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Simulating the effects of spatially variable irrigation on corn yields, costs, and revenue in Iowa

Kendall C. DeJonge [a], *Amy L. Kaleita* [b,*], *Kelly R. Thorp* [c]

[a] Hydrologic Engineering Branch, U.S. Army Corps of Engineers, Omaha, NE 68102, USA
[b] Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50011, USA
[c] U.S. Arid-Land Agricultural Research Center, Maricopa, AZ 85239, USA

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ABSTRACT

In this study, the CERES-Maize crop model was used in conjunction with Apollo, a shell program, to evaluate potential improved yield in a central Iowa cornfield on a spatially and temporally variable basis. Five years of historical yield and weather data were used to calibrate the model over 100 spatially variable grid cells for non-irrigated conditions in the 20.25 ha field. This calibrated model then used 28 years of historical weather data to simulate three irrigation scenarios: no irrigation, scheduled uniform irrigation, and precision irrigation. Irrigation improved yield by at least 500 kg ha^{-1} in half of the years simulated. Precision irrigation showed slightly lower yields than scheduled uniform irrigation. Assuming use of a center pivot system, irrigation showed economic returns in only one of the 28 years included in the study. High capital costs were the leading restrictor of economic feasibility.

1. Introduction

Water is one of the most important resources when considering the production of agricultural crops. Most semi-arid regions require irrigation to obtain high yields, while many other areas such as Iowa rely primarily on rainfall. The average rainfall in Iowa is normally sufficient for crop production, and an estimated 35% of the land is drained to remove excess moisture (Zucker and Brown, 1998). However, Or (1998) found that in countries with large amounts of rainfall, temporal variation in storm frequency and production do not always coincide with crop needs. An artificial watering system such as irrigation can improve yields by providing consistent watering, but it is not clear whether the increased yields would offset the cost of installing and maintaining such a system.

Few studies have examined the possibility of irrigation systems in Iowa and other humid regions. Schwab et al. (1958) studied the yield response of corn and soybeans to gravity irrigation in Iowa fields from 1951 to 1955, finding an average increased yield of 2150 kg ha^{-1} on one field and 1320 kg ha^{-1} on another, when comparing the best yields of each plot. Martin et al. (1985) evaluated several irrigation strategies for corn in humid regions using the CERES-Maize crop model. Johnson et al. (1987) analyzed the economics of center pivot irrigation systems in southeastern U.S. peanut fields.

Although these older studies showed limited economic return for irrigation in humid areas, recent technological progress in precision agriculture may allow irrigation in Iowa and other humid areas to be economically feasible. Precision agriculture is already being used to increase farm production in other ways. For example, utilization of precision nitrogen and pesticide application has become more prevalent in recent years. Using similar methods including Global Positioning System (GPS), remote sensing, and variable-rate spray

* Corresponding author. Tel.: +1 515 294 5167.
E-mail address: kaleita@iastate.edu (A.L. Kaleita).
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nozzles, some researchers are focusing on variable-rate precision irrigation systems (Sadler et al., 2005). Most of these systems utilize center pivot technology, due to the potential to employ real-time sensing equipment, vary application rates, and cover the entire field.

Climate and water availability are major determining factors in corn production (Morgan et al., 2003). Paz et al. (1998, 2001) found water stress to be one of the greatest limiting factors in the yield of soybeans. Spatial variability of soil characteristics also contributes to yield variation. Sadler et al. (2000, 2002, 2005) found that spatial variation in soil water relations directly contributes to spatial variation in grain yield and a large amount of spatial variation under drought stress, indicating that water relations are not homogeneous. Sadler et al. suggest use of crop models for analysis of this relationship.

One advantage of crop models is the ability to predict the outcomes of various crop management processes without performing large-scale, costly, and time-consuming experiments. Several crop model simulations have been used to examine irrigation. Guerra et al. (2004) successfully used the EPIC model to simulate crop yield and irrigation demand for several crops in Georgia. Nijbroek et al. (2000) used crop models to determine optimum irrigation management strategies for soybeans. Considering the spatial variability in the field, best results were found when applying the irrigation schedule for the largest management zone to the entire field.

Other research indicates a need for further evaluation of crop models. Heinemann et al. (2000) used the CROPGRO simulation model to analyze irrigation practices, but stated that scenarios considering different weather conditions and soil types are necessary for a wider acceptance of the simulation. Sadler et al. (2005) discuss the possibility of variable-rate irrigation systems, and also indicate that decision support systems are needed to enhance the viability of precision irrigation.

Characteristics influencing the decision to irrigate are major inputs in crop irrigation models. Machado et al. (2000) watered corn according to two irrigation regimes, based on plant 50% and 80% evapotranspiration demand according to the Penman-Monteith equation. They found that yields were consistently high when irrigating based on the larger evapotranspiration demand. Steele et al. (2000) studied four different irrigation scheduling methods, including one based on CERES-Maize estimates of plant-extractable soil water and another based on real-time sensor feedback. Due to climactic variation between years, Steele suggested that future irrigation scheduling should follow real-time monitoring or modeling of crop water use. Guerra et al. (2004) used three options to trigger irrigation: plant water stress; soil water tension in the plow layer; and soil water deficit in the root zone. In one of the few documented irrigation experiments occurring in Iowa, Schwab et al. (1958) applied irrigations when the soil moisture dropped to 60% of the total water available to plants in the soil, or a 40% management allowed depletion (MAD). MAD is a widely used criterion for irrigation scheduling (Martin et al., 1990), a value determined by considering crop type and maximum daily evapotranspiration rate.

