USE OF A CROPPING SYSTEM MODEL FOR SOIL-SPECIFIC OPTIMIZATION OF LIMITED WATER.

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ABSTRACT

In the arena of modern agriculture, system models capable of simulating the complex interactions of all the relevant processes in the soil-water-plant-atmosphere continuum are widely accepted as potential tools for decision support to optimize crop inputs of water to achieve location specific yield potential while minimizing environmental (soil and water resources) impacts. In a recent study, we calibrated, validated, and applied the CERES-Maize v4.0 model for simulating limited-water irrigation management strategies for corn in a Rago silt loam soil at Akron, Colorado. The results showed that, for different levels of irrigation, optimum production and WUE with minimum N losses were found when 20% of the available irrigation supply was applied during the vegetative (V) stage and 80% during the reproductive stage (R) (split irrigation strategy). We also found that the number of irrigations could be reduced and the water significantly saved if irrigations were initiated at 80% depletion of the plant available soil water (PAW) (later than commonly practiced). In this paper, the above model was used to evaluate similar limited irrigation management strategies for two other soil types (Nunn clay loam and Julesburg sandy loam) commonly occurring in the area. For the Nunn clay loam and Julesberg sandy loam soils, the water-level production functions, optimum irrigation levels, and WUE responses were similar. However, for the Julesberg sandy loam soil, our best results were found with the 20:80 split irrigation between V and R for all irrigation levels. For the Nunn clay loam soil, our best irrigation strategies were 20:80 split between the V and R stages for irrigations below 300 mm and above 600 mm, and 50:50 split between the stages for irrigation levels between 300 and 600 mm. For the late initiation of irrigation, optimum yields were achieved when water was applied at

60% depletion of PAW for the Nunn clay loam soil, and at 70% depletion of PAW for the Julesburg sandy loam soil.

Keywords: precision farming, corn, agricultural systems simulation, limited irrigation.

INTRODUCTION

Agricultural system models can play vital roles in the arena of precision farming through the synthesis and quantification of the effects of soil, crop and weather conditions, and varying levels of inputs (e.g., water, fertilizers) on crop production and environmental quality across different parts of the landscapes. The results can then be used for precision management to maximize the efficiency of crop inputs within relatively homogeneous areas in a field or different fields on a farm. Here, we envisage the precision farming techniques to focus on optimising the use of environmental, soil and water resources, and chemical inputs (fertilisers and pesticides) on a site-specific basis. Now, with the technological advances in agricultural system modelling, remote sensing, Geographical Information Systems (GIS), and Global Positioning Systems (GPS), this has become technically feasible.

Most of the agriculture in the Great Plains of the U.S.A. is water-limited, consisting of rain-fed, dry-land, cropping systems or range-livestock systems and some irrigated cropping systems where irrigation water is available. Prolonged drought in the last few years has aggravated the limited water situation, and greater frequency of severe droughts predicted by global climate change models is a cause for great concern, especially for the dry-land systems (Rogner et al., 2007). At the same time, the increasing water demands for drinking, sanitation, urban irrigation, industry, and environmental uses are outbidding and reducing the irrigation water available for agriculture. Similar situations exist in many other arid to semi-arid parts of the world. To obtain maximum return out of limited rainfall and irrigation water, with minimum environmental impact, the producers need whole-system and quantitative management tools to help them optimize the use of available water and minimize associated inputs on site-specific and field-specific basis. The decision tools for optimization of the complex issues require the use of process level models of cropping system as a whole to synthesize the available experimental data, extend the results beyond the experimental periods and soil conditions, and derive alternate management scenarios. Process level system models are based on synthesis and quantification of disciplinary knowledge and important interactions among the system components. These models also provide a systematic approach to design and implement a multi-disciplinary research program that will greatly enhance the efficiency of future field research for developing sustainable agriculture, enable a fast transfer of technologies to farmers, provide guides for planning and site-specific management, and inform policy makers and general public on the major issues and tradeoffs, costs and benefits of alternatives.

Corn production in Colorado has increased dramatically in the past two decades with the availability of irrigation systems and cultivars with improved radiation and water use efficiency (Norwood, 2001; Castleberry et al., 1984; Hergert et al., 1993). Crop water stress due to low precipitation and high temperatures are the main limiting factors for agricultural production in the Great Plains (Halvorson et al., 1999; Norwood, 1999). Currently in these areas, corn is primarily grown under either rainfed or full irrigation regimes. Much field research in the past focused on increasing corn production in the Great Plains by enhancing precipitation use efficiency (Staggenborg et al., 1999; Norwood and Currie, 1996). Supplemental irrigation can improve agricultural profitability in this region, but over-use of the limited water in the Great Plains areas accelerates loss of ground water, which may result in limits to irrigation for agricultural uses or a return to dryland production (Hergert et al., 1993).

