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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 1. Monthly Precipitation Received at Akron, Colorado, During 1984 to 1986 and 1993 to 1997[a]

Month	1984	1985	1986	1993	1994	1995	1996	1997	1908–2001
January	10	11	3	6	10	22	8	13	9
February	18	5	28	14	5	9	1	13	9
March	38	8	8	13	2	22	29	2	21
April	43	58	51	47	53	62	12	22	42
May	59	84	63	27	29	145	116	55	76
June	59	34	90	45	6	121	65	80	62
July	55	115	9	114	70	39	83	31	69
August	114	49	26	24	30	20	68	62	53
September	13	35	17	23	8	57	86	25	31
October	44	24	30	95	73	10	12	59	23
November	11	17	8	26	26	15	1	7	14
December	9	15	5	12	13	2	1	11	10
Total	472	454	337	446	325	524	482	380	420
May–September	300	317	205	233	143	382	418	253	292

[a]Monthly means for the period 1908 to 2001 are also included. Units are millimeters.

practices with corn where irrigation was withheld until 2 weeks prior to tasseling. They reported that the limited late season irrigated corn yielded 93% of the fully irrigated corn. The limited irrigation treatment required only 76% of the water applied in the current agricultural management (CAM). In CAM, irrigation water was applied according to the farmer's current management strategy. These strategies ranged from irrigations based on the capacity of the well to following evapotranspiration demand. Greater amounts of stored soil water were used under limited irrigation. Hence, 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.

[4] In general, studies for determining irrigation recommendations for a locality make use of field experiments that have been conducted for a limited number of years and generally at one location, and conclusions are extrapolated statistically or heuristically. For instance, the irrigation experiment reported in this paper was conducted for 3 years from 1984 to 1986 with limited irrigation treatments and replications. 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 multiyear, multilocation variability in climate, soils, etc. are nearly impossible. 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. [*Cabelguenne et al.*, 1995; *Matthews et al.*, 2002; *Knisel and Turtola*, 2000].

[5] Simulation models have been previously used to provide decision support to optimize irrigation water use and conserve rainwater 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, 2005; *Cabelguenne et al.*, 1995; *Jackson et al.*, 1990]. The Decision Support Systems for Agrotechnology Transfer (DSSAT) models have been used worldwide in the past 2 decades for various applications that include irrigation decision support [*Jones et al.*, 2003; *Panda et al.*, 2004].

[6] The CERES-maize v4.0 model that was modified and improved from its previous versions is now available in the DSSAT v4.0 for simulations of growth and development of the corn crop [*Jones et al.*, 2003]. The model was found to perform superior to the previous versions in corn production simulations in a cool environment in Spain [*Lopez-Cedron et al.*, 2005]. Our main objective for this study was to show the value of using a calibrated and validated CERES-maize v4.0 model to evaluate irrigation scenarios that have potential to optimize water use efficiency by minimizing irrigation through control of application timing and amount during the crop growth period. Specific steps were to (1) check the calibration and validation of the CERES-maize model under both dryland and irrigated corn 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.

2. Materials and Methods

2.1. Field Experiments

[7] Irrigated and rain-fed corn experiments were conducted for 8 years at the Central Great Plains Research Station 6.4 km east of Akron, Colorado, where mean annual precipitation is about 420 mm of which 290 mm is received during May to September (Table 1). Average precipitation for the corn growing season (May through September) at this location during the study years was 281 mm, and ranged from 143 to 418 mm. Soil type at the location is a Rago silt loam (fine montmorillonitic mesic Pachic Arguistoll). Soil physical and hydraulic properties used in the simulations are described by *Ma et al.* [2002]. The irrigation experiments used in the study were conducted during 1984, 1985, and 1986. Corn hybrid "Pioneer Brand 3732" (101-day relative maturity) was planted under a line-source gradient irrigation system with maximum water application next to the irrigation line and linearly declining water application with distance from the line. 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]. Irrigation dates and amounts for the line-source irrigation system during 1984 to 1986 can be found in the work of *Ma et al.* [2003]. In this paper, we included similar data for the drip irrigation treatment in 1985 [*Ma et al.*, 2002]. A detailed description of the crop and soil parameters was given by *Ma et al.* [2003]. Briefly, for the line-source gradient irrigation experiment, three irrigation levels in 1984 and four irrigation levels in 1985 and 1986 were applied, with four replications. Maximum irrigation rate was 3.2 mm h^{-1}. There were 5, 11, and 10 irrigation events in 1984, 1985, and 1986, respectively. Irrigation application varied from 23 to 106 mm in 1984, from 72 to 188 mm in 1985, and from 46 to 299 mm in 1986, and were withheld until just before tasseling (late July). No irrigation scheduling was done in this experiment. Irrigations were applied whenever wind speeds were low enough that significant shifts in the sprinkler patterns did not occur. Seeding rate

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

potentially be adapted to other locations, climates, and crops where similar limited irrigation strategies need to be developed.