Crop models have emerged as a method to evaluate different crop management practices such as irrigation without costly and time-consuming onsite experiments. The CERES-Maize crop model (Jones and Kiniry, 1986) is one such computer program developed to simulate the effects of inputs, including rainfall and irrigation, on corn growth and yield. The model calculates growth and development of the corn plant using daily time steps. Inputs for the model include management practices (genetics, population, row spacing, planting and harvest dates, fertilizer and irrigation application amounts and dates), environmental factors (soil type, drained upper limit and lower limit, saturated hydraulic conductivity), and weather (daily minimum and maximum temperature, solar radiation, and precipitation). CERES-Maize has performed well on plot-level, field-level, and regional scales for many corn hybrids, climatic conditions, and soil types around the world (Hodges et al., 1987; Carberry et al., 1989; Liu et al., 1989; Jagtap et al., 1993; Pang et al., 1998; Garrison et al., 1999, Paz et al., 1999; Fraisse et al., 2001). CERES-Maize has also been shown to successfully simulate the effects of irrigation (e.g. Howell et al., 1989; Pang et al., 1998; Panda et al., 2004; Anapalli et al., 2005).

One limitation of CERES-Maize is its ability to evaluate only one uniform area at a time. To remedy this drawback, researchers at Iowa State University have developed a new decision support software product called Apollo (Application of precision agriculture for field management optimization; Batchelor et al., 2004; DeJonge, 2006). This Windows-based product is capable of automating the CROPGRO-Soybean and CERES-Maize models for analyzing several plots at a time, thereby allowing one to simulate precision farming practices for soybeans and corn. Apollo can be used to calibrate models using historic spatial yield variability, to validate these models for various other years with historical data, and to estimate responses to nitrogen and plant population prescriptions. Recent studies have used the program to determine spatially variable nitrogen and population recommendations for maximum yield (Paz et al., 1999; Thorp et al., 2006 and Miao et al., 2006).

With increased focus on precision agriculture, new research is underway involving spatially variable irrigation systems. Several prototype systems for variable-rate irrigation application have been developed, but adequate decision support systems have not (Sadler et al., 2005). In order to increase practical functionality of precision irrigation, real-time monitoring, decision, and control systems must be developed. This research utilizes the Apollo system with the CERES-Maize crop model to evaluate the potential benefits from various irrigation systems without developing the monitoring and control systems themselves.

We have developed an additional module in Apollo that automates spatially variable irrigation scenarios. We use Apollo and the CERES-Maize crop model to predict the potential yields on an Iowa cornfield assuming an optimum amount of available water, inherently predicting the effects of an irrigation system on a typical Iowa cornfield.

Our goal is to simulate three irrigation scenarios in Central Iowa and their effects on corn yield. The scenarios include no irrigation, scheduled uniform irrigation, and automatic irrigation with fixed irrigation amounts. Specific objectives are to:

1) Determine the potential yield improvement as a result of the amount and frequency of irrigation, and examine the consistency of yields over time.

2) Evaluate potential changes in the spatial variation of yields due to irrigation, and determine what factors lead to such changes if they exist.
3) Compare economic benefits of improved yield with capital and maintenance costs of irrigation systems, and determine the economic viability of adding irrigation to the test field.

2. Methods

2.1. Data

The 20.25 ha test field, near Perry, Iowa, USA (41.93080°N, 94.07254°W), was separated into 100 even grid cells, each 45 m by 45 m. Five years of complete historical management, weather and spatially variable yield data for corn were available (1994, 1996, 1998, 2000, and 2002). During the odd-numbered years in this sequence, the field was planted in soybeans. We used data for the even-numbered years to calibrate the model, as described below, by adjusting soil properties and minimizing error between simulated and observed yield for each grid cell. A digitized soil survey indicated five primary soil types present in the test field: Canisteo silty clay loam; Clarion loam; Nicollet loam; Harps loam; and Okoboji silty clay loam. Each of the 100 grid cells was assigned the soil type that was the most dominant within the grid cell (Fig. 1).

Weather data for the calibration years were collected daily from a weather station at the test site. Also available were 28 years (1966 through 1993) of historical weather data collected from a weather station 10 km from the study site. Using the calibrated model, the second set of weather data were used to simulate crop growth with and without irrigation from 1966 to 1993. These are referred to as simulation years.

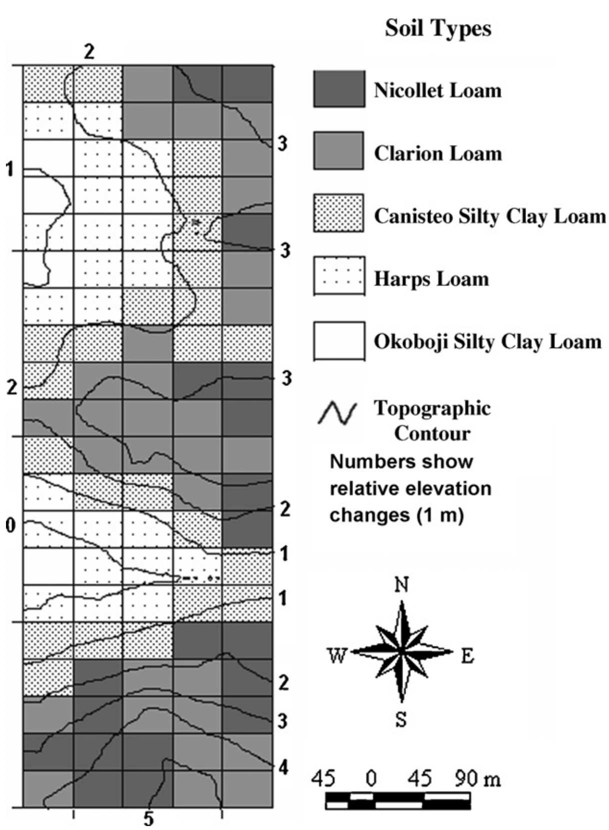

Fig. 1 – Soil types for the 20.25 ha study area divided into 100 grid cells.