In general, studies for determining irrigation recommendations for a locality make use of field experiments that have been done with limited multi-year, multi-location replications, and conclusions are extrapolated statistically or heuristically. Irrigation responses, depending on the soil and climate variability (especially precipitation) at the location, can vary a great deal among years and locations. Field experiments to capture all the multi-year, multi-location variability in climate, soils, etc. are nearly impossible. Dynamic cropping system simulation models, when well calibrated and validated against field experimental data, hold the promise of extrapolating the short duration field experimental results to other years and other locations, making use of the long-term weather and soil information (Mathews et al., 2002; Knisel and Turtola, 2000).

Simulation models can synthesize and integrate information gathered from short- or long-term field studies, and provide a way to extrapolate results to differing soils and climates. Simulation models have been previously used to provide decision support to optimize irrigation water use and conserve rain water at the field or farm level through various combinations of soil management, irrigation scheduling, crop selection, shifting sowing dates, and changing plant populations (Sadras and Hall, 1989; Rosenthal and Gerik, 1990; Singels, 1992; Sivakumar and Glinni, 2002; Debaeke, 2004; Saseendran et al., 2004; Saseendran et al., 2005). The DSSAT (Decision Support System for Agrotechnology Transfer) models have been used worldwide in the past two decades for various applications that include irrigation decision making (Jones et al., 2003).

In this paper we used CERES-maize v4.0 (a component of the DSSAT) to extend the location specific limited-water irrigation management strategies developed by Saseendran et al. (2008) for corn in a Rago silt loam soil to evaluate similar strategies for two other soil types (Nunn clay loam and Julesburg sandy loam) commonly occurring in and around Akron, Colorado. Limited irrigation management strategies were developed for 1) applying irrigation only when it will result in maximum benefit to the crop and 2) increasing WUE by withholding irrigation until the PAW in the soil is depleted to a set level. Fates of applied N associated with the above strategies were also investigated.

MATERIALS AND METHODS

Field experiments and data used for the model calibration and validation were collected in irrigated and rainfed corn experiments over a period of eight years at the Central Great Plains Research Station 6.4 km east of Akron, CO (40^o 9′ N, 103^o 9′ W, 1384 m above mean sea level). Soil type at the location is a Rago silt loam (fine montmorillonitic mesic Pachic Arguistoll). The irrigation experiments (line-source gradient irrigation system) used in the study were conducted during 1984, 1985, and 1986. Corn hybrid 'Pioneer Brand 3732' (101-d relative maturity) was used. In 1985, additional drip irrigation treatments were conducted with four irrigation levels determined by different threshold values of the Crop Water Stress Index (Nielsen and Gardner, 1987). All the experiments were fertilized with ammonium nitrate at the rate of 168 kg N ha^{-1}. The CERES-Maize model requires inputs of crop management practices, soil properties, and weather data in addition to cultivar specific parameters (Jones et al., 1994). Detailed data on irrigation dates and amounts and other data needed for the simulations, and the calibration and validation procedure and results are reported in Saseendran et al. (2008).

Simulation Studies

In the current study, the above validated CERES-Maize v4.0 model for Rago silt loam soil was used to investigate the effects of different irrigation levels and alternative water management scenarios on corn production in the Nunn clay loam and Julesburg sandy loam soils. The historical weather records for Akron from 1912 to 2005 were used as representation of the climate variability of the area in the investigations and derivation of conclusions. In all the simulations, N was applied at 168 kg N ha^{-1} as followed in the irrigation field experiments. All irrigation simulations were sprinkler-irrigated. The limited-water management strategies simulated are described below in the subsections. Concepts developed in the study can potentially be adapted to other locations, climates, and crops.

Irrigation Levels and Differential Water Allocation between Vegetative (V) and Reproductive (R) Stages.