[13] Different irrigation scenarios simulated were compared for treatment differences by two-way analysis of variance (ANOVA) without replications [*Dowdy and Wearden*, 1991]. Mean differences between treatments were estimated following the procedure PROC GLM in SAS (8.02). The 94 years of simulations were treated as blocks in the Randomized Block Design with the different irrigation scenarios as treatments.

2.4.1. Irrigation Levels and Differential Water Allocation Between Vegetative and Reproductive Stages

[14] Long-term simulations (1912 to 2005) of corn at Akron showed that the potential evapotranspiration demand (crop season) at the location is between 700 and 1000 mm, averaging about 900 mm. Our observations indicated that average date of floral initiation in the region occurs around 22 June, while tasseling, silking, and pollen shed generally occur around 15 July. Even though the floral initiation date actually marks the biological starting point of the reproductive stage, the division between vegetative and reproductive stages is usually marked in the field as the date of pollen shed and silking. Some recommendations for effective limited irrigation strategies are to limit irrigation until just before tassel emergence [*Melvin et al.*, 2004]. Hence, simulation experiments were conducted with both 22 June and 15 July dates for onset of the reproductive stage for corn.

[15] 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 proportioned between vegetative (*V*) and reproductive stages (*R*). The three hypothetical split application treatments were (1) 20% (*V*) and 80% (*R*), (2) 40% (*V*) and 60% (*R*), and (3) 50% (*V*) and 50% (*R*) (equal between the stages). The crop was planted on 3 May in all the simulations, as occurred in the line-source irrigation field experiment in 1985. Irrigations were applied weekly starting with 30 April (18 irrigations in 17 weeks; one irrigation was applied on the starting day of the first week) of every year. The last irrigation was applied on 27 August (following the irrigation schedule for the experiments in 1985). The amount of water available for irrigation according to the split application ratio between vegetative and reproductive stages (i.e., 20:80 or 40:60, or 50:50) was equally distributed between the applications at weekly intervals within each growth stage (data not shown). This irrigation scheme can represent a location where the water supply is limited to a certain amount each week (i.e., well capacity). Of the total 18 weekly irrigations, 9 occurred before 22 June, and 12 occurred before 15 July.

[16] The amount of N applied (168 kg N ha^{-1}) was adequate to keep plants free of N stress provided water levels are optimum for N uptake, and the applied N is not leached out of the root zone. In order to understand the potential for yield loss due to possible plant N stress due to leaching, simulations were also made without N stress (soil N always at optimum level). The crop was simulated without N stress by "switching off" the N simulation module in the model and assuming optimum N supply all the time.

2.4.2. Limited Area Irrigation

[17] 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 (dryland corn management). We computed the grain yield advantages associated with irrigation amounts of 100, 200, and 300 mm concentrated on 0, 25, 50, and 75% of the available crop area while leaving the remaining area under dryland corn management. In this strategy, for instance, if the water available for irrigating the whole area is 100 mm and irrigation is limited to 50% of the area, the first 50% of the area is irrigated at the rate of 200 mm, and the other 50% is unirrigated.

2.4.3. Initiation of Irrigation at Optimum PAW Depletion Levels

[18] Increased WUE may result from reductions in the amount and frequency of irrigation application. This may be accomplished by withholding irrigation until the plant-available water (PAW) in the soil is depleted to a set level. Various irrigation scheduling methods have been developed on the basis of soil-plant-water measurements and/or climatological data [*Martin et al.*, 1990].