Initial soil water content and nutrient levels were not available for this field. Therefore, appropriate levels were assumed and assigned throughout the study area. Initial soil water content was set at 0.35 $cm^3\,cm^{-3}$, a value near the drained upper limit for the soils of the field. Initial nutrient levels were set arbitrarily at 0.1 g elemental N, P, and K per Mg soil; this amount of initial nutrients was set to be negligible because it is assumed that spring fertilizer applications would supply nutrients for adequate growth. The plant population for each grid cell was collected during the 1996 growing season only, and these population values were used to approximate the plant population for all other years of the calibration. Plant populations in the simulation years were set at the average population for 1996 to eliminate any modeling error between grid cells due to population differences. Calibration model inputs for management practices (planting and harvest date, fertilizer application rate and dates) were set according to the producer's actual practice in each of the five growing seasons. Management inputs for the simulation years were assumed by taking mean values from the calibration years.

2.2. Model calibration

In this study, model calibration is the process of adjusting soil properties within their range of uncertainty to minimize error between simulated and measured yields for each grid cell over the five years (Batchelor et al., 2004). Because this study relies heavily on the hydraulic properties of the soil, the effective tile drainage rate (fraction of available water per day) and saturated hydraulic conductivity of the deep impermeable layer (cm day^{-1}) were chosen for calibration parameters. All other soil properties were kept constant throughout the calibration process. Relevant values for these were obtained from the county-level soil survey.

Calibration with Apollo utilizes the simulated annealing algorithm (Corona et al., 1987; Goffe et al., 1994), which solves for parameter values that minimize the root mean square error (RMSE) between measured and simulated yield. The model evaluates each grid cell (100 total) individually to find the best fit; therefore each grid cell has its own optimal values for the calibration parameters. During the calibration sequence, Apollo evaluates one grid cell at a time. Given default parameter values, Apollo will run CERES-Maize for each available year and compare the simulated yield with the actual yield for that grid cell and year. Apollo then goes through an iteration procedure to minimize RMSE for that grid cell, using formula (1):

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y_{m,i} - Y_{s,i})^2} \quad (1)$$

where N = total number of years evaluated, and $Y_{m,i}$ and $Y_{s,i}$ are the respective measured and simulated yields for the given grid cell in the ith year. This process was repeated up to 1500 maximum iterations for all 100 grid cells in the available 5-year dataset, an acceptable number of iterations according to Batchelor et al. (2004).

The calibration was performed using all five available datasets to ensure optimal simulation performance. Using the same field as this study, Thorp et al. (2005) examined ''leave-one-out'' (LOO) cross validation, a statistical procedure used to validate crop models in the instance of limited measured data. Those researchers determined that the ability of a calibrated model to simulate an independent dataset is improved when the calibration dataset spans a wide range of weather conditions. The calibration parameters closely modeled the yield for all of the calibration years (Fig. 2). The R^2 value for the calibration was 0.88.

2.3. Irrigation inputs

In the irrigation module developed for Apollo, the user defines various irrigation parameters depending on the scheme desired. Some parameters influence all irrigation scenarios, such as application efficiency and the crop growth stage at which irrigation is ceased. Other parameters may or may not be used, depending on the scenario desired.

The irrigation application efficiency was set at 85% for all scenarios, as typical center pivot systems have an efficiency of 75–90% (Martin et al., 1990). Management depth for automatic applications was set at 100 cm, as the effective rooting zone for maize is typically 1.0–1.7 m (Fangmeier et al., 2006). The amount of available soil water is calculated at this depth.

The threshold for automatic application is a percentage of available soil water within the management depth that triggers irrigation. The value for percent of available soil water (%ASW) is found by:

$$\%\text{ASW} = 100 \times \frac{(\text{SW} - \text{PWP})}{(\text{FC} - \text{PWP})} \qquad (2)$$

where SW is the soil water content in the layer ($cm^3\,cm^{-3}$), PWP is the permanent wilting point or lower limit of water available to plants ($cm^3\,cm^{-3}$), and FC is the field capacity or drained upper limit of water available to plants ($cm^3\,cm^{-3}$). All of these water content values are evaluated over the management depth specified by the user.

The irrigation threshold used for this investigation was based on the management allowed depletion, or MAD, of the available water. Using a maximum daily ET of 7 mm day^{-1} for July (Scherer et al., 1999), typical for the climate in Iowa, the MAD is found to be 50% (Doorenboos and Kassam, 1979). With an allowable depletion of 50%, the default irrigation threshold value for this study was set at 50% of available soil water. Similar values have been used in other crop modeling research (Jones and Ritchie, 1990).

The amount of water applied during each irrigation was set at 30 mm for all scenarios. This value is typical for most center pivot irrigation systems, in which about 25 mm of water is applied over a three-day period (Steele et al., 2000).

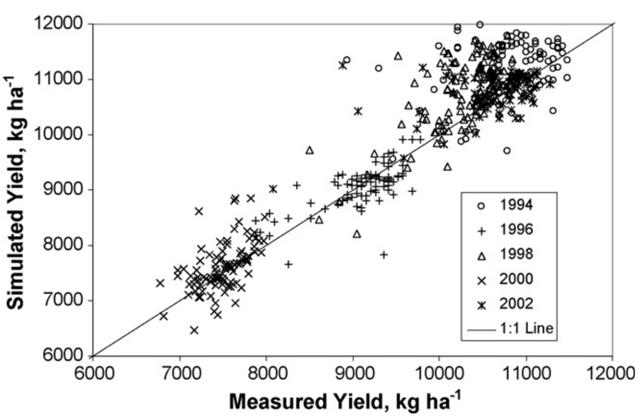

Fig. 2 – Simulated vs. measured yield for calibration.