Tasseling, silking, pollination, and early grain-filling are the most water-sensitive stages for corn (Stewart et al., 1975; Stegman, 1982; Nielsen et al., 1996). In limited-irrigation situations, it is critical that the water applied is carefully allocated between different critical water-sensitive crop growth stages to optimize production. Long-term simulations (1912 to 2005) of corn at Akron showed that the potential evapotranspiration demand at the location is between 700 and 1000 mm, averaging about 900 mm. The division between vegetative and reproductive stages is usually marked in the field as the date of pollen shed and silking, occurring on average around 25 July. We simulated the crop from 1912 to 2005 (94 years) with total season irrigations of 100, 200, 300, 400, 500, 600, and 700 mm with water applications split between vegetative (V) and reproductive stages (R). The three hypothetical split application treatments were 1) 20: 80, 2) 40:60, and 3) 50: 50 between the V and R stages. The crop was planted on 3 May each year in all the simulations.

Initiation of Irrigation at Optimum PAW Depletion Levels

Increased WUE may result from reductions in the amount and frequency of irrigation application. This may be accomplished by withholding irrigation until the PAW in the soil is depleted to a maximum level without compromising plant growth and productivity. We simulated the crop for 94 yrs (1912 to 2005) by allowing the soil water to deplete to 10, 20, 30, 40, 50, 60, 70, 80, and 90% of the PAW, and irrigated back to field capacity each time.

RESULTS AND DISCUSSION

Different Irrigation Levels and Differential Water Allocation between Vegetative (V) and Reproductive (R) Stages.

Average grain yields simulated with the three split irrigation treatments under irrigation levels ranging from 100 to 700 mm with N at 168 kg N ha^{-1} at planting are presented in Fig. 1. Differences in simulated grain yields in response to the different irrigation treatments (100 to 700 mm) across years (treated as blocks in the Randomized block Design) were highly significant ($p<0.00001$; two factor ANOVA without replication). For all three soils, for the 500 mm irrigation level, split applications at 20:80 and 40:60 simulated similar average grain yields. For irrigations from 600 mm to 700 mm, the 20:80 split irrigation treatment simulated greater average grain yields compared with the other split irrigation

Table 1. Irrigation amount (weekly) breakdown between vegetative (V) and reproductive (R) stages with 100 to 700 irrigations (12 and 6 irrigations in V and R stages, respectively).

Irrigation	20:80*		40:60*		50:50*	
	V	R	V	R	V	R
mm						
100	1.7	13.3	3.3	10.0	4.2	8.3
200	3.3	26.7	6.7	20.0	8.3	16.7
300	5.0	40.0	10.0	30.0	12.5	25.0
400	6.7	53.3	13.3	40.0	16.7	33.3
500	8.3	66.7	16.7	50.0	20.8	41.7
600	10.0	80.0	20.0	60.0	25.0	50.0
700	11.7	93.3	23.3	70.0	29.2	58.3

* ratio of irrigation split between the vegetative (V) and reproductive (R) stages.

treatments. For all irrigation levels (100 to 700 mm), water applied during the reproductive stages were higher than those applied during the vegetative stages by 8 fold in the 20:80, and by 3 fold in the 40:60 split irrigation experiments. Due to N leaching during vegetative stage, in general, from the irrigation level of 400 - 500 mm onwards, there was a yield decline in the simulated yield (Fig. 1 and 2). Mean grain yields (data not shown) simulated with ‘no N stress’ (i.e.: N supply in the soil always maintained at optimum level and not affected by N leaching) did not show this yield decline.

For the three soil types, differences in simulated WUEs in response to the different irrigation treatments (100 to 700 mm) across years (treated as blocks in the Randomized block Design) were highly significant ($p<0.00001$; two factor ANOVA without replication). In general, the simulated biomass, leaf area index, kernel number per plant, and unit kernel weight in the 20:80 split application were equal to or higher than with the other two split application treatments due to higher plant available water in the soil profile (data not shown). For the Nunn clay loam soil for irrigations less than 300 mm and greater than 600 mm, the 20:80 split, and for irrigations between 300 and 600 mm the 50:50 split irrigations between the V and R stages resulted in greater grain yield and WUEs (Fig. 1a and 3). For the Rago silt loam soil, except in the case of 100 mm irrigation, split applications at 20:80 between the V and R stages resulted in the highest WUE compared with the other split applications (Fig. 1b and 3). For the Julesberg sandy loam soil, for all the irrigation amounts, the split applications at 20:80 resulted in the highest WUE compared with the other split applications (Fig. 1c and 3).