[19] In order to demonstrate the use of the tested model to determine the soil water depletion level at which to initiate irrigation to achieve optimum grain yields, we simulated the crop for 94 yrs (1912 to 2005) by allowing the water in the surface 0.45-m soil profile to deplete to 10, 20, 30, 40, 50, 60, 70, 80, and 90% of the PAW and irrigated back to field capacity. A soil profile depth of 0.45 m was reported to cover the layer of maximum water extraction by fully irrigated corn roots [*Kar and Verma*, 2005]. Each year, the crop was planted on 3 May in all the simulations, as occurred in the line-source irrigation field experiment in 1985. Simulations were conducted under irrigation in addition to the rain received during the season.

3. Results and Discussion

3.1. Model Calibration and Validation

[20] Calibrated grain yield and biomass in the drip irrigation treatment in 1985 varied from measured by −2.4%. The sum of irrigation and precipitation was 424 mm. Notwithstanding the relatively wet conditions and that 168 kg N ha^{-1} was applied, the model-simulated water stress of 0.123 for photosynthesis, and 0.161 for growth (on a scale of 0 to 1, with 1 representing maximum and 0 minimum stress), and N stress of 0.132 for photosynthesis during the tassel initiation stage. The simulated slight water stress condition was confirmed by *Nielsen and Gardner* [1987] who showed a crop water stress index of 0.21 measured with an infrared thermometer and averaged over 21 days from 8 July through 6 September. *Ma et al.* [2002] reported the calibration 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 for accurate simulations of soil water that were used here. The model was validated by simulating the line-source sprinkler irrigation experiments from 1984 to 1986 and the rain-fed experiments from 1993 to 1997 (Figures 1, 2, and 3).

[21] During the model validation, soil water simulations in the irrigation experiments had an RMSE of 0.025 $m^3\ m^{-3}$ (Table 3). Simulations of soil water in the rain-fed experiments were less accurate, with an RMSE = 0.043 $m^3\ m^{-3}$. Soil water simulations, in general, in the top 0.15-m soil

