1.2 (58)	67 (30)	693.0	91.0	86.8
	T2			1.3 (62)	67 (30)	629.5	90.6	86.3

Grain yield for the two crop seasons is presented in Figure 2. Grain yield was not affected by the irrigation treatment in any of the experimental years. In 2009 there were not differences between irrigation treatments for aboveground biomass and harvest index. However, in 2010 the aboveground biomass was significantly reduced in the T2 treatment. Since grain yield sampling size was 324 m^2 and aboveground biomass and harvest index sampling size was only 4.5 m^2, this reduction of aboveground biomass in the T2 treatment should be considered with caution. Water productivity (determined as the ratio between grain yield and irrigation depth) was statistically different for T0, T1 and T2 in the 2009 season. In the 2010 season, water productivity in T2 was higher than in T0 and T1. The values of water productivity grew from T0 to T2 both years.

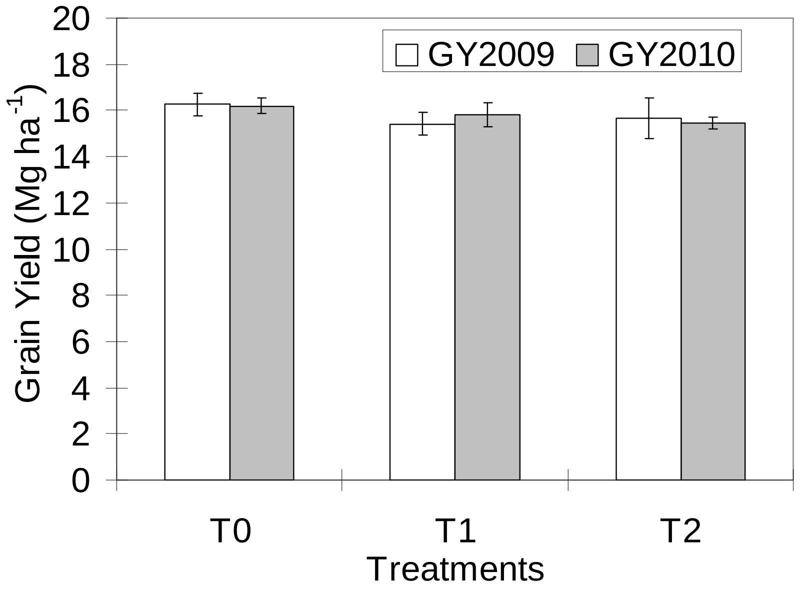

Figure 2. *Results of Mechanical Harvested Grain Yield (GY, Mg ha^{-1}) for the three treatments and the two irrigation seasons (2009 and 2010). Bars showed the standard deviation of the GY.*

The results of the field experiment indicate that the automatic controller prototype has accomplished its objective. The system has proved its potential to drastically reduce farmer dedication to irrigation. Compared with the manual treatment, the automated treatments increased irrigation efficiency, decreased irrigation depth and did not affect grain yield, which resulted in relevant increases in water productivity. In addition to these advantages related to indicators, the prototype punctually informed about incidences using the alarm protocols. Farmer intervention was only requested when needed to solve unexpected situations, mainly resulting from the irrigation hardware.

4. Conclusions

The automatic controller prototype has minimized farmer intervention on irrigation practices, reducing human errors and increasing labor and water productivity. In fact, the prototype has been able to automatically schedule and execute seasonal irrigation obtaining high irrigation performance indexes, adjusted irrigation depths and competitive grain yields. The manual treatment applied an average of 10% more water than T1, and an average of 18% more than T2, without statistical differences in grain yield. T2 water productivity was the largest in both seasons.

Further research will need to focus on the inter-year performance variability of the automatic controller, as well as on the effect of climate on its performance in comparison with manual irrigation scheduling. Finally, the interaction between the automatic controller and irrigation hardware seems to be a key issue. It is of particular relevance to analyze the benefits derived from investing on time slack (for instance, through the number of on-farm irrigation blocks).

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