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Use of crop simulation models to evaluate limited irrigation management options for corn in a semiarid environment

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[1] Increasing competition for land and water resources due to increasing demands from rapid population growth calls for increasing water use efficiency of irrigated crops. It is important to develop location-specific agronomic practices to maximize water use efficiency (WUE). Adequately calibrated and validated agricultural systems models provide a systems approach and a fast alternative method for developing and evaluating agronomic practices that can utilize technological advances in limited irrigation agriculture. The objectives of this study were to (1) calibrate and validate the CERES-maize model under both dryland and irrigated corn (*Zea mays* L.) production in northeastern Colorado and (2) use the model with a long-term weather record to determine (1) optimum allocation of limited irrigation between vegetative and reproductive growth stages and (2) optimum soil water depletion level for initiating limited irrigation. The soil series was a Rago silt loam, and the initial water content on 1 January of each year was equal to field capacity in the upper 300 mm and half of the field capacity below this depth. Optimum production and WUE with minimum nitrogen (N) losses were found when (1) a water allocation ratio of 40:60 or 50:50 (uniform) between vegetative and reproductive stages for irrigations up to 100 mm, and a ratio of 20:80 for irrigations above 100 mm was used; and (2) irrigation was initiated at 20% plant-available water (PAW) (80% depletion). When available water for irrigation is limited to 100 mm, irrigating 50% of the area with 200 mm of water at 20:80 split irrigations between the vegetative and reproductive stages produced greater yield than irrigating 100% of the area with 100 mm water. Concepts developed in the study can potentially be adapted to other locations, climates, and crops. However, precise site-specific recommendations need to be developed for each soil-climate zone using the validated system model.

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1. Introduction

[2] Declining water supplies for agriculture is one of the biggest challenges to food security for the burgeoning world population today. Climatic characteristics and historical evidence indicate that the Great Plains area of Colorado and neighboring states are prone to frequent and extended episodes of severe drought [*Clarke and Rendell*, 2003; *Meko and Woodhouse*, 2005]. Akron (40°9′N, 103°9′W, 1384 m above mean sea level), which is located in the semiarid Great Plains of Colorado, receives a mean annual precipitation of about 420 mm (1908–2001) (Table 1). Corn production in Colorado has increased dramatically in the past 2 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 rain-fed 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].

[3] Decreasing water availability and increasing irrigation costs are forcing farmers to follow the best water management strategy of applying irrigation only when it will result in maximum benefit to the crop [*Jackson et al.*, 1990]. 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]. Limited irrigation is practiced when farmers are unable to meet the evapotranspiration (*ET*) demand of the crop through supplemental irrigation. *Klocke et al.* [2004] compared yields from corn irrigated for the full growing season using best management

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Table 2. Cultivar Coefficients Calibrated for Simulations of Corn Hybrid "Pioneer Brand 3732" at Akron, Colorado, Using CERES-Maize v4.0

Number	Parameter	Values
1	Thermal time from seedling emergence to the end of Juvenile phase during which the plants are not responsive to changes in photoperiod (degree days).	290
2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development is at maximum rate, which is considered to be 12.5 hours (days).	0.8
3	Thermal time from silking to physiological maturity (degree days).	615
4	Maximum possible number of kernels per plant.	690
5	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg d^{-1}).	9.6
6	Phylochron interval (degree days).	38.9

was uniform across the irrigation gradient (about 76,000 seeds ha^{-1}). All the experiments were fertilized with ammonium nitrate at the rate of 168 kg N ha^{-1}. Soil water measurements were made at planting, harvest, and several intermediate periods with a neutron probe. Leaf area measurements were made periodically with a leaf area meter by destructive sampling 1-m lengths of row, and the same samples were used for biomass measurements. Grain yield was measured at harvest. Other experimental procedures, including experimental design, plot size, irrigation system descriptions, harvest procedures, etc., were described by *Ma et al.* [2003].

