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Optimizing irrigation management for a spatially variable soybean field

Ravic Nijbroek[a,1], Gerrit Hoogenboom[b,*], James W. Jones[a]

[a]*Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL 32611, USA*
[b]*Department of Biological and Agricultural Engineering, University of Georgia, Griffin, GA 30223, USA*

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Abstract

During the last few years, water has become a limited resource in the southeastern USA. Most farmers, however, are not using any scheduling methods to optimize their irrigation applications. The objective of this study was to determine the feasibility of spatially variable irrigation management for a typical soybean field in the Coastal Plain area. The selected field (9.94 ha) had previously been delineated into five spatially variable management zones. For each of the five selected management zones, the soil water limits were estimated from particle size distribution data. Subsequently the plant available soil water was derived from these limits. A process oriented crop model, CROPGRO-Soybean, was used to determine optimal irrigation schedules for each zone, based on 25 years of local historical weather data. The resulting sets of irrigation strategies were then applied to the entire field, with special emphasis on the strategies that (1) produced the highest yield, (2) showed the earliest sign of water stress, or (3) had the largest area. The impact of spatially variable irrigation was analyzed by meeting the optimal irrigation requirements for each zone for all years. Total production, water usage by irrigation, and water drained were calculated for the entire field based on simulation results of each management zone. An economic analysis, using a price of $222.40 per 1000 kg for soybean and costs of $1.50, $2.00, and $2.50 per ha-cm for irrigation water, was also conducted. Spatially variable irrigation resulted in the best management option. Among the uniform irrigation strategies, management according to the requirements of the largest zone gave the best response. The differences between the best and worst management option were relatively small, i.e. $16/ha. Although this projected benefit is low for the small field, benefits for large center pivot irrigation systems would be attractive to farmers. The

* Corresponding author. Tel.: +1-770-229-3438; fax: +1-770-228-7218.
E-mail address: gerrit@griffin.peachnet.edu (G. Hoogenboom).

1 Present address: Department of Computer Science, Louisiana State University, Baton Rouge, LA 70803, USA

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approach used in this study is an excellent method to analyze spatially variable irrigation management strategies under weather uncertainty.

Keywords: Decision support system; Crop simulation ; Water conservation; Drought

1. Introduction

Many important agricultural areas in the United States, as well as globally, are suffering from an inadequate supply of water (Postel, 2001). In addition, residential and industrial demands for water are increasing, due to urbanization and growth. Recently the issue of water use has become critical in Georgia, especially water used by farmers for irrigation (Houser et al., 2001; Thomas et al., 2001). In 2001, this resulted in the implementation of the Flint River Drought Protection Act. As part of this act, farmers can participate in a voluntary auction to provide bids on acreage that they are willing to remove from irrigation (Thomas et al., 2000). However, other alternatives, such as irrigation scheduling and application of spatially variable irrigation have not been sufficiently studied and could provide an alternative solution.

The existence of spatial yield variability has been well documented. Many farmers have implemented site-specific management to address spatial variability, although profitability is not always guaranteed (Swinton and Lowenberg-DeBoer, 1998). In particular, the spatial variability of soil properties that influence soil water holding limits is a major source of uncertainty in crop management (Bresler et al., 1981; Moore and Tyndale-Biscoe, 1999; Sadler et al., 2000a, b). Paz et al. (1998) showed that 69% of the variability in soybean yield over 3 years within a 16-ha Iowa field could be explained by variations in soil water holding characteristics that resulted in spatially variable drought stress. A later study by Paz and Batchelor (2000) showed similar results. Other sources of yield variability, such as weather, genetic factors, biotic stress factors, including pests, diseases and weeds, are more random (Morkoc et al., 1985; Dagan and Bresler, 1988; Baksh et al., 2000; Paz and Batchelor, 2000). Managing spatial yield variability may therefore be achieved more easily when the spatial variability of plant available soil water is better understood (Sadler et al., 1998).

Plant available soil water (PASW) is dependent on the soil profile texture and bulk density and plant rooting characteristics, which are a function of crop size and age. Soil characteristics are normally static, while plant characteristic change temporally. The main sources of PASW are rainfall and irrigation. Rainfall varies randomly and can not be controlled. Therefore, historical patterns are studied to improve our understanding of how future weather conditions may affect yield, profit, and the uncertainties associated with these outcomes. Using historical weather data and computer models, irrigation management can be optimized for specific field conditions. Moreover, irrigation management is critical because under-irrigation can cause a reduction in yield and over-irrigation can result in a waste of natural resources, lower profit associated with too much irrigation, and potential pollution through nutrient leaching and runoff (Aboitiz et al., 1986).

Crop simulation models and other decision aids have been used extensively for determining optimum irrigation management strategies in the southeastern Coastal

Plain. Hook and Threadgill (1988) showed that a simple computer-based water balance model was an effective irrigation management tool for corn. The application of the dynamic crop simulation models CERES-Maize and SOYGRO for irrigation management showed an increase in net returns and resulted in a reduction in water use (Fortson et al., 1989; Epperson et al., 1992, 1993). Hook (1994) used the crop models to determine regional water withdrawals needed for irrigation during drought years in Georgia.

Few site-specific irrigation management studies have been conducted thus far. Ritchie and Amato (1990) compared irrigation strategies in a field with pre-defined zones using 30 years of weather data. The management zones were derived from soil color imagery and were defined as regions with the lowest, highest, and intermediate PASW. Variable rate irrigation resulted in the best irrigation management option in terms of yield, but not total usage of water. An economic analysis to compare the two factors was not conducted. Site-specific management of irrigation is difficult, because traditional center pivot or linear irrigation systems are not equipped with individual nozzle controls. Several studies have reported on the modifications of irrigation systems needed for site-specific management (Camp and Sadler, 1998; King et al., 1999; Feinerman and Voet, 2000). Sadler et al. (2000c) presented some recommendations for model improvement for site-specific management.

