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Maize yield potential; critical processes and simulation modeling in a high-yielding environment

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Abstract

Understanding processes of maize (*Zea mays* L.) growth and production of grain in high-yielding, irrigated conditions offers hope to understand yield potential in many other environments. In this study we investigated such processes at the plant level, and attempted to simulate maize yields at the field level and county level in the high yielding region of the High Plains of Texas. In addition, we used the normalized difference vegetation index (NDVI) from satellite data of year 2000 to update leaf area index for yield simulation in three counties. In the field study, we measured maize leaf area index (LAI), the fraction of photosynthetically active radiation intercepted (FIPAR), and the harvest index (HI) in irrigated plots near Dumas, Texas. The light extinction coefficient (k) for Beer's law was calculated with the FIPAR and the LAI. The radiation use efficiency (RUE) was determined with sequential measurements of the fraction of photosynthetically active radiation (PAR) intercepted and biomass harvests. The RUE was 3.98 g of above-ground biomass per MJ of intercepted PAR in 1999 and 3.41 in 2000 for three sampling dates prior to silking. These values are 106 and 93% of the expected RUE values at the measured vapor pressure deficits, using a previously published response function. The mean k value was −0.46 in 1999 and −0.47 in 2000, similar to the expected value of −0.43 reported in the literature for this row spacing. The mean HI measured in 2000 was 0.52, similar to values of 0.53 and 0.54 in the literature. Application of these parameters to maize simulation with the Agriculture Land Management Alternatives with Numerical Assess-

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ment Criteria (ALMANAC) model for 13 center pivot irrigated fields near Dumas in 1999 provided simulations within 1.0 Mg ha^{-1} with a mean error of 0.03 Mg ha^{-1} and a mean square error of 0.10. For five years of grain yields reported for each of four counties in this region of Texas, ALMANAC simulations were within 5% of the mean measured yields. Introduction of PAR interception, based on the satellite-derived normalized difference vegetation index (NDVI), into ALMANAC resulted in slight increases in accuracy of yield prediction for two counties and a slight decrease in accuracy in one county for year 2000. Consistency in values of RUE, k, and HI in this study as compared with values reported in the literature will aid modelers simulating maize growth and grain yields in similar high-yielding, irrigated conditions.

Abbreviations: ALMANAC, Agriculture Land Management Alternatives with Numerical Assessment Criteria; FIPAR, fraction of photosynthetically active radiation intercepted by plants; HI, harvest index; IPAR, photosynthetically active radiation intercepted by plants, MJ plant^{-1} d^{-1}; k, light extinction coefficient for Beer's law; LAI, leaf area index; NASS, National Agricultural Statistical Service; NDVI, normalized difference vegetation index; PAR, photosynthetically active radiation, MJ m^{-2} d^{-1}; RUE, radiation use efficiency, g per MJ intercepted photosynthetically active radiation

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1. Introduction

Accurate grain yield prediction by crop models requires realistic simulation of yield potential and realistic simulation of environmental reductions in yield. Accuracy for yield potential requires accuracy in processes such as leaf area growth, light interception, biomass production, and partitioning of biomass into grain yield. The High Plains of Texas is an excellent region for such high-yielding maize research. County maize grain yield estimates there are the largest reported in the US (National Agricultural Statistical Service (NASS, 2001). Of the county grain yields for 1995–1999, maximum values for this region were 9.9 Mg ha^{-1} in Castro and Hansford Counties, 10.7 Mg ha^{-1} in Moore County, and 11.2 Mg ha^{-1} in Dallam County (186–212 bu acre^{-1}). Throughout this paper, grain yields in Mg ha^{-1} are dry weight and grain yields in bu acre^{-1} are with 15.5% moisture. For comparison, the highest county values for maize in 1995–1999 were 8.4 Mg ha^{-1} for Ohio, 8.5 Mg ha^{-1} for Indiana and Wisconsin, 9.0 Mg ha^{-1} for Idaho, 9.1 Mg ha^{-1} for Iowa, and 9.4 Mg ha^{-1} for Nebraska. Except for the Nebraska value, which was only for irrigated maize, these were for all the maize in a county.