2.4. Irrigation scenarios

The three irrigation scenarios used in this study include no irrigation, scheduled uniform irrigation on reported dates, and precision irrigation that automatically applies a fixed amount when required by an individual grid cell.

The no irrigation scenario simulates the crop growth and seasonal yield under normal weather conditions for all 28 years of the simulation, and assumes that natural rainfall is the only source of water.

The scheduled uniform scenario irrigates according to a user-defined irrigation schedule. To determine an appropriate schedule for all 28 years of the simulation, a schedule first had to be created. The field was evaluated as one single grid cell, containing average soil properties of the existing 100 grid cells, and calibrated using the same parameters discussed in Section 2.2. The single field was then modeled for all test years using automatic irrigations of 30 mm when the %ASW fell below 50%. The schedule of these irrigations was noted, and was later evaluated using all 100 grid cells on an individual basis, irrigating 30 mm equally and simultaneously according to the schedule.

The precision irrigation scenario applies 30 mm of water when the available soil water in each grid cell reaches a level of 50%. This scenario evaluates each grid cell independently and is intended to simulate a precision irrigation system.

2.5. Economics

The costs of irrigation systems were compared with net returns based on improved yield. Due to widespread use in the irrigation industry and recent developments in precision irrigation systems, center pivot irrigation costs were chosen as an economic basis. Cost estimates in this study were developed by Scherer (2005). All costs and benefits were compared on an annual dollar (USD) per hectare basis.

Fixed costs were based on normal capital costs of irrigation systems:

- Depreciation was calculated assuming a 25-year life and zero salvage value for all components.
- Interest on investment, or opportunity cost, was calculated using a 5% annual interest rate on the total capital costs.
- Insurance was assumed as \$0.50 per \$100 of capital investment.
- Labor costs were estimated at \$10 per hour, with 0.3 h of annual labor per hectare.

- Annual maintenance was assumed as 1.5% of the capital cost.

Modern center pivot systems usually use diesel fuel or electricity to pump water from a well. An electric motor and pump were assumed for this study. Electric costs can be separated into energy costs and power demand costs.

Energy costs are typically billed per kilowatt-hour (KWH) used, which is a function of the amount of water used and the time applied. The first step to determine the energy requirements is to find the water horsepower (WHP) used by the pump. This is found by:

$$WP = \frac{Q \times TH}{3.6} \quad (3)$$

where WP = water power in kilowatts, Q = discharge in cfs, TH = total head in meters, and 3.6 is a conversion constant. Total head is normally assumed as the depth of the well, in this case assumed to be 30.5 m for a basis of comparison. Brake power (BP) is the actual power requirement when considering inefficiencies of the pump and drive. The BP is calculated by:

$$BP = \frac{WP}{E_{pump}E_{drive}} \quad (4)$$

where BP = brake power in kilowatts, E_{pump} = pump efficiency at operating conditions, and E_{drive} = drive efficiency between the pump and the power unit. Assumed values for E_{pump} and E_{drive} were 0.75 and 1.00, respectively. Actual power required at the power meter is often higher than brake power due to electric demand. This phenomenon is fixed by using a power adjustment factor:

$$MP = \frac{BP}{PF} \quad (5)$$

where MP = meter power in kilowatts and PF is an adjustment factor assumed to be 0.90. Power is then converted to energy by multiplying the meter power by the total time used at that power. In this study, average power during use was calculated and then multiplied by the total time used, assuming the pivot would run 24 h for each day on which irrigation occurred. Total energy use is found by:

$$E = MP \times t \quad (6)$$

where E = energy in KWH and t = time in hours. Assumed billing for energy was $0.045 per KWH.

Power demand costs are billed on a monthly basis, based on the maximum demand experienced within the month. In most irrigation systems, this typically occurs upon starting of the pump. In this study, the demand was assumed to be the power needed to pump the maximum amount of water required for that month. The assumed charge for power demand was $9 per KW per month. If irrigation did not occur in the given month, this value was assumed to be zero for that month.

The net economic benefit was determined by considering the improved yields and increased costs due to irrigation. A value of $0.0787 per kg ($2 per bushel) was assumed as a baseline corn price. Net return due to irrigation was determined by

$$NR = PY - C \quad (7)$$

where NR = net return in $/ha, P = corn price in $/kg, Y = corn yield in kg/ha, and C is total irrigation cost in $/ha.

3. Results and discussion

3.1. *Yield improvement*

Overall, irrigation was shown to improve yields over the duration of the study (Fig. 3). The average annual yield is the mean yield of all 100 grid cells for the given year and scenario.

These improvements were more dramatic in many years with low non-irrigated yields, such as 1977 and 1980. The largest improvements were observed in 1980 (4231 and 4073 kg ha^{-1} for scheduled and precision irrigation, respectively). However, yield improvements in other years with historically low yields such as 1983 and 1988 were less dramatic. Yield improvements in those years might be constrained by generally undesirable growing conditions, independent of available rainfall or supplemental irrigation. For example, in 1988, rainfall was limiting and average

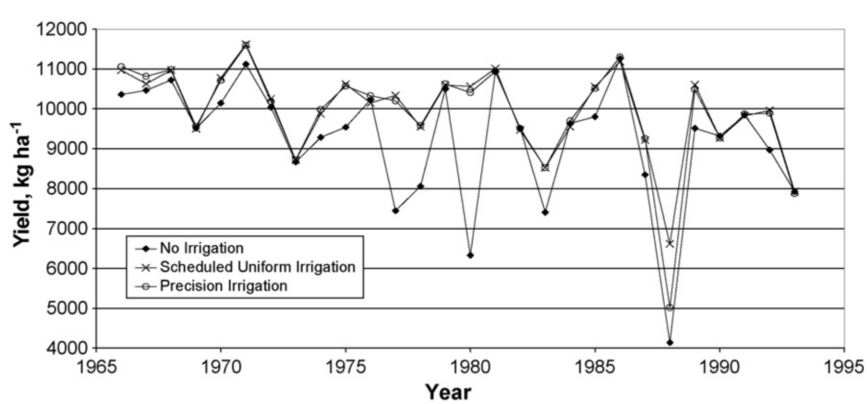

Fig. 3 – Average annual yield over duration of study.