Based on earlier research, we assumed that the main contributor of spatially variable PASW and crop yield are the soil water holding limits, rainfall, and irrigation (Moulin et al., 1994; Jaynes and Colvin, 1997; Paz et al., 1998; Paz and Batchelor, 2000). The soil water holding limits and rainfall are variables that can not be managed by farmers. However, an optimal irrigation strategy, which minimizes water use while maximizing net returns, can be identified and applied by a farmer if resources are available. The overall goal of this study was to improve the understanding of irrigation management for fields with defined management zones. Our specific objective was to study the potential value of spatially variable irrigation management using a crop simulation model.

2. Materials and methods

2.1. Research location and field conditions

The field experiment was conducted in 1998 in southwest Georgia on a 12.6-ha field of the Tony Smith Farm in Arlington. The field had slopes less than 2% and the main soils were well-drained Norfolk loamy sand and moderately well-drained Goldsboro loamy sand. Researchers at the National Environmentally Sound Production and Agriculture Laboratory (NESPAL) had previously identified nine management zones for the study site (Usery et al., 1995; Kvien and Pocknee, 1999). The classification of the zones was based on the following sources of information:

- 1995 and 1996 corn yield maps.
- Enhanced imagery of remotely sensed soil color aerial photographs.

- Normalized Difference Vegetation Index (NDVI) of a 1996 corn crop image.
- Farmer's knowledge and experience.
- Natural Resource Conservation Service (NRC) soil survey maps.

Two of these management zones were considered as separate from the main production area of the field (0.7 ha) because they were located in the corners of the field and were not irrigated. In our experimental component of this study, only five management zones were used due instrument failure in two other zones (Fig. 1). The total study area was comprised of 9.94 ha (Table 1). The preceding winter crop was canola, planted during the fall of 1997 and harvested prior to planting of soybean. The soybean crop was planted on June 10 (day of year 161) at a row spacing of 45 cm; the cultivar was Hartz 5566RR.

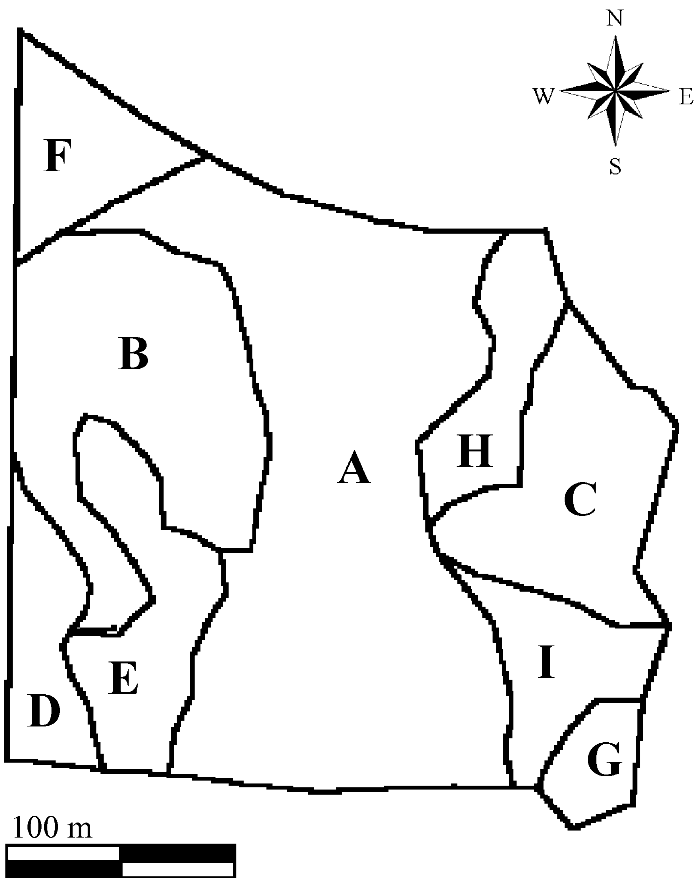

Fig. 1. Crop management zones (A = Largest area; B = Earliest stress; C = Highest yield; D & E = Small zones; F&G = Rainfed; I&H = Not used due to mechanical problems).

2.2. Crop model

The crop simulation model CROPGRO-Soybean v3.5 (98.0), distributed as part of the Decision Support System for Agrotechnology Transfer (DSSAT) (Tsuji et al., 1994; Hoogenboom et al., 1999), was used to simulate soybean yield (Hoogenboom et al., 1994). The model calculates growth and development on a daily basis (Boote et al., 1997, 1998) and includes a detailed soil water and nitrogen balance (Godwin and Singh, 1998; Ritchie, 1998). The inputs for the soil water balance include soil surface parameters, such as the runoff curve number (SCS, 1985), albedo, drainage, and permeability, and soil profile characteristics. The main profile parameters define the lower limit of plant extractable plant water (LL), the drained upper limit (DUL), and the saturated soil water content (SAT) for each individual soil layer.