[8] The rain-fed (dryland) corn experiments were part of a larger ongoing crop rotation experiment conducted at the same location since 1990. In these experiments, various tillage and crop sequences are assessed for effects on productivity, soil quality, and economic viability. Detailed descriptions of cultural practices, plot area, and experimental design were reported by *Bowman and Halvorson* [1997] and *Anderson et al.* [1999]. The corn hybrid "Pioneer Brand 3732" used in the irrigation studies was also used in the rain-fed crop rotation study from 1993 to 1997. Crop growth, yield, and water use data from these experiments from 1993 to 1997 were used in the simulations. These experiments used a randomized complete block design with three replications. Grain yield and biomass data were collected at harvest. Fertilizer N application rates were based on annual soil tests and a corn yield goal of 4100 kg ha^{-1}. Actual fertilizer applied in different years ranged between 34 and 95 kg N ha^{-1}. Soil water measurements were made every 2 weeks with a neutron probe at two locations near the center of each experimental plot at depths of 0.45, 0.75, 1.05, 1.35, and 1.65 m. Time domain reflectometry was used to measure soil water in the 0.00–0.30-m depth.

2.2. Other Input Data for Simulations

[9] The CERES-maize model requires inputs of crop management practices, soil properties, and weather data in addition to genetic coefficients (cultivar specific parameters) [*Jones et al.*, 1994]. Management practices are crop variety, row spacing, planting depth, plant population at planting (and/or emergence), and fertilizer and irrigation application rates. Soil properties needed to include the lower limit of water availability to plants, drained upper limit, saturated soil water content, saturated soil hydraulic conductivity, and a root weighting factor for determining the relative partitioning of roots in different soil layers. Above input parameters are listed by *Ma et al.* [2003]. Six genetic coefficients specific to the corn hybrid must be defined for the model simulation. In this study, genetic coefficients for the corn hybrid "Pioneer Brand 3732" were calibrated and used in the simulations (Table 2).

[10] The weather data needed for simulations included daily precipitation, maximum and minimum air temperature, and solar radiation. Daily precipitation and maximum and minimum air temperature data from 1912 to 2005 were available from a weather station situated approximately 400 m from the experimental area. Solar radiation data were available only from 1983 through 2005. As such, the solar radiation data records were extended backward through 1912 using the Weatherman utility in DSSAT [*Hansen et al.*, 1994]. Precipitation during the corn growing season from 1912 to 2005 exhibited high interannual variability in amount and temporal distribution. The May through September precipitation totals varied between 127 mm in 1994 and 513 mm in 1946 (data not shown), with an average of 292 mm (Table 1) and a coefficient of variation of 30%.

2.3. Model Calibration and Validation

[11] *Ma et al.* [2002] used the data from the irrigation experiments from 1984 to 1986 in evaluating CERES-maize v3.5 for simulating crop responses to water stress in the Great Plains. Our calibration of the model parameters used the values reported in that study as the starting point. The *Ma et al.* [2002] calibrated values of the first stage evaporation limit and the root weighting factor (for different soil layers) related to the soil physical and hydraulic properties of the Rago silt loam soil that provided good simulation of soil water and biomass. We left these parameters unchanged. However, we further refined the cultivar specific coefficients for simulating corn hybrid "Pioneer Brand 3732" by calibrating, through trial and error, with the grain yield data collected from drip irrigation treatment 4 (wettest, 213 mm applied) in 1985 (Table 2). The calibrated cultivar specific coefficients were then used for simulating the crop in the 10 remaining irrigation treatments from 1984 to 1986, and 5 rain-fed experiments from 1993 to 1997. Grain yield, LAI, and biomass (no biomass measurements in 1986) measured at about weekly intervals, and a few soil water measurements were available for validation of the irrigation experiments. For validation of the rain-fed experiments, grain yield and biomass measured at harvest were available.

2.4. Simulation Studies

[12] In the current study, the CERES-maize v4.0 model, once tested and validated, was used to investigate the effects of different irrigation levels and alternative water management scenarios on corn production. The previously described weather records 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, nitrogen was applied at 168 kg N ha^{-1} as followed in the irrigation field experiments. All irrigation simulations were sprinkler-irrigated. Three limited water management strategies were simulated as described below in the subsections. Concepts developed in the study can