Yield trials in four recent years in Moore County Texas had grain yield values even larger (Pietsch et al., 1996, 1997, 1998, 1999). The mean yield of the five highest yielding hybrids each year was 13.3 Mg ha^{-1} (250 bu acre^{-1}). This is similar to the mean of 13.0 Mg ha^{-1} (244 bu acre^{-1}) for the four highest yielding treatments in an irrigated experiment in Argentina in 1991/1992 (Otegui et al., 1995). In this Argentine experiment, measured grain yields were larger in the previous year, with a mean of 16.0 Mg ha^{-1} (302 bu acre^{-1}) for the highest four treatments. These higher yields were attributed to higher incident solar radiation after silking in that year.

Studies with high-yielding, irrigated maize in this region of Texas have raised questions which have made field measurements of crop development in such conditions invaluable. Attempts at simulating irrigated maize in the High Plains near Dumas, Texas using five years of measured yield trial results showed mean simulations with the ALMANAC model (Kiniry et al., 1992) only 90% of mean measured grain yields (Kiniry and Bockholt, 1998). Field determination of the maximum leaf area index (LAI), the light extinction coefficient (*k*) for Beer's law (Monsi and Saeki, 1953), radiation use efficiency (RUE), and the harvest index (HI) under such conditions could greatly improve efforts to simulate maize yield potential in such environments.

The National Oceanic and Atmospheric Administration (NOAA) satellite provides real-time information that can augment simulation models by improving their simulation of interception of PAR. The advanced very high-resolution radiometer (AVHRR) sensor onboard the NOAA-14 satellite provides daily data at 1 km × 1 km spatial resolution. The NDVI from AVHRR data is often correlated with the photosynthetically active radiation (PAR) interception during vegetation growth (Coops et al., 1998; Sakai et al., 1997; Baez-Gonzalez et al., 2002). The intercepted PAR is strongly related to the accumulation of biomass or primary production (Kiniry et al., 1989).

Our first objective of the present study was to investigate whether previously published values for LAI. *k*, RUE, and HI need to be revised for such a high-yielding environment. We derived values for LAI and *k* on different dates and RUE during the season for two maize growing seasons in the high-yielding conditions of the High Plains near Dumas, Texas. In addition, HI values were measured in the second year. The ALMANAC model was then applied for one year to 13 center pivot irrigated fields with differential irrigation amounts on the same farm as where the measurements were taken. Next, the ALMANAC model was tested using five years of irrigated maize grain yield averages for four counties in this region using plant parameters derived from this field study. Finally, the ALMANAC model, with updated LAI based on NDVI values of year 2000, was applied to three counties in the region. The objective of using satellite image data was to apply weekly maximum NDVI values to estimate daily fraction of intercepted PAR for irrigated maize fields in three counties in this region and to assess the accuracy of maize yield simulation with such inputs.

2. Materials and methods

2.1. Dumas field study

Pioneer maize hybrid 31A13 (Pioneer Hi-Bred Int., Inc., Amarillo, TX) was planted on 13 May, 1999 and 15 April, 2000 on a Sherm silty clay loam (fine, mixed, mesic Torrertic Paleustolls) on the farm of Mr. Harold Grail near Dumas, Texas (35°52′N, 101°58′W; 1114 m above sea level) (Fig. 1). This soil is 2.0 m deep and has 300 mm of plant-available-water at field capacity. For several years Texas

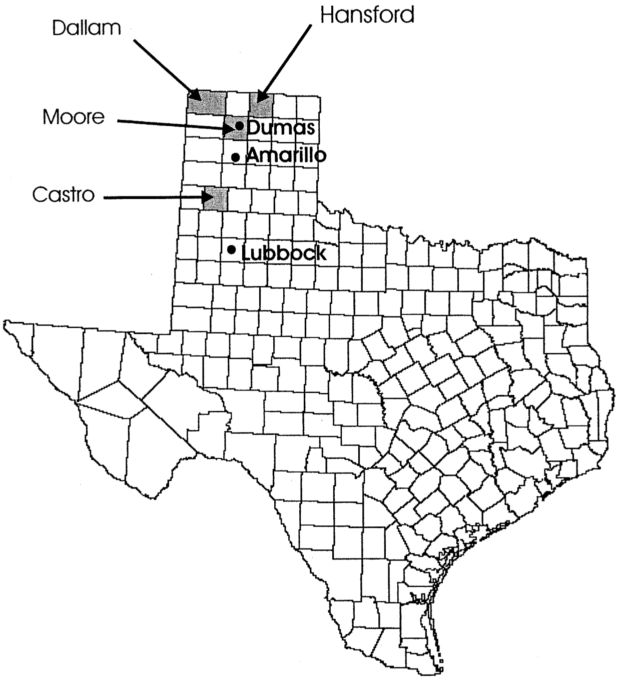

Fig. 1. Map of the region for field measurements and simulations of high yielding, irrigated maize.