Table 1
Measured and calculated crop model input parameters for all management zones[a]

Zone	Depth (cm)	Sand (%)	Clay (%)	Silt (%)	ITHRL	DUL (cm^3 cm^{-3})	LL (cm^3 cm^{-3})	PASW (cm^3 cm^{-3})	SAT[b] (cm^3 cm^{-3})	BD (g cm^{-3})
(A) Largest management zone					49					
4.78 ha	0–30	82.24	5.68	12.08		0.143	0.070	0.073	0.328	1.78
	30–60	70.60	19.52	9.88		0.202	0.132	0.070	0.372	1.66
	60–90	65.76	24.40	9.84		0.229	0.156	0.073	0.366	1.68
	90–120	66.40	25.12	8.48		0.230	0.160	0.071	0.350	1.72
(B) Earliest sign of stress					51					
2.04 ha	0–30	87.82	3.12	9.06		0.123	0.057	0.066	0.382	1.64
	30–60	85.44	5.76	8.80		0.122	0.063	0.060	0.377	1.65
	60–90	85.30	6.16	8.54		0.124	0.065	0.059	0.398	1.60
	90–120	69.20	24.32	6.48		0.222	0.156	0.066	0.355	1.71
(C) Highest yield					41					
1.65 ha	0–30	78.50	5.12	16.38		0.149	0.067	0.082	0.350	1.72
	30–60	79.42	8.00	12.58		0.143	0.074	0.069	0.328	1.78
	60–90	72.42	17.68	9.90		0.191	0.122	0.069	0.372	1.66
	90–120	69.36	22.88	7.76		0.216	0.148	0.068	0.357	1.70
(D)					47					
0.43 ha	0–30	78.28	3.92	17.80		0.145	0.061	0.084	0.379	1.65
	30–60	87.08	2.08	10.84		0.106	0.044	0.062	0.315	1.81
	60–90	83.50	8.08	8.42		0.135	0.074	0.060	0.361	1.69
	90–120	85.44	6.96	7.60		0.127	0.069	0.058	0.333	1.77
(E)					41					
1.04 ha	0–30	83.50	5.44	11.06		0.140	0.069	0.071	0.391	1.61
	30–60	61.20	25.68	13.12		0.243	0.162	0.080	0.326	1.79
	60–90	60.28	26.48	13.24		0.247	0.166	0.081	0.368	1.67
	90–120	57.84	28.40	13.76		0.259	0.176	0.083	0.358	1.70

[a] SAT = 1 - BD/2.65.
[b] ITHRL: Irrigation threshold; DUL: Drained Upper Limit; LL: Lower Limit of plant water availability; PASW: Plant Extractable Soil Water; SAT: Saturated volumetric soil water content; BD: Bulk Density.

Three different irrigation options are available in the CROPGRO-Soybean model (Hoogenboom et al., 1994). These include a non-irrigated or rainfed option; a user provided irrigation schedule, and an automatic irrigation option. The non-irrigated option simulates crop growth using only rainfall data, whereas the automatic irrigation option applies irrigation as a function of threshold parameters that can be defined by the user of the crop model. These threshold variables include the depth of the profile that is checked each day for soil moisture and the soil moisture threshold value at which irrigation is triggered. The automatic irrigation adds water to raise the soil profile to the drained upper limit when the soil water content (SWC) of the top of the profile drops below this threshold value.

The CROPGRO-Soybean model and the previous version of the model, called SOYGRO, and the related CERES models have been extensively calibrated and evaluated for conditions in Georgia and the southeastern USA (Fortson et al., 1989; Epperson et al., 1992; Hook, 1994; Sadler et al., 2000c). Recent studies have shown the stability of crop model-determined cultivar coefficients across multiple sites (Irmak et al., 2000; Mavromatis et al., 2001). Based on these prior results, this study did not include a specific model evaluation component, except for the simulation of the soil water balance.

2.3. Weather

Weather data for the Tony Smith Farm at Arlington for 1997 and 1998 were obtained from the Georgia Automated Environmental Monitoring Network (AEMN) (www.Georgiaweather.net; Hoogenboom, 2000). This weather network records rainfall, air temperature, solar radiation, and other variables that can be used for modeling applications. The AEMN weather station was located in a neighboring field (latitude 31.353; longitude −84.631) and the weather data recorded by this station were used for evaluation of the soil water balance simulation. Long-term historical weather data for 1974 through 1998 were obtained from the Cooperative Observer Network of the National Weather Service for Colquitt, Georgia (latitude 31.167, longitude −84.767, elevation 47 m). Colquitt is approximately 20 km from the experimental site in Arlington. Since spatially variable historical rainfall data were not available, rainfall was assumed to be uniform across the field for the long-term simulations.

2.4. Irrigation

During the 1998 field study, irrigation was applied with a center pivot irrigation system during the critical plant development stages for soybean, including one irrigation immediately after planting to establish uniform germination and emergence. The farmer, based on his experience made all irrigation decisions. Four tipping bucket rain gauges with Hobo data loggers were installed to measure irrigation and rainfall in the five main management zones, with one rain gauge representing the two smallest zones.

2.5. Soil

Soil water content was measured weekly for 10 weeks by gravimetric sampling in each management zone during the course of this field study. The first measurement was made 5 days prior to planting and sampling was terminated when the crop stand was mature and had ceased extracting significant soil water quantities. The soil samples were collected at six 30-cm depth intervals up to a depth of 1.20 m and inside a 2-m radius around each rain gage. In addition, two bulk density (BD) measurements were obtained during the growing season. It was assumed that the soil characteristics within each management zone were uniform, based on the NRCS soil survey maps. Subsequently, the volumetric SWC values were computed by multiplying gravimetric SWC and the BD. The lower limit, drained upper limit and saturated soil water content parameters, required for the crop model, were calculated using the pedotransfer functions developed by Rawls and Brakensiek (1982). These functions performed best when compared to similar soil water estimation techniques used in the field (Nijbroek, 1999).