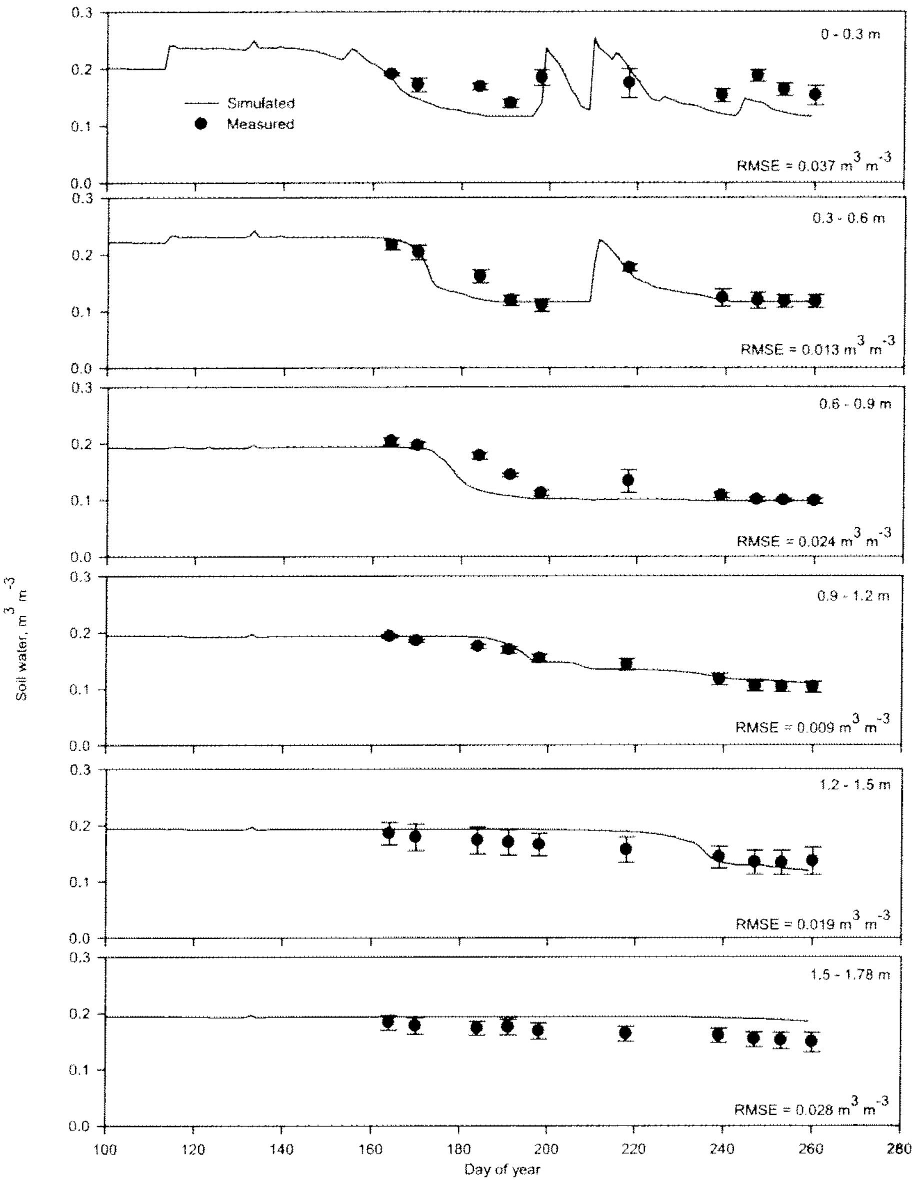

Figure 1. Measured and simulated soil water for irrigated corn in the line-source gradient irrigation treatment 1 [*Ma et al.*, 2003] at Akron, Colorado, in 1985.

layer were less accurate than layers below, reflecting the high heterogeneity in soil properties in the top layer. In addition, there were high spatial variations in crop residue cover in the field. The simulation used average soil properties. As an example representing the simulation accuracy, a comparison of the simulated and measured soil water in 1985 for the line-source irrigation treatment 1 is presented (Figure 1).

[22] Biomass simulations had a RMSE of 1708 kg ha^{-1} (mean absolute error (MAE) was 1226 kg ha^{-1}). A comparison of the measured and simulated biomass under different line-source irrigation treatments in 1984 and 1985 is presented in Figure 2. There was no biomass measurement conducted in 1986. Grain yield simulations deviated from the measured values between −13 and +24%, with a RMSE of 982 kg ha^{-1} (Mean Relative Error (MRE) = 864 kg ha^{-1}) in the irrigation experiments (Figure 3). In the rain-fed experiments, grain yield simulations had a RMSE of 576 kg ha^{-1} (MRE = 564 kg ha^{-1}). Simulated grain yields for the years 1993 to 1996 were between −14 and +22% of the observed values.