A&M University has conducted yield trials for maize and sorghum (*Sorghum bicolor* L. (Moench)) on this farm. Measured planting density in both years of our study was 84,000 plants ha^{-1} in 0.76 m rows. Plots were fertilized with 308 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1} and 2 kg K_2O ha^{-1} each year before planting. In both years the plots were sufficiently irrigated to insure no drought limitations to crop growth, using a center pivot irrigation system.

On four dates prior to grain filling each year, measurements of fraction of PAR intercepted, LAI, and plant dry weights were taken. We measured PAR interception during each growing season with a 0.8-m-long Sunfleck Ceptometer (Decagon, Pullman, Washington, US). In each of 10 areas of the field, we took a series of measurements in rapid succession, consisting of 10 PAR measurements above the canopy, 10 below the canopy, and 10 more above the canopy. The fraction of PAR intercepted was calculated with the mean of the above-canopy measurements and the mean of the below-canopy measurements. While taking the readings below the canopy, the light meter was moved across the plant rows. Measurements were taken between 1020 and 1200 h during times with relative stable incident solar radiation (without intermittent clouds).

Destructive samples consisted of all the plants in five, 1.0 m lengths of row. All the plants of a sample and one representative plant from each sample were weighed fresh. Each representative plant was then overnight-mailed to Temple, Texas where leaf area was measured with a LiCor LI-3100 leaf area meter (LiCor Inc., Lincoln, Nebraska), the plant dried, and the plant weighed again. Weights of the plants were measured after drying in a forced-air drying oven at 70 °C until the weight stabilized. Leaf area of the entire sample was calculated from the leaf area of the one plant and the ratio of the total fresh weight of all plants divided by the fresh weight of the one plant. Similarly, dry weights of an entire 1.0 m sample was calculated by the dry weight of one plant and the ratio described above.

With these techniques, we derived values for LAI, above-ground dry weight per square meter ground area, and intercepted PAR. The light extinction coefficient (k) for Beer's law (Monsi and Saeki, 1953) was calculated from the fraction of PAR intercepted (FIPAR) and the LAI. Values for k were calculated for each harvest date as

$$k - [\ln(1 - \mathrm{FIPAR})]/\mathrm{LAI}. \tag{1}$$

Daily intercepted PAR was determined by linearly interpolating fraction intercepted PAR between measurement dates, using the incident total solar radiation each day. PAR was assumed to be 45% of the total solar radiation (Monteith, 1965; Meek et al., 1984). Daily intercepted PAR was summed during the season. RUE was calculated from the slope of the above-ground dry weight (g m^{-2}) as a function of summed intercepted PAR (MJ m^{-2}). Thus, the slope was in units of g of dry weight per MJ of intercepted PAR.

At maturity, on 4 September 2000, plants were harvested, mailed to Temple as described above, dried as before, and weighed. The harvest index was the dry weight of the grain divided by the dry weight of the entire above-ground plant.

2.2. Description of the ALMANAC crop model

The model used in this project was ALMANAC (Kiniry et al., 1992). This model simulates the soil water balance, the soil and plant nutrient balance, and interception of solar radiation. This model includes subroutines and function from the erosion-productivity impact calculator (EPIC) model (Williams et al., 1984, 1989) with added details for plant growth. The model has a daily time step. It simulates plant growth for a wide range of species and is implemented easily.

ALMANAC simulates plant growth using LAI. The model simulates population density by adjusting potential LAI. Maximum potential simulated LAI at high planting densities is 6.0 for maize.