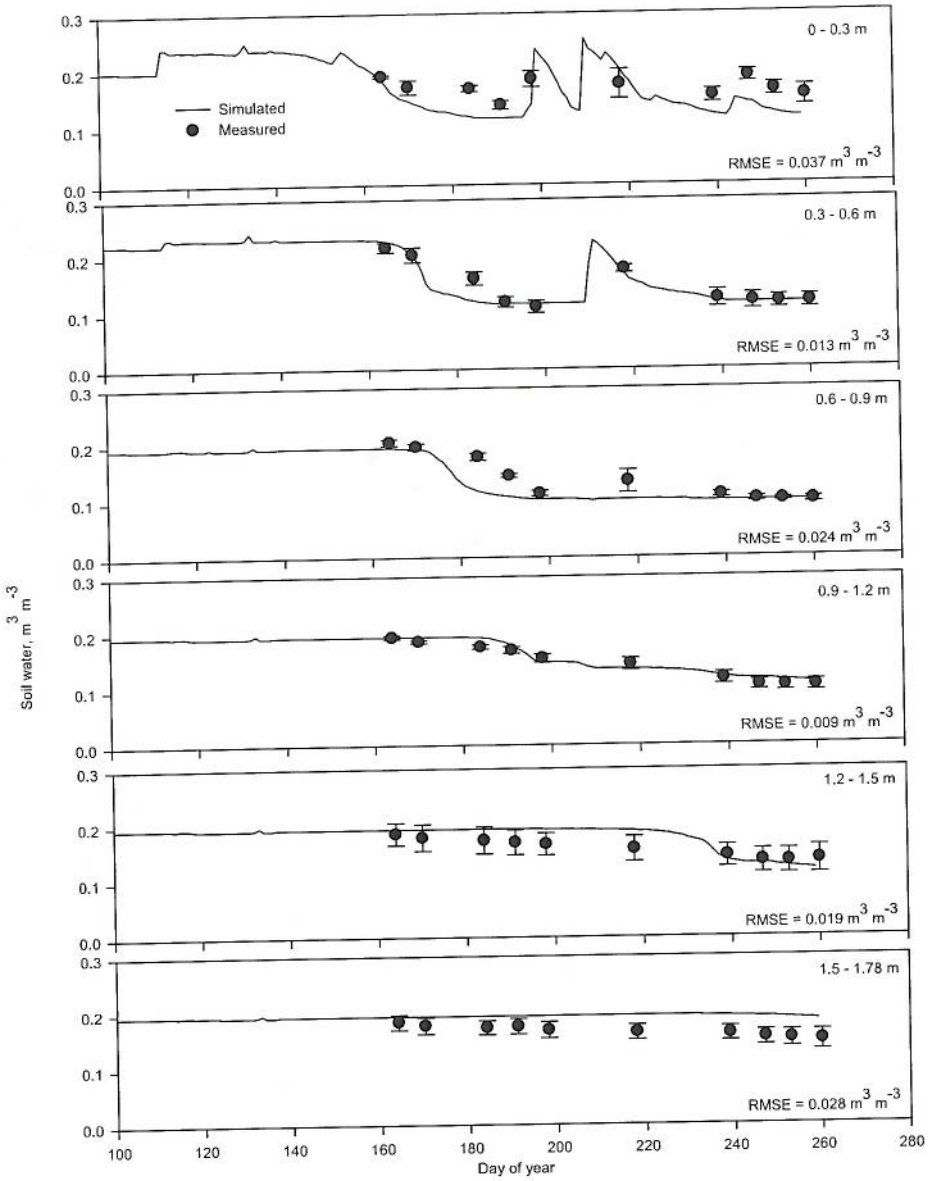

Figure 1. Measured and simulated soil water for irrigated corn in the line-source gradient irrigation treatment 1 [*Ma et al.*, 2003] at Akron, Colorado, in 1985.

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

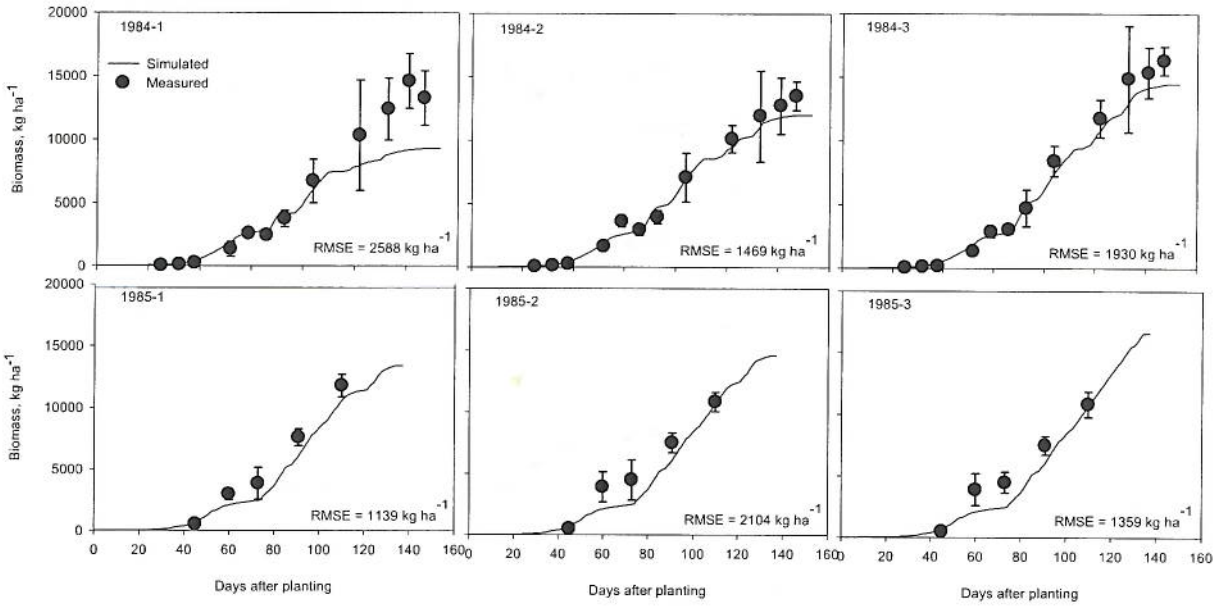

Figure 2. Measured and simulated biomass of corn in three line-source gradient irrigation treatments [*Ma et al.*, 2003] at Akron, Colorado, in 1984 and 1985 (biomass measurements for the experiments in 1986 were not conducted).

index of 0.383, a kernel number of 295 kernels plant^{-1}, and a kernel weight of 0.225 g kernel^{-1}. When the irrigation application was increased to 213 mm, simulated values of the respective parameters were 224 kg N ha^{-1}, 4.69, 23519 kg ha^{-1}, 0.435, 424 kernels plant^{-1}, and 0.298 g kernel^{-1}. Growing season precipitation received was 317 mm. The simulated results agree with the observations of *Moser et al.* [2006].