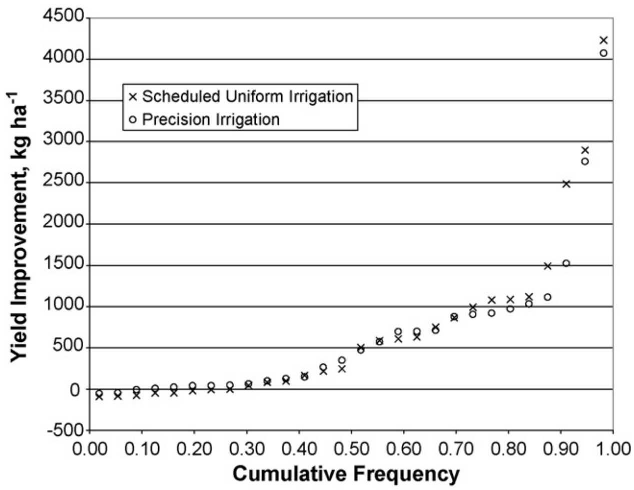

Fig. 4 – Cumulative frequency of yield improvement by irrigation.

temperatures and solar radiation were higher than in all other years of the study. Yield improvements were very small in 10 years of the study, including 1988. In all of those years, the non-irrigated yield was at least 7900 kg ha^{-1}.

Cumulative frequency plots are helpful in depicting the degree to which irrigated yields exceeded non-irrigated yields in the study. For example, in about 30% of the years, there was little or no improvement in yield (Fig. 4). In fact, in some years irrigated yields were smaller than non-irrigated yields. However, irrigated yields exceeded non-irrigated yields by at least 500 kg ha^{-1} in 50% of the years, and by at least 1000 kg ha^{-1} in 20% of the years.

A cumulative frequency plot of average annual yield shows that irrigation provides not only higher yields, but also more temporally consistent yields (Fig. 5). Irrigated yields are greater than 10,000 kg ha^{-1} in 55% of the years and greater than 8000 kg ha^{-1} in 95% of the years, whereas non-irrigated yields are greater than 10,000 kg ha^{-1} in only 34% of the years, and greater than 8000 kg ha^{-1} in only 80% of the years.

During the 28 years simulated, the average non-irrigated yield was 9250 kg ha^{-1}, while average irrigated yields were 9963 and 9909 kg ha^{-1} for scheduled and precision irrigation, respectively. Therefore, on average, respective yields increased by 713 and 659 kg ha^{-1}. The yield increase achieved with precision irrigation was slightly smaller and more variable than the yield improvement achieved with scheduled irrigation. The minimal difference in yield improvement between the two irrigation scenarios likely occurred because the water delivery was very similar in both cases, despite precision irrigation being spatially independent. The total amount of water delivered in both irrigation scenarios was nearly the same in all years (Fig. 6), and in many cases, individual grid cell irrigation requirements in the precision scenario were the same as requirements in the scheduled uniform scenario.

3.2. *Spatial variability*

Yield was spatially variable in this field for all irrigation scenarios. Fig. 7 shows the non-irrigated average yield over all years, simulated for each grid cell. Areas with the highest yield occurred among the Clarion Loam soils. The lowest extreme yields also occurred among the Clarion loams (Clarion was the most abundant soil type in 30 of the 100 grid cells), but the Canisteo silty clay loams had the most consistently low yields.

Both irrigated scenarios behaved similar to the non-irrigated scenario, in that the areas of high and low yield occurred at the same places (Fig. 8). As expected, the largest improvements in yield occurred where the non-irrigated yields were low and the smallest improvements where the non-irrigated yields were high (Fig. 9). Okoboji silty clay loam showed the largest improvement in yields (although there were only three such grid cells), and Nicollet loam and

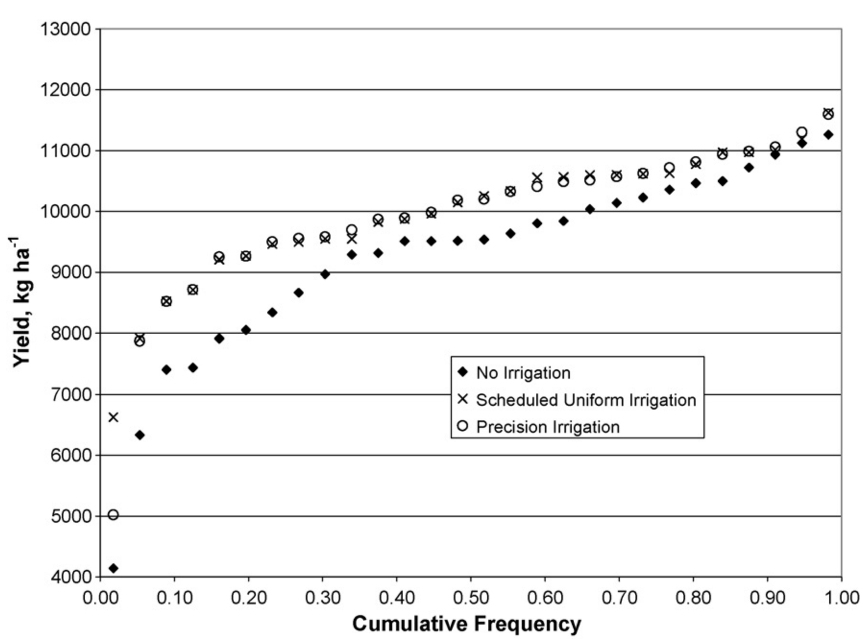

Fig. 5 – Cumulative frequency of yield for irrigation scenarios.