[23] *Moser et al.* [2006] reported significant reductions in field grown corn yield components such as number of kernel rows, number of kernels per row, and 1000-kernel weight due to preanthesis drought. Different irrigation levels produced varying levels of simulated plant N uptake, LAI, biomass, harvest index (HI), kernel numbers, and kernel weights. For example, in 1985 with 65 mm of irrigation, the model simulated a plant N uptake of 165 kg N ha^{-1}, a leaf area index of 2.78, a biomass of 14043 kg ha^{-1}, a harvest

Table 3. Average Differences Between Measured and Simulated Soil Water, Grain Yield, Biomass, and LAI in the Irrigated (1984–1986) and Rain-Fed (1993–1997) Corn Experiments, Akron, Colorado[a]

Simulated Variables	RMSE	MAE
	Irrigation Experiments	
Soil water (m^3 m^{-3})	0.025	0.022
Grain yield (kg ha^{-1})	982	864
Biomass (kg ha^{-1})	1708	1226
LAI	0.742	0.863
	Rain-Fed Experiments	
Soil water (m^3 m^{-3})	0.043	0.043
Grain yield (kg ha^{-1})	576	564
Biomass (kg ha^{-1})	617	528
LAI	*	*

[a] There were 3, 8, and 4 irrigation treatments in 1984, 1985 and 1986, respectively. Asterisk indicates no measurements available. RMSE: root-mean-square error; MAE: mean absolute error; LAI: leaf area index.

for research and improvement of simulation models. However, the model adequately simulated crop performance for a majority of the years in response to a very wide gradient of water availability generated by the precipitation received (Table 1) and the various water application levels in the irrigation experiments during 1984 to 1986 [*Ma et al.*, 2002, 2003] (Figure 3) and the rain-fed experiments during 1993 to 1996 (Figure 3). As such, we could build enough confidence in the model calibration for applying it further for developing limited water irrigation management decision support strategies presented below.

3.2. Model Application Studies

3.2.1. Differential Water Allocation Between Vegetative and Reproductive Stages With 22 June as the Split Date

[25] Average grain yields and their standard deviations simulated with the three ratios of split irrigation between vegetative and reproductive stages under irrigation levels ranging from 100 to 700 mm are presented in Figure 4a (with and without N stress). In general, grain yields increased with irrigation levels, peaking at 400 mm, and then decreased with further increase in irrigation. The yield decline for irrigations above 400–500 mm was due to the leaching induced N stress at the effective crop root zone. Grain yields simulated with "no N stress" (N at optimum level and not affected by N leaching) did not show this yield decline (Figure 4a, no N stress, and Figure 5). Minimum yield reduction and leaching loss of N were found with the 20:80 split irrigation. Compared to the 20:80 irrigation, there was higher yield reduction induced by greater N leaching loss in the 40:60 and 50:50 irrigation ("with N stress" in Figures 4a and 5).

[26] For all irrigation levels (100 to 700 mm), split applications at 20:80 resulted in higher yield returns and WUE (grain yield/(rain + irrigation)) compared with other ratios (Figure 4a, with N stress, and Figure 6a). In general, irrigation at equal ratios (50:50 between the two growth stages) yielded less grain yield and WUE, and greater N leaching compared with the other split applications. Differences in simulated grain yield and 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 replications).

[27] In general, the simulated biomass, LAI, grain number per plant, and unit grain weight with the 20:80 split irrigations were greater than under the other two split irrigation levels. The model-simulated higher water stress (data not shown) during the reproductive stage (floral induction to end of grain fill stage) under 40:60 and 50:50 split irrigation ratios compared with the 20:80 ratio. However, N stresses simulated under the three split irrigation treatments were comparable. For the 20:80 split irrigation between the vegetative and reproductive stages, irrigation at 400 mm of water (in addition to rainfall received) yielded the maximum mean grain (average grain yield simulated in

