IMPROVING IRRIGATED CROPPING SYSTEMS ON THE HIGH PLAINS USING CROP SIMULATION MODELS

by

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ABSTRACT

Irrigated cropping systems on the High Plains are dominated by water intensive continuous corn (*Zea mays* L.) production, which along with other factors has caused a decline in the Ogallala aquifer. Potentially demand for water from the aquifer could be decreased by including drought tolerant crops, like grain sorghum (*Sorghum bicolor* L.) and cotton (*Gossypium hirsutum* L.), in the cropping systems. This study calibrated the CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton models for the High Plains and studied the simulated effects of different irrigation amounts and initial soil water contents on corn, cotton, and grain sorghum. Input files for calibration were created from irrigated and dryland research plots across Kansas. Information was collected on: soil physical properties, dry matter, leaf area, initial and final soil water content, management, and weather. CERES-Maize simulated grain yield, kernel number, ear number, and seed weight across the locations with root mean square errors (RMSE) of 2891 kg ha^{-1}, 1283 kernels m^{-2}, 1.6 ears m^{-2}, and 38.02 mg $kernel^{-1}$, respectively. CERES-Sorghum simulated grain yield, kernel number, head number, and seed weight with RMSEs of 2150 kg ha^{-1}, 5755 kernels m^{-2}, 0.13 heads m^{-2}, and 4.51 mg $kernel^{-1}$. CROPGRO-Cotton simulated lint yield and boll number with RMSEs of 487 kg ha^{-1} and 25.97 bolls m^{-2}.

Simulations were also conducted with CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton to evaluate the effects of irrigation amounts and initial soil water content on yield, evapotranspiration (ET), water use efficiency (WUE), available soil water at maturity, and gross income per hectare. Simulations used weather data from Garden City, KS from 1961 to 1999. Irrigation amounts were different for all variables for corn and grain sorghum. For cotton, yield, WUE, soil water, and gross income were not different between the top two irrigation amounts. For corn and grain sorghum, initial soil water content was only different at 50% plant available water. Initial soil water had no affect on cotton, except for ET at 50%. Simulations showed that cotton yields are similar at lower irrigation. Also, cropping systems that include cotton have the potential to reduce overall irrigation demand on the Ogallala aquifer, potentially prolonging the life of the aquifer.

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CHAPTER I

INTRODUCTION

The High Plains aquifer is one of the largest fresh water aquifer systems in the world and underlies an area of approximately 45-million hectares of the Great Plains. Of the almost 45-million hectare area, the majority is cropland of which approximately 23 percent is irrigated. This irrigated cropland accounts for 94 percent of the total ground-water use on the High Plains (Waskom et al., 2006). In 2002 there was 1.1 million hectares of irrigated cropland in Kansas, with over 50 percent of the irrigated cropland being utilized for corn production (NASS, 2002).

Aquifer recharge across much of the Great Plains is negligible in comparison to current consumptive use due to low average rainfall and high evapotranspiration. Based on current use the aquifer is essentially a non-renewable resource. Significant water-level declines have been measured in the aquifer and these declines can be attributed to the large amount of water withdrawn for irrigation. An estimated 1.9 million hectare meter of water is withdrawn from the aquifer for irrigation each year (Waskom et al., 2006). The average water-level change measured in Kansas from 1950 to 2003 was a decline of 5.8 meters, with some areas in southwest Kansas have seen declines of greater than 15 meters (McGuire, 2004).

Historically, research to prolong the life of the aquifer has been focused on more efficient irrigation methods, irrigation timing, and limited versus full irrigation. Limited research has been done to this point on prolonging the aquifer through the inclusion of drought tolerant crops, like cotton or grain sorghum, into traditional crop rotations, mainly continuous corn. However, traditional cropping systems research requires significant investments of time, labor, money, and long-term experiments to take into account variations in yearly climatic conditions. Crop models have the potential to study the effects of changes in cropping systems, using historical weather data, in a much shorter time while decreasing the investments in labor and money.

Therefore, the objectives of my research were:

1) To calibrate the CERES-Maize, CERES-Sorghum, CROPGRO-Cotton models for the High Plains region.
2) To study the simulated effects of different irrigation amounts and initial soil water contents on corn, cotton, and grain sorghum.

CHAPTER II

LITERATURE REVIEW

Crop Modeling

Background

Crop modeling is the use of computer software to accurately and reasonably simulate crop growth, development, and yield by using weather, soils, and management practices data as input. Monteith (1996) defined a crop model as a quantitative scheme for predicting the growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables. Crop modeling began with the computer age and the first models attempted to simulate individual processes within a plant, such as light interception in crop canopies (Loomis and Williams, 1963). Currently many different models simulate plant growth and development for many different crops and individual crop models have been combined into comprehensive programs allowing modeling of various crops in rotation.

Crop models have conventionally been divided into two different types, empirical and mechanistic. Empirical models describe relationships between variables without referring to any underlying biological or physical structure that may exist between the variables (Whisler et al., 1986). Whereas mechanistic models are usually based on physiological and physical processes, and consider the cause and effect at the process level (Boote et al.,1996). However, most models contain a mixture of these two types.

Utilization and advantage of crop models

Crop simulation modeling can be utilized for many different things; Whisler et al. (1986) grouped them into three main categories: (1) aids in interpreting experimental results, (2) agronomic research tools, or (3) agronomic grower tools. Crop simulation models can also be categorized as a tool for policy analysis and decision making as well as an educational tool. Models, once validated can reduce the need for years of expensive and timely in-field research to study the effects of fertilizer rates, plant spacing and population, and other different management practices. They also have the potential as a tool for farmers to evaluate risk and profit associated with changes in management practices such as the addition of new crops into their rotations. Models can be used by policy makers to analyze the long term effects of climate change or of management practices on natural resources, such as water, or to gauge the impact new laws and regulations that change current management practices have on producers. Finally, these models could allow students to study the processes involved in crop growth and development and how changes to these processes impact crop development and yield.

Crop models pose distinct advantages for use in scientific research. Traditional in-field research requires significant investments of time, labor, money, and other resources. Cropping systems research usually requires long-term experiments to take into account variations in yearly climatic conditions, such as temperature and precipitation. Crop models, once calibrated, allow researchers to simulate multiple years of experiments, utilizing historical weather data, in a matter of hours. Staggenborg and Vanderlip (2005) used CERES-Wheat and CERES-sorghum to simulate a wheat-sorghum-fallow and wheat-fallow rotations and successfully showed that crop models could be used as dryland cropping systems research tools.

Validation and calibration of crop models

Before a crop model can provide accurate and reliable results, a researcher must first ensure that the model has been validated and that it will accurately simulate what it was designed to predict. Also, the model must be calibrated to the conditions for which the researcher wants to simulate. Validation is the process of assessing whether the crop model accurately predicts things such as crop phenology, dry matter accumulation, leaf area, yield, yield components, and other variables through the use of independent data sets. Singh (1989) referred to validation as the cornerstone of model evaluation. The problem with this process is that when validation shows poor prediction of some variable, researchers work to identify and correct these errors with the end result being a model that is not completely validated and needs further testing with new independent data. However, with time and use by many researchers, for various applications, confidence in the model can be established (Boote et al., 1996). Once validated a model can be used to simulate yields, dry matter production, leaf area, etc. in different environments with reasonable reliability and accuracy.

No crop model is universal however, and considerable work, calibration, is required to make the model account for differences in cropping conditions, cultivars, and the cropping environment for the researcher's desired site (Sinclair & Seligman, 1996). Boote et al. (1996) defined model calibration as adjusting model parameters or relationships to make the model work for a site. Calibration of a model requires researchers to collect or obtain several years of field data from the location or locations for the crop or crops under the conditions that they are wanting to simulate. The researcher then simulates these conditions and compares the simulated and observed results and makes adjustments to coefficients in the model to reduce errors between the simulated and observed results.

The Models

DSSAT

As mentioned previously, crop models have grown to the point of combining several individual models into one software program which can be used to simulate full cropping systems instead of individual crops. One of the most widely used and researched systems is the Decision Support System for Agrotechnology Transfer (DSSAT). Singh (1989) defined DSSAT as a computerized system to help resource planners and farmers make decisions as they seek solutions to specific agricultural problems. DSSAT is a result of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project, which is an international network of an interdisciplinary team of scientists from over 25 countries (Uehara & Tsuji, 1998). DSSAT was designed so that users can (1) input, organize, and store data on crops, soils, and weather, (2) retrieve, analyze and display data, (3) calibrate and evaluate crop growth models, and (4) evaluate different management practices at a site (Jones et al., 1998). It provides users with easy access to data bases of soil, crop, and climatic data; individual crop models; weather generators; expert systems; strategy evaluation; and utility programs for formatting, retrieving, and graphing information (Singh, 1989). Users can utilize the software to simulate crop growth, development, and yield on their own farms or research sites over multiple years seasonally or sequentially. DSSAT mainly contains crop models from two distinct families, Crop Estimation through Resource and Environment Synthesis, CERES, models for cereal crops and CROPGRO models for legume and other crops. The CERES models predict the duration of growth, the growth rates, and the amount of assimilate partitioned to plant components (Ritchie et al., 1998). The CROPGRO models are a generic crop model that share the same FORTRAN code with all species attributes for the different crops being input from external 'species' files, the CROPGRO model is based on the SOYGRO, PNUTGRO, and BEANGRO models (Boote et al., 1998).

CERES-Maize

CERES-Maize (Jones and Kiniry, 1986) is a daily time-step model that simulates phenology, biomass accumulation, carbon and nitrogen pools, soil water, soil nitrogen, yield, and yield components. The model is one of the first models created in the CERES family of cereal grain models and shares many of the same features and level of detail as other models in the family. CERES-Maize has been extensively tested and used throughout the world, with a large amount of research being done on corn production in the Great Plains.

Kiniry et al. (1997) evaluated the CERES-Maize model along with another crop simulation model to simulate grain yield of rainfed maize from 1983 to 1992 in locations across nine of the top maize producing states in the United States, including Kansas. They found that the models simulated mean grain yields within five percent of the measured mean yields for all nine locations. The model simulated the yield trends in all of the pooled data and did not tend to overestimate or underestimate yields in years with relatively low or high measured yields. The CERES model simulated mean yields over the 10 years with RMSEs less than 2 Mg ha^{-1} for all locations and RMSEs less than 1 Mg ha^{-1} for five of the locations. Dogan et al. (2006) simulated irrigated corn production from 1999-2001 in south central Kansas. CERES-Maize simulated yields that were not significantly different from actual yield in 2000, 2001, and for the three year mean and slightly underestimated yields in 1999 (p=0.058). The average measured yield over the three years was 11.1 Mg ha^{-1} and the average simulated yield was 11.2 Mg ha^{-1}. Xevi et al. (1996) used the model to predict above ground biomass, leaf area index (LAI), and soil water content for the 1988 growing season in Nebraska. Biomass, LAI, and soil moisture content were all predicted within the 95 percent confidence limit of the measured data. The model had RMSEs of 31.9 and 35.7 percent for biomass and LAI and RMSEs of 16.6, 9.8, 12.3, 13.4 percent for soil water content at 0-30, 30-60, 60-90, 90-120 cm, respectively.

Hodges et al. (1987) used the model to simulate corn production from 1982 to 1985 in the U.S. Cornbelt, with data from 51 locations in 14 states of the Cornbelt which account for approximately 85 percent of the U.S. corn production. The study estimated production fluctuations over a large region as a result of yearly variation in weather using data that is available during the growing season. The model simulated production for the region from 1982 through 1985 at 92, 97, 98, and 101 percent, respectively, of reported production by the USDA/NASS/ASB. Kiniry and Bockholt (1998) studied the model's ability to accurately simulate yield and year-to-year yield variability over a five year period at four irrigated and five dryland sites in Texas. The model simulated mean grain yields within 10% of the measure means at all but one of the locations. The CERES model simulated mean yield over the period with RMSEs of less than 2 Mg ha^{-1} for all but one location and less than 1 Mg ha^{-1} at 2 of the locations. The model was also able to account for more than 65 percent of the variability in yield for the five years of data and all measured yields as a function of simulated yields were significant (α=0.05). CERES-Maize has been used to simulate site-specific crop development and yield on claypan soils in Missouri (Fraisse et al., 2001). Grain yield under water-limiting conditions was simulated in Texas (Xie et al., 2001). The model's water and nitrogen balances were evaluated under tile-drained conditions in Iowa (Garrison et al., 1999). The model was used as an irrigation scheduling tool in North Dakota (Steele et al., 1994). Other work has been done on the CERES-Maize model by Pang et al. (1998), Pang et al. (1997), Carberry et al. (1989), and Panda et al. (2004).

CERES-Sorghum

CERES-Sorghum (Ritchie and Alagarswamy, 1989a) is a daily time-step model that predicts grain sorghum yield, phenology, yield components, biomass, root growth, soil water balance, and soil nitrogen balance (Gangadhar et al., 1991). The model is a member of the CERES family of cereal grain models having many of the same features and level of detail. Little work has been done with the CERES-Sorghum model in the last few years and of the work that has been done, little of it has been done in the United States. The CERES-Sorghum model has not been validated or calibrated, especially for grain sorghum production in the Great Plains.

Alagarswamy and Ritchie (1991) tested the phenology predictions of the model with two independent data sets, one from Texas and the other from India. In Texas, the model simulated the mean days to panicle initiation and flowering with RMSEs of 5.9 and 6.9 days, respectively. However the model did not simulate physiological maturity accurately with an RMSE of 12.9 days. With the data set from India, the model simulated panicle initiation, flowering, and physiological maturity with reasonable accuracy with RMSEs of 2.5, 4.3, and 5.5 days, respectively. Ritchie and Alagarswamy (1989b) also evaluated the sorghum model's ability to simulate grain yield and it's responsiveness to nitrogen rates. The model was evaluated with observed data from three different growing regions, Texas, Australia, and India. Grain yield was simulated accurately in India and for most of the plots in Australia. The model overestimated yield in Texas because of the model's inability to model tiller contribution to yield. The model underestimated yield in Australia in the zero nitrogen plots due to either severe N deficiency predictions by the model or errors in initial soil N values. The model also did not simulate crop response at lower and higher nitrogen fertilizer rates accurately.

Absolute sensitivity analysis was conducted on the CERES-sorghum model by Suchit et al. (2004b) with measured data from India. The study showed that the model simulated improper tillering response to changes in plant density. The model also overcompensated caryopsis weight when periods of water surplus or water stress occurred during grain fill, especially at populations below 60,000 plants ha^{-1}. Varshneya et al. (1998) studied the model's applicability to rainfed conditions in India. They showed that the model predicted phenology and biomass yields accurately under normal sowing conditions, populations, and with adequate moisture. However, biomass varied significantly under conditions of water stress and kernel weight was underestimated due to the model's inability to account for changes in panicle size under receding soil moisture conditions. The model was used to study the impacts of climate change on sorghum productivity in India (Gangadhar et al., 1995). Work also has been done with the model in India on forage sorghum, predicting biomass, yield, and yield components (Suchit and Gupta, 2004; Suchit et al., 2004a). Other work has been done with the CERES-Sorghum model by Gangadhar and Srinivas (1995), Folliard et al. (2004), and Varshneya et al. (2004).

CROPGRO-Cotton

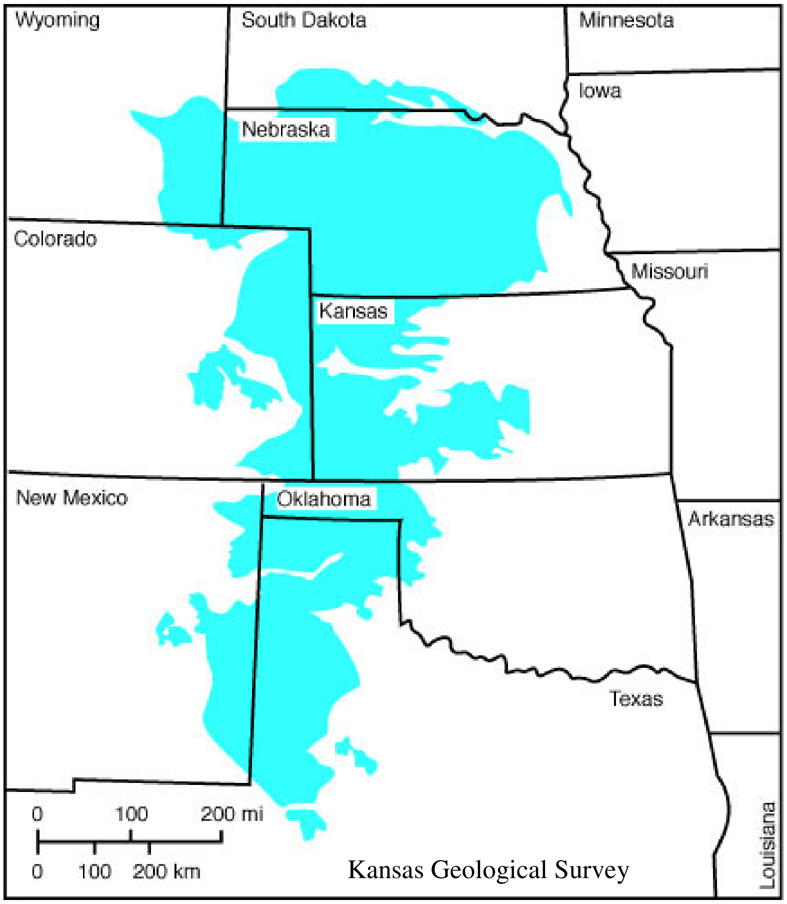
The CROPGRO-Cotton is a process-oriented model that simulates the daily processes of crop development, crop carbon balance, crop and soil N balance, and soil water balance. The model is a member of the CROPGRO family of legume models and was develop from the CROPGRO-Peanut model. The cotton model has many of the same features and level of detail as the other CROPGRO-legume models. The CROPGRO-Cotton model is still relatively new with little previous work having been completed. Further validation and calibration is needed, especially for cotton production in the Great Plains.

Guerra et al. (2005) evaluated the CROPGRO-cotton model's ability to simulate cotton growth and development in southwest Georgia. After calibration, the model simulated leaf, stem, and boll biomass with RMSEs of 165, 195, 509 kg ha^{-1}, respectively. The model also accurately simulated final yield, with an RMSE of 312 kg ha^{-1}. Soler and Hoogenboom (2006) also evaluated the model's capability to simulate growth and development, along with the potential of the model as a tool for irrigation scheduling. They used the model to define irrigation threshold treatments. The model accurately simulated cotton phenology, above-ground biomass, and yield. They also showed that the model can be a promising tool for irrigation scheduling with the use of correct characterization of the soil properties. Guerra et al. (2006) evaluated the CROPGRO-Cotton model’s ability to simulate soil moisture and yield under irrigated and rainfed conditions.

Declining Ogallala Aquifer

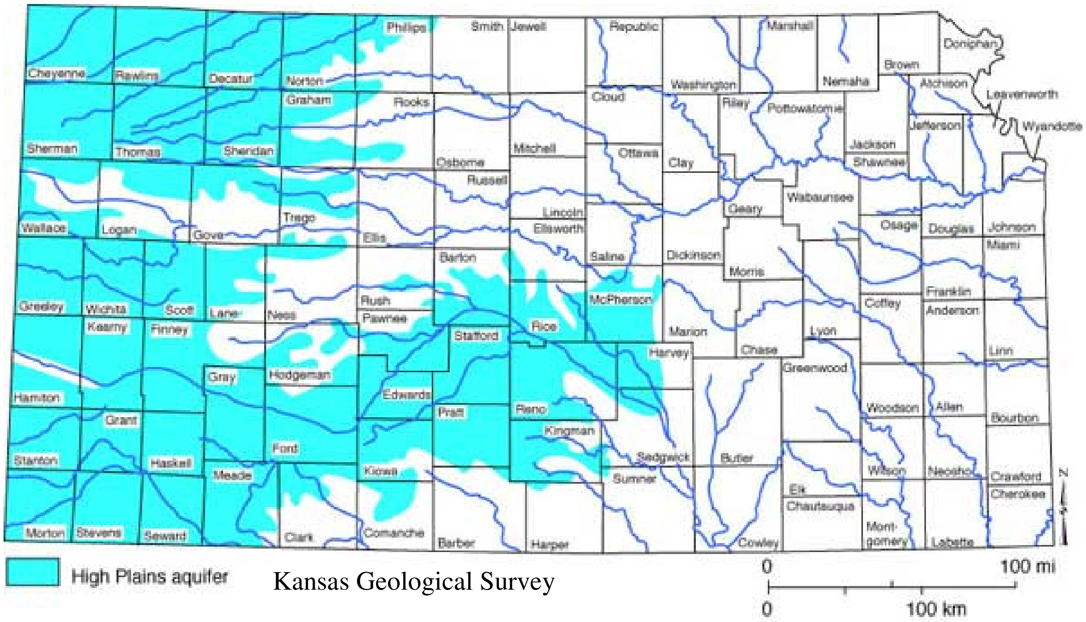
Facts

The High Plains aquifer is one of the largest fresh water aquifer systems in the world and underlies 44.9-million hectares of the Great Plains. The aquifer is located under parts of eight states which include: Kansas, Nebraska, Colorado, New Mexico, Oklahoma, South Dakota, Wyoming, and Texas. Of the 44.9-million hectares, the majority is cropland of which approximately 23 percent is irrigated, accounting for 94 percent of the total ground-water use on the High Plains. The principle geologic unit of the High Plains aquifer is the Ogallala formation which underlies 80 percent of the High Plains. The Ogallala aquifer has a saturated thickness of approximately 426.7 meters with an average water bearing formation of 61.0 meters. Currently, there are an estimated 165,000 wells that pump water out of the Ogallala (Waskom et al., 2006). The aquifer is recharged primarily from precipitation. However, recharge is negligible, in comparison to current consumptive use due to low average rainfall and high evapotranspiration, across most of



Kansas Geological Survey

Figure 2.1 The High Plains aquifer.



Kansas Geological Survey

Figure 2.2 The High Plains aquifer in Kansas.

the High Plains. The Ogallala aquifer is essentially a non-renewable resource, based on current use.

Significant water-level declines have been measured in the Ogallala which have been attributed to the massive amounts of water withdrawn for irrigation. An estimated 1.9 million hectare meter of water is withdrawn for irrigation each year (Waskom et al., 2006). Extensive irrigation from the aquifer started in the 1930's and 1940's, with substantial irrigation development occurring about 1950. From 1950 to 2003 water level changes ranged from a rise of 26.2 meters to a decline of 68.0 meters in some areas. The average area-weighted water-level changes across the High Plains was a decline of 3.8 meters, with approximately 24 percent of the area having a decline of more than 3 meters, 17 percent having a decline more than 7.6 meters, and 9 percent having a decline more than 15.2 meters. One of the largest areas with a decline of greater than 15.2 meters was in southwest Kansas. The area-weighted average water-level change in Kansas from 1950 to 2003 was a decline of 5.8 meters, with a 0.5 meter decline from 2002 to 2003. The total water in storage in the aquifer in 2003 was about 362 million hectare-meters, which is a decline of approximately 29 million hectare-meters since 1950. Kansas has seen a decline of 6.9 million hectare-meters of water in storage since 1950, with a decline of 0.5 million hectare-meters from 2002 to 2003 (McGuire, 2004).

Irrigated cropping systems are a major part of crop production in the central Great Plains, specifically western Kansas. In 2002, there was approximately 1.1 million hectares of irrigated cropland in Kansas with almost 50 percent of the irrigated cropland in corn (NASS, 2004). Annually, gross receipts exceed $600 million for irrigated crop production in the western three crop-reporting districts of Kansas (KSU, 1998). In 2000 irrigation was the largest use of water in Kansas, about 84 percent, with withdrawals of 14.1 million kiloliters per day or 0.5 million hectare-meters per year. Of these withdrawals for irrigation, 92 percent was from ground water (Kenney and Hansen, 2004). With declining water levels, the cost of irrigation increases as a result of the need for deeper wells, larger pumps, and increased energy use to get the water to the surface. Also, with continued decline in saturated thickness of the aquifer, well yields decline resulting in less effective irrigation. This loss in well capacity equals a loss of crop production as irrigated areas and crop yields decline (Waskom et al., 2006).

Much of the economies for the High Plains on a regional, state, and local scale are tied to the Ogallala aquifer. Crop, livestock, and meat processing sectors are major parts of the economies of the eight states that are tied to the aquifer. In western Kansas, as stated above, crop production exceeds $600 million annually. Along with crop production in western Kansas, fed cattle sales are upwards of $2.5 billion per year and there is $5.2 billion in wholesale value from packing plants annually. 4,064 million kilograms of feed grains are produced annually to support the local demand of 4,826 million kilograms in western Kansas. If all the irrigated acres had to be converted to dryland, due to the depletion of the aquifer, feed grain production in the region would decrease by 1,778 million kilograms equaling a loss of $300 million in gross revenue a year (KSU, 1998).