2.6. Model evaluation

The first analysis included a comparison between measured and simulated soil water content for each layer of each zone to evaluate the soil water balance simulations. The soil water limits presented in Table 1 and the weather data in Fig. 2 were used to simulate the respective water balances for each individual management zone. For irrigation, the actual management scenario applied by the farmer was used. The simulations were started on the planting date and terminated when the crop

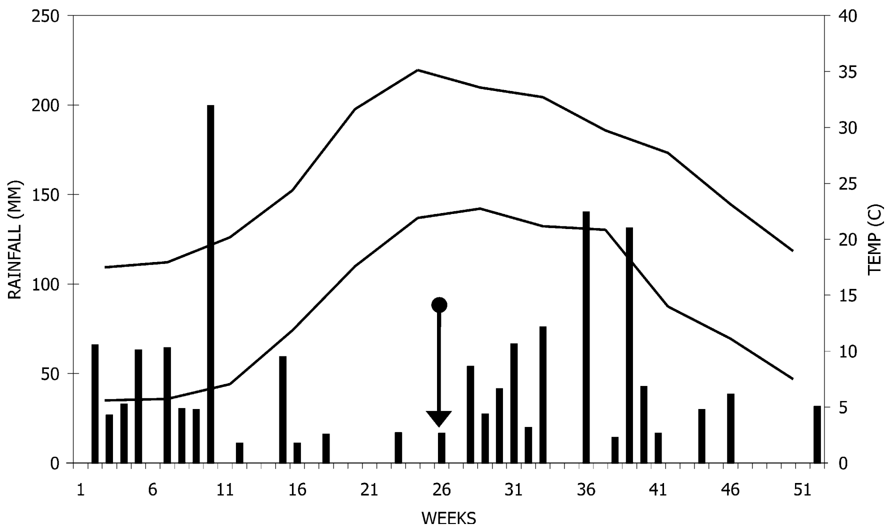

Fig. 2. Monthly minimum and maximum temperature and rainfall for the 1998 growing season. The arrow indicates planting date (10 June 1998, day of year 161).

simulation model predicted harvest maturity. The arrow in Fig. 2 shows the planting date on 10 June.

2.7. Economic analysis

A simple economic analysis that included final yield, soybean price, irrigation cost and fixed production costs, was conducted [Eq. (1)]. Until 2000, farmers have had unlimited and unregulated access to surface water, for example, rivers and streams, or groundwater through private wells. These wells or irrigation ponds are connected through above- and below-ground pipes to center pivot and linear irrigation systems, drip irrigation systems and various other methods (Thomas et al., 2001). An irrigation cost of $ 2.50/ha-cm was used, based on information obtained from a 1989 Florida Cooperative Extension Service bulletin (Pitts and Smajstrla, 1989). This irrigation cost was adjusted by either subtracting or adding $0.50/ha-cm to reflect different pricing schemes for water. The market price for soybean was based on a 10 year low of $222.40 per 1000 kg ($6/bushel), reached in 1998 (Good et al., 1998). The initial investment for spatially variable irrigation was not considered; it was assumed that the irrigation system was already in place. The main objective of this study was to determine if spatially variable irrigation would lead to higher profits and lower water use and leaching. A combined simulation–optimization approach was used, making use of the CROPGRO-Soybean model.

$$\text{Gross Margin} = \text{Soybean Price} \times \text{Yield} - \text{Irrig. Cost} \times \text{Irrig. Amount-Fixed Cost} \tag{1}$$

The fixed cost in Eq. (1) was assumed to be independent of the management strategy and remained constant regardless of the irrigation strategy. This avoided having to account for higher investment costs for a variable rate pivot versus a conventional pivot. Fixed cost was therefore assigned a value of $0.00. As a result, the final gross margin amounts were all relative to the fixed cost.

2.8. Optimization

2.8.1. Irrigation threshold factor

The irrigation threshold (ITHRL) factor of the model reflects a percentage of the PASW in the top part of the profile as defined by the user and is used to trigger an automatic irrigation event (Hoogenboom et al., 1994). The default threshold value in the model is 50%. However, for optimum irrigation management it requires adjustment for each management zone due to varying soil texture. In this study, crop yield and water use were simulated using 25 years of historical weather data while incrementally increasing the threshold factor by 2% over a specific range, i.e. 15–65%, for each management zone. The gross margin was then calculated for all years, using Eq. (1), and the optimal ITHRL factor resulting in the highest gross margin for each zone was selected.

2.8.2. Simulated irrigation

Three different management scenarios were evaluated for the entire field, using a blanket or uniform application and using spatially variable irrigation. These whole field strategies included the irrigation schedule from largest zone, the schedule from the zone that showed the earliest sign of drought stress, and the schedule from the zone that produced the highest crop yield. The schedule for the largest management area was designated as zone A and for the management area with the earliest sign of stress, zone B. This latter zone was selected by investigating which zone was first irrigated under the automatic irrigation option for the 1998 conditions. Because the initial SWC conditions were critical for this process, the DUL values for each zone were used as the initial conditions at the start of the simulations. The schedule for the zone with both the highest simulated and observed yield for the 1998 conditions was designated as zone C. In the final analysis for computing total production and water use for the entire field, all five zones were included.

For each selected zone, 25 optimal simulated irrigation schedules were determined based on 25 years of historical weather data. These schedules were then uniformly applied to the remainder of the field under the different scenarios. Additionally, spatially variable irrigation management was investigated by independently simulating each zone using the automatic irrigation option. Finally, total production, water use, drainage, and gross margin for the entire field were computed for each year and summarized for the period of study.

3. Results

A summary of the weather conditions observed during the 1998 season in Arlington, Georgia is presented in Fig. 2. The monthly minimum temperature varied between 5 and 23 °C, while the monthly maximum temperature varied between 18 and 35 °C. The winter and spring seasons for 1998 were relatively dry, except for one 200-mm rainstorm in March. The summer and fall seasons for 1998 were relatively wet, with rainfall spread very evenly over the growing season. For the entire year, total rainfall for 1998 was only 30.5 mm below normal, based on the 1961–1990 normal period.