The model uses a modified HI approach to simulating grain yield. For maize, HI reported for temperate regions usually were between 0.46 and 0.58 (Kiniry et al., 1997). In a study with several sites in Texas, Kiniry and Bockholt (1998) used a HI value of 0.53.

2.3. Dumas 1999 simulation study

On the same farm as where the field measurements were made, we used the ALMANAC model to simulate maize grain yield of 13 irrigated fields. The fields varied in size from 48 to 198 ha. The runoff curve number was set to 60 for these fields and for simulations in the following section to avoid runoff of irrigation water. Amounts of irrigation each field received during the growing season varied from 430 to 809 mm. All fields were irrigated with center pivot systems.

We assumed all fields had the same soil as described above. The recorded irrigation dates and amounts for each field were used as inputs. Measured grain yields were compared with simulated yields.

2.4. Four county yield simulation study

Four counties in the Texas High Plains were simulated for 1995–1999 (Fig. 1). Measured maize grain yields were the yield averages for each county for each year as reported by NASS (2001). These counties had large areas of irrigated maize and differed in grain yield potential. Counties and their associated weather stations were Hansford County with Morse, Texas (36°04′N, 101°29′W; 969 m above sea level); Moore County with Etter, Texas (35°52′N, 101°58′W; 1114 m above sea level); Castro County with Dimmitt, Texas (34°36′N, 102°19′W; 1173 m above sea level); and Dallam County with Dalhart, Texas (36°05′N, 102°29′W; 1220 m above sea level).

In each case, we simulated the major soil for irrigated production in the county. Hansford and Castro Counties were simulated with Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll), Moore County was simulated with a Sherm silty clay loam (fine, mixed, mesic Torrertic Paleustoll). and Dallam County was simulated with a Dallam fine sandy loam (fine-loamy, mixed, mesic Ardic Paleustalf).

2.5. Using NDVI data to update intercepted PAR in ALMANAC

AVHRR high-resolution picture transmission (HRPT) data of the maize growing season between April and September 2000 were downlinked daily from the NOAA-14 satellite to the receiving station located at the Blackland Research and Extension Center in Temple, Texas. The raw visible (VIS) and near-infrared (NIR) data were calibrated to top-of-atmosphere (TOA) reflectance factor. A simplified method for atmosphere correction (SMAC) developed by Rahman and Dedieu (1994) was applied to compute surface reflectance. The NDVI values were computed from surface reflectance (after atmosphere correction). A cloud detection method developed by Chen et al. (2002) for the state of Texas was applied for cloud removal. Cloud-contaminated pixels were assigned a specific value to differentiate them from clear-sky pixels. Weekly NDVI composites were built from cloud-screened data based on the method of maximum value compositing (Holben, 1986 and Chen et al., 2003).

FIPAR was measured on 9 June, 22 June, 6 July, and 20 July, 2000 in the study site near Dumas. Maize silking occurred near 6 July, 2000. FIPAR decreased gradually after silking, because leaves started withering and turning yellow. Therefore, the weekly maximum NDVI values of the first three sampled dates were correlated to the sampled FIPAR. The weekly FIPAR values were simulated using weekly maximum NDVI values based on the sampled correlation. The simulated weekly FIPAR values were determined as the FIPAR of the end of week date. The daily FIPAR values in a week were linearly interpolated. The daily FIPAR values based on the NDVI replaced the daily values simulated by ALMANAC. In addition, the sampled correlation was applied to the other high-yield maize sites in Castro County, Dallam County and Moore County to estimate their daily FIPAR and to further simulate maize yield using the ALMANAC model. Hansford County was not included because it lacked sufficiently large, uniform irrigated areas where NDVI values could be calculated correctly.

3. Results

3.1. Dumas field study

Values for LAI and *k* were similar to potential LAI of 6.0 used to simulate this site previously (Kiniry and Bockholt, 1998) and the k value of −0.43 predicted for a 0.76 m row spacing of maize (Flénet et al., 1996). Maximum LAI values were 7.9 in 1999 and 5.2 in 2000 (Figs. 2 and 3). Values for *k* varied somewhat during the season but the annual means were within 10% of the expected value. The mean *k* was −0.46 in 1999 and was −0.47 in 2000.