Prolonging the life of the aquifer

Cropping systems research to prolong the life of the aquifer has been mainly focused around the use of more efficient irrigation methods, irrigation timing, or the effects of limited versus full irrigation. Limited research has been done, however, on improving cropping systems through the inclusion of different crops, especially drought tolerant crops like grain sorghum and cotton, into traditional crop rotations as an effective tool to prolonging the life of the aquifer. Norwood (1995) compared an irrigated continuous wheat and an irrigated continuous sorghum system with a wheat-sorghum-fallow cropping system, where either, one, both, or neither of the crops was irrigated in southwest Kansas. He showed that irrigated rotated wheat and sorghum yields were 19 and 8% higher than those of the irrigated continuous wheat and sorghum. Irrigation water use efficiency was also higher for wheat and sorghum grown in rotation versus either crop grown continuously. Schneekloth et al. (1991) showed benefits to a wheat-corn-soybean rotation compared to continuous corn in west central Nebraska.

Along with the potential to increase the water use of a cropping system, inclusion of different crops into a rotation, especially a continuous corn system, can increase yields of the other crop or crops in the rotation because of the increase diversity of the system. Reddy et al. (2006) found a 1-11% increase in corn yield compared to continuous corn when rotated with cotton and a 14-19% yield increase in cotton compared to continuous cotton when rotated with corn in Mississippi. Maloney et al. (1999) demonstrated that corn yields can be increased by the inclusion of soybeans into traditional continuous corn cropping systems.

CHAPTER III

CALIBRATION OF THE CERES-MAIZE, CERES-SORGHUM, AND GROPGRO-COTTON MODELS

Introduction

Crop modeling is the use of computer software to accurately and reasonably simulate crop growth, development, and yield by using weather, soils, and management practices data as input. Monteith (1996) defined a crop model as a quantitative scheme for predicting the growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables. Crop models, once calibrated, allow researchers to simulate multiple years of experiments, utilizing historical weather data, in a matter of hours.

No crop model is universal and considerable work, calibration, is required to make the model account for differences in things such as cropping conditions, cultivars, and the cropping environment for the researcher's desired site (Sinclair & Seligman, 1996). Boote et al. (1996) defined model calibration as adjusting certain model parameters or relationships to make the model work for your site. Calibration of a model requires researchers to collect or obtain several years of field data from the location or locations for the crop or crops under the conditions that they are wanting to simulate. The researcher then simulates these conditions and compares the simulated and observed results and makes adjustments to coefficients in the model to reduce errors between the simulated and observed results. The objective of this research was to calibrate the CERES-Maize, CERES-Sorghum, CROPGRO-Cotton models for the High Plains region.

Materials and Methods

Data was collected for the calibration of the CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton models from several locations in Kansas. In 2005 data were collected on irrigated corn and cotton from producers' fields near Moscow and Cullison, KS. Data were collected on second crop irrigated grain sorghum from a producer's field near Preston, KS. Dryland plots were established at the South Central Experiment Field near Hutchinson, KS, but were lost due to a hail storm in June. In 2006 data were collected on irrigated corn and cotton at producers' fields near Moscow and Cullison, KS, on dryland corn at the Agronomy Research Farm in Manhattan, KS, and dryland corn and cotton at the Partridge Experiment Field of the South Central Experiment Field. Data on dryland grain sorghum were also collected at the agronomy North Farm and Partridge Experiment Field.

All plots consisted of at least 12 rows (76 cm row spacing) with the 2 middle rows, 6.1 meters long, set aside for yield harvest with a row of buffer on either side. All remaining rows were used for destructive sampling to measure dry matter and leaf area during the growing season. Irrigated corn plots were established in producers' fields in late April after the field was planted by the producer. Four replications were established at different locations in each field. Corn was planted at Cullison on 19 April 2005 and 24 April 2006 and at Moscow on 18 April 2005 and on 26 April 2006. Cotton plots were established in bulk areas of the Kansas Cotton Variety Performance Trials in late May, with two to four plots established at each location. Planting dates for the cotton were 19 May and 20 May 2005 at Moscow and Cullison, respectively and 3 May, 23 May, and 30 May 2006 at Cullison, Moscow, and Partridge, respectively. The second crop grain sorghum was replicated at four different locations in the producer's field after it was planted by the producer on 7 July 2005. All plots at experiment stations and fields were established in bulk areas that were planted specifically for this research project. Plots in 2006 at Manhattan where planted on 19 April and 5 June and on 14 April and 30 May at Partridge for corn and grain sorghum, respectively. Daily management was handled by the producers or experiment station staff at all locations except Manhattan, where I did any necessary field work. Site, cultivar, and planting information are reported in Tables 3.1 and 3.2.

Beginning and ending (after harvest) soil moisture levels were determined in all plots, except for ending soil moisture in 2006 for Cullison, Partridge, and Moscow as the soil profile was deemed to be at or near full due to excessive fall moisture. Samples were collected by pulling soil cores at 0-15, 15-30, 30-61, 61-91, 91-122, 122-152, and 152-183 cm depths, shortly after planting with a Giddings probe (Model GSRTS, Giddings Machine Company Inc., Ft. Collins, CO) in 2005 and a Cone Penotrometer, built by the agricultural engineering department, in 2006. Soil samples were dried in a forced-air dryer at 105° C for a minimum of 48 hours then weighed to determine soil volumetric water content. Bulk densities were obtained in 2005 from the National Resource Conservation Service (NRCS) soil characterization database and in 2006 from field measurements. In 2005 the soil cores were also analyzed by the KSU soil testing laboratory for texture and nitrate. Soil nutrient samples were also collected at this time and analyzed by the KSU soil testing laboratory for pH, P, K, and organic matter content. All other soil properties needed for crop modeling were obtained from the NRCS soil characterization database.

Table 3.1. Specific research location data for 2005.

Location	Crop	Hybrid	Planting Date	Established Population (plants ha^{-1})	Previous Crop	Soil Type
Latitude & Longitude						
Cullison 37°38' N 98°58' W	Corn	Pioneer 32B33	19-Apr	69 936	Cotton	Naron Fine-loamy, mixed, superactive, thermic Udic Argiustoll
Cullison 37°38' N 98°58' W	Cotton	D & PL PM 2145RR	20-May	95 489	Corn	Naron Fine-loamy, mixed, superactive, thermic Udic Argiustoll
Moscow 37°21' N 101°14' W	Corn	Pioneer 31N26	18-Apr	66 977	Grain Sorghum	Ulysses Fine-silty, mixed, superactive, mesic Aridic Haplustoll
Moscow 37°21' N 101°12' W	Cotton	D & PL PM 2145RR	19-May	95 220	Fallow	Richfield Smectitic, mesic Aridic Argiustoll
Preston 37°46' N 98°29' W	Grain Sorghum	Mycogen 1G600	07-Jul		Wheat	Carway Fine-loamy, mixed, superactive, mesic Aeric

Table 3.2. Specific research location data for 2006.

Location Latitude & Longitude	Crop	Hybrid	Planting Date	Established Population (plants ha^{-1})	Previous Crop	Soil Type
Cullison 37°38' N 98°58' W	Corn	Stafford 2721	24-Apr	68 322	Cotton	Naron Fine-loamy, mixed, superactive, thermic Udic Argiustoll
Cullison 37°38' N 98°58' W	Cotton	Fibermax 960B2R	03-May	44 472	Corn	Naron Fine-loamy, mixed, superactive, thermic Udic Argiustoll
Manhattan 39°13' N 96°35' W	Corn	Pioneer 32B29	19-Apr	63 749	Corn	Smolan Fine, smectitic, mesic Typic Argiudoll
Manhattan 39°13' N 96°35' W	Grain Sorghum	Pioneer 87G57	05-Jun	138 795	Corn	Smolan Fine, smectitic, mesic Typic Argiudoll
Moscow 37°22' N 101°15' W	Corn	Pioneer 33B51	26-Apr	74 239	Cotton	Ulysses Fine-silty, mixed, superactive, mesic Aridic
Moscow 37°21' N 101°14' W	Cotton	D & PL PM 2145RR	23-May	101 407	Corn	Ulysses Fine-silty, mixed, superactive, mesic Aridic Haplustoll
Partridge 37°58' N 98°07' W	Corn	Pioneer 32B29	14-Apr	49 852	Grain Sorghum	Funmar Fine-loamy, mixed, superactive, mesic Pachic

Stand counts were taken approximately one month after planting for all plots. Plants were counted in each of the two harvest rows of 6.1 meters. Destructive sampling was done on all plots two to three times each growing season, except in Manhattan where sampling was done every 7 to 10 days in 2006. At these times, dry matter and leaf area index (LAI) were determined. One meter of row was removed each sampling date from each plot out of the rows surrounding the two harvest and two border rows. Growth stage, plant height, node number, and reproductive numbers (ears m^{-2}, heads m^{-2}, squares m^{-2}, and bolls m^{-2}) were also measured.

Leaf area was determined by one of three methods: measuring the length and width of individual leaves, using a LI-COR (LI-COR, Inc., Lincoln, NE) LI-3000 Portable Area Meter, or using a LI-COR (LI-COR, Inc., Lincoln, NE) LI-3100 Area Meter. When leaf area was determined by measuring the length and width, leaf area was found for corn and grain sorghum with the equation: LA=L*W*0.76 and found for cotton with the equation: LA=(0.7596*L*W*)-1.3375.

The dry matter samples were divided into leaf, stem, and reproductive parts and wet weights were taken in the field. Samples were then dried in a forced-air dryer at 65°C until dry and then weighed to obtain a dry weight.

Irrigation amounts at the irrigated fields in Cullison, Moscow, and Preston were obtained in several different ways. Irrigation at Preston and Cullison, except the 2006 corn, was measured with tipping bucket rain gauges (Model RG2, Onset Computer Corp., Bourne, MA) in the plots. All measured values were also checked and corrected with the producer’s irrigation records. At Moscow and for the 2006 corn at Cullison, GPS receivers (Model HI-204S, Haicom Electronics Corp., Taipei, Taiwan) along with data loggers (Model DGPS-XM4, Australia) were attached to the pivots to track when the pivot moved across the plots. Irrigation amounts were obtained from the producer's records. Rain gauges were not used at Moscow because drop nozzles on the pivot were too low and for the 2006 corn at Cullison because inaccurate measurements were obtained with the rain gauge in 2005 due to plant height.

All plots were harvested by hand and final total dry matter samples were taken on a meter of row for all plots, except for cotton in 2005. For corn in 2005, 4.6 meters of each of the two harvest rows were hand harvested and in 2006 6.1 meters of each of the two rows were harvested. The ear corn was shelled using an ear corn sheller (Model ECS, ALMACO, Nevada, IA) and moisture and test weight were measured with a DICKEY-john GAC 2000 (DICKEY-john Corp., Springfield, IL). Final yield was standardized at 15.5 percent moisture. Kernel weight was determined by weighing 200 kernels after drying them in a forced-air dryer at 65°C for 72 hours. Kernel number (kernels m^{-2}) was calculated using total grain weight and kernel weight. Grain sorghum yield was determined by hand harvesting two rows, 4.6 meters long in 2005 and 6.1 meters long in 2006. Heads were threshed using a plot thresher (Model LPR, ALMACO, Nevada, IA) and moisture and test weight were measured with a DICKEY-john GAC 2000 (DICKEY-john Corp., Springfield, IL). Final yield was standardized at 12.5 percent moisture. Kernel weight was determine by weighing 1000 kernels after drying them in a forced-air dryer at 65°C for 72 hours. Kernel number (kernels m^{-2}) was calculated using total grain weight and kernel weight. One row, 6.1 meters long, of the two harvest rows was hand harvested for cotton in both 2005 and 2006. The cotton was deburred by hand and then ginned to obtain final yield. Bolls were counted as they were harvested and boll number (bolls m^{-2}) was calculated. Lint per boll was also calculated from yield and boll number.

All simulations used DSSAT 4.0.2.0 suite, specifically with the CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton models. Weather data for model simulations were obtained from several different sources. Tipping bucket rain gauges (Model RG2, Onset Computer Corp., Bourne, MA) were set-up along the edge of the field at Cullison, Moscow, Preston, and Partridge to measure daily rainfall. Daily rainfall along with solar radiation and maximum and minimum daily temperatures at the Agronomy Research Farm and South Central Experiment Field were obtained from onsite weather stations. Maximum and minimum daily temperatures along with solar radiation for Cullison were obtained from an automated weather station near Cullison. Daily temperatures for Moscow were obtained from a National Weather Service site near Hugoton and solar radiation from a weather station at the experiment station in Garden City. Temperatures for Preston were obtained from a National Weather Service site near Pratt and solar radiation came from an automated weather station near St. John. At Partridge, maximum and minimum temperatures along with solar radiation were obtained from the weather station at the South Central Experiment Field.

Multiple simulations were run during the calibration process with each model. Parameters were changed one at a time and the outputs were compared with the measured data. Yield, yield components, dry matter partioning, and LAI were the main focus. Model output was compared with previous simulations to see if the change resulted in the difference between the simulated and measured data became smaller or larger.

Root means square errors (RMSE) were calculated for the different plant characteristics compared, by calculating the error (measured minus simulated) for each characteristic at each location-year. The error at each location was squared; the squared errors were then summed for all locations- years. The sum of squared errors was then divided by the number of locations-years; the square root was then taken of this value. Percent error was also calculated for each of the plant characteristics by taking the error, measured minus the simulated, value and then dividing it by the measured value.

Results and Discussion

CERES-Maize

Calibrations

During calibrations several changes were made to the model, mainly in the cultivar file. Due to some errors in model inputs during the first run of simulations we considered the second run of simulations (S2) as the initial simulation for comparative purposes. For simulation three (S3) a new cultivar was created, based on the cultivar IB0047, by changing the G2 coefficient (maximum possible number of kernels per plant) from 917.4 to 1100. Nitrogen and symbiosis simulation options were changed from yes to no and from no to unlimited N, respectively, for simulation four (S4). Another cultivar was created for simulation five (S5) that changed the following: P1 (thermal time from seedling emergence to the end of juvenile phase [expressed as degree days above a base temperature of 8°C]) from 255 to 220, P2 (extent to which development [expressed as days] is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate) from 0.76 to 0.52, and P5 (thermal time from silking to physiological maturity [expressed as degree days above a base temperature of 8°C]) from 685 to 880. In simulation six (S6) another new cultivar was created by changing P5 from 880 to 780. For simulation seven (S7) G2 was changed from 1100 to 1000 and then from 1000 to 920, but no effect was seen with either change.

Yield and yield component simulation

The initial run of CERES-Maize simulated yield across the six location-years with a RMSE of 3552 kg ha^{-1}. Yield components of kernel number, ear number, and seed weight were simulated with RMSEs of 968 kernels m^{-2}, 1.6 ears m^{-2}, and 40.1 mg kernel^{-1}, respectively. Through calibration of the model we were able to reduce the RMSE for yield and seed weight to 2891 kg ha^{-1} and 38.0 mg kernel^{-1}, respectively. However, through calibration to decrease the yield gap, the RMSE for kernel number increased to 1283 kernels m^{-2}. None of the calibrations had any effect on ear number.

In S3 we decreased the RMSE for yield but increased it for kernel number and seed weight. S4 caused another decrease in the RMSE for yield and seed weight, but caused the RMSE for kernel number to increase further. Simulation 5 resulted in a decrease in the kernel number RMSE, but increased the RMSE for yield and seed weight. In S6, yield and seed weight RMSEs decrease and no change occurred to kernel number. The RMSEs for yield, seed weight, and kernel number was lowest during all the calibration simulations in S6, S6, and S2, respectively.

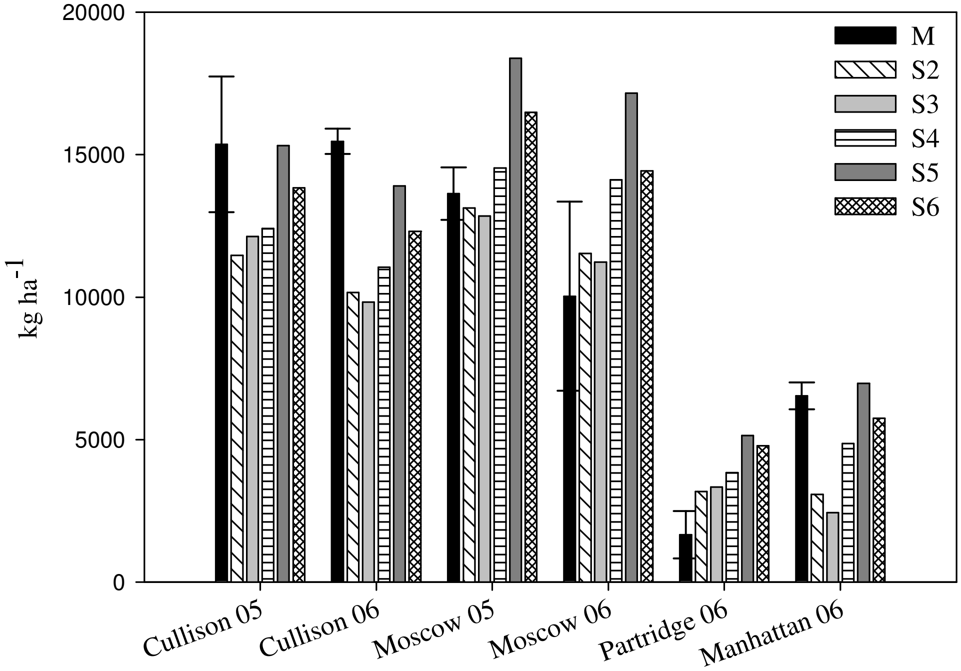


Figure 3.1 Measured and simulated corn yield at six location-years in Kansas.

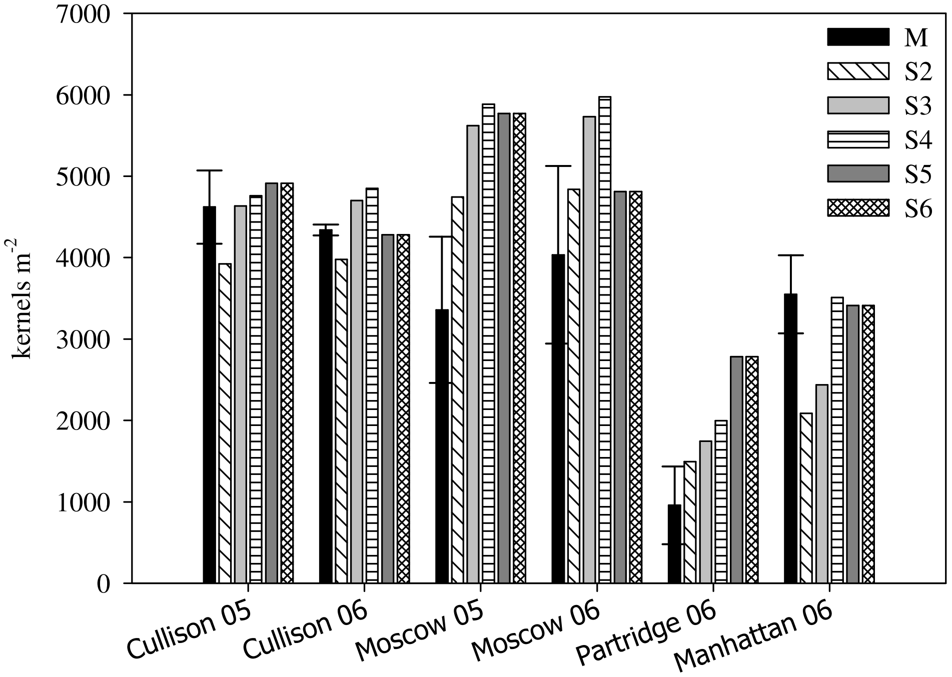


Figure 3.2 Measured and simulated corn kernel number at six location-years in Kansas.

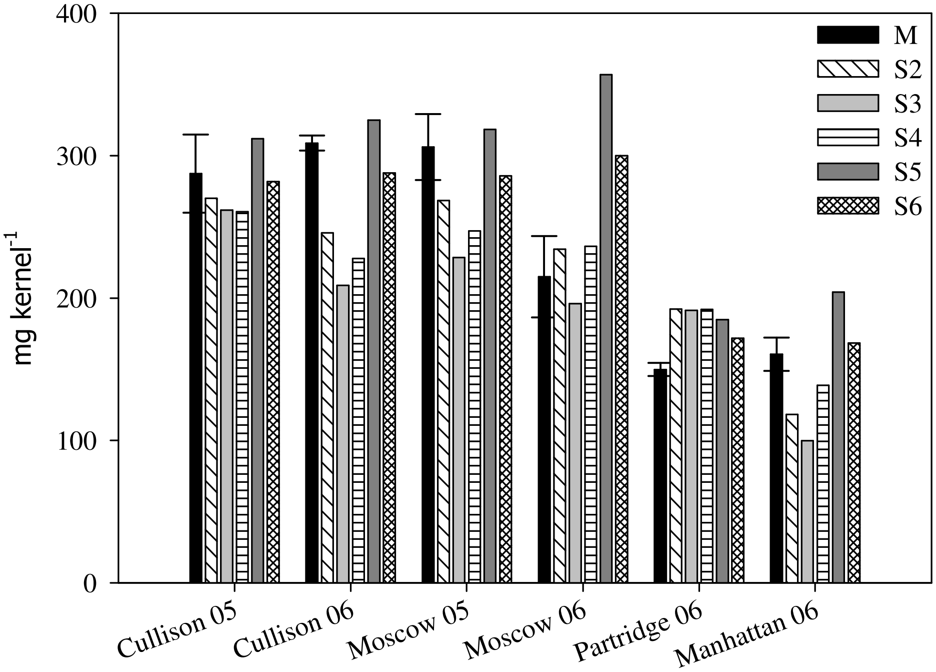


Figure 3.3 Measured and simulated corn seed weight at six location-years in Kansas.

The model consistently over predicted yield at Moscow, in both 2005 and 2006, and at Partridge; simulated yields in S6 had percent errors of 21.0, 43.9, and 187.7 percent of the measured yield, respectively. However it under predicted yield at Cullison, in both 2005 and 2006, and at Manhattan; simulated yields in S6 had percent errors of -9.9, -20.4, -12.0 percent of the measured yield. Simulations predicted kernel number relatively close at Cullison, in both years, and at Manhattan, with percent errors of 6.3, -1.3, and -3.8 percent but drastically over predicted kernel number at Moscow, in both years, and at Partridge with percent errors of 71.9, 19.2, and 191.2 percent, respectively. Seed weight simulations were variable across the simulations at all locations except Partridge, where it was consistently over predicted. Ear number simulation was good at Cullison in 2005 and Moscow in 2005, but under predicted at Cullison in 2006, Moscow

Table 3.3 Yield and yield component RMSEs, individual location errors, and percent errors for corn simulations 2 and 3 for the six location-years in Kansas.

Location	M	S2	Error	% Error	S3	Error	% Error
Yield (kg ha^{-1})							
Cullison 05	15 361	10 590	-4771	-31.1%	12 123	-3238	-21.1%
Cullison 06	15 468	9771	-5697	-36.8%	9826	-5642	-36.5%
Moscow 05	13 632	12 732	-900	-6.6%	12 847	-785	-5.8%
Moscow 06	10 028	11 338	1310	13.1%	11 232	1204	12.0%
Partridge 06	1662	2872	1210	72.8%	3336	1674	100.7%
Manhattan 06	6532	2471	-4061	-62.2%	2434	-4098	-62.7%
RMSE			3552			3265	
Avg				-8.5%			-2.2%
Kernel Number (kernels m^{-2})							
Cullison 05	4621	3922	-699	-15.1%	4633	12	0.3%
Cullison 06	4337	3978	-359	-8.3%	4702	365	8.4%
Moscow 05	3357	4744	1387	41.3%	5622	2265	67.5%
Moscow 06	4034	4840	806	20.0%	5730	1696	42.1%
Partridge 06	956	1494	538	56.3%	1744	788	82.4%
Manhattan 06	3549	2087	-1462	-41.2%	2438	-1111	-31.3%
RMSE			968			1291	
Avg				8.8%			28.2%
Ear Number (ears m^{-2})							
Cullison 05	6.7	7	0.3	4.5%	7	0.3	4.5%
Cullison 06	8.9	7	-1.9	-21.3%	7	-1.9	-21.3%
Moscow 05	7.0	7	0.0	0.0%	7	0.0	0.0%
Moscow 06	9.8	7	-2.8	-28.6%	7	-2.8	-28.6%
Partridge 06	3.9	5	1.1	28.2%	5	1.1	28.2%
Manhattan 06	7.6	6	-1.6	-21.1%	6	-1.6	-21.1%
RMSE			1.6			1.6	
Avg				-6.4%			-6.4%
Seed Weight (mg $kernel^{-1}$)							
Cullison 05	287.3	270.0	-17.3	-6.0%	261.7	-25.6	-8.9%
Cullison 06	308.8	245.7	-63.1	-20.4%	209.0	-99.8	-32.3%
Moscow 05	306.0	268.4	-37.6	-12.3%	228.5	-77.5	-25.3%
Moscow 06	214.9	234.2	19.3	9.0%	196.0	-18.9	-8.8%
Partridge 06	149.8	192.2	42.4	28.3%	191.3	41.5	27.7%
Manhattan 06	160.5	118.4	-42.1	-26.2%	99.8	-60.7	-37.8%
RMSE			40.1			61.1	
Avg				-4.6%			-14.2%

Table 3.4 Yield and yield component RMSEs, individual location errors, and percent errors for corn simulations 4, 5, and 6 for the six location-years in Kansas.