The measured parameters for soil texture and bulk density and the corresponding calculated soil water holding limits for LL, DUL and SAT for each layer of the five management zones (A–E) are presented in Table 1. Plant extractable soil water varied from 0.066 to 0.084 cm^3/cm^3 for the surface soil layer and from 0.058 to 0.083 cm^3/cm^3 for the bottom soil layer. Zone E had the highest amount of PASW, while zone B had the lowest.

3.1. Model evaluation

An example of simulated and observed soil water content for the individual layers of zone B is presented in Fig. 3. Simulated and observed soil water contents were similar, except for the third sampling point for the deepest two layers and the sixth sampling point for the deepest layer. The model also responded very well to the individual rainfall events, as shown by the changes in the simulated soil water content for the top three soil layers. The results for the soil layers of these other management zones (data not shown) were very similar. Overall the model simulated soil water content fairly well for the different management zones and individual soil layers.

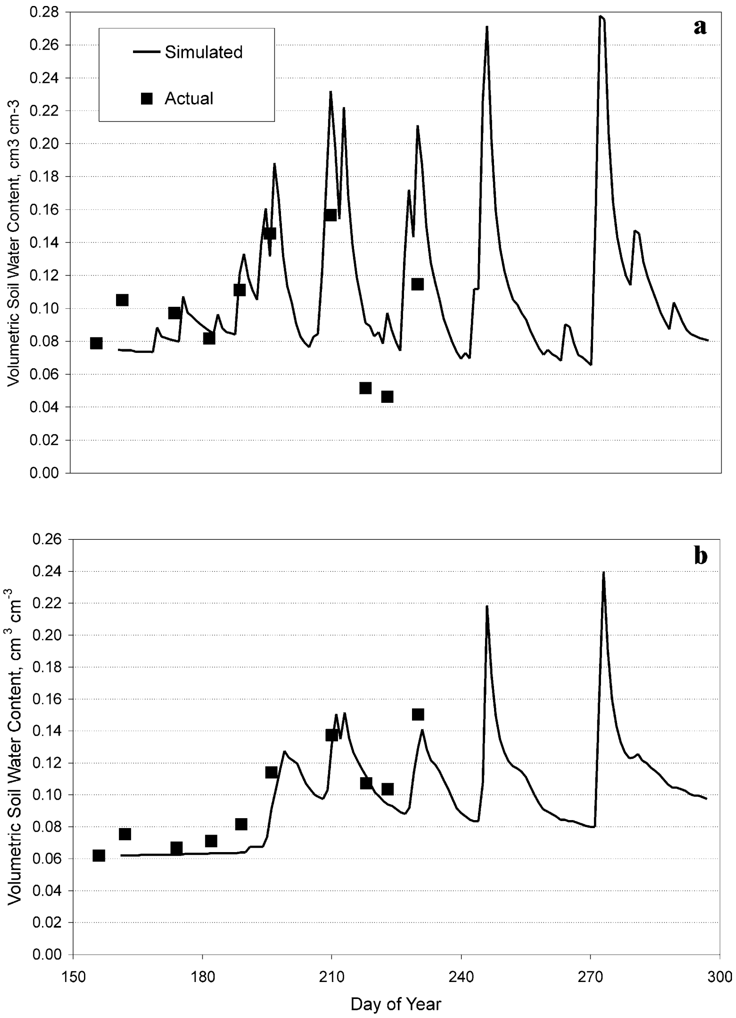

Fig. 3. Simulated and observed volumetric soil water content values in the soil profile of Zone B. 0–30 cm (a), 30–60 cm (b), 60–90 cm (c) and 90–120 cm (d).

3.2. Optimization

3.2.1. Irrigation threshold factor

Following model evaluation, an optimal value was determined for the irrigation threshold factor for each management zone, using the CROPGRO-Soybean simulation model. These irrigation threshold factors were necessary as input parameters to be able to simulate 25-years of yield, irrigation water use, and water drainage for each individual zone. The final threshold values ranged from 41 to 51% (Table 1). As expected, the management scenario that showed the earliest stress, for example,