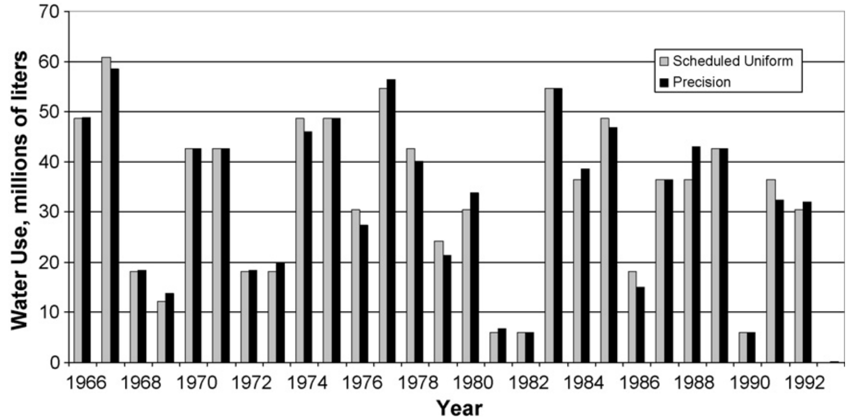

Fig. 6 – Annual irrigation water deliveries for both irrigation scenarios.

Canisteo silty clay loam also showed significant yield improvement. Canisteo soils especially showed large improvements, as the top half of improved yields were between 780 and 1739 kg ha^{-1} for scheduled irrigation and between 709 and 1689 kg ha^{-1} for precision irrigation. In the Des Moines lobe region, where this field is located, the distribution of soil types is closely linked to landscape position, with Clarion and Nicollet soils near hilltop areas, Canisteo soil on midslopes, and Okoboji soil in pothole sections. Geographically, the largest yield improvements occurred in the southern half of the field, while the smallest yield improvements occurred in the Clarion soils near the middle of the plot and in the southeastern corner.

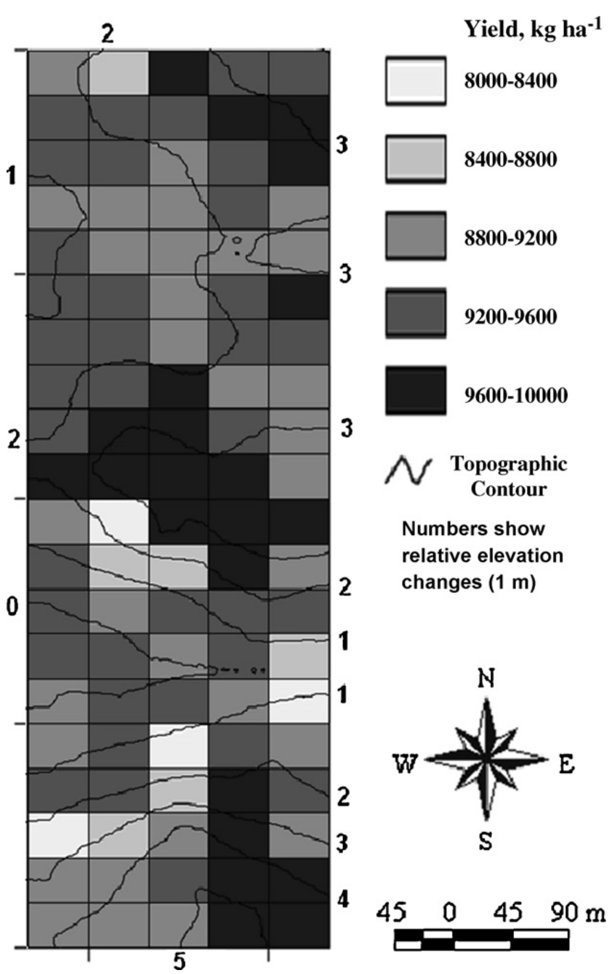

Fig. 7 – Non-irrigated average yield over 28 years.

Precision irrigation showed more variability in yield improvement than scheduled irrigation, possibly due to the variability of evaluating 100 grid cells independently as opposed to irrigating based on a uniform schedule. Irrigation not only increased average yield throughout the field, but also contributed to more spatially consistent yields. The average spatial standard deviation among grid cells was 680 kg ha^{-1} for the non-irrigated scenario, which was reduced to 317 and 335 kg ha^{-1} for scheduled and precision irrigation, respectively.

3.3. *Economic analysis*

The fixed costs per hectare were found to be $174.03 and $208.71 for scheduled uniform and precision irrigation, respectively. Fixed costs for precision irrigation were higher due to extra equipment costs. In both cases, the largest contributors to the fixed costs were the capital recovery costs, which accounted for about 70% of fixed costs (Table 1).

The variable costs of electricity per hectare ranged from 0 to $68.63 for scheduled uniform irrigation and from $8.79 to $43.84 for precision irrigation. Electric costs were typically less for precision irrigation due to lower demand costs. With precision irrigation, there were many more days where irrigation occurred, but rarely involved all 100 grid cells, thus creating a lower maximum demand each month. Neither scenario showed a significant water savings over the other.