Location	S4	Error	% Error	S5	Error	% Error	S6	Error	% Error
Yield (kg ha^{-1})									
Cullison 05	12 409	-2952	-19.2%	15 312	-49	-0.3%	13 837	-1524	-9.9%
Cullison 06	11 052	-4416	-28.5%	13 906	-1562	-10.1%	12 314	-3154	-20.4%
Moscow 05	14 536	904	6.6%	18 380	4748	34.8%	16 490	2858	21.0%
Moscow 06	14 113	4085	40.7%	17 165	7137	71.2%	14 428	4400	43.9%
Partridge 06	3836	2174	130.8%	5144	3482	209.5%	4782	3120	187.7%
Manhattan 06	4866	-1666	-25.5%	6968	436	6.7%	5750	-782	-12.0%
RMSE		2978			3835			2891	
Avg			17.5%			52.0%			35.0%
Kernel Number (kernels m^{-2})									
Cullison 05	4761	140	3.0%	4913	292	6.3%	4913	292	6.3%
Cullison 06	4852	515	11.9%	4280	-57	-1.3%	4280	-57	-1.3%
Moscow 05	5884	2527	75.3%	5771	2414	71.9%	5771	2414	71.9%
Moscow 06	5973	1939	48.1%	4809	775	19.2%	4809	775	19.2%
Partridge 06	1997	1041	108.9%	2784	1828	191.2%	2784	1828	191.2%
Manhattan 06	3509	-40	-1.1%	3414	-135	-3.8%	3414	-135	-3.8%
RMSE		1385			1283			1283	
Avg			41.0%			47.3%			47.3%
Ear Number (ears m^{-2})									
Cullison 05	7	0.3	4.5%	7	0.3	4.5%	7	0.3	4.5%
Cullison 06	7	-1.9	-21.3%	7	-1.9	-21.3%	7	-1.9	-21.3%
Moscow 05	7	0.0	0.0%	7	0.0	0.0%	7	0.0	0.0%
Moscow 06	7	-2.8	-28.6%	7	-2.8	-28.6%	7	-2.8	-28.6%
Partridge 06	5	1.1	28.2%	5	1.1	28.2%	5	1.1	28.2%
Manhattan 06	6	-1.6	-21.1%	6	-1.6	-21.1%	6	-1.6	-21.1%
RMSE		1.6			1.6			1.6	
Avg			-6.4%			-6.4%			-6.4%
Seed Weight (mg kernel^{-1})									
Cullison 05	260.6	-26.7	-9.3%	311.7	24.4	8.5%	281.6	-5.7	-2.0%
Cullison 06	227.8	-81	-26.2%	324.9	16.1	5.2%	287.7	-21.1	-6.8%
Moscow 05	247.1	-58.9	-19.2%	318.5	12.5	4.1%	285.8	-20.2	-6.6%
Moscow 06	236.3	21.4	10.0%	356.9	142	66.1%	300.0	85.1	39.6%
Partridge 06	192.1	42.3	28.2%	184.8	35	23.4%	171.8	22	14.7%
Manhattan 06	138.7	-21.8	-13.6%	204.1	43.6	27.2%	168.4	7.9	4.9%
RMSE		47.4			63.6			38.0	
Avg			-5.0%			22.4%			7.3%

in 2006, and Manhattan, and over predicted at Partridge, percent errors were 4.5, 0.0, -21.3, -28.6, -21.2, and 28.2 percent, respectively. The RMSEs, individual location errors, and percent errors across the simulation runs are listed in Tables 3.3 and 3.4.

Biomass and leaf area simulation

The model tended to over predict total biomass, at most locations, throughout the growing season, but usually followed the trend observed in the measured data (Figure 3.4, 3.5, 3.6, 3.7, 3.8, and 3.9). For S2, the RMSE for total biomass near silking and at harvest was 2745 kg ha^{-1} and 4611 kg ha^{-1}; through calibration these values increased to 3166 kg ha^{-1} and 5256 kg ha^{-1}, respectively. Looking at partioning of the biomass, the model tended to over predict, at most locations, reproductive and leaf weight, while under predicting stem weight.

Across all the calibration simulations, the RMSEs for total biomass near silking and at harvest increased, when compared to the initial simulation. The RMSEs for reproductive biomass near silking and at harvest also increased in all simulations. Root Mean Square Errors for stem weight and leaf weight were variable across the simulations. The RMSEs, individual location errors, and percent errors across the calibration simulation are listed in Tables 3.5, 3.6, 3.7, and 3.8.

Leaf area index simulation was variable across the six locations. Leaf area index was over predicted, through ought the growing season at Cullison in 2006, Moscow in 2005 and 2006, and Partridge. It was under predicted at Cullison in 2005 and Manhattan (Figure 3.10 and 3.11). Simulated LAI at most of the locations peaked prior to that observed in the field. Through calibration the RMSE was decreased from 1.07 to 0.85.

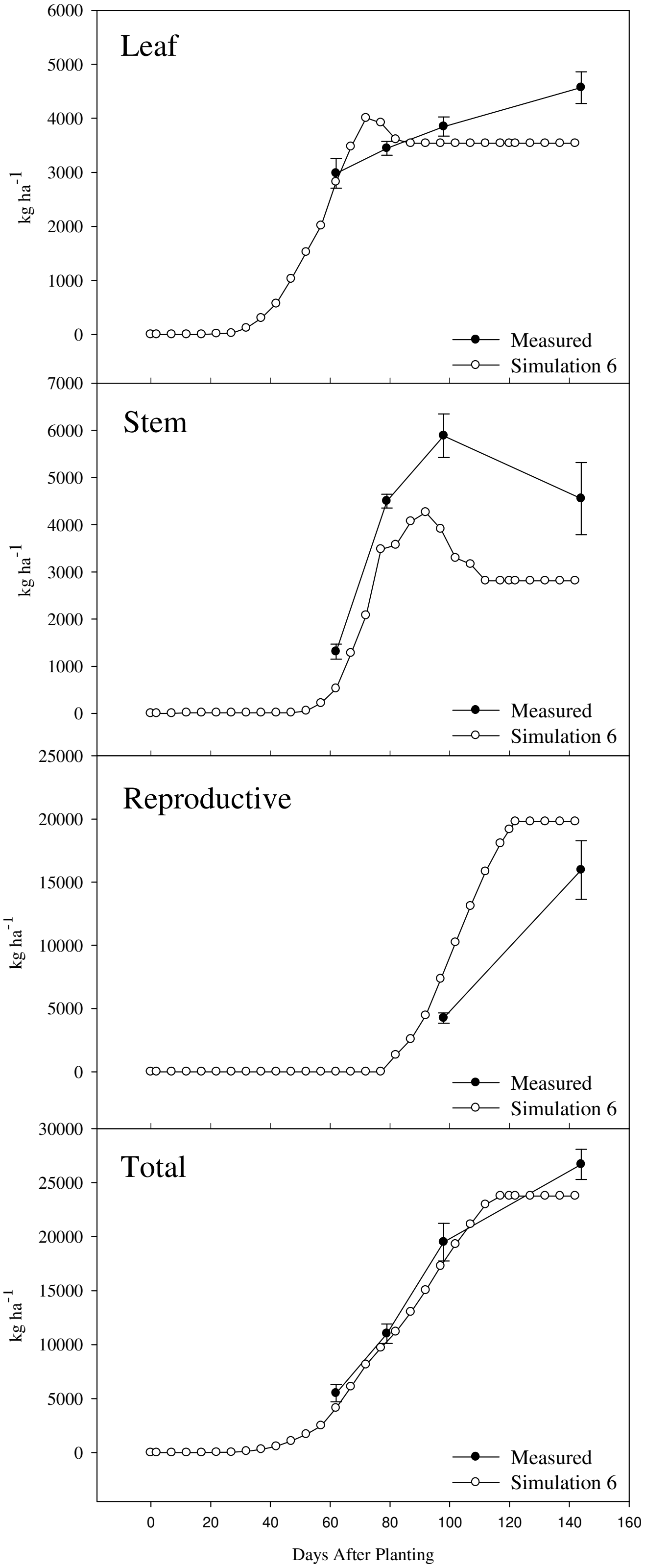


Figure 3.4 Measured and simulated corn leaf, stem, reproductive, and total biomass at Cullison, KS in 2005.

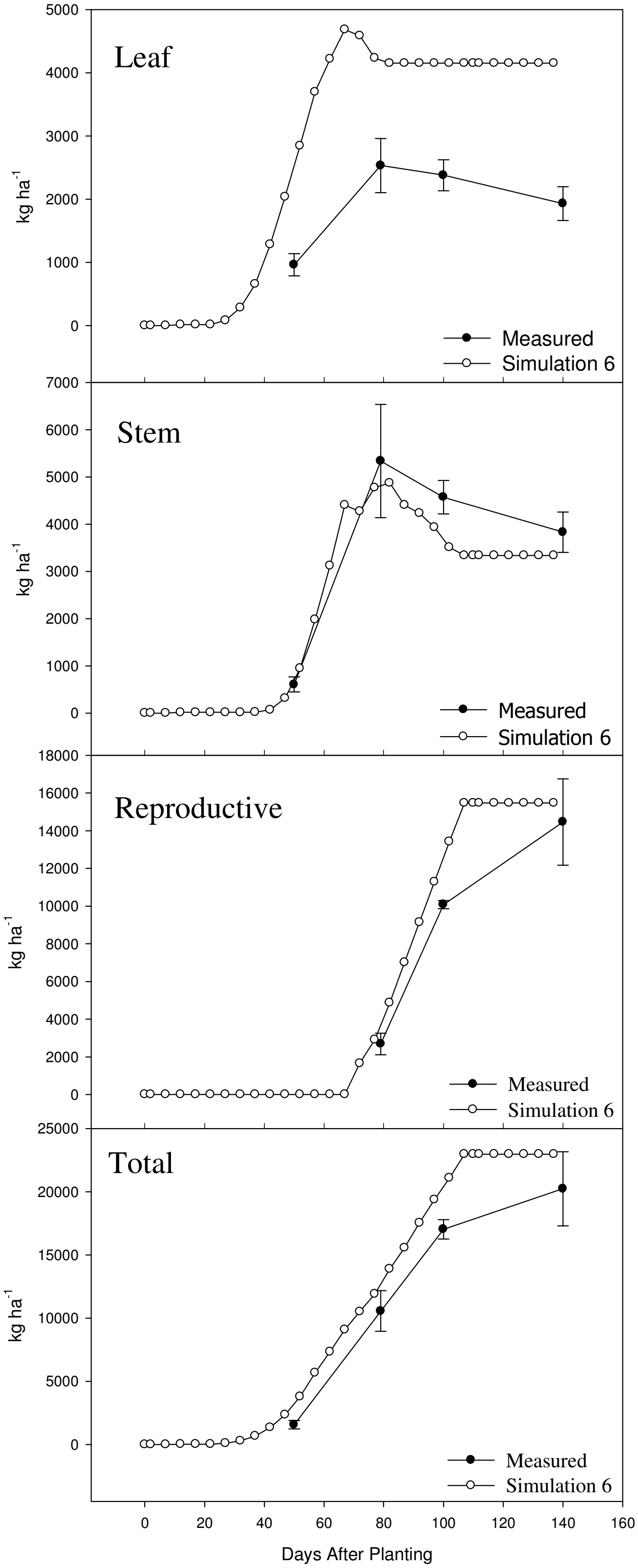


Figure 3.5 Measured and simulated corn leaf, stem, reproductive, and total biomass at Cullison, KS in 2006.

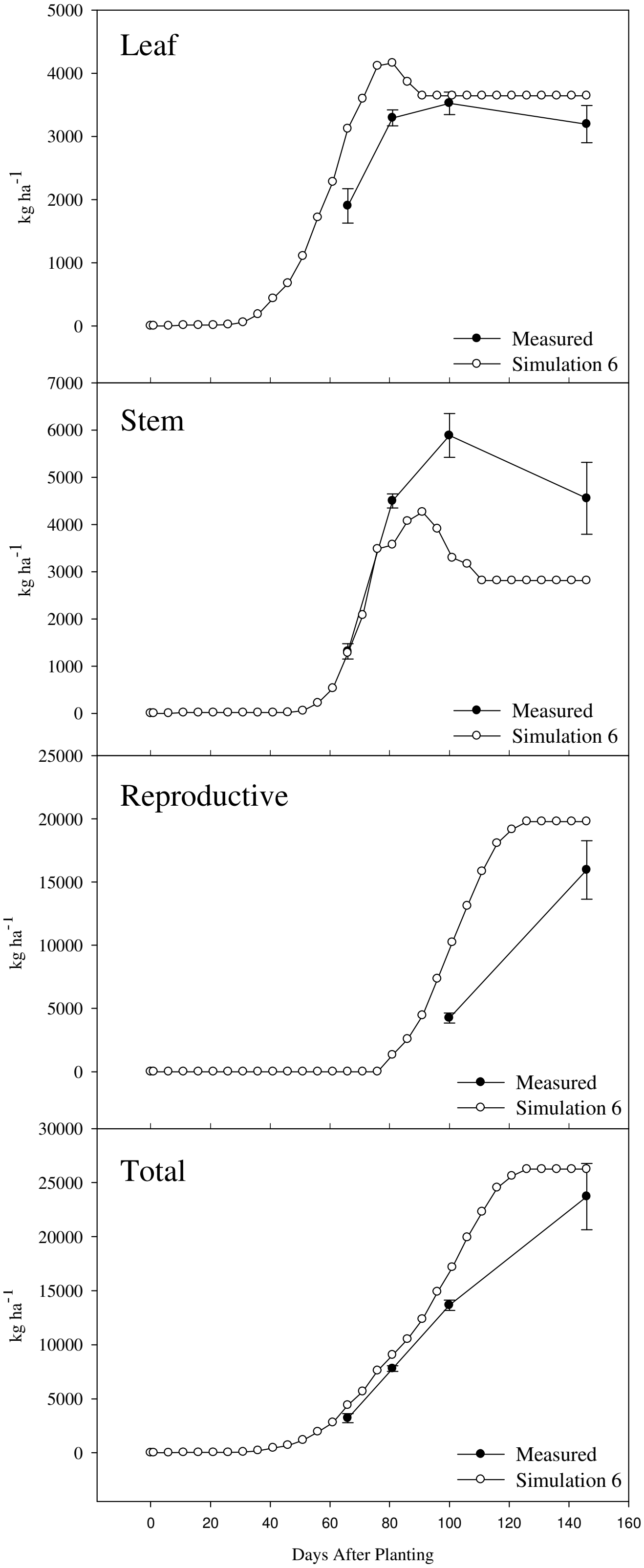


Figure 3.6 Measured and simulated corn leaf, stem, reproductive, and total biomass at Moscow, KS in 2005.

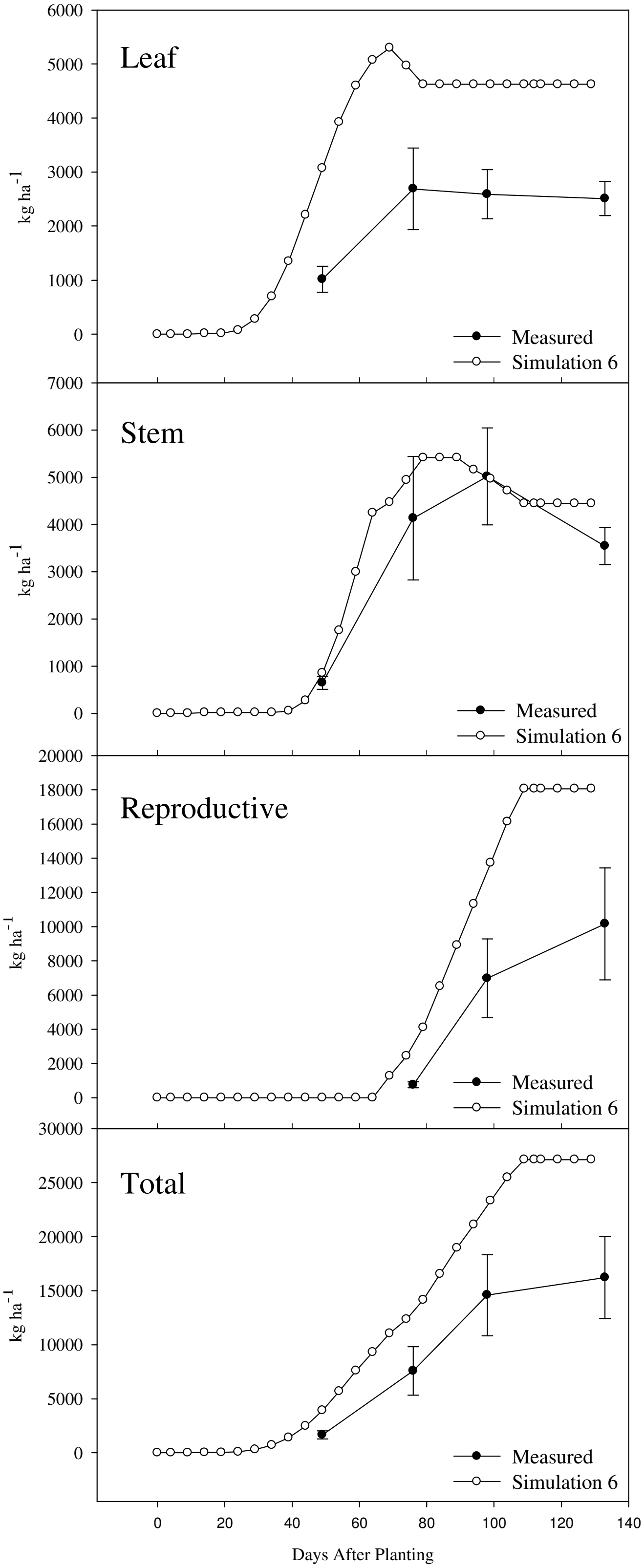


Figure 3.7 Measured and simulated corn leaf, stem, reproductive, and total biomass at Moscow, KS in 2005.

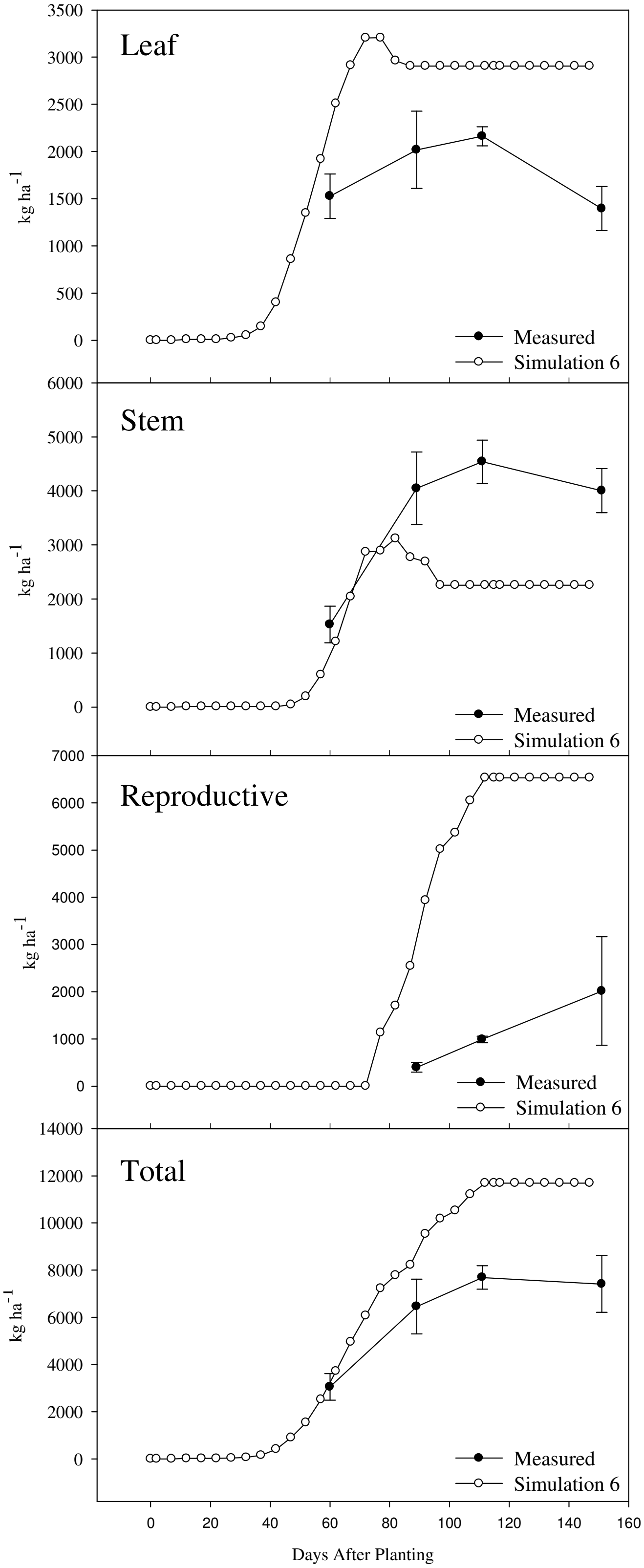


Figure 3.8 Measured and simulated corn leaf, stem, reproductive, and total biomass at Partridge, KS in 2006.

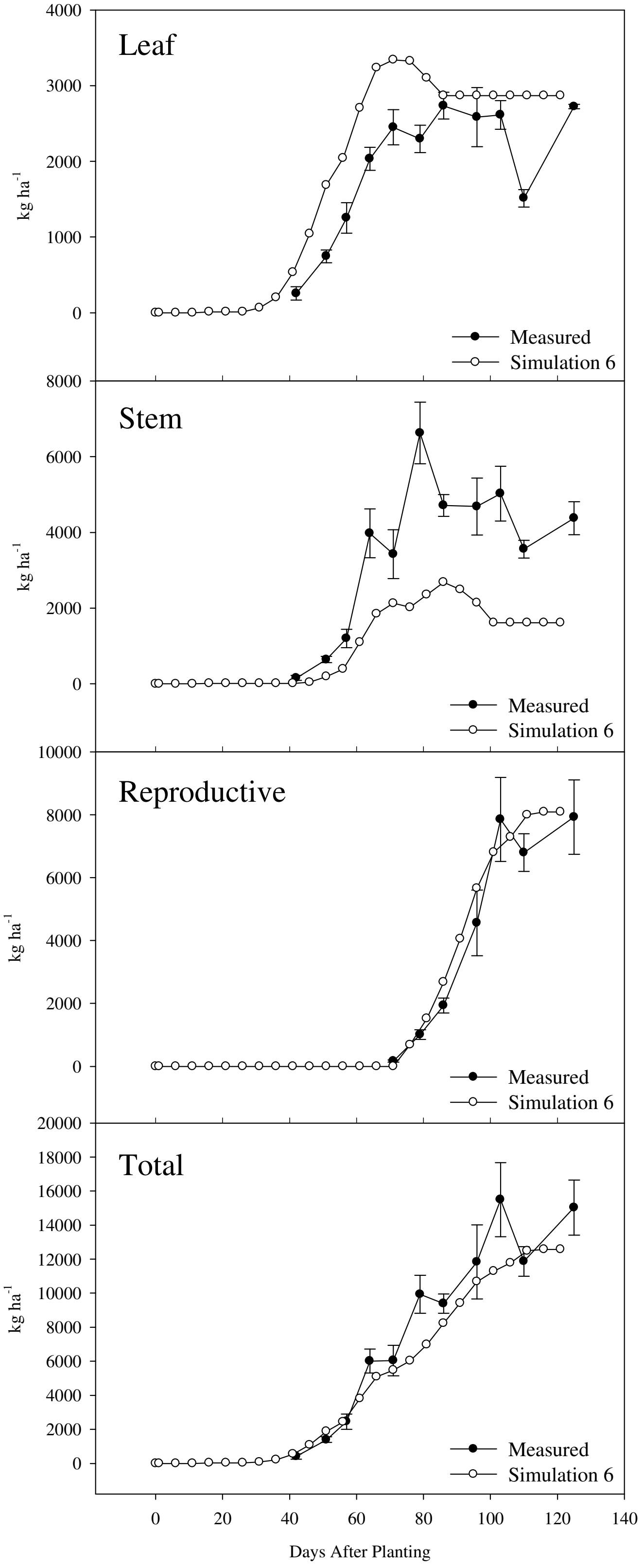


Figure 3.9 Measured and simulated corn leaf, stem, reproductive, and total biomass at Manhattan, KS in 2006.