[24] In the year 1997, simulated dryland yield (1470 kg ha^{-1}) substantially exceeded the measured yield (357 kg ha^{-1}) by 312%. In this year, the simulated biomass (3735 kg ha^{-1}) exceeded the measured (3535 kg ha^{-1}) by only 5.7%. The model-simulated water stress of 0.151 for photosynthesis, and 0.195 for growth (on a scale of 0 to 1, with 1 = maximum stress and 0 = no stress) during the tassel initiation stage; 0.640 and 0.760 during early grain filling stage; and 0.413 and 0.499 during the late grain filling stages, respectively. Water deficit in the period just before and after anthesis reduced corn grain yields substantially, with less severe yield reductions due to water stress occurring during the other growth stages [*Grant et al.*, 1989; *Shaw*, 1988]. In the Great Plains, dryland corn yield response to available soil water and growing season precipitation is highly dependent on the amount of precipitation occurring from 15 July to 25 August [*Nielsen et al.*, 1996, 2005], with grain yields declining by 18.5 kg ha^{-1} for every mm less precipitation received during that 6-week period. In the rain-fed experiments, though the lowest measured grain yield was recorded in 1997, the total precipitation recorded during the corn season (May–September) was not the lowest. When corn season in 1997 received 253 mm of rainfall, the seasons in 1993 and 1994 received only 233 mm and 143 mm (Table 1). There can be many other factors other than water availability that contributed to the low crop performance that year. In general, extreme weather events like hail, pest and diseases, and instrument failures and other data collection problems that were not reported are some of the factors that can contribute to the low measured yield but not simulated by the model. There can also be other reasons for low field-measured harvest indices (measured HI in 1997 was 0.1) in dryland farming conditions in the semiarid regions like low pollen viability, pollination efficiency, and grain shriveling due to hot and dry winds. However, these processes and their effects on the HI are not well understood to enable us to properly quantify them and incorporate them in the simulation models. This is an area

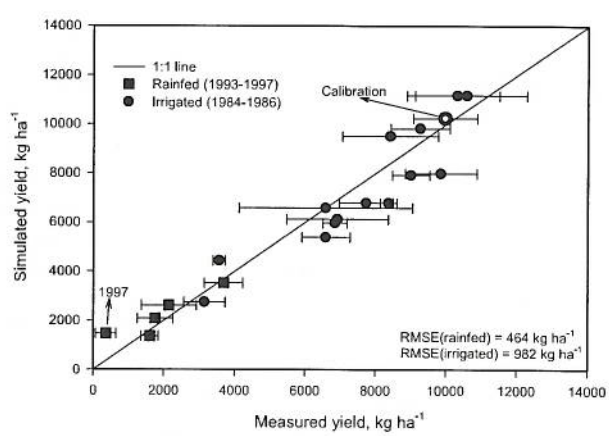

Figure 3. Measured and simulated corn grain yield in the irrigated (1984 to 1986) and rain-fed experiments (1993 to 1997) at Akron, Colorado. Error bars indicate 1 standard deviation about the mean of the treatment replications. RMSE = root-mean-square error.