In general, for all three soils at all irrigation levels above 400 mm, the model simulated higher nitrogen stress (due to high N leaching) (e.g.: Fig. 2 for Rago silt loam soil) during the reproductive stage (floral induction to end of grain fill stage) under 40:60 and 50:50 split irrigation treatment compared with the 20:80 treatment. This resulted in lower grain yield simulations. Simulations with 400 mm of water produced the best combination of average grain yield (e.g.: for Rago silt loam soil: 9601 kg ha^{-1} with a standard deviation of 1408 kg ha^{-1}) and WUE (e.g.: for Rago silt loam soil:14.1 kg ha^{-1} mm^{-1}) (Fig. 3 a and b). However, the irrigation level at which the maximum WUE was simulated did not coincide with the maximum grain yield simulated. For example, for the Rago silt loam soil, the maximum WUE simulated (15.8 kg ha^{-1} mm^{-1}; Fig. 3) occurred with 300 mm irrigation yielding a lower average grain yield of 9141 kg ha^{-1}, and the maximum grain yield occurred with the 600 mm irrigation (9752 kg ha^{-1}) with a much lower WUE of 11.0 kg ha^{-1} mm^{-1}. For the 400 mm irrigation level, the model simulated average N leaching of 3.4 kg N ha^{-1}, residual N at harvest of 28.5 kg N ha^{-1}, plant N uptake of 229.70 kg N ha^{-1}, and N mineralization of 47.5 kg N ha^{-1}. Amount of N leached increased, and plant N uptake decreased with further increases in irrigation amounts. The 40:60 and 50:50 split applications simulated similar average grain yields for irrigation levels up to 400 mm. For irrigation levels above 400 mm, the 40:60 split applications simulated better grain yields compared to the 50:50 split application.

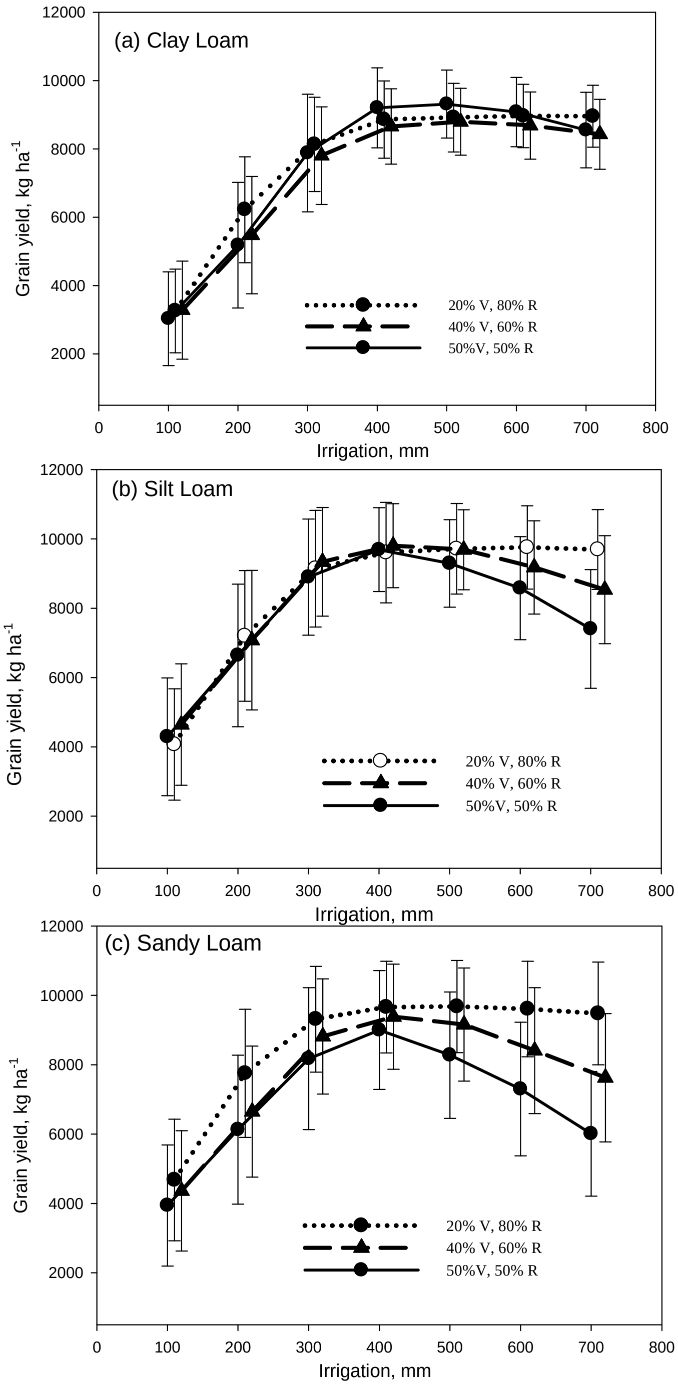

Fig. 1. Simulated grain yield response to 100 to 700 mm irrigations (gross irrigation), split between vegetative and reproductive stages at 20:80, 40:60, and 50:50 under (a) clay loam, (b) silt loam, and (c) sandy loam soils. Distribution of average seasonal potential evapotranspiration demand between the vegetative and reproductive growth stages was 55:45. Error bars represent one standard deviation from the mean. Deviations of grain yields from the mean value were due to variation in rainfall, temperature and solar irradiance during the crop growth period from 1912 to 2005. Average crop season rainfall was 284 mm.