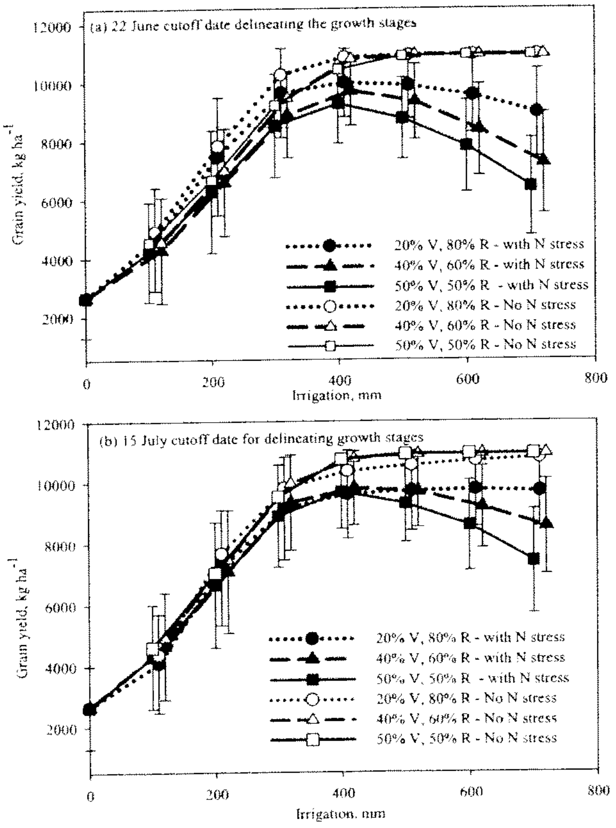

Figure 4. Simulated grain yield response to 100 to 700 mm irrigations (gross irrigation), split between vegetative and reproductive stages at 20:80, 40:60, and 50:50 with (a) 22 June and (b) 15 July as cutoff dates differentiating between growth stages for corn grown at Akron, Colorado. Distribution of average seasonal potential evapotranspiration demand between the vegetative and reproductive growth stages were 38:62 for Figure 4a and 55:45 for Figure 4b. Yields simulated both with and without N stress are shown. Error bars represent 1 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.

than those applied during the vegetative stages by fourfold in the 20:80, and 1.5 fold in the 40:60 split irrigations. The fourfold application of irrigation (limited) during the reproductive stage in the 20:80 split led to least amount of water stress during that stage and better yield compared to other split irrigations. As such, we conclude that the simulation results qualitatively followed the general observations reported in field experiments in the literature.

3.2.2. Differential Water Allocation Between Vegetative and Reproductive Stages With 15 July as the Split Date

[29] The 15 July split between vegetative and reproductive stages automatically increased late season irrigation because of the fewer number of weeks split in that stage. 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 Figure 4b. The trends of yield responses to increasing level of irrigation, with and without N stress were similar to those for the 22 June split data (Figure 4a). 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 replications). However, for irrigations from 100 to 400 mm, all three split application treatments (20:80, 40:60, and 50:50 between *V* and *R* stages) simulated similar average (94 years) grain yields (Figure 4b, with N stress). 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 treatments. For all irrigation levels (100 to 700 mm), water applied during the reproductive stages was higher than those applied during the vegetative stages by eightfold in the 20:80, and by threefold in the 40:60 split irrigation experiments. With similar arguments as in the case of 22 June cutoff date (for delineating the vegetative and reproductive stages) for split irrigation, the eightfold application of limited irrigation during the reproductive stage in the 20:80 split, here as well, led to the least amount of water stress during the stage and better yield compared to other split irrigations. As such, we conclude that the simulation results qualitatively followed the general observations reported in field experiments reported in the literature.

[30] Except in the case of 100 mm irrigation (with-rain scenario with N stress), split applications at 20:80 between the vegetative and reproductive stages resulted in the highest WUE compared with the other split application treatments (Figure 6b). 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 replications). 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).

[31] For all irrigation levels above 400 mm, the model-simulated higher nitrogen stress (due to high N leaching) (Figure 4b, with N stress) 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 (compare "with N stress" and "no N stress" simulated grain yields in Figure 4b). Simulations with 400 mm of water produced the best combination of average grain yield (9601 kg ha^{-1} with a standard deviation of 1408 kg ha^{-1}) and WUE (14.1 kg ha^{-1} mm^{-1}) with minimum N leaching (Figure 4b, with N stress, and Figure 6b). However, the maximum WUE simulated (15.8 kg ha^{-1} mm^{-1}) 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.

[32] Results discussed above showed that under a N level of 168 kg ha^{-1} 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 yield of 9974 (10,838 with no N stress) and 9601 (10,362 with no N stress) kg ha^{-1} for 22 June and 15 July dates, respectively, for differentiating between the vegetative and reproductive stages. However, splitting with 15 July is more advantageous to reduce leaching loss of N and associated yield loss with increase in irrigation amount.