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

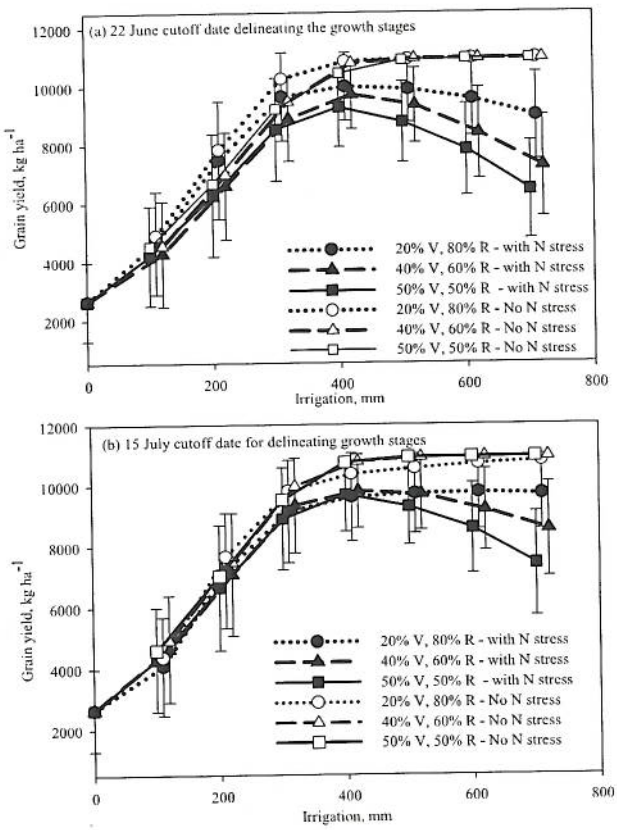

Figure 4. Simulated grain yield response to 100 to 700 mm irrigations (gross irrigation), split between vegetative and reproductive stages at 20:80, 40:60, and 50:50 with (a) 22 June and (b) 15 July as cutoff dates differentiating between growth stages for corn grown at Akron, Colorado. Distribution 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.

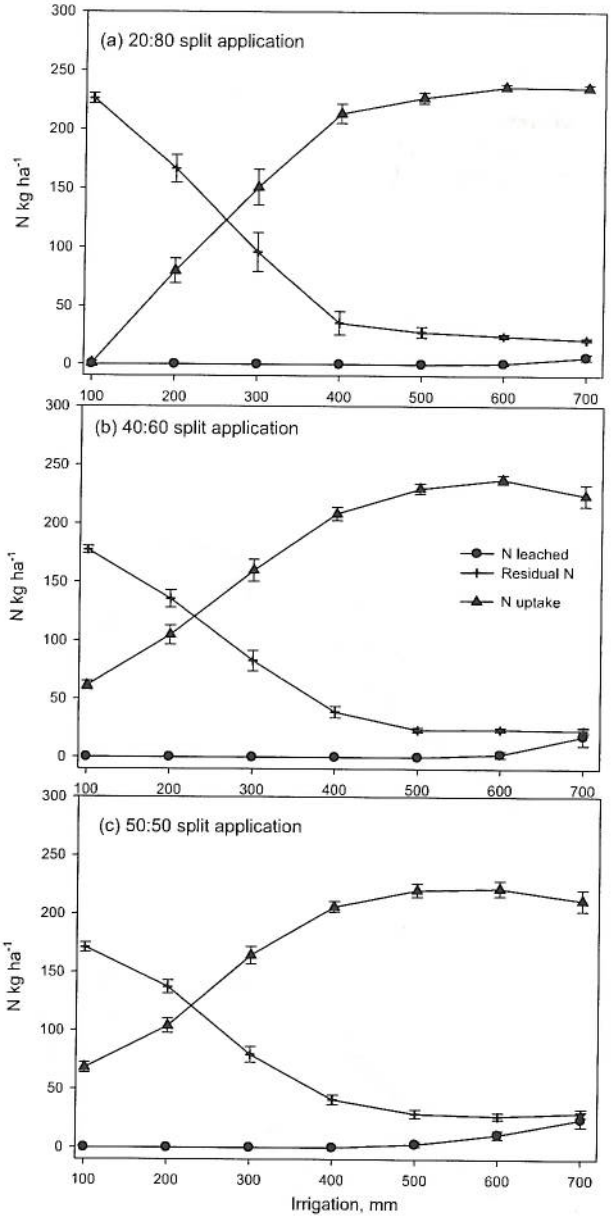

Figure 5. Simulated average N leached, residual soil N at crop harvest, and plant N uptake for corn grown at Akron, Colorado, in response to 100 to 700 mm irrigations (gross irrigation) split between vegetative and reproductive stages at (a) 20:80, (b) 40:60, and (c) 50:50 (22 June as the cutoff date differentiating between the growth stages). Error bars represent 1 standard deviation from the mean.

94 years was 9974 kg ha^{-1}, with a standard deviation of 1167 kg ha^{-1}) compared with amounts more and less than 400 mm. This irrigation level achieved a WUE of 14.4 kg ha^{-1} mm^{-1}. The maximum WUE simulated, i.e., 16.2 kg ha^{-1} mm^{-1}, was for 300 mm irrigation yielding a lower average grain yield of 9628 kg ha^{-1} with a standard deviation of 1518 kg ha^{-1}. For the 400 mm irrigation level, the model-simulated average N leaching of 2.5 kg ha^{-1}, residual N at harvest of 24.8 kg ha^{-1}, plant N uptake of 235.0 kg ha^{-1}, and N mineralization of 68.9 kg ha^{-1}. Amount of N leached increased, and plant N uptake decreased, with further increase in irrigation amounts (Figure 5).