RUE values calculated with the first three sample dates showed values similar to RUE predicted for the vapor pressure deficit (VPD) conditions (Figs. 2 and 3). Values for RUE using these sampling dates were 6–7% different from expected values from previous studies (Stockle and Kiniry, 1990; Kiniry et al., 1998). The differences from expected were much less than the SEs of the RUE values. The mean VPD dur-

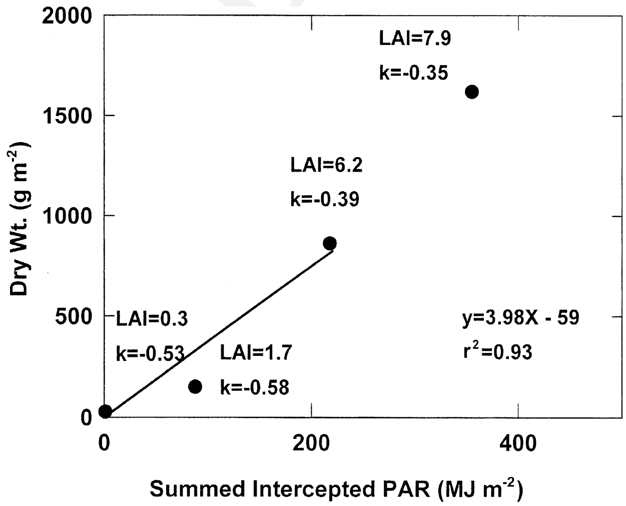

Fig. 2. In 1999, the relation between above-ground dry weight and cumulative intercepted photosynthetically active radiation (IPAR) for maize near Dumas, Texas.

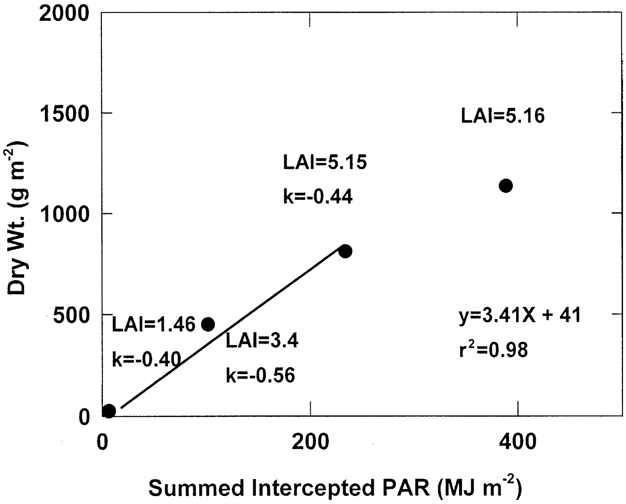

Fig. 3. In 2000, the relation between above-ground dry weight and cumulative intercepted photosynthetically active radiation (IPAR) for maize near Dumas, Texas.

ing the measurements in 1999 was 1.10 kPa. The expected RUE at this VPD is 3.75 g of biomass per MJ of intercepted PAR. The measured value of 3.98 (±SE of 1.11) was 6% greater than this. The mean VPD during the period of the first three samplings in 2000 was 1.26. Expected RUE at this VPD is 3.65. The measured RUE was 3.41 ± 0.48 g MJ^{-1}, 7% less than expected. Thus, these data support the previously reported values of RUE at such low VPD values.

Using data from all four sampling dates showed RUE values more divergent from expected values. In 1999, the fourth sampling was at silking, whereas in 2000, silking occurred near the third sampling. Mean VPD values over the interval for the four samplings were 1.11 kPa in 1999 and 1.44 in 2000. Predicted RUE for these values are 3.75 in 1999 and 3.53 in 2000. Values from the measured data for the four dates were 4.69 ± 0.57 in 1999 (125% of predicted)and 2.83 ± 0.34 in 2000 (80% of expected).

Grain yields measured in 2000 were high, as expected. The mean was 12.3 Mg ha^{-1} with a SD of 1.9 (232 ± 36 bu $acre^{-1}$). The mean harvest index was 0.52.