Table 3.5 RMSEs, individual location errors, and percent errors for corn simulations 2 and 3 for biomass and LAI near silking for the six location-years in Kansas.

Location	M	S2	Error	% Error	S3	Error	% Error
LAI							
Cullison 05	5.80	4.83	-0.97	-16.7%	4.83	-0.97	-16.7%
Cullison 06	3.83	4.98	1.15	30.0%	4.98	1.15	30.0%
Moscow 05	5.11	4.05	-1.06	-20.7%	4.05	-1.06	-20.7%
Moscow 06	4.68	4.72	0.04	0.9%	4.72	0.04	0.9%
Partridge 06	3.16	2.87	-0.29	-9.2%	2.87	-0.29	-9.2%
Manhattan 06	3.80	1.94	-1.86	-48.9%	1.94	-1.86	-48.9%
RMSE			1.07			1.07	
Avg				-10.8%			-10.8%
Leaf Biomass (kg ha^{-1})							
Cullison 05	3444	4583	1139	33.1%	4583	1139	33.1%
Cullison 06	2531	5079	2548	100.7%	5079	2548	100.7%
Moscow 05	3524	3643	119	3.4%	3643	119	3.4%
Moscow 06	2690	4880	2190	81.4%	4880	2190	81.4%
Partridge 06	2018	3319	1301	64.5%	3319	1301	64.5%
Manhattan 06	2297	2890	593	25.8%	2890	593	25.8%
RMSE			1562			1562	
Avg				51.5%			51.5%
Stem Biomass (kg ha^{-1})							
Cullison 05	6357	3935	-2422	-38.1%	3935	-2422	-38.1%
Cullison 06	5336	4554	-782	-14.7%	4554	-782	-14.7%
Moscow 05	5884	4317	-1567	-26.6%	3853	-2031	-34.5%
Moscow 06	4132	4642	510	12.3%	4642	510	12.3%
Partridge 06	4047	3009	-1038	-25.6%	3009	-1038	-25.6%
Manhattan 06	6625	1900	-4725	-71.3%	1900	-4725	-71.3%
RMSE			2331			2390	
Avg				-27.3%			-28.6%
Reproductive Biomass (kg ha^{-1})							
Cullison 05	1219	1225	6	0.5%	1225	6	0.5%
Cullison 06	2685	2252	-433	-16.1%	2252	-433	-16.1%
Moscow 05	4244	6838	2594	61.1%	7540	3296	77.7%
Moscow 06	757	1622	865	114.3%	1622	865	114.3%
Partridge 06	396	1301	905	228.5%	1301	905	228.5%
Manhattan 06	1008	0	-1008	-100.0%	0	-1008	-100.0%
RMSE			1258			1507	
Avg				48.0%			50.8%
Total Biomass (kg ha^{-1})							
Cullison 05	11 021	9742	-1279	-11.6%	9742	-1279	-11.6%
Cullison 06	10 551	11 885	1334	12.6%	11 885	1334	12.6%
Moscow 05	13 652	14 798	1146	8.4%	15 036	1384	10.1%
Moscow 06	7579	11 143	3564	47.0%	11 143	3564	47.0%
Partridge 06	6461	7629	1168	18.1%	7629	1168	18.1%
Manhattan 06	9929	4790	-5139	-51.8%	4790	-5139	-51.8%
RMSE			2745			2763	
Avg				3.8%			4.1%

Table 3.6 RMSEs, individual location errors, and percent errors for corn simulations 4, 5, and 6 for biomass and LAI near silking for the six location-years in Kansas.

Location	S4	Error	% Error	S5	Error	% Error	S6	Error	% Error
LAI									
Cullison 05	5.09	-0.71	-12.2%	4.50	-1.30	-22.4%	4.50	-1.30	-22.4%
Cullison 06	5.21	1.38	36.0%	4.71	0.88	23.0%	4.71	0.88	23.0%
Moscow 05	4.45	-0.66	-12.9%	4.26	-0.85	-16.6%	4.16	-0.95	-18.6%
Moscow 06	5.53	0.85	18.2%	4.97	0.29	6.2%	4.97	0.29	6.2%
Partridge 06	3.67	0.51	16.1%	2.97	-0.19	-6.0%	2.97	-0.19	-6.0%
Manhattan 06	3.34	-0.46	-12.1%	2.89	-0.91	-23.9%	2.89	-0.91	-23.9%
RMSE		0.82			0.83			0.85	
Avg			5.5%			-6.6%			-7.0%
Leaf Biomass (kg ha^{-1})									
Cullison 05	4887	1443	41.9%	3804	360	10.5%	3804	360	10.5%
Cullison 06	5546	3015	119.1%	4150	1619	64.0%	4150	1619	64.0%
Moscow 05	4148	624	17.7%	3642	118	3.3%	3642	118	3.3%
Moscow 06	6312	3622	134.6%	4804	2114	78.6%	4804	2114	78.6%
Partridge 06	3621	1603	79.4%	2905	887	44.0%	2905	887	44.0%
Manhattan 06	3969	1672	72.8%	3198	901	39.2%	3198	901	39.2%
RMSE		2238			1213			1213	
Avg			77.6%			39.9%			39.9%
Stem Biomass (kg ha^{-1})									
Cullison 05	4137	-2220	-34.9%	4272	-2085	-32.8%	4272	-2085	-32.8%
Cullison 06	4922	-414	-7.8%	4871	-465	-8.7%	4871	-465	-8.7%
Moscow 05	4157	-1727	-29.4%	3641	-2243	-38.1%	3639	-2245	-38.2%
Moscow 06	5463	1331	32.2%	5167	1035	25.0%	5167	1035	25.0%
Partridge 06	3411	-636	-15.7%	2742	-1305	-32.2%	2742	-1305	-32.2%
Manhattan 06	2898	-3727	-56.3%	2258	-4367	-65.9%	2258	-4367	-65.9%
RMSE		2006			2289			2289	
Avg			-18.6%			-25.5%			-25.5%
Reproductive Biomass (kg ha^{-1})									
Cullison 05	1290	71	5.8%	2217	998	81.9%	2217	998	81.9%
Cullison 06	2431	-254	-9.5%	3582	897	33.4%	3582	897	33.4%
Moscow 05	7959	3715	87.5%	9643	5399	127.2%	9643	5399	127.2%
Moscow 06	1838	1081	142.8%	3013	2256	298.0%	3013	2256	298.0%
Partridge 06	1449	1053	265.9%	3099	2703	682.6%	3099	2703	682.6%
Manhattan 06	0	-1008	-100.0%	1274	266	26.4%	1274	266	26.4%
RMSE		1691			2690			2690	
Avg			65.4%			208.2%			208.2%
Total Biomass (kg ha^{-1})									
Cullison 05	10 314	-707	-6.4%	10 293	-728	-6.6%	10 293	-728	-6.6%
Cullison 06	12 899	2348	22.3%	12 603	2052	19.4%	12 603	2052	19.4%
Moscow 05	16 264	2612	19.1%	16 925	3273	24.0%	16 924	3272	24.0%
Moscow 06	13 614	6035	79.6%	12 985	5406	71.3%	12 985	5406	71.3%
Partridge 06	8481	2020	31.3%	8746	2285	35.4%	8746	2285	35.4%
Manhattan 06	6867	-3062	-30.8%	6729	-3200	-32.2%	6729	-3200	-32.2%
RMSE		3233			3166			3166	
Avg			19.2%			18.5%			18.5%

Table 3.7. RMSEs, individual location errors, and percent errors for corn simulations 2 and 3 for biomass at harvest for the six location-years in Kansas.

Location	M	S2	Error	% Error	S3	Error	% Error
Leaf Biomass (kg ha^{-1})							
Cullison 05	4569	4049	-520	-11.4%	4049	-520	-11.4%
Cullison 06	1929	4824	2895	150.1%	4824	2895	150.1%
Moscow 05	3192	3643	451	14.1%	3643	451	14.1%
Moscow 06	2509	4425	1916	76.4%	4425	1916	76.4%
Partridge 06	1395	3255	1860	133.3%	3255	1860	133.3%
Manhattan 06	2723	2531	-192	-7.1%	2531	-192	-7.1%
RMSE			1634			1634	
Avg				59.2%			59.2%
Stem Biomass (kg ha^{-1})							
Cullison 05	5493	4166	-1327	-24.2%	3184	-2309	-42.0%
Cullison 06	3829	3376	-453	-11.8%	3376	-453	-11.8%
Moscow 05	4551	2919	-1632	-35.9%	2919	-1632	-35.9%
Moscow 06	3543	3690	147	4.1%	3690	147	4.1%
Partridge 06	4005	2714	-1291	-32.2%	2396	-1609	-40.2%
Manhattan 06	4376	1390	-2986	-68.2%	1390	-2986	-68.2%
RMSE			1593			1813	
Avg				-28.0%			-32.3%
Reproductive Biomass (kg ha^{-1})							
Cullison 05	16 618	13 742	-2876	-17.3%	15 275	-1343	-8.1%
Cullison 06	14 467	12 839	-1628	-11.3%	12 893	-1574	-10.9%
Moscow 05	15 960	15 775	-185	-1.2%	15 890	-70	-0.4%
Moscow 06	10 165	14 725	4560	44.9%	14 620	4455	43.8%
Partridge 06	1151	4322	3171	275.5%	4787	3636	315.9%
Manhattan 06	7928	3994	-3934	-49.6%	3957	-3971	-50.1%
RMSE			3090			2976	
Avg				40.2%			48.4%
Total Biomass (kg ha^{-1})							
Cullison 05	26 680	21 956	-4724	-17.7%	22 507	-4173	-15.6%
Cullison 06	20 226	21 039	813	4.0%	21 093	867	4.3%
Moscow 05	23 703	22 337	-1366	-5.8%	22 452	-1251	-5.3%
Moscow 06	16 217	22 841	6624	40.8%	22 735	6518	40.2%
Partridge 06	7412	10 291	2879	38.8%	10 437	3025	40.8%
Manhattan 06	15 027	7915	-7112	-47.3%	7878	-7149	-47.6%
RMSE			4611			4518	
Avg				2.2%			2.8%

Table 3.8. RMSEs, individual location errors, and percent errors for corn simulations 4, 5, and 6 for biomass at harvest for the six location-years in Kansas.

Location	S4	Error	% Error	S5	Error	% Error	S6	Error	% Error
Leaf Biomass (kg ha^{-1})									
Cullison 05	4325	-244	-5.3%	3537	-1032	-22.6%	3537	-1032	-22.6%
Cullison 06	5273	3344	173.4%	4150	2221	115.1%	4150	2221	115.1%
Moscow 05	4148	956	29.9%	3642	450	14.1%	3642	450	14.1%
Moscow 06	5755	3246	129.4%	4623	2114	84.3%	4623	2114	84.3%
Partridge 06	3552	2157	154.6%	2905	1510	108.2%	2905	1510	108.2%
Manhattan 06	3534	811	29.8%	2868	145	5.3%	2868	145	5.3%
RMSE		2160			1470			1470	
Avg			85.3%			50.7%			50.7%
Stem Biomass (kg ha^{-1})									
Cullison 05	3346	-2147	-39.1%	3128	-2365	-43.1%	3128	-2365	-43.1%
Cullison 06	3650	-179	-4.7%	3336	-493	-12.9%	3336	-493	-12.9%
Moscow 05	3235	-1316	-28.9%	2810	-1741	-38.3%	2810	-1741	-38.3%
Moscow 06	4369	826	23.3%	3661	118	3.3%	4444	901	25.4%
Partridge 06	2774	-1231	-30.7%	2255	-1750	-43.7%	2255	-1750	-43.7%
Manhattan 06	2165	-2211	-50.5%	1616	-2760	-63.1%	1616	-2760	-63.1%
RMSE		1498			1806			1842	
Avg			-21.8%			-32.9%			-29.3%
Reproductive Biomass (kg ha^{-1})									
Cullison 05	15 720	-898	-5.4%	18 563	1945	11.7%	17 087	469	2.8%
Cullison 06	14 331	-136	-0.9%	17 060	2593	17.9%	15 467	1000	6.9%
Moscow 05	17 788	1828	11.5%	21 675	5715	35.8%	19 785	3825	24.0%
Moscow 06	17 819	7654	75.3%	20 794	10 629	104.6%	18 057	7892	77.6%
Partridge 06	5446	4295	373.2%	6894	5743	499.0%	6532	5381	467.5%
Manhattan 06	7095	-833	-10.5%	9307	1379	17.4%	8089	161	2.0%
RMSE		3694			5643			4225	
Avg			73.8%			114.4%			96.8%
Total Biomass (kg ha^{-1})									
Cullison 05	23 391	-3289	-12.3%	25 228	-1452	-5.4%	23 752	-2928	-11.0%
Cullison 06	23 253	3027	15.0%	24 547	4321	21.4%	22 954	2728	13.5%
Moscow 05	25 172	1469	6.2%	28 127	4424	18.7%	26 237	2534	10.7%
Moscow 06	27 942	11 725	72.3%	29 078	12 861	79.3%	27 124	10 907	67.3%
Partridge 06	11 772	4360	58.8%	12 054	4642	62.6%	11 692	4280	57.7%
Manhattan 06	12 794	-2233	-14.9%	13 791	-1236	-8.2%	12 573	-2454	-16.3%
RMSE		5532			6176			5256	
Avg			20.9%			28.0%			20.3%

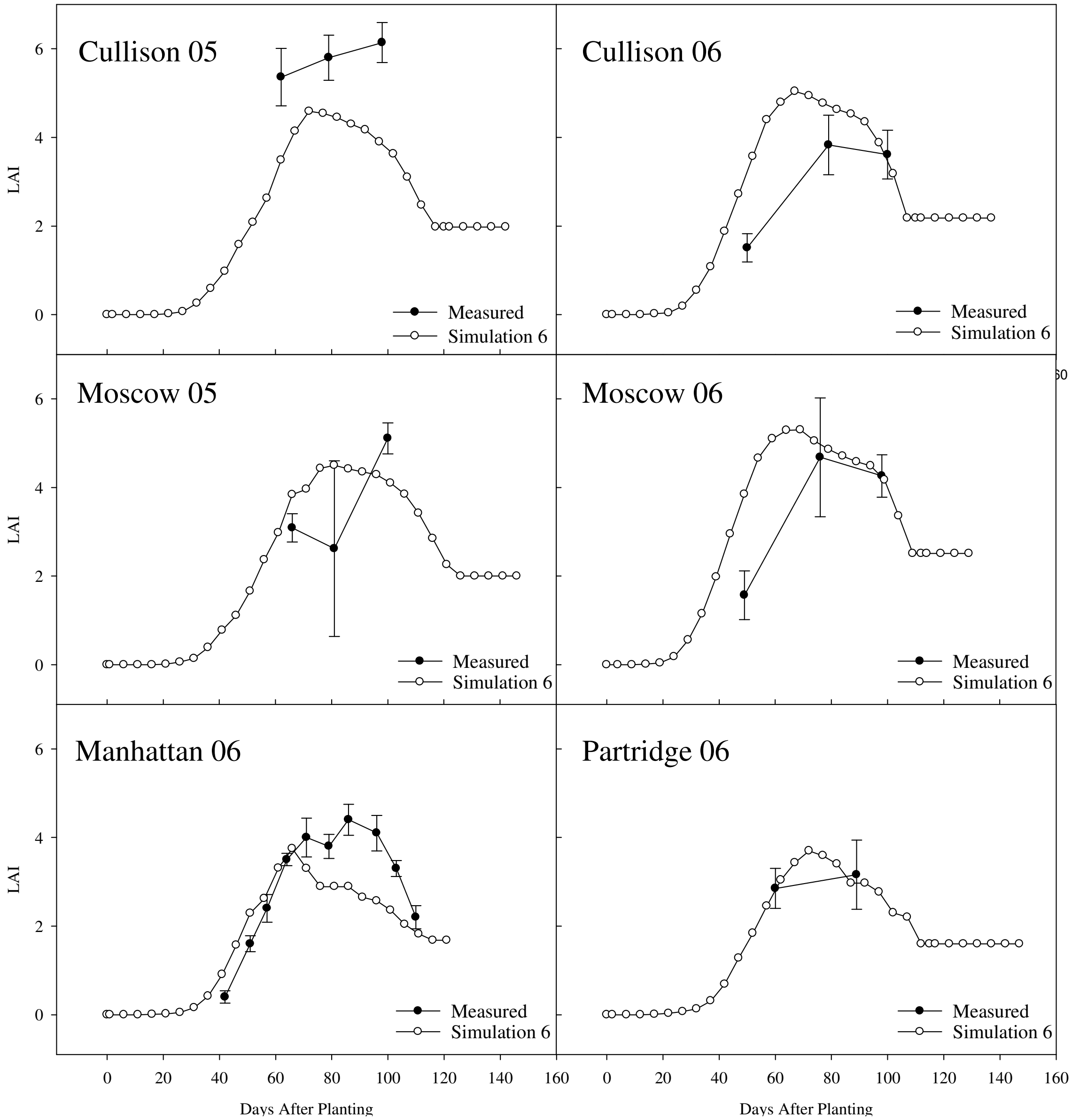


Figure 3.10 Measured and simulated corn LAI for the six location-years in Kansas.

Rule data

CERES-Maize calibration simulations were also conducted on dryland and irrigated corn data collected by Dwain Rule in 2005 and 2006 at the Ashland Bottoms Research Station near Manhattan (Rule, 2007). Simulation one (S1) is considered our initial simulation for comparison purposes. For simulation two (S2) P1 was changed from

255 to 225. Nitrogen and symbiosis were changed from yes to no and yes to unlimited, respectively, for simulation three (S3). In simulation four (S4) changes were made to: P1 to 220, P2 from 0.760 to 0.520, P5 from 685 to 880, and G2 from 917.4 to 1100.

Initial yield simulation (S1) by the model predicted yield with an RMSE of 5722 kg ha^{-1}. During the four simulations the model consistently under predicted yield in both years and in both environments, except for the 2005 dryland in S4. All three of the changes made during calibration resulted in a decrease in the RMSE for yield (Figure 3.11). However, changes in S4 had the biggest impact and reduced the RMSE for yield to 2833 kg ha^{-1}. The RMSEs, individual year and environment errors, and percent errors for the calibration simulation are listed in Table 3.6

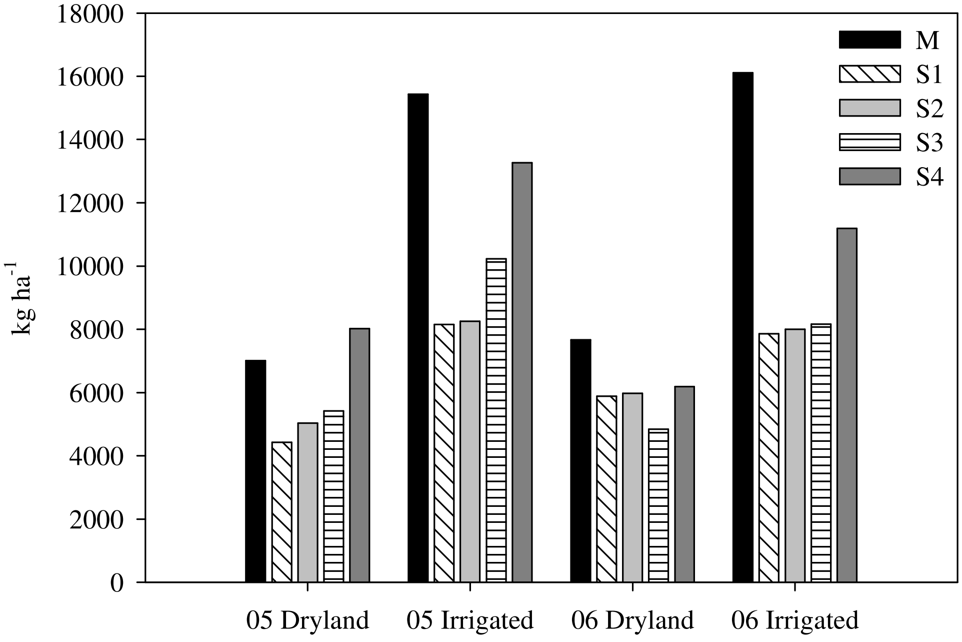


Figure 3.11 Rule measured and simulated corn yield at Ashland, KS.

Through calibration, RMSEs for total biomass at the VT stage and at harvest where reduced (Tables 3.9, 3.10, 3.11 and 3.12). Calibration also reduced the RMSEs for leaf, stem, and reproductive biomass, except for stem biomass at harvest. The model simulated total biomass well throughout the growing season, but tended to under predict stem biomass while over predicting leaf biomass (Figures 3.13, 3.14, 3.15, and 3.16).

The model initially simulated LAI and leaf number at VT with RMSEs of 1.21 and 4.3 leaves plant^{-1}, respectively. Through model calibration, RMSEs for LAI and leaf number at VT were reduced to 1.15 and 3.6 leaves plant^{-1}, respectively (Tables 3.10 and 3.11). Leaf number was consistently over predicted by the model throughout vegetative development. Simulated leaf number at VT had an average error of approximately 20% through all the calibration simulations. Simulated LAI peaked close to that observed in the field however; simulated peak LAI was lower than that measured (Figure 3.17).

Table 3.9 Yield and biomass at harvest RMSEs, individual location errors, and percent errors for corn simulations 1 and 2 for Rule study at Ashland, KS.

Location	M	S1	Error	% Error	S2	Error	% Error
Yield (kg ha^{-1})							
05 Dryland	7005	4431	-2574	-36.7%	5032	-1973	-28.2%
05 Irrigated	15 435	8152	-7283	-47.2%	8254	-7181	-46.5%
06 Dryland	7665	5880	-1785	-23.3%	5974	-1691	-22.1%
06 Irrigated	16 108	7855	-8253	-51.2%	8003	-8105	-50.3%
RMSE			5722			5568	
Avg				-39.6%			-36.8%
Leaf Biomass (kg ha^{-1})							
05 Dryland	2525	3963	1438	57.0%	3439	914	36.2%
05 Irrigated	3642	3977	335	9.2%	3446	-196	-5.4%
06 Dryland	2816	3631	815	29.0%	2949	133	4.7%
06 Irrigated	4057	5341	1284	31.6%	4650	593	14.6%
RMSE			1060			557	
Avg				31.7%			12.5%
Stem Biomass (kg ha^{-1})							
05 Dryland	3071	2636	-435	-14.2%	2485	-586	-19.1%
05 Irrigated	4693	2663	-2030	-43.3%	2498	-2195	-46.8%
06 Dryland	3161	2553	-608	-19.2%	2272	-889	-28.1%
06 Irrigated	5742	3363	-2379	-41.4%	3172	-2570	-44.8%
RMSE			1608			1772	
Avg				-29.5%			-34.7%
Reproductive Biomass (kg ha^{-1})							
05 Dryland	11 644	6672	-4972	-42.7%	7448	-4196	-36.0%
05 Irrigated	18 743	10 647	-8096	-43.2%	10 821	-7922	-42.3%
06 Dryland	8307	7968	-339	-4.1%	8113	-194	-2.3%
06 Irrigated	19 733	10 568	-9165	-46.4%	10 923	-8810	-44.6%
RMSE			6602			6285	
Avg				-34.1%			-31.3%
Total Biomass (kg ha^{-1})							
05 Dryland	17 240	13 271	-3969	-23.0%	13 372	-3868	-22.4%
05 Irrigated	27 077	17 287	-9790	-36.2%	16 765	-10 312	-38.1%
06 Dryland	14 284	14 152	-132	-0.9%	13 334	-950	-6.7%
06 Irrigated	29 532	19 272	-10 260	-34.7%	18 745	-10 787	-36.5%
RMSE			7363			7723	
Avg				-23.7%			-25.9%

Table 3.10 Yield and biomass at harvest RMSEs, individual location errors, and percent errors for corn simulations 3 and 4 for Rule study at Ashland, KS.