[28] In field experiments, soil moisture stress imposed at different stages of growth in corn produced contrasting effects on its development and yield [*Denmead and Shaw*, 1960; *Grant et al.*, 1989]. Water deficit during the reproductive period (after tasseling) can increase the interval from silking to pollen shed [*Herrero and Johnson*, 1981] and shorten the grain filling period [*Westgate*, 1994], resulting in decreased yield. Water deficit before tasseling delayed silking but not tasseling, also resulting in grain yield loss [*Kefale and Ranamukhaarachchi*, 2004]. *Çakir* [2004] observed 66–93% yield losses because of extended water stress during tasseling and ear formation stages, and highest yields in fully irrigated treatments with water stress only during the vegetative growth stage. In the simulation experiments, for all the irrigation levels (100 to 700 mm), water applied during the reproductive stages were higher

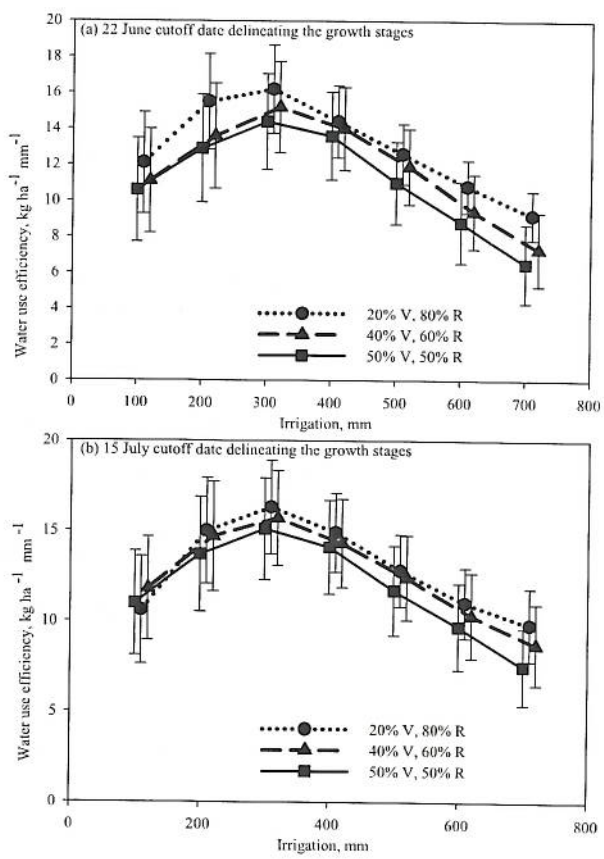

Figure 6. Simulated average water use efficiency (WUE) for seasonal irrigation levels of 100 to 700 mm split at 20:80, 40:60, and 50:50 between the vegetative and reproductive stages of corn, with N stress. V = vegetative and R = reproductive stages. (a) Simulations using 22 June and (b) simulations using 15 July as the split date between V and R stages. 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.

Table 4. Average Simulated Corn Grain Yield From Limited Area Irrigations at Akron, Colorado[a]

Percent Area Irrigated (Remaining Area Rain-Fed)	Irrigation Amount, 22 June as Split Date Between Growth Stages (mm)			Irrigation Amount, 15 July as Split Date Between Growth Stages (mm)		
	100	200	300	100	200	300
	Yield (kg ha^{-1})					
25	4355(±1144)c[b]	3945(±1065)c	3362(±1051)d	4261(±1074)b	4251(±1096)c	4162(±1088)d
50	4973(±1624)b	6228(±1030)b	6010(±956)c	4840(±1555)a	6041(±987)b	6117(±1041)c
75	4221(±1647)c	7146(±1814)b	8101(±1357)b	3672(±1531)b	7476(±1713)b	7821(±1472)b
100	4641(±1773)a	7465(±2027)a	9625(±1527)a	4069(±1615)b	7198(±1896)a	9141(±1692)a

[a]Yield is for the entire field; units are kg ha^{-1}. Irrigations were split at 20:80 between the vegetative and reproductive stages, with 15 July and 22 June as dates for differentiating between the vegetative and reproductive stages. Values given in parenthesis are 1 standard deviation from the mean.
[b]Values in a column followed by the same letter are not significantly different at the 5% level using the procedure PROC GLM in SAS (8.02).