3.2. Dumas 1999 simulation study

The ALMANAC model realistically simulated the variability in grain yields among fields with different irrigation treatments (Fig. 4). The mean error (simulated minus measured) was 0.03 Mg ha^{-1} and the root mean square error was 0.32 Mg ha^{-1}. The model realistically simulated the two highest yielding fields, the two lowest yielding fields, and the intermediate fields. The regression slope was 0.94 (±SE of 0.15), the y-intercept was 0.72, and the r^2 was 0.78. The regression line was close to the 1:1 line. Thus, the model shows promise as a tool for effectively simulating grain yield responses to different center pivot irrigation amounts.

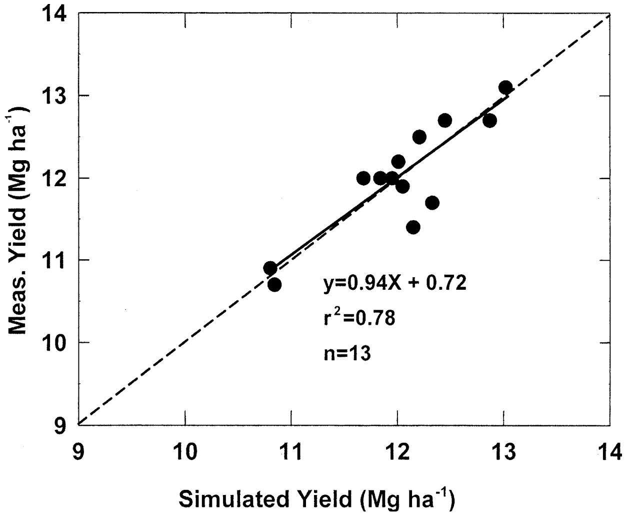

Fig. 4. Maize simulations with ALMANAC on fourteen fields in 1999 near Dumas, Texas. The darker solid line is the regression line with all data, the lighter solid line is the regression line, and the dashed line is the 1:1 line through the origin.

259 3.3. Four county yield simulation study

260 The yield trend across locations was reasonably simulated by ALMANAC 261 (Fig. 5). While ALMANAC's mean simulated grain yields for the four locations were

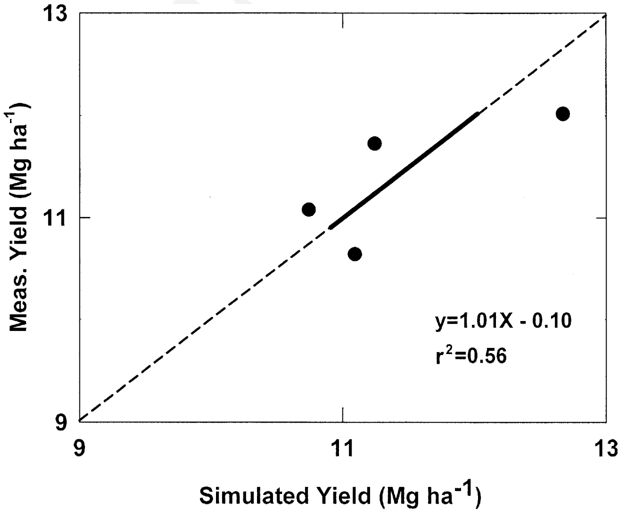

Fig. 5. Mean maize simulated grain yields with ALMANAC on four counties in the Texas High Plains for 1995–1999. Measured grain yields are from the county yield estimates for the years. The solid line is the regression line and the dashed line is the 1:1 line through the origin.

not significantly ($\alpha = 0.05$) related to the mean measured grain yields, the slope was close to 1.0 and the *y*-intercept was small. The slope of 1.01 (±SE of 0.64) was not significantly different from 1.0 and the *y*-intercept of −0.10 (±SE of 0.69) was not significantly different from 0.0. The mean simulated grain yields for the five years were 5% too large for the highest yielding site (Dalhart), 4% too large for the lowest yielding site (Morse), 4% too small for Etter, and 3% too small for Dimmitt.

The model did not significantly account for year-to-year variation in grain yields within each of these locations, as indicated by slopes that were not significant. For Morse, the slopewas 0.42 and the r^2 was 0.07. For Etter, the slope was −0.3 and r^2 was 0.10. For Dimmitt, the slope was 0.12 and r^2 was 0.002. Finally, for Dalhart the slope was −0.3 and r^2 was 0.33. Thus the mean model simulations for each site were within 5% of the mean reported grain yield for the county, but something not simulated by the model was causing the variability among years in the reported county grain yields.