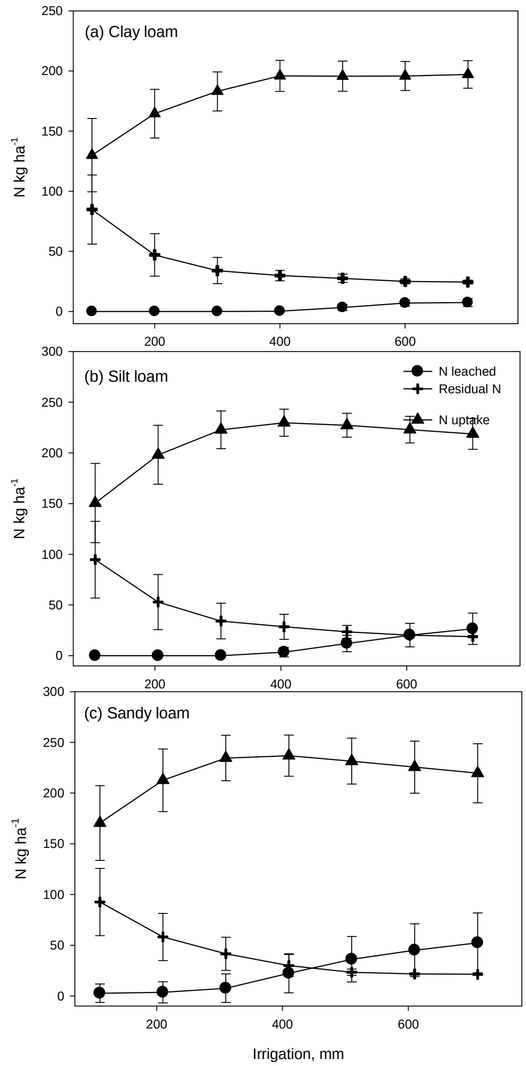

Fig. 2. Average simulated N leached, residual soil N at crop harvest, and plant N uptake for corn in response to 100 to 700 mm irrigations (gross irrigation) split between vegetative and reproductive stages at 20:80 (a) Nunn clay loam, (b) Rago silt loam, and (c) Julesberg sandy loam soils. Error bars represent one standard deviation from the mean.

Results discussed above showed that under any given soil and average rainfall conditions in northeastern Colorado, 400 mm of irrigation split at 20:80 between the vegetative and reproductive stages is adequate to achieve the simulated maximum average.

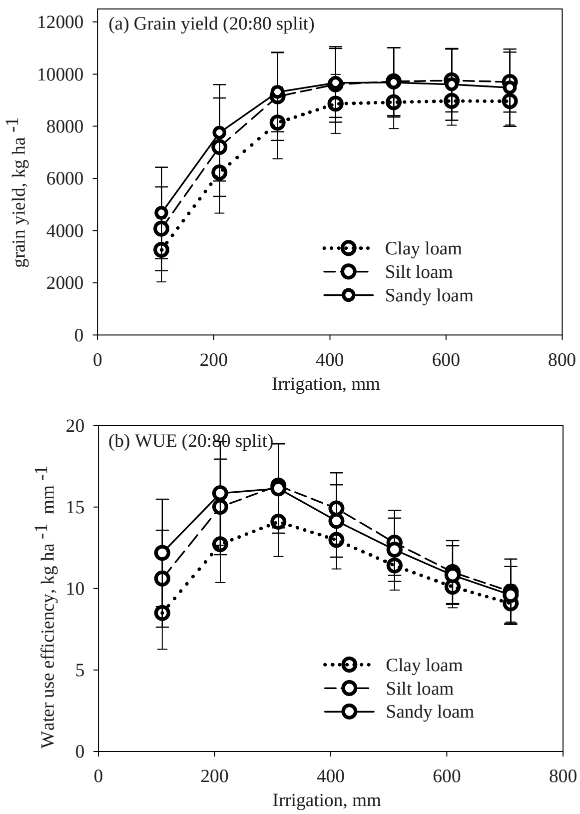

Fig. 3. Simulated average (a) grain yield, and (b) water use efficiency (WUE) for seasonal irrigation levels of 100 to 700 mm split at 20:80 between the vegetative and reproductive stages of corn, under the Nunn clay loam, Rago silt loam and Julesberg sandy loam soils. Average crop season rainfall was 284 mm.