Amounts of irrigation water applied decreased from 513 to 256 mm, and the number of irrigation applications needed decreased from 42 to 5 (Figure 7a). Probability of achieving greater grain yield with initiation of irrigation at lower water depletion levels increased substantially only between the 10% and 20% PAW (Figure 7b). WUE decreased and probability of achieving grain yield did not increase further with initiation of irrigations at lower available soil water depletion levels (i.e., higher PAW levels). Average grain yield gain with initiation of irrigation at 20% was 605 kg ha^{-1} with one additional irrigation application and 31 mm more water. From the foregoing, we conclude that irrigation initiation at 20% PAW would yield optimum benefits in terms of grain yield return, water applied and the number of irrigations needed, and N and water use efficiency. On average (94 years), 303 mm of water applied in six irrigations was needed for irrigation at this level. Frequency distribution of total amount of water applied at the 20% PAW level over the 94 years of simulation showed that irrigations fell between 100 and 150 mm in 1 year, 150 and 200 mm in 5 years, 200 and 250 mm in 17 years, 250 and 300 mm in 32 years, 300 and 350 in 29 years, 350 and 400 mm in 9 years, and 400 and 450 mm in 1 year. This simulated irrigation recommendation was questioned by some of the earlier reviewers of this data. To corroborate our simulation findings, we made a search in the literature for field experiments in which threshold PAW level at which to initiate irrigation for corn was investigated. 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. As irrigation amounts and timing are directly linked to the water holding capacities of the soil (soil texture and structure), simulation results obtained from the simulations can be specific to the Rago silt loam soil at the location (Akron, Colorado).

[35] Current version of the model does not have the capability for triggering irrigations at different PAW levels during different crop development stages. The model is being modified to incorporate this facility. Further simulation experiments to trigger irrigations at different PAW levels between crop development stages [*Klocke et al.*,

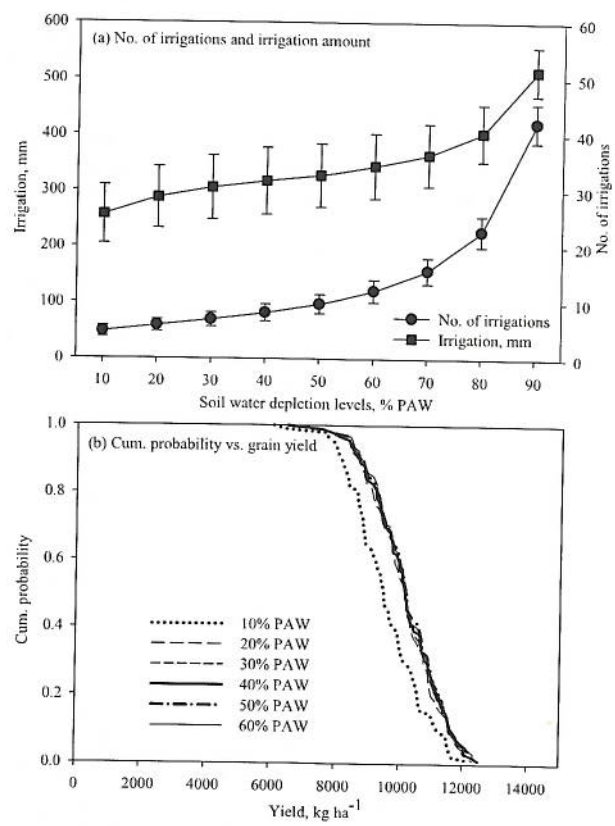

Figure 7. Simulated corn grain yield response to initiation of irrigation at different soil water depletion levels (depletion levels are expressed in terms of the corresponding percent plant-available water (PAW)) at Akron, Colorado. (a) Number of irrigations and irrigation amounts simulated with the 94-year weather record in response to initiation of irrigations at soil water depletions until 10 to 90% PAW and (b) cumulative probabilities for corn grain yields simulated with the 94–year weather record in response to initiation of irrigations at soil water depletions until 10 to 40% PAW.

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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