Location	S3	Error	% Error	S4	Error	% Error
Yield (kg ha^{-1})						
05 Dryland	5425	-1580	-22.6%	8018	1013	14.5%
05 Irrigated	10 225	-5210	-33.8%	13 266	-2169	-14.1%
06 Dryland	4839	-2826	-36.9%	6184	-1481	-19.3%
06 Irrigated	8159	-7949	-49.3%	11 192	-4916	-30.5%
RMSE		5020			2833	
Avg			-35.6%			-12.4%
Leaf Biomass (kg ha^{-1})						
05 Dryland	3836	1311	51.9%	3159	634	25.1%
05 Irrigated	3836	194	5.3%	3159	-483	-13.3%
06 Dryland	3168	352	12.5%	2999	183	6.5%
06 Irrigated	4872	815	20.1%	4597	540	13.3%
RMSE		798			490	
Avg			22.5%			7.9%
Stem Biomass (kg ha^{-1})						
05 Dryland	2998	-73	-2.4%	2414	-657	-21.4%
05 Irrigated	3002	-1691	-36.0%	2414	-2279	-48.6%
06 Dryland	2423	-738	-23.3%	2161	-1000	-31.6%
06 Irrigated	3311	-2431	-42.3%	3179	-2563	-44.6%
RMSE		1526			1816	
Avg			-26.0%			-36.6%
Reproductive Biomass (kg ha^{-1})						
05 Dryland	7287	-4357	-37.4%	10 414	-1230	-10.6%
05 Irrigated	13 264	-5479	-29.2%	16 279	-2464	-13.1%
06 Dryland	7043	-1264	-15.2%	8410	103	1.2%
06 Irrigated	11 165	-8568	-43.4%	14 086	-5647	-28.6%
RMSE		5568			3142	
Avg			-31.3%			-12.8%
Total Biomass (kg ha^{-1})						
05 Dryland	14 121	-3119	-18.1%	15 986	-1254	-7.3%
05 Irrigated	20 102	-6975	-25.8%	21 852	-5225	-19.3%
06 Dryland	12 635	-1649	-11.5%	13 569	-715	-5.0%
06 Irrigated	19 347	-10 185	-34.5%	21 862	-7670	-26.0%
RMSE		6419			4696	
Avg			-22.5%			-14.4%

Table 3.11 RMSEs, individual location errors, and percent errors for LAI, leaf number, and biomass at VT for corn simulations 1 and 2 for Rule study at Ashland, KS.

Location	M	S1	Error	% Error	S2	Error	% Error
LAI							
05 Dryland	5.57	4.00	-1.57	-28.2%	3.77	-1.80	-32.3%
05 Irrigated	5.46	4.01	-1.45	-26.6%	3.78	-1.68	-30.8%
06 Dryland	4.27	3.24	-1.03	-24.1%	2.89	-1.38	-32.3%
06 Irrigated	5.86	5.42	-0.44	-7.5%	5.15	-0.71	-12.1%
RMSE			1.21			1.46	
Avg				-21.6%			-26.9%
Leaf Number (leaves plant^{-1})							
05 Dryland	19.3	23.0	3.7	19.2%	22.0	2.7	14.0%
05 Irrigated	18.9	23.0	4.1	21.7%	22.0	3.1	16.4%
06 Dryland	16.0	22.0	6.0	37.5%	22.0	6.0	37.5%
06 Irrigated	19.0	22.0	3.0	15.8%	22.0	3.0	15.8%
RMSE			4.3			3.9	
Avg				23.5%			20.9%
Leaf Biomass (kg ha^{-1})							
05 Dryland	2614	3989	1375	52.6%	3685	1071	41.0%
05 Irrigated	2681	3992	1311	48.9%	3687	1006	37.5%
06 Dryland	2248	3306	1058	47.1%	2954	706	31.4%
06 Irrigated	3044	5087	2043	67.1%	4762	1718	56.4%
RMSE			1492			1184	
Avg				53.9%			41.6%
Stem Biomass (kg ha^{-1})							
05 Dryland	3414	2257	-1157	-33.9%	2767	-647	-19.0%
05 Irrigated	3527	2263	-1264	-35.8%	2773	-754	-21.4%
06 Dryland	2352	1446	-906	-38.5%	1867	-485	-20.6%
06 Irrigated	5299	2487	-2812	-53.1%	3011	-2288	-43.2%
RMSE			1708			1270	
Avg				-40.3%			-26.0%
Total Biomass (kg ha^{-1})							
05 Dryland	6963	6246	-717	-10.3%	6452	-511	-7.3%
05 Irrigated	7023	6255	-768	-10.9%	6460	-563	-8.0%
06 Dryland	4856	4752	-104	-2.1%	4821	-35	-0.7%
06 Irrigated	9666	7574	-2092	-21.6%	7773	-1893	-19.6%
RMSE			1172			1020	
Avg				-11.3%			-8.9%

Table 3.12 RMSEs, individual location errors, and percent errors for LAI, leaf number, and biomass at VT for corn simulations 3 and 4 for Rule study at Ashland, KS.

Location	S3	Error	% Error	S4	Error	% Error
LAI						
05 Dryland	4.63	-0.94	-16.9%	4.19	-1.38	-24.8%
05 Irrigated	4.63	-0.83	-15.2%	4.19	-1.27	-23.3%
06 Dryland	3.17	-1.10	-25.8%	3.08	-1.19	-27.9%
06 Irrigated	5.39	-0.47	-8.0%	5.24	-0.62	-10.6%
RMSE		0.87			1.15	
Avg			-16.5%			-21.6%
Leaf Number (leaves plant^{-1})						
05 Dryland	22.0	2.7	14.0%	21.0	1.7	8.8%
05 Irrigated	22.0	3.1	16.4%	21.0	2.1	11.1%
06 Dryland	22.0	6.0	37.5%	22.0	6.0	37.5%
06 Irrigated	22.0	3.0	15.8%	22.0	3.0	15.8%
RMSE		3.9			3.6	
Avg			20.9%			18.3%
Leaf Biomass (kg ha^{-1})						
05 Dryland	4025	1411	54.0%	3629	1015	38.8%
05 Irrigated	4025	1344	50.2%	3629	948	35.4%
06 Dryland	3171	923	41.0%	3093	845	37.6%
06 Irrigated	4983	1939	63.7%	4789	1745	57.3%
RMSE		1450			1192	
Avg			52.2%			42.3%
Stem Biomass (kg ha^{-1})						
05 Dryland	3221	-193	-5.7%	2937	-477	-14.0%
05 Irrigated	3221	-306	-8.7%	2937	-590	-16.7%
06 Dryland	2010	-342	-14.6%	2128	-224	-9.5%
06 Irrigated	3157	-2142	-40.4%	3478	-1821	-34.4%
RMSE		1099			993	
Avg			-17.3%			-18.7%
Total Biomass (kg ha^{-1})						
05 Dryland	7245	282	4.0%	7380	417	6.0%
05 Irrigated	7245	222	3.2%	7380	357	5.1%
06 Dryland	5182	326	6.7%	5221	365	7.5%
06 Irrigated	8141	-1525	-15.8%	8267	-1399	-14.5%
RMSE		800			773	
Avg			-0.5%			1.0%

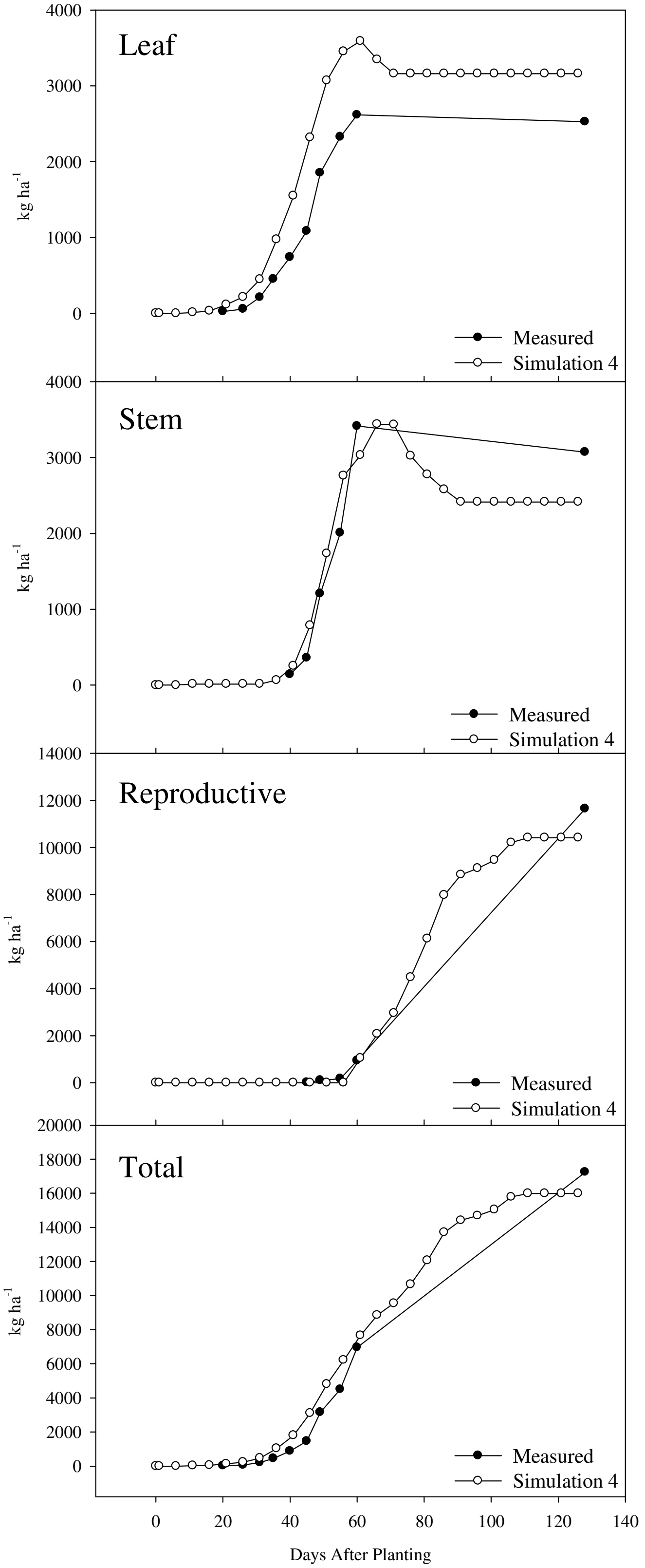


Figure 3.12 Measured and simulated dryland corn leaf, stem, reproductive, and total biomass at Ashland, KS in 2005.

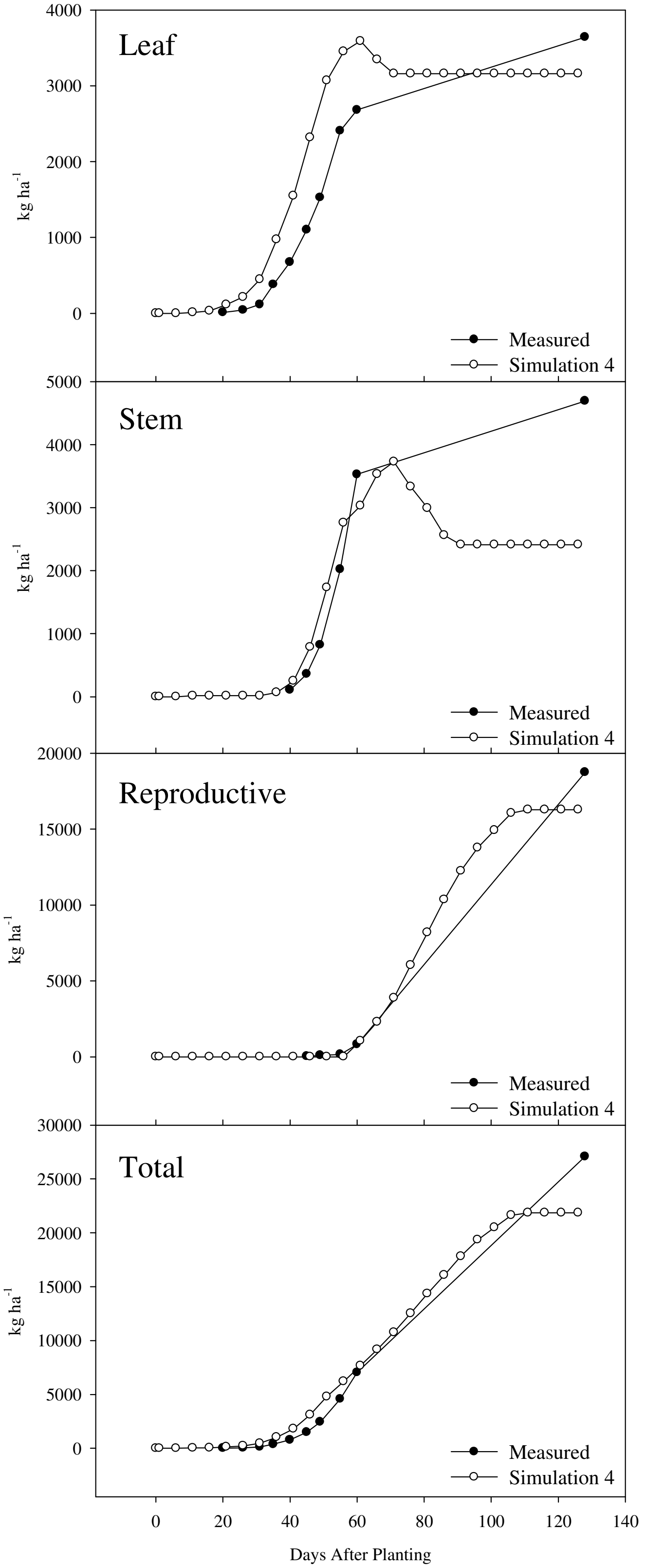


Figure 3.13 Measured and simulated irrigated corn leaf, stem, reproductive, and total biomass at Ashland, KS in 2005.

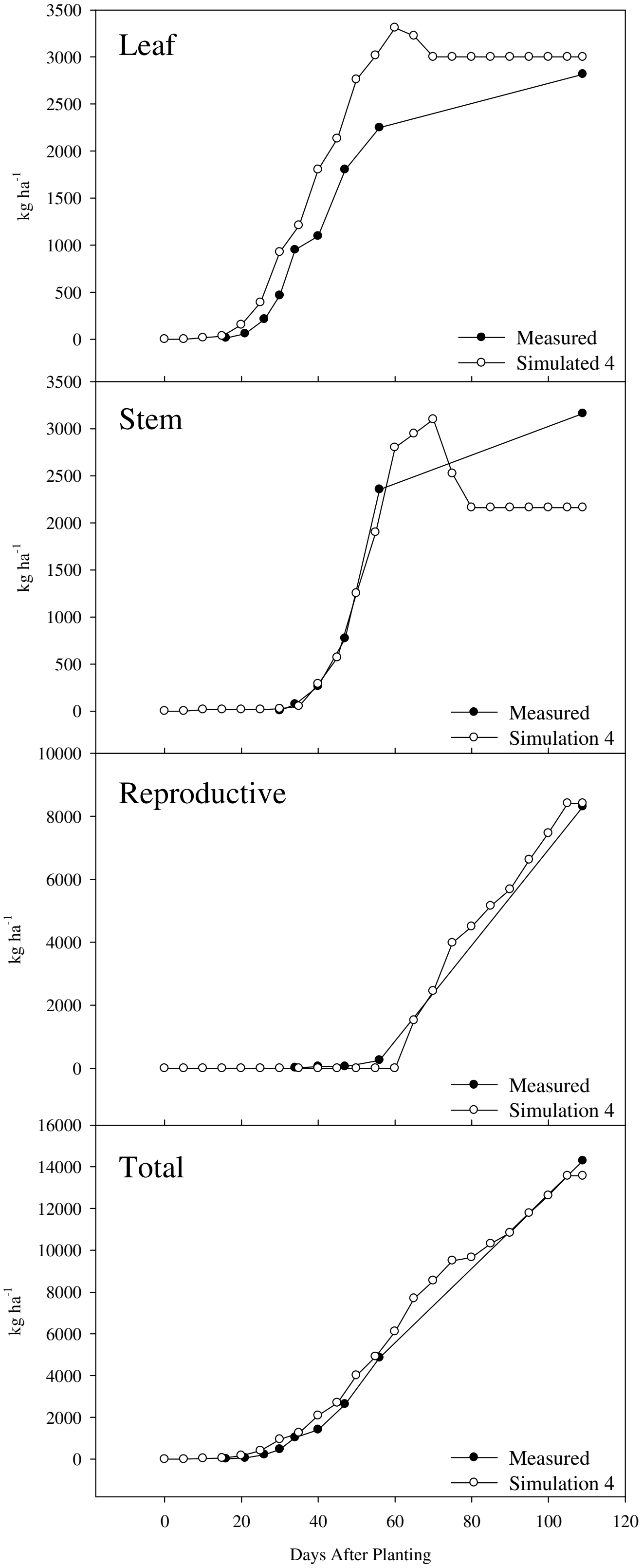


Figure 3.14 Measured and simulated dryland corn leaf, stem, reproductive, and total biomass at Ashland, KS in 2006.

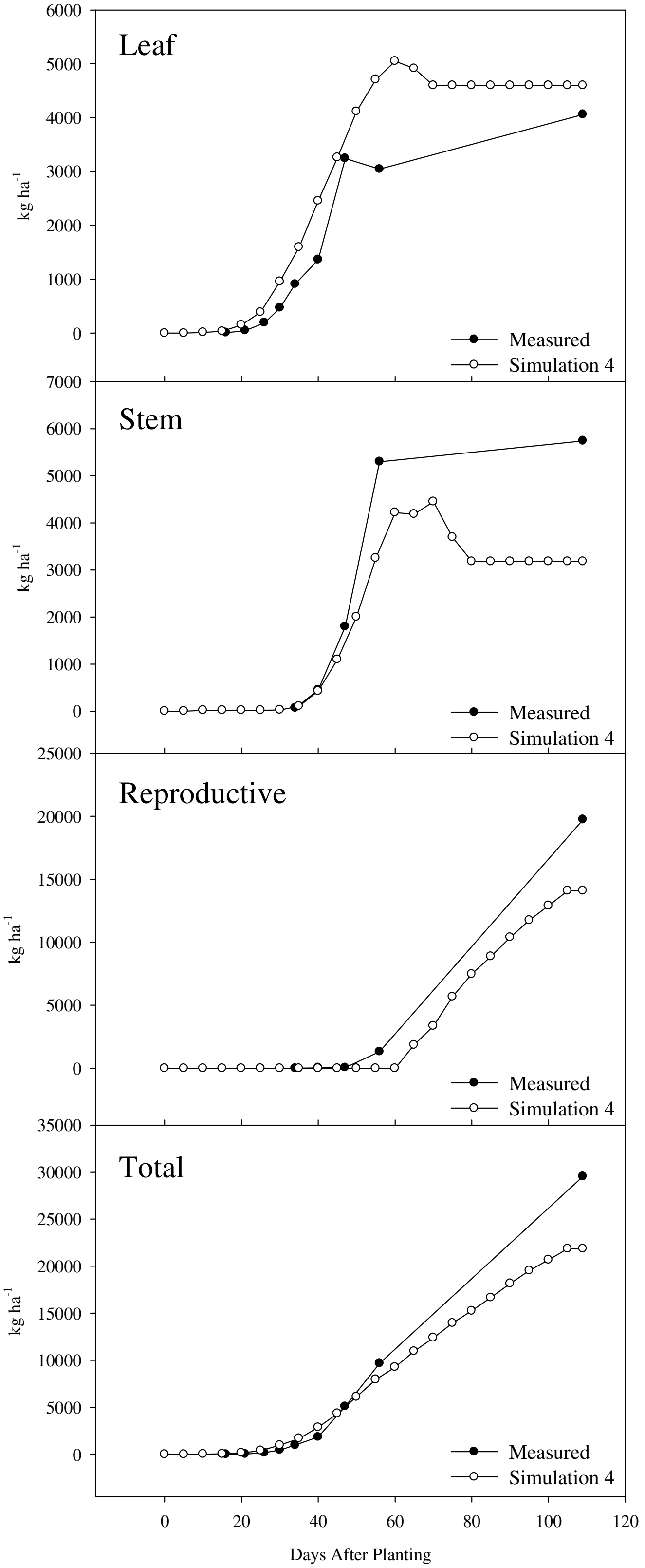


Figure 3.15 Measured and simulated irrigated corn leaf, stem, reproductive, and total biomass at Ashland, KS in 2006.

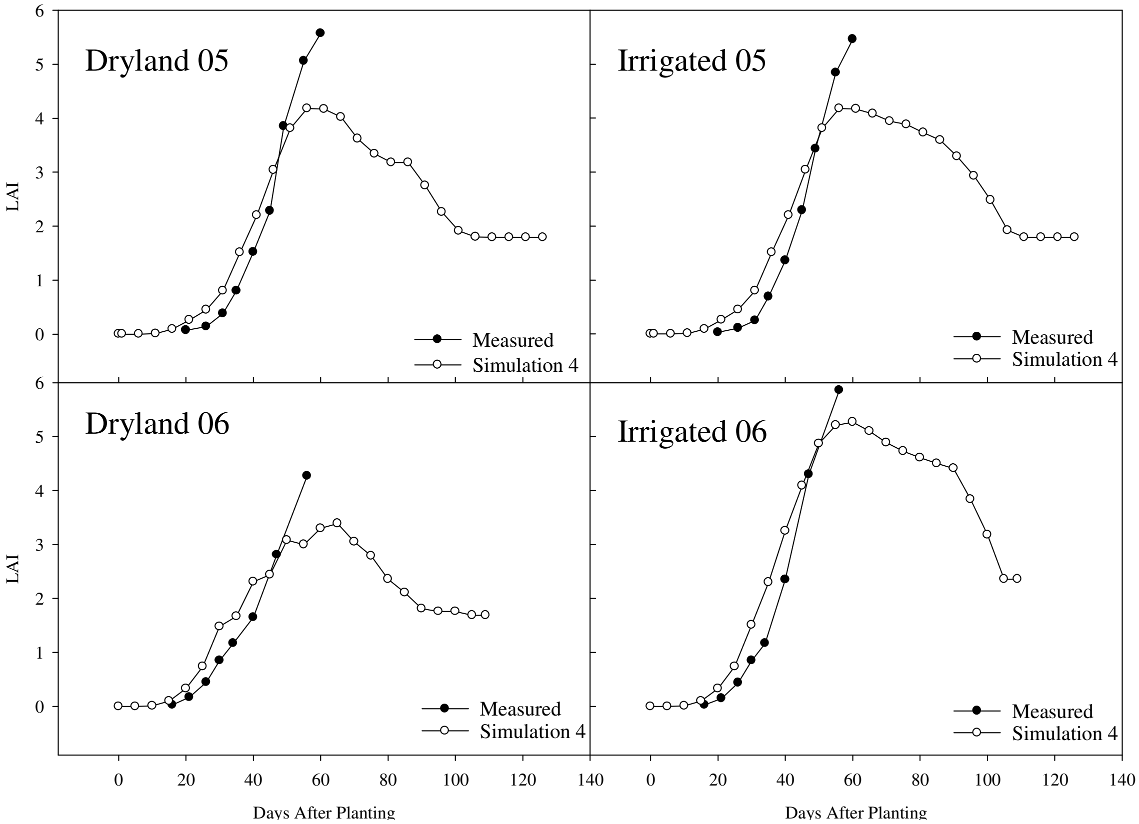


Figure 3.16 Measured and simulated dryland and irrigated corn LAI for the four location-years at Ashland,KS.

Discussion

CERES-Maize had problems simulating yield components. The model consistently had problems simulating kernel number. Also, ear number simulations seemed to be directly tied to plant population and only allowing one ear per plant. Its ability to compensate for multiple ears per plant or barren plants appears to be deficient. Biomass partioning to the individual plant parts and LAI simulation, specifically peak LAI, was also fairly variable.

In comparison to other published work with CERES-Maize model, our results were less accurate. Kiniry et al. (1997) simulated mean yields with RMSEs less than 2.x Mg ha^{-1} across all locations and less than 1 Mg ha^{-1} at the majority of the locations. We were only able to simulate yield across the location-years with an RMSE of almost 3.x Mg ha^{-1}. Hodges et al. (1987) simulated corn production for a region within 10 percent of the actual; whereas our average percent error for the location- years was 35%.