Overall, irrigation was unprofitable in both irrigation scenarios (Fig. 10). Scheduled irrigation and precision irrigation showed respective annual net losses of $157.28 and $186.17 per hectare during the duration of the study. Irrigation was profitable in just 1 year in both scenarios (1980), a dry year in which yields were increased by at least 4000 kg ha^{-1}. Scheduled irrigation slightly exceeded the break-even point in 1977 and neared it in 1988, while precision irrigation was also close to increasing profits in 1977. Profitability was limited by the large capital costs of the irrigation systems and the

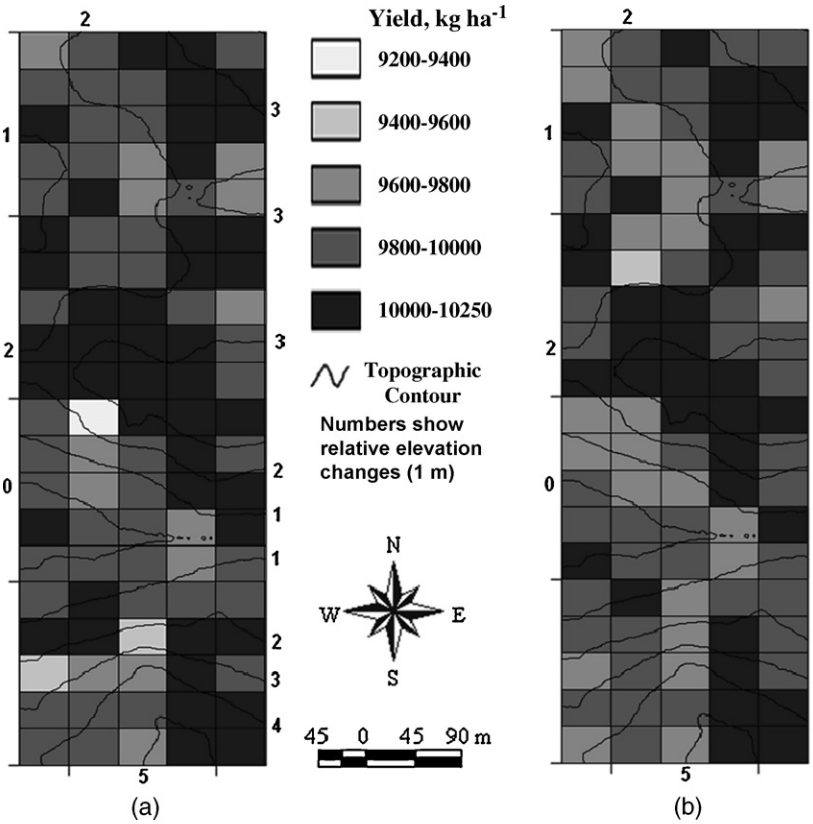

Fig. 8 – Average yield for scheduled uniform (a) and precision (b) irrigation over 28 years.

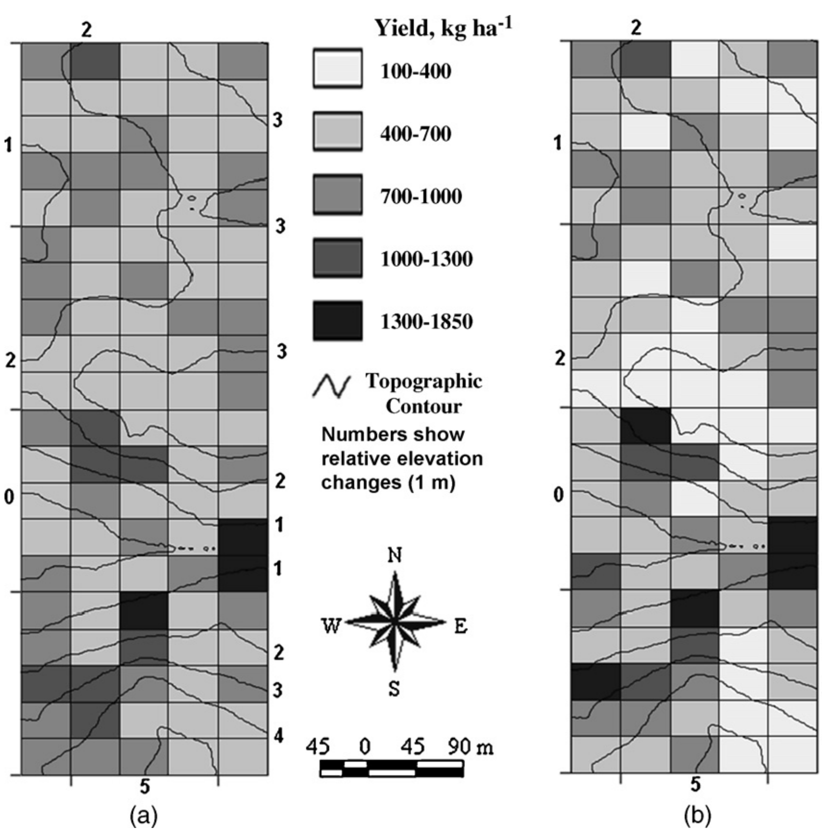

Fig. 9 – Average improvement in yield for scheduled uniform (a) and precision (b) irrigation over 28 years.