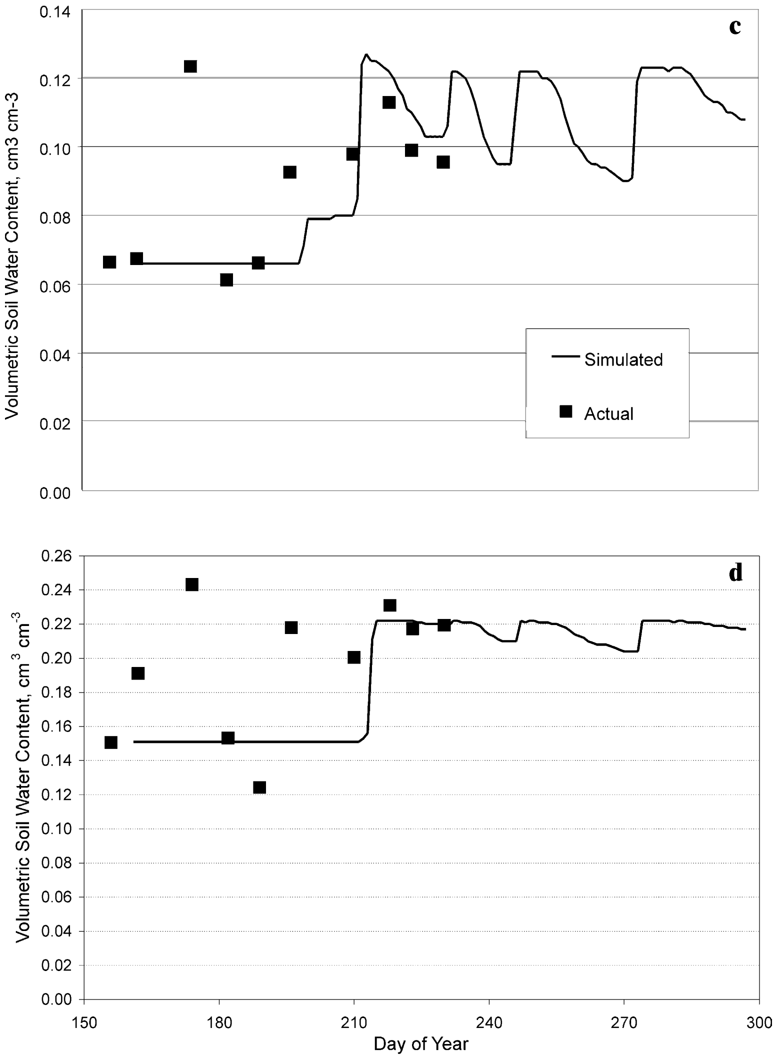

Fig. 3 *(continued)*.

the scenario for zone B, had the highest threshold factor, triggering irrigation earlier and more frequently than the other management zones. The optimal threshold for the zone with the highest yield, for example, zone C, was lowest, showing that this zone was most tolerant to changes in soil moisture conditions.

3.2.2. Simulated irrigation at a field scale

The three different management irrigation management strategies for the largest zone (A), the earliest stress (B) and the highest yield (C) were applied to the entire field. The results were summarized by total production, water usage for irrigation, and drainage. A comparison was made for these three factors between spatially variable irrigation management and the three uniform management regimes for each individual year (Figs. 4–6). A 25-year average and a statistical summary was also calculated (Table 2).

The 25 irrigation schedules of the largest zone (A) applied to the entire field resulted in an average annual production of 33.1 t of soybean (Table 2). Although this amount was similar to that of the earliest stress management scenario (zone B) applied to the entire field, it used much less water for irrigation, for example, 23.4×10^6 l versus 27.2×10^6 l. As a result, drainage was much less compared to the earliest stress treatment, for example, 14.8×10^6 l versus 16.1×10^6 l. The simulated irrigation schedules for the earliest stress zone (B) applied to the entire field produced an average yield of 33.1 t of soybean for the entire field. Although this production value was the second highest after spatially variable irrigation, it required more irrigation water than any other management practice, i.e. 27.2×10^6 l and resulted in the largest amount of water drained out of the bottom of the profile, i.e.

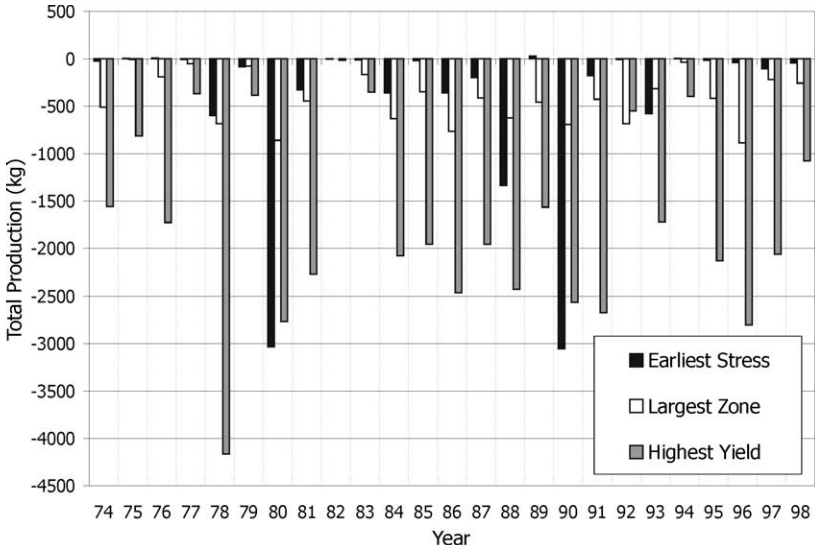

Fig. 4. Annual differences in production between a spatially variable irrigation (zero line) and three uniform irrigation management scenarios.

16.1×10^6 l. When irrigation management of the entire field was based on the irrigation schedule of the most productive zone (C), total production was 31.8 t. Additionally, the total amount of water used for irrigation was only 20.4×10^6 l, while 13.7×10^6 l drained from the profile. Although these were the lowest required

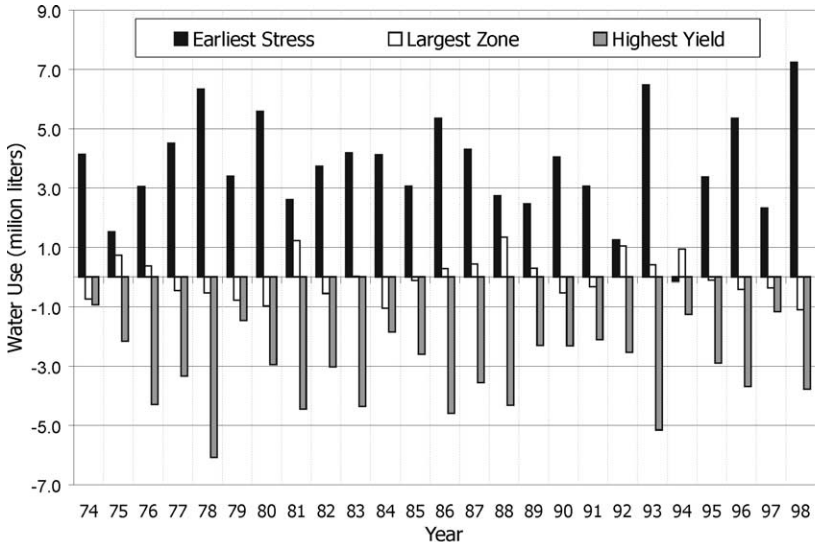

Fig. 5. Annual differences in irrigation water applied between spatially variable irrigation (zero line) and three uniform irrigation management scenarios.