CERES-Sorghum

Calibrations

During the simulations several changes were made to the cultivar coefficients and to the ecotype file. Simulation two (S2) was considered the initial simulation for comparison purposes. In simulation three (S3) the coefficient P1 (Thermal time from seedling emergence to the end of the juvenile phase [expressed in degree days above a base temperature of 8°C]) was changed from 411 to 375. Sorghum populations at emergence were changed from those measured at emergence to the number of heads m^{-2} measured at harvest in simulation four (S4). Also in S4, P1 was changed back to 411. A sensitivity analysis was conducted in simulations five (S5), six (S6), and seven (S7) on the G1 (scaler for relative leaf size) and G2 (scaler for partitioning of assimilates to the panicle) coefficients. In S5, several cultivars were created with G1 set to 5, 10, 15, 20, or 25. In S6, several more cultivars were created with G1 was set to 20 and G2 set to 2, 4, 6, 8, 10, 12, 14, or 16. In S7, G1 was set to 0 with G2 set to 2, 4, 6, 8, 10, 12, 14, or 16. It was determined that G1 be set to 20 and G2 to 8 based on this sensitivity analysis. The original values were G1 = 0 and G2 = 6. In S6, G1 is set to 20 and G2 is set to 8. For simulation eight (S8) P1 was changed from 411 to 435. A new ecotype file was created in simulation nine (S9) which changed RUE (radiation use efficiency [g plant dry matter/MJ

PAR]) from 3.2 to 3.5. Finally in simulation ten (S10), the nitrogen and symbiosis options in the model were turned from yes to no and from no to unlimited, respectively.

Yield and yield component simulation

The initial simulations by the model predicted yield at the three locations with an RMSE of 3599 kg ha^{-1}. Through calibration, the RMSE was decreased to 2150 kg ha^{-1}. Yield was consistently under predicted at all locations through all the simulations, except in Manhattan for S9 and S10 (Figure 3.17). At Preston and Partridge, the best simulated yields, which occurred in S10, still had percent errors of -43.2 and -39.5%. The RMSE for kernel number decreased through the calibration process from 11 157 kernels m^{-2}, in S2, to 5755 kernels m^{-2}, in S10. However, kernel number was under predicted at all locations for all simulations, except at Manhattan in S10 (Figure 3.18). The initial RMSE

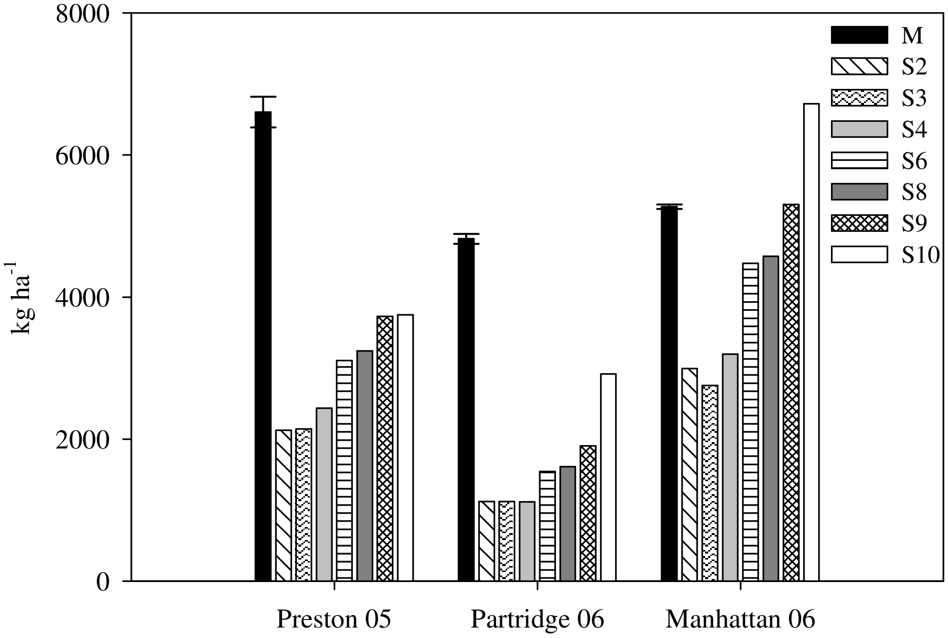


Figure 3.17 Measured and simulated grain sorghum yield at three location-years in Kansas.

for seed weight decreased through calibration from 7.56 mg kernel^{-1} to 4.51 mg kernel^{-1}, in S10. However, seed weight prediction was variable across all locations. It was consistently over predicted at Manhattan during all the simulations and drastically under predicted at Partridge in all simulations but S9 and S10 (Figure 3.19). Head number was not affected by any of the changes made during the calibration process except S4, when population at emergence was set equal to head number measured at harvest, which resulted in equal simulated and measured head numbers at all three locations.

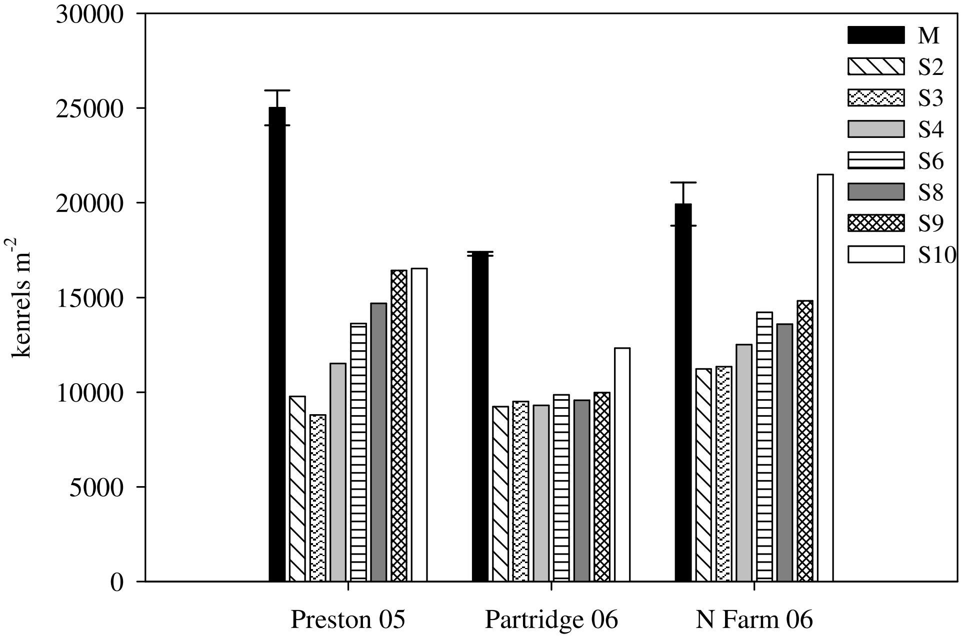


Figure 3.18 Measured and simulated grain sorghum kernel number at three location-years in Kansas.

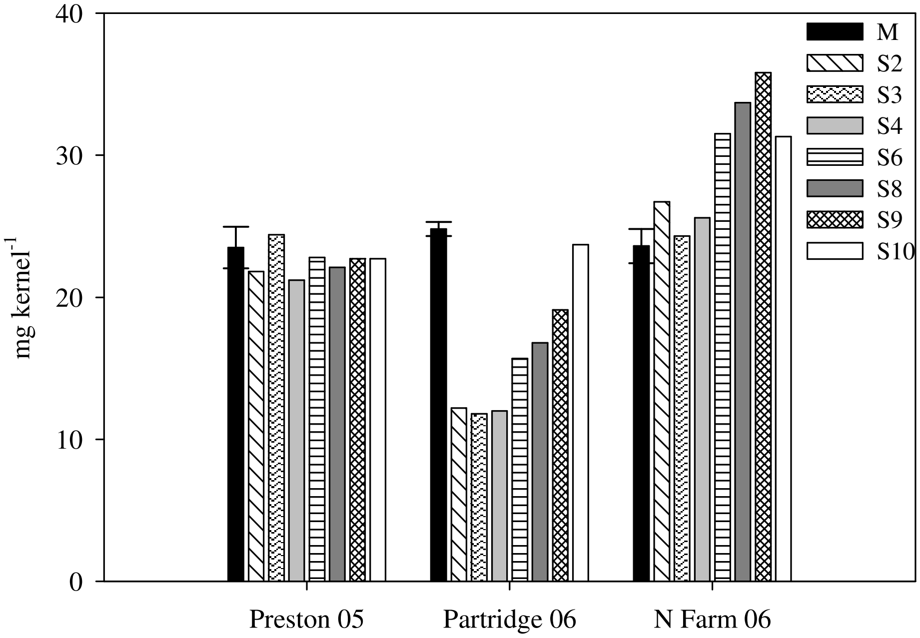


Figure 3.19 Measured and simulated grain sorghum seed weight at three location-years in Kansas.

Changes made in S3 resulted in a slight decrease in the RMSE for seed weight and increased the RMSEs for yield and kernel number. Simulation 4 caused the RMSEs for yield and kernel number to decrease and the RMSE for seed weight to increase. Simulation 6 (result of the sensitivity analysis) drastically decreased the RMSEs for yield, kernel number, and seed weight. Changes in S8 and S9 reduced yield and kernel number RMSEs but increased the RMSE for seed weight. Changes made in S10 caused the RMSE for yield, kernel number, and seed weight all to decrease and were the lowest of all the calibrations. The RMSEs, individual location errors, and overall errors are listed in Tables 3.13 and 3.14.

During the sensitivity analysis simulations, S5 through S7, a range of numbers for the G1 and G2 coefficients were tested, as mentioned above. As the G1 coefficient increased, simulated yield and kernel number increased. Seed weight increased at all three locations, except for Preston. Also as the G2 coefficient was increased, simulated yield and seed weight drastically increased, and were still continuing to increase at G2 equal to 16. Changes in G2 had no effect on kernel number. However, as G2 increased, simulated stem weight decreased to unrealistic values.

Biomass and leaf area simulation

Model calibration decreased the RMSE for mid-season total biomass and total biomass at harvest. Initial RMSEs for mid-season total biomass and at harvest were 3844 kg ha^{-1} and 6322 kg ha^{-1}, respectively. Root mean square errors for S10 for total biomass were 1786 kg ha^{-1} and 3443 kg ha^{-1}. Total biomass simulation was variable across locations. Total biomass during the growing season was modeled well at Manhattan but under predicted at Preston and Partridge. Biomass partioning by the model was problematic, with stem and reproductive biomass consistently under predicted and leaf biomass consistently over predicted across the locations (Figures 3.20, 3.21, and 3.22). In S10 simulated mid-season stem biomass and stem biomass at harvest had average errors of -40.5 and -49.1%, respectively, while simulated mid-season leaf and leaf biomass at harvest had average errors of 55.5 and 63.0%, respectively. The RMSEs, individual location errors, and percent errors for the calibration simulation are listed in Tables 3.15, 3.16, 3.17, and 3.18.

Model calibration decreased the RMSE for mid-season LAI from 1.81 in S2 to 0.82 in S10. Initial simulation of mid-season LAI had an average error across the three location-years of -52.8%. In S10, LAI simulation was had an average error of 8.9%, with errors at Preston and Partridge of -7.4 and -7.0%, respectively (Table 3.15 and 3.16).

Table 3.13 Yield and yield component RMSEs, individual location errors, and percent errors for grain sorghum simulations 2, 3, and 4 for the three location-years in Kansas.

Location	M	S2	Error	% Error	S3	Error	% Error	S4	Error	% Error
Yield (kg ha^{-1})										
Preston 05	6602	2127	-4475	-67.8%	2144	-4458	-67.5%	2435	-4167	-63.1%
Partridge 06	4819	1122	-3697	-76.7%	1122	-3697	-76.7%	1120	-3699	-76.8%
Manhattan 06	5271	2996	-2275	-43.2%	2754	-2517	-47.7%	3196	-2075	-39.4%
RMSE			3599			3646			3433	
Avg				-62.6%			-64.0%			-59.7%
Kernel Number (kernels m^{-2})										
Preston 05	25 011	9764	-15 247	-61.0%	8794	-16 217	-64.8%	11 504	-13 507	-54.0%
Partridge 06	17 308	9224	-8084	-46.7%	9509	-7799	-45.1%	9297	-8011	-46.3%
Manhattan 06	19 923	11 225	-8698	-43.7%	11 343	-8580	-43.1%	12 504	-7419	-37.2%
RMSE			11157			11510			10027	
Avg				-50.4%			-51.0%			-45.8%
Head Number (heads m^{-2})										
Preston 05	14.9	10.0	-4.9	-32.9%	10.0	-4.9	-32.9%	15.0	0.1	0.7%
Partridge 06	9.8	10.0	0.2	2.0%	10.0	0.2	2.0%	10.0	0.2	2.0%
Manhattan 06	19.0	14.0	-5.0	-26.3%	14.0	-5.0	-26.3%	19.0	0.0	0.0%
RMSE			4.0			4.0			0.1	
Avg				-19.1%			-19.1%			0.9%
Seed Weight (mg $kernel^{-1}$)										
Preston 05	23.50	21.80	-1.70	-7.2%	24.40	0.90	3.8%	21.20	-2.30	-9.8%
Partridge 06	24.80	12.20	-12.60	-50.8%	11.80	-13.00	-52.4%	12.00	-12.80	-51.6%
Manhattan 06	23.60	26.70	3.10	13.1%	24.30	0.70	3.0%	25.60	2.00	8.5%
RMSE			7.56			7.53			7.60	
Avg				-15.0%			-15.2%			-17.6%

Table 3.14 Yield and yield component RMSEs, individual location errors, and percent errors for grain sorghum simulations 6, 8, 9, and 10 for the three location-years in Kansas.

Location	S6	Error	% Error	S8	Error	% Error	S9	Error	% Error	S10	Error	% Error
Yield (kg ha^{-1})												
Preston 05	3108	-3494	-52.9%	3241	-3361	-50.9%	3730	-2872	-43.5%	3747	-2855	-43.2%
Partridge 06	1543	-3276	-68.0%	1611	-3208	-66.6%	1903	-2916	-60.5%	2917	-1902	-39.5%
Manhattan 06	4473	-798	-15.1%	4574	-697	-13.2%	5302	31	0.6%	6722	1451	27.5%
RMSE		2803			2712			2363			2150	
Avg			-45.3%			-43.6%			-34.5%			-18.4%
Kernel Number (kernels m^{-2})												
Preston 05	13 627	-11 384	-45.5%	14 682	-10 329	-41.3%	16 421	-8590	-34.3%	16 519	-8492	-34.0%
Partridge 06	9854	-7454	-43.1%	9567	-7741	-44.7%	9985	-7323	-42.3%	12 330	-4978	-28.8%
Manhattan 06	14 206	-5717	-28.7%	13 583	-6340	-31.8%	14 820	-5103	-25.6%	21 495	1572	7.9%
RMSE		8521			8303			7152			5755	
Avg			-39.1%			-39.3%			-34.1%			-18.3%
Head Number (heads m^{-2})												
Preston 05	15.0	0.1	0.7%	15.0	0.1	0.7%	15.0	0.1	0.7%	15.0	0.1	0.7%
Partridge 06	10.0	0.2	2.0%	10.0	0.2	2.0%	10.0	0.2	2.0%	10.0	0.2	2.0%
Manhattan 06	19.0	0.0	0.0%	19.0	0.0	0.0%	19.0	0.0	0.0%	19.0	0.0	0.0%
RMSE		0.1			0.1			0.1			0.1	
Avg			0.9%			0.9%			0.9%			0.9%
Seed Weight (mg kernel^{-1})												
Preston 05	22.80	-0.70	-3.0%	22.10	-1.40	-6.0%	22.70	-0.80	-3.4%	22.70	-0.80	-3.4%
Partridge 06	15.70	-9.10	-36.7%	16.80	-8.00	-32.3%	19.10	-5.70	-23.0%	23.70	-1.10	-4.4%
Manhattan 06	31.50	7.90	33.5%	33.70	10.10	42.8%	35.80	12.20	51.7%	31.30	7.70	32.6%
RMSE		6.97			7.48			7.79			4.51	
Avg			-2.1%			1.5%			8.4%			8.3%

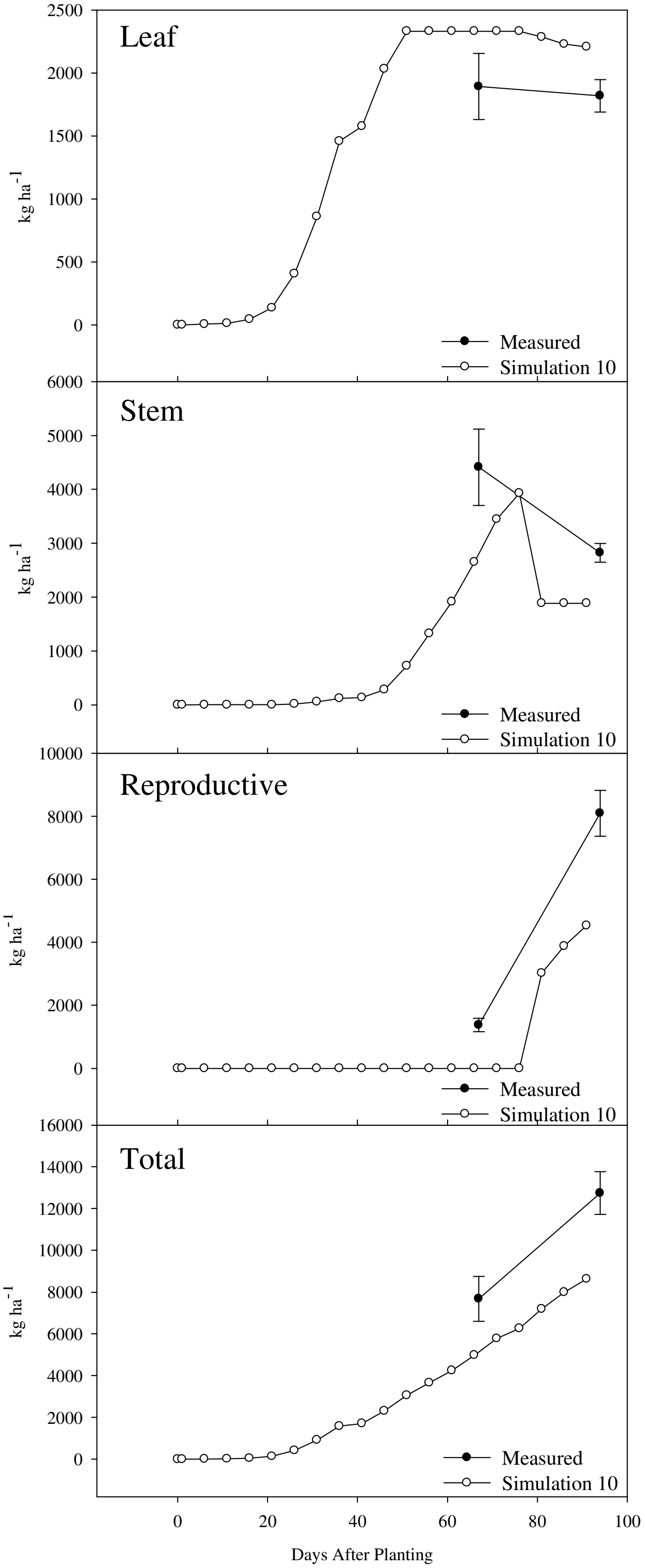


Figure 3.20 Measured and simulated grain sorghum leaf, stem, reproductive, and total biomass at Preston, KS in 2005.

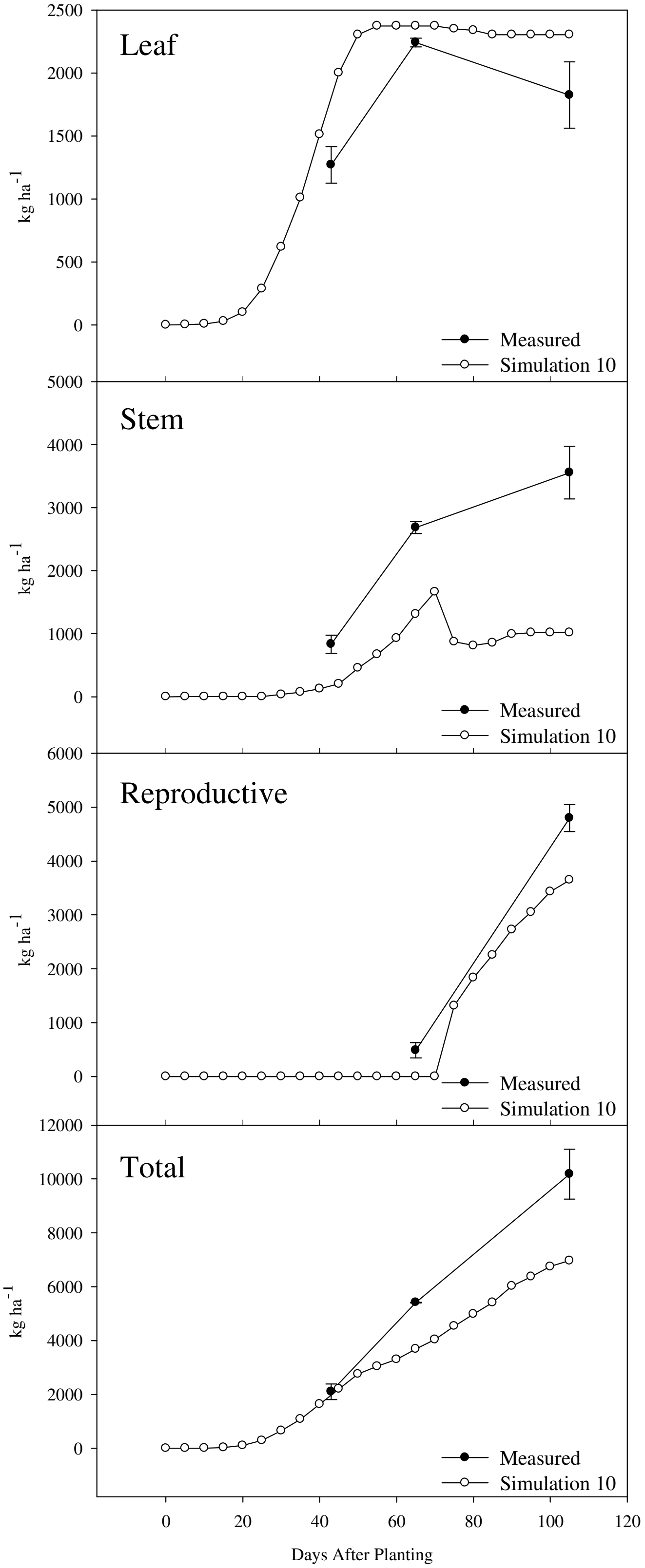


Figure 3.21 Measured and simulated grain sorghum leaf, stem, reproductive, and total biomass at Partridge, KS in 2006.

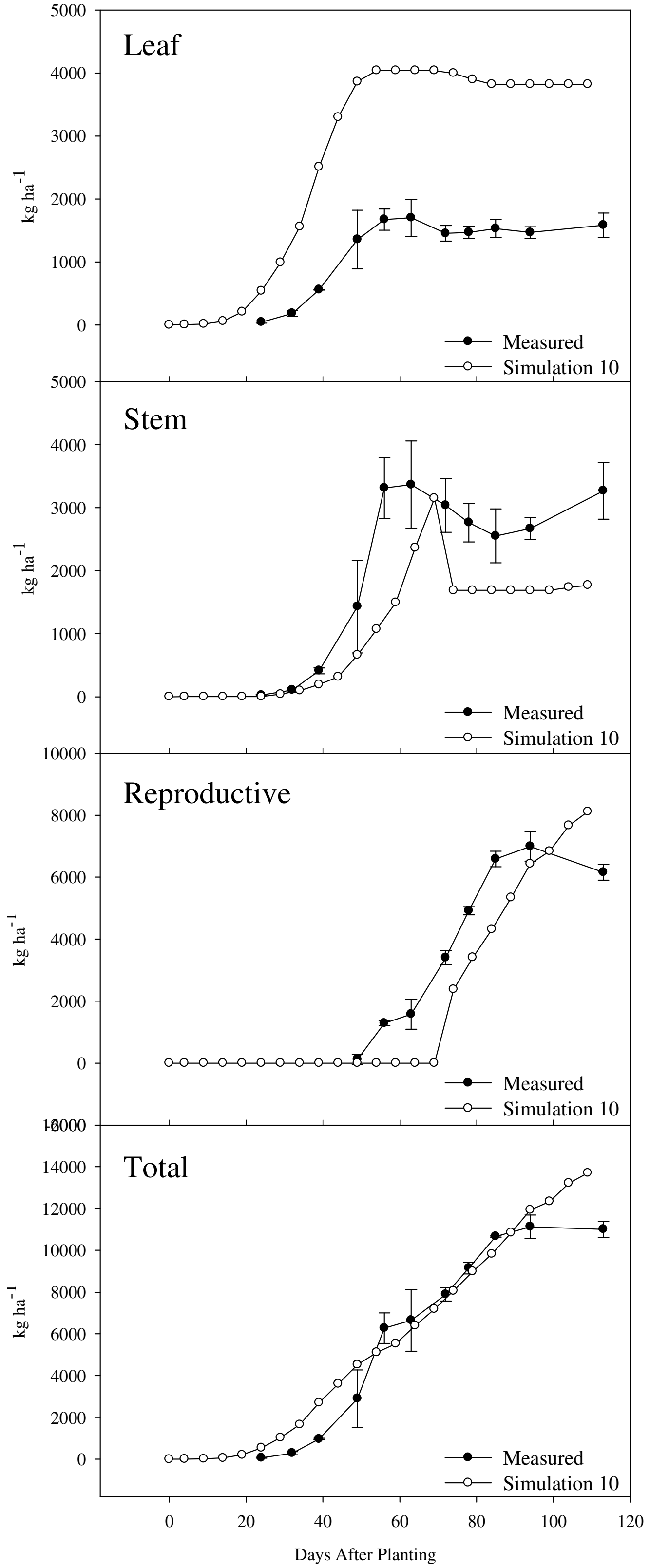


Figure 3.22 Measured and simulated grain sorghum leaf, stem, reproductive, and total biomass at Manhattan, KS in 2006.