Initiation of Irrigation at Optimum PAW Depletion Levels

Averaged over the 94 years of simulation, WUEs achieved by initiating irrigations at PAW depletions from 90 to 10% PAW increased from 5.6 kg ha^{-1} mm^{-1} (average for the three soils) at 90% PAW to 15.0 kg ha^{-1} mm^{-1} (average for the three soils) at 60% PAW with little response at higher depletion (i.e. lower PAW) levels. On average for the three soils, amounts of irrigation water applied decreased from 513 to 256 mm, and the number of irrigation applications needed decreased from 42 to 5 (data not shown). Probability of achieving greater grain yield with initiation of irrigation at lower water depletion levels increased substantially only between the 10, 20, 30 and 40% PAW for Nunn clay loam (Fig. 4a); 10 and 20% PAW for the Rago silt loam (Fig. 4b); and 10, 20, and 30% for the Julesberg sandy loam soils. WUE decreased and probability of achieving grain yield did not increase further with initiation of irrigations at lower available soil water depletion levels than 40%, 20%, and 30% for the respective soils (i.e.: higher PAW levels).

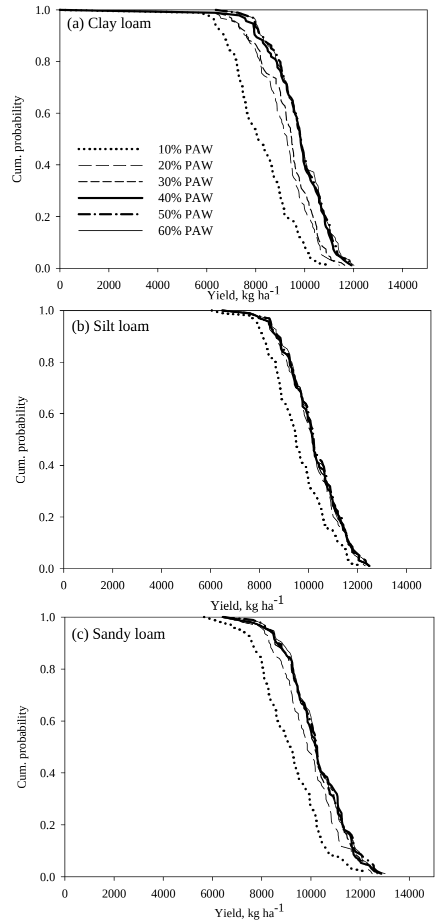

Fig. 4. Cumulative probabilities for corn grain yields simulated with the 94–yr weather record in response to initiation of irrigations at soil water depletions at 10 to 60% PAW levels [depletion levels are expressed in terms of the corresponding % PAW] for (a) Nunn clay loam, (b) Rago silt loam, and (c) Julesberg Sandy loam soils.

In soil textures varying from fine sand to sandy loam, irrigating at 30 % PAW until 2 weeks before tasseling and at 50 % PAW afterwards, Klocke et al. (2004) obtained 93 % as much grain yield return as that obtained from irrigation treatments in which water was applied according to the farmer's current management strategy (these strategies ranged from irrigations from the capacity of the well to following evapotranspiration demand). However, in that study there were no attempts to investigate options to initiate irrigation above or below the 30 % PAW level. In addition, the same irrigation levels were not tried from the vegetative stage through to the end of the reproductive stage of the crop.

CONCLUSIONS

Agricultural system models are potential tools for the synthesis and integration of site-specific information on the various components of the agricultural system for input management. Saseendran et al. (2008) calibrated and validated the CERES-maize v4.0 model for corn production in Rago silt loam soil at Akron, Colorado and used it with long-term weather data (94 years), and developed site-specific limited water irrigation management scenarios. In this paper, we extended that study further and developed soil-specific water management scenarios for the Nunn clay loam and Julesberg sandy loam soils commonly occurring in the region. The limited water management strategies developed varied considerably between the three soils. The study highlighted the potential of agricultural system (cropping system) models for site-specific synthesis and integration of soil-crop-water-atmosphere information for decision support in precision agriculture.

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