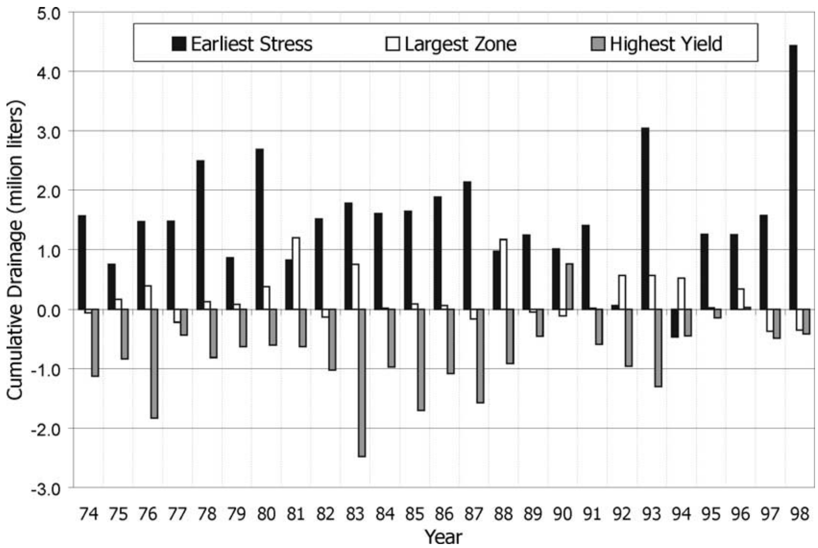

Fig. 6. Annual differences in cumulative drainage between spatially variable irrigation (zero line) and three uniform irrigation management scenarios.

amounts of water among the management strategies analyzed, this option also resulted in the second lowest total soybean production. Among the management options analyzed (Table 2), spatially variable irrigation resulted in the highest total soybean production, i.e. 33.5 t. However, both the total amount of irrigation required to reach this yield level as well as the total drainage resulted in relatively high amounts of water, for example, 23.4×10^6 l mm for irrigation and 14.6×10^6 l for drainage.

Annual variation for production, irrigation requirements and drainage were very high. Coefficients of variation varied between 8 and 9% for production, 32 and 37% for irrigation and 49 and 50% for drainage (Table 2). There were therefore no statistically significant differences between treatments with respect to production, water use for irrigation, deep drainage and therefore the risk of pollution. This annual variation was also clearly shown in the annual differences between spatially variable irrigation and the three management regimes for production (Fig. 4), water use for irrigation (Fig. 5) and drainage (Fig. 6). For only a few years the earliest stress management regime showed a slightly higher yield, but in most years all three management regimes showed a reduction in production compared to the spatially variable irrigation management regime. The highest yielding management regimes performed the poorest, except for 2 years, forexample, 1980 and 1990, in which the earliest stress showed a more significant reduction in yield (Fig. 4). Because yield was reduced, water consumption was also less compared to the spatially variable irrigation regime. For 24 out of 25 years, more irrigation water was applied for the earliest stress management regime than for the spatially variable irrigation regime. Results based on the largest management zone varied but were very similar to the irrigation applied by the spatially variable management regime (Fig. 5). The annual variation for drainage (Fig. 6) showed a similar pattern as the annual variation in irrigation usage (Fig. 5).

3.3. Economic analysis

For the highest cost of irrigation, the practices could be ranked using net returns as follows: management based on the optimal irrigation by zone, the largest zone

Table 2
Averages and standard deviations for 25 years of simulations for total soybean production, water usage and deep drainage for different irrigation management scenarios

Irrigation management based on:	Production		Irrigation		Drainage	
	t	S.D.	$l\times10^6$	S.D.	$l\times10^6$	S.D.
Variable rate irrigation	33.5	3.0	23.4	7.9	14.6	8.2
Zone A—Largest area	33.1	2.9	23.4	7.7	14.8	8.1
Zone B—Earliest stress	33.1	3.0	27.2	8.8	16.1	7.9
Zone C—Highest yield	31.8	2.6	20.4	7.6	13.7	8.1
Zone D	32.2	2.6	21.8	7.7	14.1	8.2
Zone E	31.5	2.6	21.8	7.9	14.0	8.2

(A), the earliest irrigated zone (B), zone D, the most productive zone (C), and zone E. An analysis for the annual values of gross margins is presented in Fig. 7. Among the uniform irrigation management practices, which are currently available to the farmer, irrigation management according to the largest zone resulted in the highest gross margin. However, the spatially variable irrigation regime clearly showed superior results for all years, except for 1982 and 1983, compared with the other irrigation management regimes.

The box plots presented in Fig. 8 give an indication of the risk related to each management option. Irrigation management according to the earliest stress zone (B), for example, ranked high among the available options, but also demonstrated the largest difference between the 25 and 75 percentiles (Fig. 8). Similarly, the gross margin resulting from field management according to zones C, D, and E did not exceed $375 for any of the 25 years. The first quartiles did not show much difference. This is most likely the result of the generally high rainfall in southwest Georgia, resulting in little water stress during wet years.