Table 3.15 Mid-season biomass and LAI RMSEs, individual location errors, and percent errors for grain sorghum simulations 2,3 and 4 for the three location-years in Kansas.

Location	M	S2	Error	% Error	S3	Error	% Error	S4	Error	% Error
LAI										
Preston 05	3.49	1.35	-2.14	-61.3%	1.13	-2.36	-67.6%	1.64	-1.85	-53.0%
Partridge 06	3.30	1.59	-1.71	-51.8%	1.28	-2.02	-61.2%	1.60	-1.70	-51.5%
Manhattan 06	3.34	1.83	-1.51	-45.2%	1.73	-1.61	-48.2%	2.03	-1.31	-39.2%
RMSE			1.81			2.02			1.64	
Avg				-52.8%			-59.0%			-47.9%
Leaf Biomass (kg ha^{-1})										
Preston 05	1892	1045	-847	-44.8%	905	-987	-52.2%	1255	-637	-33.7%
Partridge 06	2241	1432	-809	-36.1%	1183	-1058	-47.2%	1457	-784	-35.0%
Manhattan 06	1700	1878	178	10.5%	1822	122	7.2%	2241	541	31.8%
RMSE			684			838			662	
Avg				-23.5%			-30.7%			-12.3%
Stem Biomass (kg ha^{-1})										
Preston 05	4414	1830	-2584	-58.5%	1833	-2581	-58.5%	2191	-2223	-50.4%
Partridge 06	2684	1089	-1595	-59.4%	1401	-1283	-47.8%	1088	-1596	-59.5%
Manhattan 06	3364	1176	-2188	-65.0%	1287	-2077	-61.7%	1306	-2058	-61.2%
RMSE			2161			2051			1977	
Avg				-61.0%			-56.0%			-57.0%
Total Biomass (kg ha^{-1})										
Preston 05	7680	2875	-4805	-62.6%	2739	-4941	-64.3%	3445	-4235	-55.1%
Partridge 06	5412	2521	-2891	-53.4%	2584	-2828	-52.3%	2546	-2866	-53.0%
Manhattan 06	6643	3055	-3588	-54.0%	3109	-3534	-53.2%	3546	-3097	-46.6%
RMSE			3844			3869			3452	
Avg				-56.7%			-56.6%			-51.6%

Table 3.16 Mid-season biomass and LAI RMSEs, individual location errors, and percent errors for grain sorghum simulations 6, 8, 9, and 10 for the three location-years in Kansas.

Location	S6	Error	% Error	S8	Error	% Error	S9	Error	% Error	S10	Error	% Error
LAI												
Preston 05	2.23	-1.26	-36.1%	2.58	-0.91	-26.1%	3.18	-0.31	-8.9%	3.23	-0.26	-7.4%
Partridge 06	2.24	-1.06	-32.1%	2.35	-0.95	-28.8%	2.59	-0.71	-21.5%	3.07	-0.23	-7.0%
Manhattan 06	2.90	-0.44	-13.2%	3.03	-0.31	-9.3%	3.27	-0.07	-2.1%	4.71	1.37	41.0%
RMSE		0.98			0.78			0.45			0.82	
Avg			-27.1%			-21.4%			-10.8%			8.9%
Leaf Biomass (kg ha^{-1})												
Preston 05	1660	-232	-12.3%	1874	-18	-1.0%	2294	402	21.2%	2331	439	23.2%
Partridge 06	2136	-105	-4.7%	2187	-54	-2.4%	2281	40	1.8%	2373	132	5.9%
Manhattan 06	3137	1437	84.5%	3202	1502	88.4%	3399	1699	99.9%	4036	2336	137.4%
RMSE		843			868			1008			1374	
Avg			22.5%			28.3%			41.0%			55.5%
Stem Biomass (kg ha^{-1})												
Preston 05	2554	-1860	-42.1%	2591	-1823	-41.3%	2813	-1601	-36.3%	2815	-1599	-36.2%
Partridge 06	998	-1686	-62.8%	913	-1771	-66.0%	975	-1709	-63.7%	1310	-1374	-51.2%
Manhattan 06	1520	-1844	-54.8%	1361	-2003	-59.5%	1516	-1848	-54.9%	2213	-1151	-34.2%
RMSE		1798			1868			1722			1387	
Avg			-53.3%			-55.6%			-51.6%			-40.5%
Total Biomass (kg ha^{-1})												
Preston 05	4214	-3466	-45.1%	4466	-3214	-41.8%	5108	-2572	-33.5%	5146	-2534	-33.0%
Partridge 06	3134	-2278	-42.1%	3100	-2312	-42.7%	3256	-2156	-39.8%	3683	-1729	-31.9%
Manhattan 06	4658	-1985	-29.9%	4563	-2080	-31.3%	4915	-1728	-26.0%	6249	-394	-5.9%
RMSE		2655			2582			2179			1786	
Avg			-39.0%			-38.6%			-33.1%			-23.6%

Table 3.17 RMSEs, individual location errors, and percent errors for grain sorghum simulations 2, 3, and 4 for biomass at harvest for the three location-years in Kansas.

Location	M	S2	Error	% Error	S3	Error	% Error	S4	Error	% Error
Leaf Biomass (kg ha^{-1})										
Preston 05	1818	989	-829	-45.6%	857	-961	-52.9%	1187	-631	-34.7%
Partridge 06	1823	1424	-399	-21.9%	1148	-675	-37.0%	1450	-373	-20.5%
Manhattan 06	1583	1869	286	18.1%	1822	239	15.1%	2207	624	39.4%
RMSE			556			692			556	
Avg				-16.5%			-24.9%			-5.3%
Stem Biomass (kg ha^{-1})										
Preston 05	2823	1370	-1453	-51.5%	1268	-1555	-55.1%	1654	-1169	-41.4%
Partridge 06	3557	866	-2691	-75.7%	1038	-2519	-70.8%	866	-2691	-75.7%
Manhattan 06	3269	1125	-2144	-65.6%	1086	-2183	-66.8%	1255	-2014	-61.6%
RMSE			2156			2124			2055	
Avg				-64.2%			-64.2%			-59.6%
Reproductive Biomass (kg ha^{-1})										
Preston 05	8096	2659	-5437	-67.2%	2680	-5416	-66.9%	3044	-5052	-62.4%
Partridge 06	4799	1403	-3396	-70.8%	1403	-3396	-70.8%	1400	-3399	-70.8%
Manhattan 06	6157	3745	-2412	-39.2%	3442	-2715	-44.1%	3995	-2162	-35.1%
RMSE			3954			4010			3731	
Avg				-59.0%			-60.6%			-56.1%
Total Biomass (kg ha^{-1})										
Preston 05	12 737	5018	-7719	-60.6%	4805	-7932	-62.3%	5885	-6852	-53.8%
Partridge 06	10 179	3693	-6486	-63.7%	3589	-6590	-64.7%	3716	-6463	-63.5%
Manhattan 06	11 009	6739	-4270	-38.8%	6349	-4660	-42.3%	7457	-3552	-32.3%
RMSE			6321			6534			5812	
Avg				-54.4%			-56.4%			-49.9%

Table 3.18 RMSEs, individual location errors, and percent errors for grain sorghum simulations 6, 8, 9, and 10 for biomass at harvest for the three location-years in Kansas.

Location	S6	Error	% Error	S8	Error	% Error	S9	Error	% Error	S10	Error	% Error
Leaf Biomass (kg ha^{-1})												
Preston 05	1571	-247	-13.6%	1774	-44	-2.4%	2171	353	19.4%	2206	388	21.3%
Partridge 06	2042	219	12.0%	2101	278	15.2%	2191	368	20.2%	2303	480	26.3%
Manhattan 06	2969	1386	87.6%	3030	1447	91.4%	3217	1634	103.2%	3819	2236	141.3%
RMSE		823			851			988			1339	
Avg			28.7%			34.7%			47.6%			63.0%
Stem Biomass (kg ha^{-1})												
Preston 05	1629	-1194	-42.3%	1732	-1091	-38.6%	1884	-939	-33.3%	1886	-937	-33.2%
Partridge 06	706	-2851	-80.2%	672	-2885	-81.1%	741	-2816	-79.2%	1016	-2541	-71.4%
Manhattan 06	1230	-2039	-62.4%	1252	-2017	-61.7%	1447	-1822	-55.7%	1877	-1392	-42.6%
RMSE		2138			2128			2011			1758	
Avg			-61.6%			-60.5%			-56.1%			-49.1%
Reproductive Biomass (kg ha^{-1})												
Preston 05	3885	-4211	-52.0%	4052	-4044	-50.0%	4663	-3433	-42.4%	4683	-3413	-42.2%
Partridge 06	1929	-2870	-59.8%	2014	-2785	-58.0%	2379	-2420	-50.4%	3647	-1152	-24.0%
Manhattan 06	5591	-566	-9.2%	5718	-439	-7.1%	6627	470	7.6%	8403	2246	36.5%
RMSE		2960			2846			2440			2451	
Avg			-40.3%			-38.4%			-28.4%			-9.9%
Total Biomass (kg ha^{-1})												
Preston 05	7086	-5651	-44.4%	7557	-5180	-40.7%	8718	-4019	-31.6%	8776	-3961	-31.1%
Partridge 06	4676	-5503	-54.1%	4786	-5393	-53.0%	5311	-4868	-47.8%	6965	-3214	-31.6%
Manhattan 06	9789	-1220	-11.1%	10 000	-1009	-9.2%	11 291	282	2.6%	14 099	3090	28.1%
RMSE		4608			4356			3648			3443	
Avg			-36.5%			-34.3%			-25.6%			-11.5%

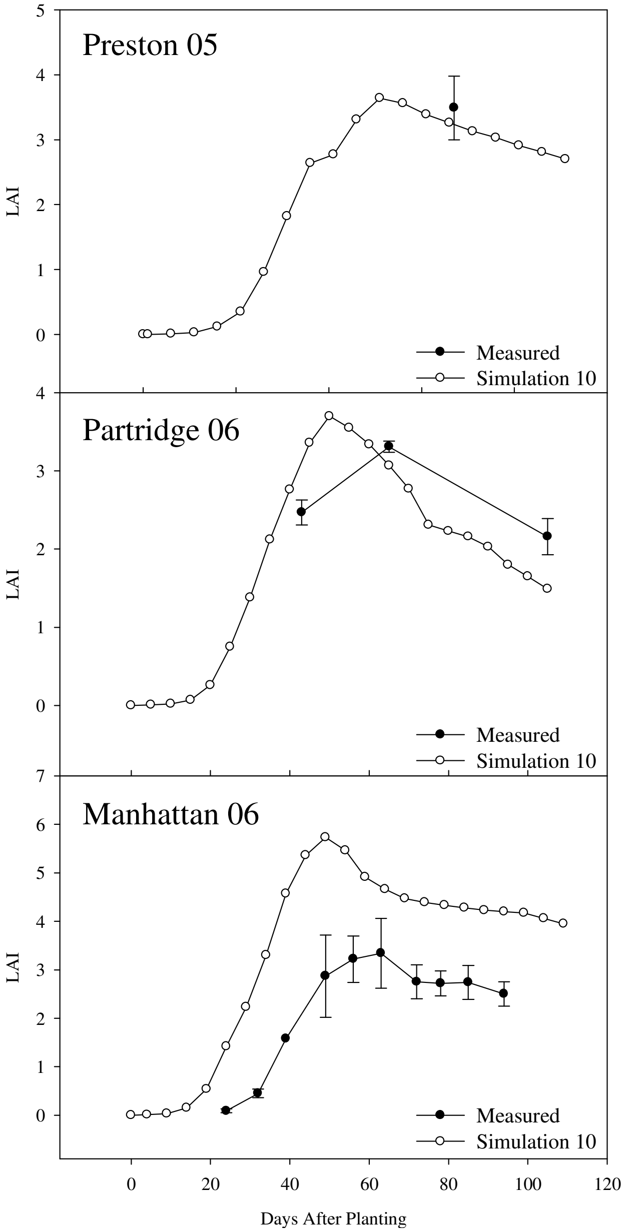


Figure 3.23 Measured and simulated grain sorghum LAI for the three location-years in Kansas.

Simulated LAI peaked earlier at Partridge and Manhattan during the growing season than actually seen in the field. Leaf area index was over predicted throughout the growing season at Manhattan, but under predicted during most of the season at Partridge (Figure 3.23).

Discussion

The model had problems with yield component simulation. Kernel number simulation was the primary limitation. The model also has problems simulating head number which can be attributed to the models inability to account for tillering, which is consistent with published literature. Total biomass simulation was adequate, but partioning of the biomass to the different parts was inconsistent. Simulation of LAI was also a bit of a problem, specifically peak LAI.

Many of the limitations discovered through the calibration process have also been seen in other published work done on the model. Varshneya et al. (1998) showed the model underestimated kernel weight due to an inability to account for changes in panicle size in receding soil moisture conditions. Our simulations at Partridge would correspond with this; however at Preston, where soil moisture should not have been an issue, seed weight was still underestimated. Suchit et al. (2004b) showed improper tillering response, our simulations also showed no tillers being estimated.

CROPGRO-Cotton

Calibrations

Most of the changes made to the CROPGRO-Cotton model during the calibration process were made to cultivar coefficients. Due to errors in model inputs during the first simulations, simulation two (S2), was considered the initial simulation for comparative purposes. For simulation three (S3), created a cultivar, based on IB0004 DP 555 BG/RR, by changing the coefficient EM-FL (time between plant emergence and flower appearance [photothermal days]) from 36 to 33. In simulation four (S4), the coefficient

SD-PM (time between first seed and physiological maturity [photothermal days]) was changed from 45 to 42. For simulation five (S5), the coefficient SD-PM was changed back to 45 and the coefficient EM-FL was changed from 33 to 30. The nitrogen and symbiosis options were changed from yes to no and yes to unlimited, respectively, for simulation six (S6).

Yield and yield component simulation

Yield was determined by multiplying the reproductive biomass, boll weight, by 0.27, which is an average gin out for Kansas. Yield simulation at Cullison in 2005, Moscow in 2005, and Partridge was acceptable, but yield was under predicted at Cullison and Moscow in 2006. (Figure 3.24). Yield was simulated in S6 at Cullison in 2005, Moscow in 2005, and Partridge with errors of only 1.5, 8.4, and 3.7%, respectively. However, yield at Cullison and Moscow in 2006 had errors of -34.4 and -48.8%. Through calibration, the RMSE for yield was reduced from 563 kg ha^{-1} in S2 to 487 kg ha^{-1} in S6. Simulated boll number varied across the locations, but was generally over predicted (Figure 3.25). Boll number had errors of 38.7, 25.4, and 23.3% at Cullison in 2005, Moscow in 2005, and Partridge, respectively, in S6. Boll number in S6 at Cullison and at Moscow in 2006 had errors of -13.4 and -40.5%, respectively. Calibration reduced bull number RMSE from 26.9 in S2 to 26.0 in S6. The RMSEs, individual location errors, and errors for the simulations are listed in Tables 3.19 and 3.20.

Changes made in S3 resulted in a decrease in the RMSE for both yield and boll number. Changes for S4 had no real impact on the RMSE for yield or boll number. S5 resulted in another decrease in the RMSE for both yield and boll number, with the RMSE

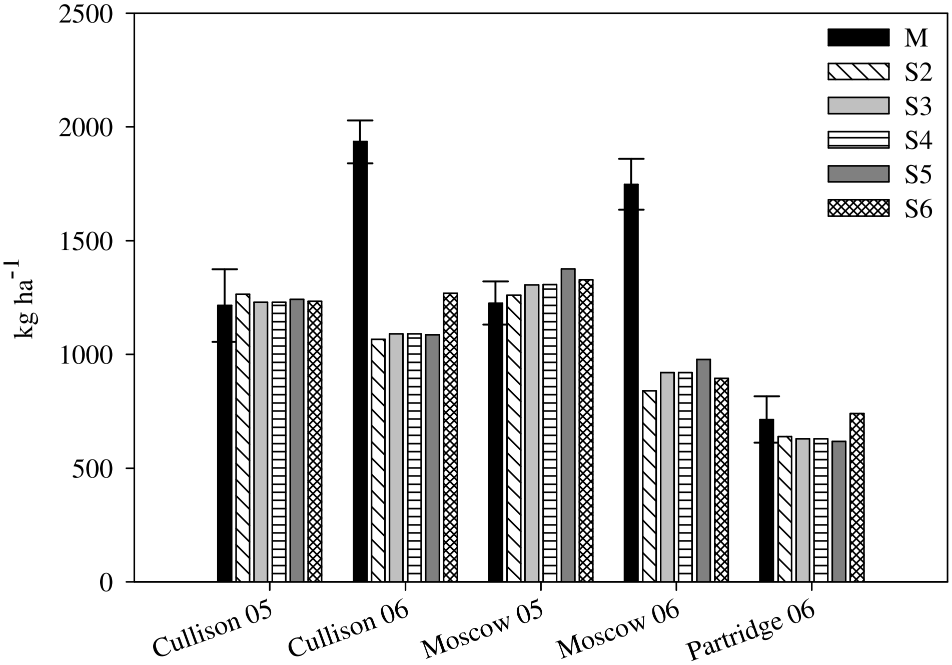


Figure 3.24 Measured and simulated cotton yield at five location-years in Kansas.

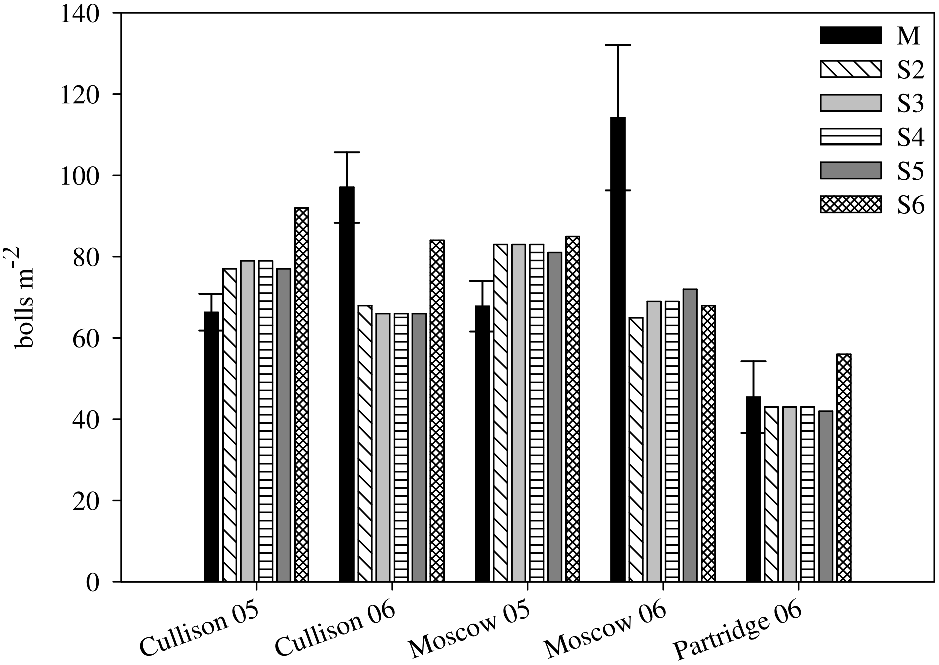


Figure 3.25 Measured and simulated cotton boll number at five location-years in Kansas.

Table 3.19 Yield and yield component RMSEs, individual location errors, and percent errors for cotton simulations 2 and 3 for the five location-years in Kansas.

Location	M	S2	Error	% Error	S3	Error	% Error
Yield (kg ha^{-1})							
05 Cullison	1215	1264	49	4.0%	1230	15	1.2%
06 Cullison	1934	1067	-867	-44.8%	1089	-845	-43.7%
05 Moscow	1225	1260	35	2.8%	1305	80	6.5%
06 Moscow	1747	839	-908	-52.0%	919	-828	-47.4%
06 Partridge	714	638	-76	-10.6%	628	-86	-12.0%
RMSE			563			532	
Avg				-20.1%			-19.1%
Boll Number (bolls m^{-2})							
05 Cullison	66.3	77.0	10.7	16.1%	79.0	12.7	19.1%
06 Cullison	97.1	68.0	-29.1	-29.9%	66.0	-31.1	-32.0%
05 Moscow	67.8	83.0	15.2	22.4%	83.0	15.2	22.4%
06 Moscow	114.2	65.0	-49.2	-43.1%	69.0	-45.2	-39.6%
06 Partridge	45.4	43.0	-2.4	-5.3%	43.0	-2.4	-5.3%
RMSE			26.9			26.1	
Avg				-8.0%			-7.1%

Table 3.20 Yield and yield component RMSEs, individual location errors, and percent errors for cotton simulations 4, 5, and 6 for the five location-years in Kansas.

Location	S4	Error	% Error	S5	Error	% Error	S6	Error	% Error
Yield (kg ha^{-1})									
05 Cullison	1230	15	1.2%	1242	27	2.2%	1233	18	1.5%
06 Cullison	1089	-845	-43.7%	1086	-849	-43.9%	1268	-666	-34.4%
05 Moscow	1307	81	6.7%	1376	151	12.3%	1328	103	8.4%
06 Moscow	920	-827	-47.3%	978	-769	-44.0%	894	-853	-48.8%
06 Partridge	629	-85	-11.9%	618	-96	-13.4%	740	26	3.7%
RMSE		531			519			487	
Avg			-19.0%			-17.4%			-13.9%
Boll Number (bolls m^{-2})									
05 Cullison	79.0	12.7	19.1%	77.0	10.7	16.1%	92.0	25.7	38.7%
06 Cullison	66.0	-31.1	-32.0%	66.0	-31.1	-32.0%	84.0	-13.1	-13.4%
05 Moscow	83.0	15.2	22.4%	81.0	13.2	19.5%	85.0	17.2	25.4%
06 Moscow	69.0	-45.2	-39.6%	72.0	-42.2	-37.0%	68.0	-46.2	-40.5%
06 Partridge	43.0	-2.4	-5.3%	42.0	-3.4	-7.6%	56.0	10.6	23.3%
RMSE		26.1			24.7			26.0	
Avg			-7.1%			-8.2%			6.7%

for boll number being the lowest for all the simulations. Simulation 6 resulted in the lowest RMSE for yield of all simulations and a RMSE for boll number that was lower than all other simulations except S5.

Biomass and leaf area simulation

Initial simulation of total biomass had an RMSE of 1123 kg ha^{-1} during boll development and 2059 kg ha^{-1} at harvest. After calibration, the RMSE for total biomass during boll development increased to 1370 kg ha^{-1} and the RMSE for total biomass at harvest decreased to 1626 kg ha^{-1}. Total biomass simulation throughout the growing season was suitable, especially at Cullison in 2005, Moscow in 2005, and Moscow in 2006. However, total biomass was over predicted throughout the growing season at Partridge and under predicted during the season at Cullison in 2006 (Figures 3.26, 3.27, 3.28, 3.29, and 3.30). Total biomass at harvest in S6 had errors of -27.1, -15.4, and 25.2% at Cullison, Moscow, and Partridge in 2006, respectively.