3.4. Using NDVI data to update LAI in ALMANAC

ALMANAC simulations in 2000 were improved with the updated fraction intercepted PAR based on satellite data for two of the three counties considered. County yields reported in 2000 were 10.44 Mg ha^{-1} for Dallam County, 10.51 for Moore County, and 10.80 for Castro County. The simulations without NDVI data were 12.01 (115% of measured) for Dallam, 11.72 (111% of measured) for Moore, and 12.90 (119% of measured) for Castro. After including the NDVI data to improve intercepted PAR values, simulated yields were 12.19 (117% of measured), 10.84 (103% of measured) and 12.41 (115% of measured), respectively. Thus, using satellite data to update ALMANAC's simulation in intercepted PAR provided a more accurate simulation for two of the three counties for yield simulation.

4. Discussion

To accurately simulate maize grain yields in diverse environments, crop models must realistically simulate key processes of plant growth and of yield production under non-limiting conditions. The region of this study arguably produces the highest maize grain yields in the US. Previously described values for LAI, *k* for Beer's law, RUE, and HI appeared reasonable for these conditions and offer promise for accurate grain yield simulation in high yielding conditions.

The measured values for LAI, *k*, RUE, and HI reported herein support previously published values and provide guidance for future simulation modeling in high-yielding environments. The values for LAI were similar to those used by Kiniry and Bockholt (1998) when simulating grain yields near Dumas. The values of *k* were similar to those reported by Flénet et al. (1996) for the row spacing used. The harvest index value was also similar to the HI used by Kiniry and Bockholt (1998).

The measured radiation use efficiency values add credence to the VPD response published by Stockle and Kiniry (1990). This function predicted RUE values in these high yielding conditions that were within 7% of measured, just as it had provided accurate maize simulations under drought stress conditions in central and southern Texas (Xie et al., 2001). The function improves the simulation of biomass and grain yields over a wide range of environments.

By using parameter values derived in this study, the ALMANAC model realistically simulated grain yields with different amounts of irrigation applied by center pivots. Thus the model, with these parameters, can be a valuable tool for simulating grain yield with variable irrigation amounts.

The ALMANAC model was capable of simulating differences among counties in mean county yields, but could not account for factors causing year to year variability in each county. Accurate simulation of the five-year means illustrated the model's ability to simulate maize yield potential. However, the model's inability to simulate individual year yields needs further study. Under such irrigated conditions, it appeared that factors contributing to year to year variability are not adequately described by the model. Future research could involve investigation of these factors in the region. It appears that such a model based on incident solar radiation, with yield reductions due to soil moisture deficiency and soil nutrient deficiency, may not be sensitive to some yield determining factors in these high yielding conditions.

The improvements in ALMANAC's simulated yields as a result of the NDVI information offer some hope for improving large area yield simulations. As more such satellite data becomes available, further model testing will be valuable. It will be especially important to test this model with independent data for several years.

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References

Baez-Gonzalez, A.D., Chen, P.Y., Tiscareño-Lopez, M., Srinivasan, R., 2002. Satellite-based method of estimating corn yield in real time under irrigated and non-irrigated conditions in Mexico. Crop Sci., in press.

Chen, P.Y., Srinivasan, R., Fedosejevs, G., Narasimhan, B., 2002. An automated cloud detection method for daily NOAA-14 AVHRR data for Texas, USA. Int. J. Remote Sensing 23, 2939–2950.

Chen, P.Y., Srinivasan, R., Fedosejevs, G., Kiniry, J.R., 2003. Evaluating different NDVI composite techniques using NOAA-14 AVHRR data. Int. J. Remote Sensing, in press.

Coops, N.C., Warning, R.H., Landsberg, J.J., 1998. Assessing forest productivity in Australia and New Zealand using a physiologically based model driven with averaged monthly weather data and satellite-derived estimates of canopy photosynthetic capacity. Forest Ecol. Manage. 104, 113–127.

Flénet, F., Kiniry, J.R., Board, J.E., Westgate, M.E., Reicosky, D.C., 1996. Row spacing effects on light extinction coefficients of corn, sorghum, soybean, and sunflower. Agron. J. 88, 185–190.