3.2.3. Limited Area Irrigation

[33] One of the goals of limited irrigation is to achieve the maximum net return from the total crop area. This may involve strategies that restrict the irrigated area and leave the remaining area as rain-fed. Simulations for the 94-year period showed that if available irrigation water for the whole area is 100 mm, irrigating 50% of the area with 200 mm of water at 20:80 split irrigation produced greater yield than irrigating 100% of the area with 100 mm water (Table 4). Differences in simulated grain yields in response to the different percent areas irrigated with different water levels (100 to 300 mm; Table 4) across years (treated as blocks in the Randomized Block Design) were highly significant ($p < 0.00001$; two factor ANOVA without replications). If water available for irrigation is 200 mm or more, irrigating 100% of the area resulted in the greatest grain yield. However, with 200 mm irrigation water for the 15 July split date for differentiating between vegetative and reproductive stages, irrigating 75% area and leaving 25% in dryland corn management is a better option compared to the 100% area irrigation.

3.2.4. Initiation of Irrigation at Optimum PAW Depletion Levels

[34] 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} at 90% PAW to 15.0 kg ha^{-1} mm^{-1} at 60% PAW with little response at higher depletion (i.e., lower PAW) levels.

2004] can be conducted as and when the model has the capability to do so.

4. Summary, Conclusions, and Further Discussion

[36] The CERES-maize v4.0 model was calibrated and validated for simulations of corn growth and yield with various levels of irrigation over a 3-year period (1984–1986) in the semiarid climate of northeastern Colorado. The model was also successfully tested for simulation of dryland (rain-fed) corn production at the location during 1993–1997. Maximizing returns while practicing limited irrigation in the Great Plains region is a challenge facing farmers of the region today. The model was used to develop limited irrigation management strategies using long-term weather data recorded at the Akron location from 1912 to 2005 for the potential effects of weather variability on corn water use and grain yield. When available water for irrigation was 100 mm or less, maximum yields and WUE were obtained when 40% of the irrigation was applied during the vegetative stage and 60% applied during the reproductive stage, or when the irrigation was uniformly split between the two growth stages. When more than 100 mm of irrigation water was available, yield was maximized when 20% of the water was applied in the vegetative stage and 80% was applied in the reproductive stage. Maximum grain yield and WUE were obtained with 400 mm of irrigation, which also maximized N uptake with only small N losses to leaching. At higher irrigation levels, higher N leaching and lower N uptake led to lower grain yields. Splitting vegetative and reproductive stages on 15 July is more advantageous than on 22 June to reduce leaching loss of N and associated yield loss with increase in irrigation amount. Irrigating 50% of the area with 200 mm of water and leaving the remaining area in dryland corn management yielded greater than irrigating 100% of the area with 100 mm water. When more than 100 mm of irrigation water was available, corn yields were maximized when the irrigation was spread across 100% of the crop area. Under irrigated corn management at Akron, Colorado, simulations showed saving of water with little grain yield loss by delaying the initiations of irrigation to when plant-available soil water was 20% (80% depletion).

[37] Optimization of irrigation water in agriculture is extremely important for maximizing return from the declining water allocation to this sector competing with various other pressing needs of the burgeoning human population. With increasing complexities of modern agriculture consequent to environmental concerns and more frequent droughts, there is need for a whole system quantitative approach to optimize the use of limited water, as well as N and other inputs, for varying weather conditions. Well calibrated and validated cropping system models that quantify the various physical, chemical, and biological processes in the soil-plant- atmosphere system, and their dynamics and management effects that contribute to crop growth and development, are being widely recognized as promising tools for decision support in this direction. Results of the study reinforce the high potential and promise of crop simulation models for the above purpose. They also enable faster and cheaper transfer of agrotechnology developed at the experimental stations to the farmer's fields or other locations.

[38] Conceptually, the results obtained in this study can be generalized to other semiarid environments and locations, but there is a need for site-specific simulations to define specific recommendations for managing limited water. To apply the models this way, there is a need for regional experimental programs to collect a balanced set of data about the crop, soil, and weather with which the model can be tested, improved, and used. This emphasizes the need for integrating these models into the regional agricultural research programs by adopting a system framework for the crop and agrometeorology data collection. In addition, a variety of technologies are available today to trigger irrigation in the field, e.g., based on actual *ET* demand of the crop, canopy temperature, plant and soil water potential, etc. In this study, we primarily focused on triggering irrigations based on the level of plant-available soil moisture within the primary plant root zone. Further studies (experimental and simulations) are needed to validate and optimize irrigations scheduled on the basis of the other methods of scheduling irrigations.

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