Table 1 – Fixed costs for both irrigation scenarios

	Scheduled uniform	Precision
Capital costs		
System life (years)	25	25
Hectares irrigated (in 64.75)	52.61	52.61
Irrigation system cost	$50,000	$50,000
Well, pump, motor	$30,000	$30,000
Pipe, meter, valves	$3,000	$3,000
Electric panel and wire	$7,000	$7,000
Precision equipment retrofit	$0	$20,000
Total capital cost	$90,000	$110,000
Capital cost per hectare	$1,710.70	$2,091.25
Ownership cost (per hectare)		
Annual cost capital recovery[a]	$121.38	$148.38
Insurance ($0.50/$100 capital)	$8.55	$10.46
Total annual ownership cost per hectare	$129.93	$158.84
Operating costs (per hectare)		
Power (electric)	Variable	Variable
Labor @ $10/h, 1.85 h/ha	$18.50	$18.50
Maintenance (1.5% new cost)	$25.66	$31.37
Total annual operating cost per hectare[b]	$44.10	$49.87
Operating and owership cost per hectare[b]	$174.03	$208.71

Source: Scherer, 2005.
[a] Includes both interest and depreciation, assuming 5% compounded annually.
[b] Not including variable power costs.

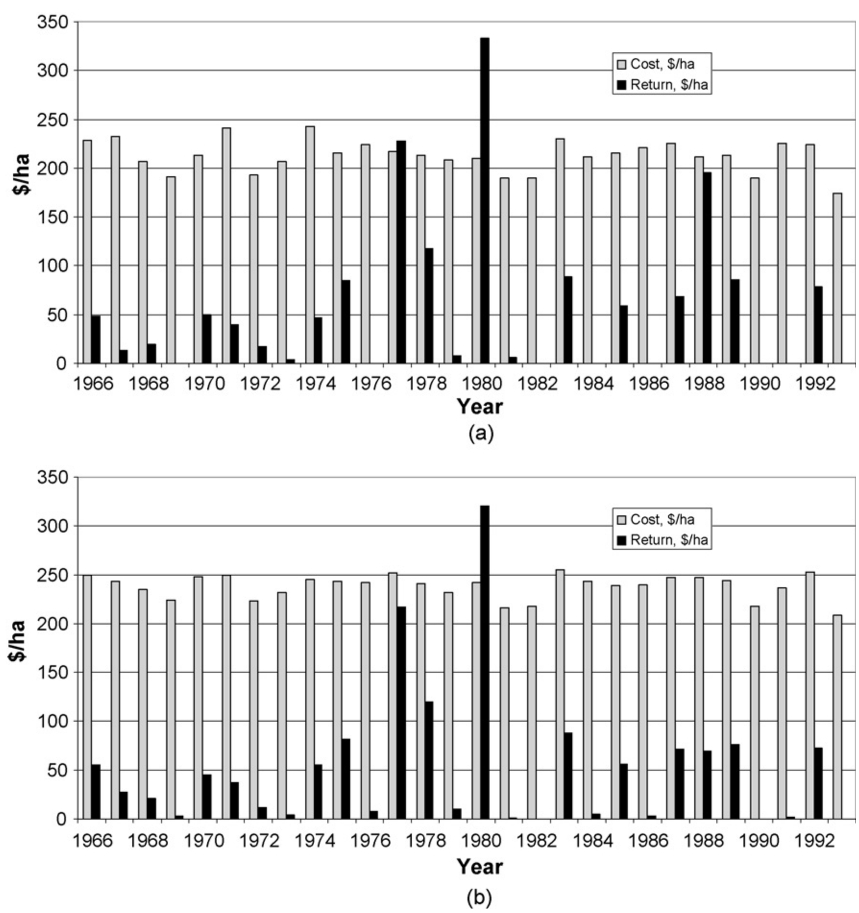

Fig. 10 – Field total annual cost and benefit per hectare for scheduled uniform (a) and precision (b) irrigation.

inability to consistently generate large increases in yields. To overcome fixed costs alone during the study, a corn price of $0.182 kg^{-1} for scheduled irrigation and $0.241 kg^{-1} for precision irrigation would have been required.

A decrease in capital costs could possibly improve the economic viability of irrigation in this field. However, in order to break even during the duration of the study, even with the crop price doubled to $0.0787 per kg, the total capital costs would have to be decreased to $31,324 for scheduled uniform irrigation and $32,366 for precision irrigation. As both of these values are approximately one-third of assumed current costs, it is unlikely that the costs would ever be this low.

4. Conclusions

Overall, irrigation improved corn yields during the study. The improvement in yield was at least 500 kg ha^{-1} in half of the years simulated for both irrigation scenarios, and at least 1000 kg ha^{-1} in 20% of the years. Precision irrigation showed lower overall yields than scheduled uniform irrigation. In this study, the schedule for the uniform irrigation scenario was based on average available soil water properties that were recalculated on a daily basis. One could expect smaller improvements with the less data-intensive scheduling processes that are prevalent in agriculture today.

Irrigation not only improved yields over time, but also created more consistency in yields between years. Spatial variability in yield was influenced by soil type. With no irrigation, yield was typically the highest on Clarion loam soils. The largest yield improvements occurred on the Canisteo silty clay loam and Nicollet loam soils. Irrigation not only reduced variability temporally, but spatially as well. Neither irrigation scenario was profitable. The incremental net return due to irrigation was positive in only one of the 28 simulation years. The largest economic limitation was the capital cost for a center pivot irrigation system, with fixed annual costs of $121.38 and $148.38 per hectare for scheduled uniform and precision irrigation, respectively.

While this study was helpful in determining the feasibility of irrigation in a cornfield near Perry, Iowa, some recommendations can be made for further research. First, it would be interesting to perform a similar study on a field more suitable for irrigation, such as fields in western Iowa with sandier soils and drier climates. Also, the irrigation module used in this project might be used in conjunction with a nitrogen transport model to examine issues pertaining to irrigation and nitrogen management.

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