Holben, B.N., 1986. Characteristics of maximum values composite images from temporal AVHRR data. Int. J. Remote Sensing 7, 1417–1434.

Kiniry, J.R., Jones, C.A., O'Toole, J.C., Blanchet, R., Cabelguenne, M., Spanel, D.A., 1989. Radiation-use efficiency and biomass accumulation prior to grain filling for five grain-crop species. Field Crops Res. 20, 51–64.

Kiniry, J.R., Williams, J.R., Vanderlip, R.L., Atwood, J.D., Reicosky, B.C., Mulliken, J.A., Cox, W.J., Mascagni Jr., H.J., Hollinger, S.E., Wiebold, W.J., 1997. Evaluation of two maize models for nine US locations. Agron. J. 88, 421–426.

Kiniry, J.R., Bockholt, A.J., 1998. Maize and sorghum simulation in diverse Texas environments. Agron. J. 90, 682–687.

Kiniry, J.R., Landivar, J.A., Witt, M., Gerik, T.J., Cavero, J., Wade, L.J., 1998. Radiation-use efficiency response to vapor pressure deficit for maize and sorghum. Field Crops Res. 56, 265–270.

Kiniry, J.R., Williams, J.R., Gassman, P.W., Debaeke, P., 1992. A general, process-oriented model for two competing plant species. Trans. ASAE 35, 801–810.

Meek, D.W., Hatfield, J.L., Howell, T.A., Idso, S.B., Reginato, R.J, 1984. A generalized relationship between photosynthetically active radiation and solar radiation. Agron. J. 76, 939–945.

Monsi, M., Saeki, T., 1953. Über den lichtfaktor in den pflanzengesellschaften und seine bedeutung fur die stoffproduktion. Jpn. J. Bot. 14, 22–52.

Monteith, J.L., 1965. Light distribution and photosynthesis in field crops. Ann. Bot. 29, 17–37.

NASS (National Agricultural Statistical Service), 2001. USDA Economics and Statistics System data sets: Crops. [On-line, updated at least yearly.] Available from <www.nass.usda.gov:81/ipedb/> (verified 3 December 2002).

Otegui, M.E., Nicolini, M.G., Ruiz, R.A., Dodds, P.A., 1995. Sowing date effects on grain yield components for different maize genotypes. Agron. J. 87, 29–33.

Pietsch, D., Synatschk, L., Foyt III, F., 1997. 1997 Corn performance tests in Texas. Technical Report 97-10. Texas Agricultural Experiment Station, College Station.

Pietsch, D., Bockholt, A.J., Synatschk, L., Foyt III, F., 1996. 1996 Corn performance tests in Texas. Technical Report 96-4. Texas Agricultural Experiment Station, College Station.

Pietsch, D., Synatschk, L., Bertran, J., Foyt III, F., 1998. 1998 Corn performance tests in Texas. Technical Report 98-07. Texas Agricultural Experiment Station, College Station.

Pietsch, D., Synatschk, L., Bertran, J., Foyt III, F., 1999. 1999 Corn performance tests in Texas. Technical Report 99-25. Texas Agricultural Experiment Station, College Station.

Rahman, H., Dedieu, G., 1994. SMAC: a simplified method for the atmospheric correction of satellite measurements in the solar spectrum. Int. J. Remote Sensing 15, 123–143.

Sakai, R.K., Fitzjarrald, D.R., Moore, K.E., 1997. Detecting leaf area and surface resistance transition seasons. Agric. Forest Methodol. 84, 273–284.

Stockle, C.O., Kiniry, J.R., 1990. Variability in crop radiation-use efficiency associated with vapor pressure deficit. Field Crops Res. 25, 171–181.

Williams, J.R., Jones, C.A., Dyke, P.T., 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27, 129–144.

Williams, J.R., Jones, C.A., Kiniry, J.R., Spanel, D.A., 1989. The EPIC crop growth model. Trans. ASAE 32, 497–511.

Xie, Y., Kiniry, J.R., Nedbalek, V., Rosenthal, W.D., 2001. Maize and sorghum simulations with CERES-Maize, SORKAM, and ALMANAC under water-limiting conditions. Agron. J. 93, 1148–1155.