4. Discussion

The differences in gross margins of the irrigation options were small. However, this was partially due to the very small area of the study site, i.e. 9.94 ha. It was therefore more difficult to identify the potential impact of selected irrigation practices. Irrigation management according to the largest zone, for example, ranked high based on gross margins because it constituted 48% of the total study area. An

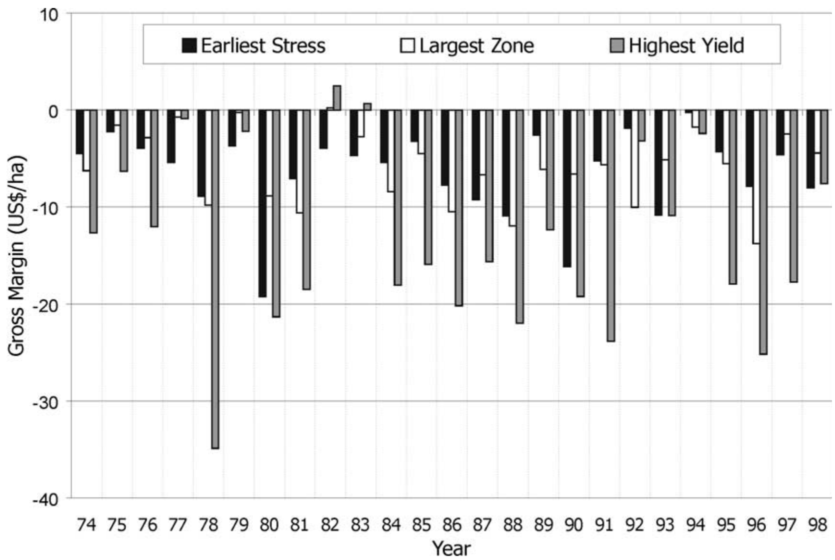

Fig. 7. Annual differences in gross margin between spatially variable irrigation (zero line) and three uniform irrigation management scenarios.

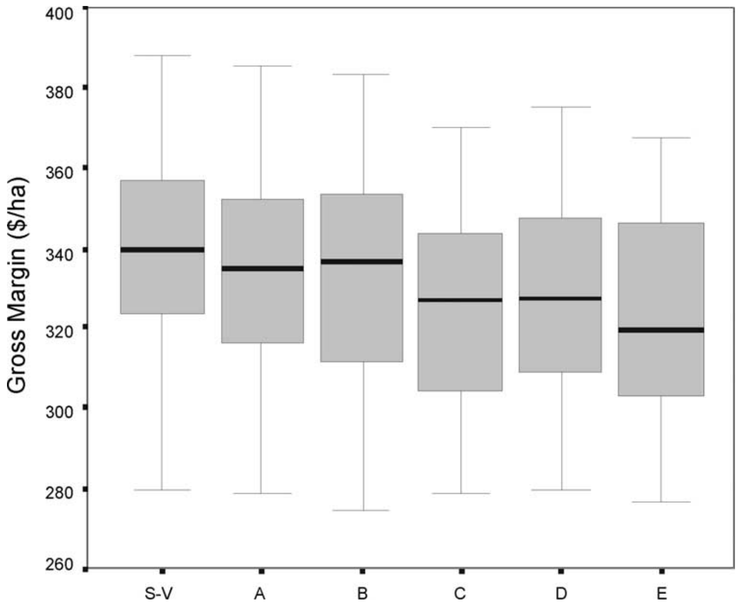

Fig. 8. Box plot of gross margins resulting from 25 years of simulations according to management scenarios based on spatially variable irrigation (S–V), the largest management zone (A), the earliest sign of stress zone (B), the highest yielding zone (C), and remaining zones (D and E). The soybean price was based on $222.40 per 1000 kg ($6/bushel) and the cost of irrigation was $2/ha-cm.

Table 3
Simulated gross margins for 25 years of simulation, using a soybean price of $222.40 per 1000 kg ($6/bushel) for different irrigation management scenarios

Irrigation cost ($/ha-cm)	1.50		2.00		2.50	
Irrigation management based on:	Gross margin	S.D.	Gross margin	S.D.	Gross margin	S.D.
			($/ha)			
Variable rate irrigation	345	30	339	29	334	29
Zone A–largest area	341	29	333	28	328	28
Zone 331B—earliest stress	339	30	333	30	326	30
Zone C—highest yield	331	27	326	27	321	27
Zone D	334	27	329	27	323	26
Zone E	329	28	323	28	318	28

increase in field size and number of management zones will likely increase the economic differences among the management practices. In addition, the generally high rainfall in southwest Georgia also resulted in little water stress in some seasons and in some times during a growing season. The farmers in this region usually irrigate their soybean crop immediately after planting, or in the event of an unusually long dry period. Although not part of this study, the years 1999, 2000 and 2001 were some of the driest on record, with, respectively annual deficits of 300, 371 and 406 mm below normal. As water is becoming a more limiting resource, farmers may have to choose which crops to irrigate.

The method of analysis that was used to study the potential value of spatially variable irrigation can be applied to other fields where farmers may be considering an investment in new equipment. The actual economic value of spatially variable irrigation would have to take into account investment, maintenance, depreciation, and other costs not considered in this study. The approach used in this study provides average as well as annual estimates of gross margin above costs of applying water so that uncertainty and risk can be considered. In addition, this study provided information on water resources required for achieving these yield levels. This information will become more important as farmers have to decrease their water use. This study showed that the spatially variable irrigation management strategy was superior with respect to total production and gross margins, compared to all the other irrigation scenarios analyzed. With advances in irrigation technologies, including controls for individual nozzles and valves on center pivot and linear irrigation systems, spatially variable irrigation management has a high potential for implementation.

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