Simulation of biomass partioning between leaves, stem, and reproductive parts was variable throughout the growing season and across most of the locations. At Partridge leaf, stem, and reproductive biomass were over predicted during most of the growing season, but at Cullison in 2006 leaf, stem and reproductive biomass was under predicted. In S6, reproductive biomass at harvest was under predicted with errors of -33.4 and -32.7% at Cullison and Moscow in 2006, respectively, while the error was 11.1% at Partridge. Stem biomass at harvest was over predicted at both Moscow in 2006 and Partridge with errors of 57.6 and 67.8%. The RMSEs, individual location errors, and errors across the calibration simulation are listed in Tables 3.21, 3.22, 3.23, and 3.24.

The RMSE for LAI, measured during boll development, increased through the calibration simulations, from 1.08 in S2 to 1.12 in S6. Leaf area index simulation was variable through the growing season and across location-years. Specifically, LAI was consistently under predicted throughout the season at Cullison in 2006, while it was

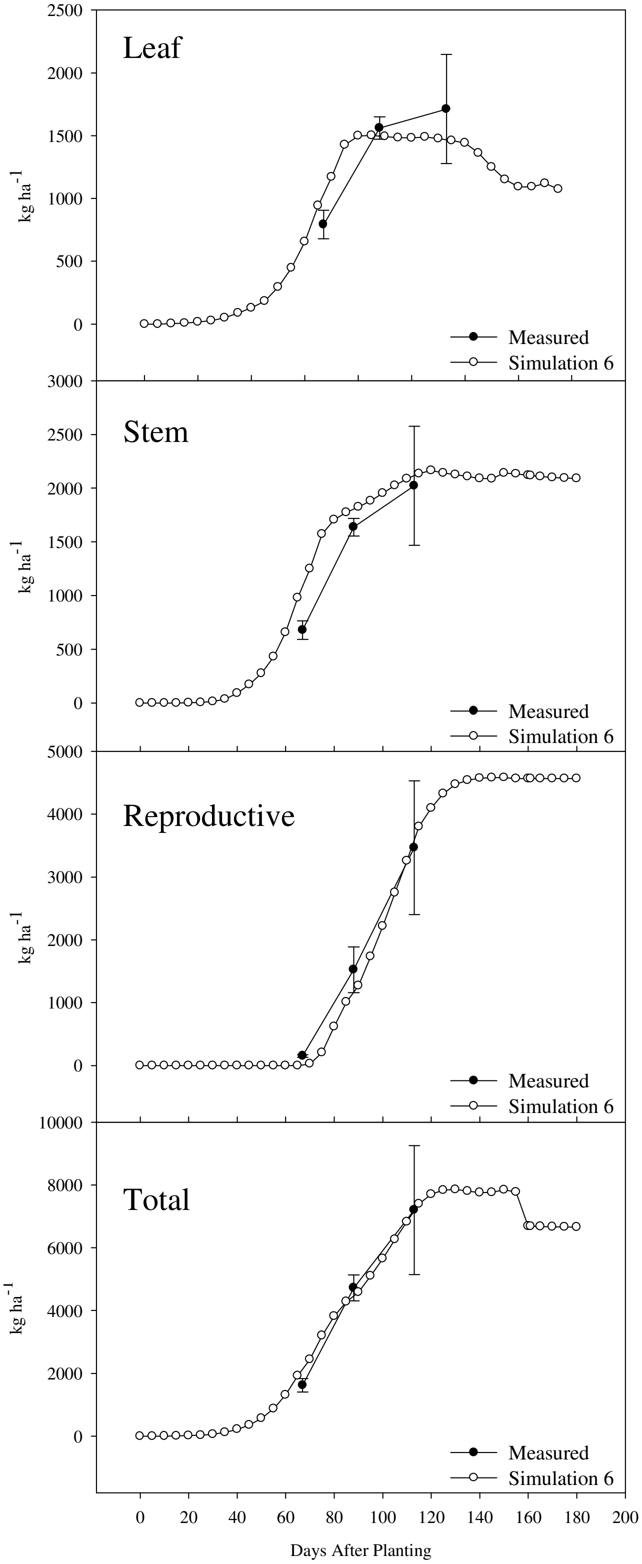


Figure 3.26 Measured and simulated cotton leaf, stem, reproductive, and total biomass at Cullison, KS in 2005.

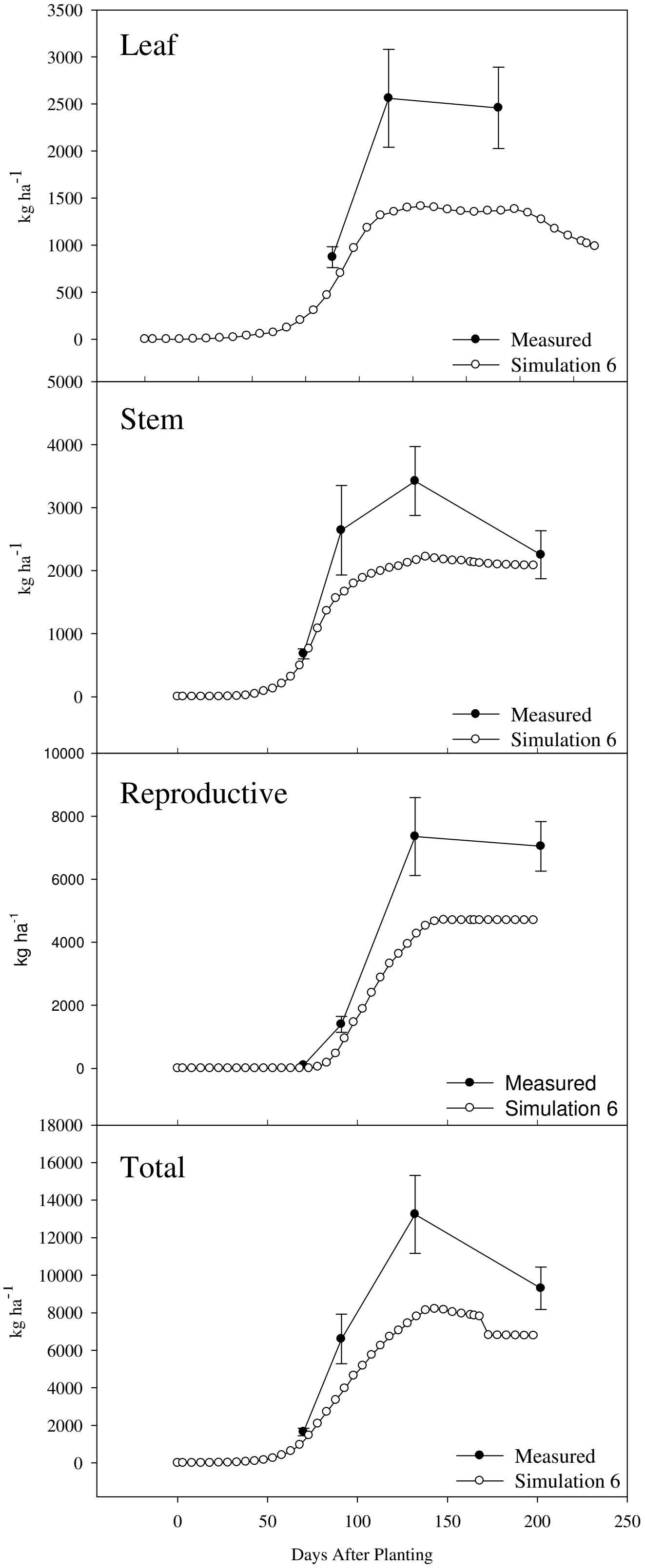


Figure 3.27 Measured and simulated cotton leaf, stem, reproductive, and total biomass at Cullison, KS in 2006.

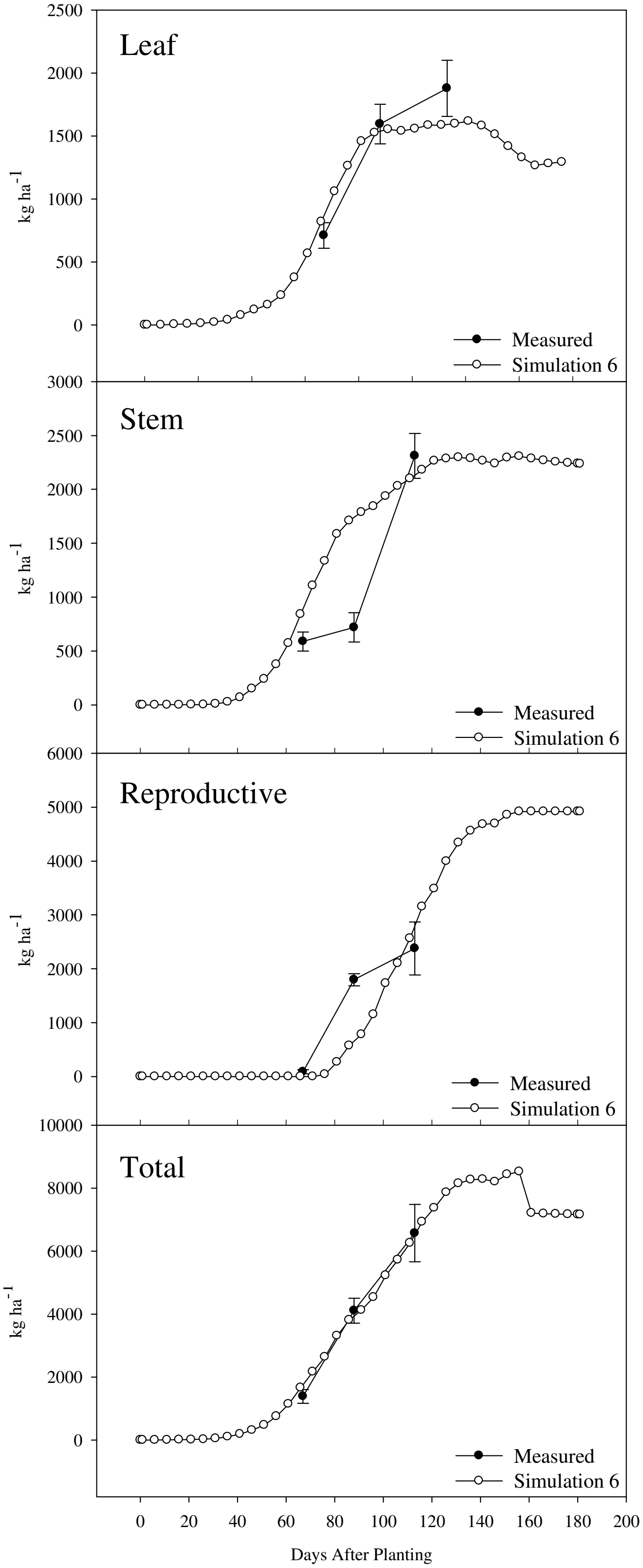


Figure 3.28 Measured and simulated cotton leaf, stem, reproductive, and total biomass at Moscow, KS in 2005.

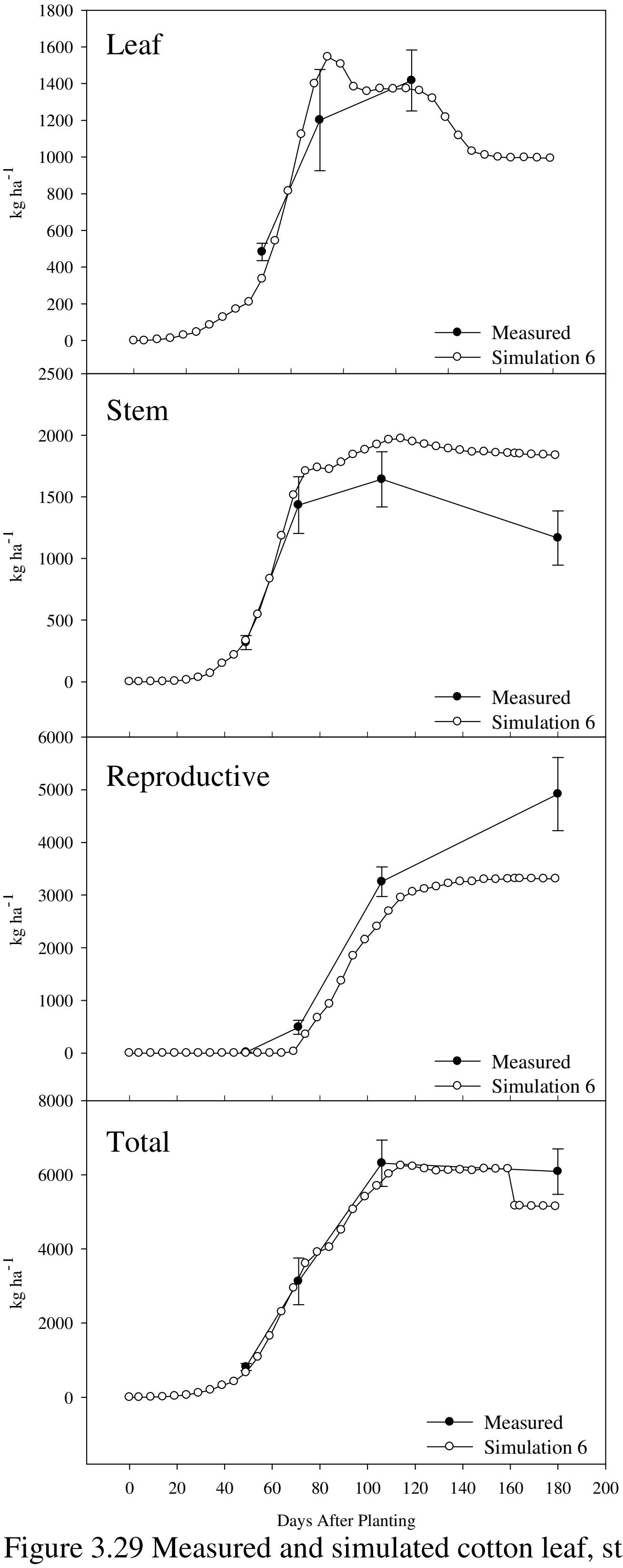


Figure 3.29 Measured and simulated cotton leaf, stem, reproductive, and total biomass at Moscow, KS in 2006.

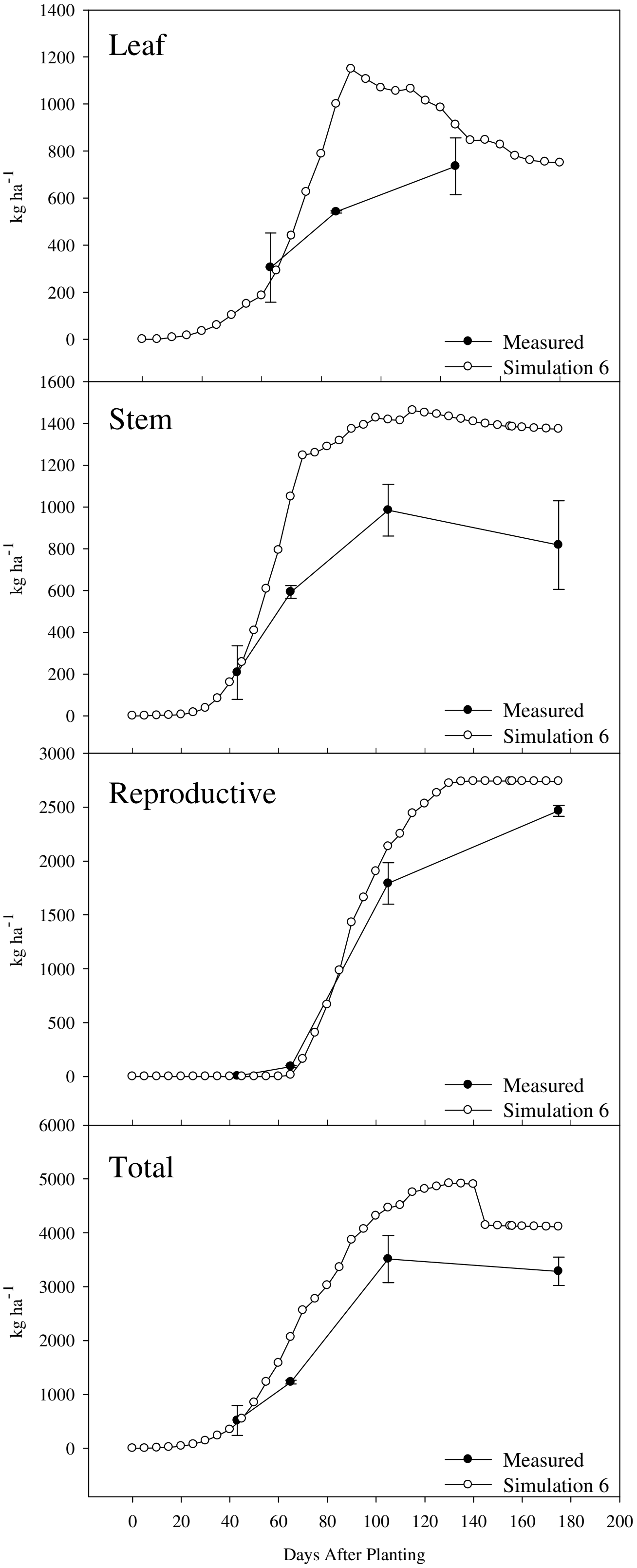


Figure 3.30 Measured and simulated cotton leaf, stem, reproductive, and total biomass at Partridge, KS in 2006.

Table 3.21 RMSEs, individual location errors, and percent errors for biomass and LAI, measured during boll development, for cotton simulations 2 and 3 for the five location-years in Kansas.

Location	M	S2	Error	% Error	S3	Error	% Error
LAI							
05 Cullison	1.69	1.89	0.2	11.8%	1.89	0.2	11.8%
06 Cullison	4.53	2.4	-2.13	-47.0%	2.24	-2.29	-50.6%
05 Moscow	2.11	2.7	0.59	28.0%	2.52	0.41	19.4%
06 Moscow	1.64	2.32	0.68	41.5%	2.32	0.68	41.5%
06 Partridge	0.97	1.67	0.7	72.2%	1.63	0.66	68.0%
RMSE			1.08			1.13	
Avg				21.3%			18.0%
Leaf Biomass (kg ha^{-1})							
05 Cullison	793	1087	294	37.1%	1108	315	39.7%
06 Cullison	2561	1514	-1047	-40.9%	1454	-1107	-43.2%
05 Moscow	1594	1880	286	17.9%	1805	211	13.2%
06 Moscow	1201	1545	344	28.6%	1582	381	31.7%
06 Partridge	735	833	98	13.3%	808	73	9.9%
RMSE			528			551	
Avg				11.2%			10.3%
Stem Biomass (kg ha^{-1})							
05 Cullison	679	1311	632	93.1%	1282	603	88.8%
06 Cullison	2643	2333	-310	-11.7%	2168	-475	-18.0%
05 Moscow	719	2137	1418	197.2%	1989	1270	176.6%
06 Moscow	1433	1846	413	28.8%	1798	365	25.5%
06 Partridge	985	1891	906	92.0%	1760	775	78.7%
RMSE			836			766	
Avg				79.9%			70.3%
Reproductive Biomass (kg ha^{-1})							
05 Cullison	152	0	-152	-100.0%	0	-152	-100.0%
06 Cullison	1397	575	-822	-58.8%	700	-697	-49.9%
05 Moscow	1796	251	-1545	-86.0%	408	-1388	-77.3%
06 Moscow	493	0	-493	-100.0%	2	-491	-99.6%
06 Partridge	1792	1716	-76	-4.2%	1796	4	0.2%
RMSE			817			732	
Avg				-69.8%			-65.3%
Total Biomass (kg ha^{-1})							
05 Cullison	1624	2399	775	47.7%	2390	766	47.2%
06 Cullison	6601	4422	-2179	-33.0%	4322	-2279	-34.5%
05 Moscow	4109	4268	159	3.9%	4201	92	2.2%
06 Moscow	3127	3391	264	8.4%	3382	255	8.2%
06 Partridge	3512	4440	928	26.4%	4365	853	24.3%
RMSE			1123			1147	
Avg				10.7%			9.5%

Table 3.22 RMSEs, individual location errors, and percent errors for biomass and LAI, measured during boll development, for cotton simulations 4, 5, and 6 for the five location-years in Kansas.

Location	S4	Error	% Error	S5	Error	% Error	S6	Error	% Error
LAI									
05 Cullison	1.89	0.2	11.8%	1.89	0.2	11.8%	1.85	0.16	9.5%
06 Cullison	2.24	-2.29	-50.6%	2.12	-2.41	-53.2%	2.27	-2.26	-49.9%
05 Moscow	2.52	0.41	19.4%	2.29	0.18	8.5%	2.08	-0.03	-1.4%
06 Moscow	2.32	0.68	41.5%	2.26	0.62	37.8%	2.13	0.49	29.9%
06 Partridge	1.62	0.65	67.0%	1.55	0.58	59.8%	1.93	0.96	99.0%
RMSE		1.13			1.15			1.12	
Avg			17.8%			13.0%			17.4%
Leaf Biomass (kg ha^{-1})									
05 Cullison	1108	315	39.7%	1130	337	42.5%	1017	224	28.2%
06 Cullison	1454	-1107	-43.2%	1414	-1147	-44.8%	1353	-1208	-47.2%
05 Moscow	1805	211	13.2%	1680	86	5.4%	1520	-74	-4.6%
06 Moscow	1582	381	31.7%	1571	370	30.8%	1455	254	21.1%
06 Partridge	805	70	9.5%	783	48	6.5%	912	177	24.1%
RMSE		551			561			568	
Avg			10.2%			8.1%			4.3%
Stem Biomass (kg ha^{-1})									
05 Cullison	1282	603	88.8%	1245	566	83.4%	1069	390	57.4%
06 Cullison	2167	-476	-18.0%	1989	-654	-24.7%	1643	-1000	-37.8%
05 Moscow	1989	1270	176.6%	1719	1000	139.1%	1717	998	138.8%
06 Moscow	1798	365	25.5%	1685	252	17.6%	1584	151	10.5%
06 Partridge	1749	764	77.6%	1640	655	66.5%	1418	433	44.0%
RMSE		764			669			687	
Avg			70.1%			56.4%			42.6%
Reproductive Biomass (kg ha^{-1})									
05 Cullison	0	-152	-100.0%	0	-152	-100.0%	1	-151	-99.3%
06 Cullison	700	-697	-49.9%	804	-593	-42.4%	740	-657	-47.0%
05 Moscow	408	-1388	-77.3%	666	-1130	-62.9%	638	-1158	-64.5%
06 Moscow	2	-491	-99.6%	140	-353	-71.6%	125	-368	-74.6%
06 Partridge	1798	6	0.3%	1871	79	4.4%	2136	344	19.2%
RMSE		732			597			640	
Avg			-65.3%			-54.5%			-53.3%
Total Biomass (kg ha^{-1})									
05 Cullison	2390	766	47.2%	2374	750	46.2%	2088	464	28.6%
06 Cullison	4321	-2280	-34.5%	4207	-2394	-36.3%	3736	-2865	-43.4%
05 Moscow	4201	92	2.2%	4064	-45	-1.1%	3875	-234	-5.7%
06 Moscow	3382	255	8.2%	3396	269	8.6%	3164	37	1.2%
06 Partridge	4353	841	23.9%	4293	781	22.2%	4466	954	27.2%
RMSE		1146			1181			1370	
Avg			9.4%			7.9%			1.6%

Table 3.23 Biomass at harvest RMSEs, individual location errors, and percent errors for cotton simulations 2 and 3 for three locations in Kansas in 2006.

Location	M	S2	Error	% Error	S3	Error	% Error
Stem Biomass (kg ha^{-1})							
06 Cullison	2252	1901	-351	-15.6%	1701	-551	-24.5%
06 Moscow	1166	2109	943	80.9%	1888	722	61.9%
06 Partridge	818	1216	398	48.7%	1141	323	39.5%
RMSE			625			557	
Avg				38.0%			25.6%
Reproductive Biomass (kg ha^{-1})							
06 Cullison	7048	3952	-3096	-43.9%	4035	-3013	-42.7%
06 Moscow	4919	3109	-1810	-36.8%	3405	-1514	-30.8%
06 Partridge	2467	2363	-104	-4.2%	2326	-141	-5.7%
RMSE			2071			1949	
Avg				-28.3%			-26.4%
Total Biomass (kg ha^{-1})							
06 Cullison	9300	5853	-3447	-37.1%	5736	-3564	-38.3%
06 Moscow	6085	5218	-867	-14.2%	5294	-791	-13.0%
06 Partridge	3284	3580	296	9.0%	3468	184	5.6%
RMSE			2059			2110	
Avg				-14.1%			-15.2%

Table 3.24 Biomass at harvest RMSEs, individual location errors, and percent errors for cotton simulations 4, 5, and 6 for three locations in Kansas in 2006.

Location	S4	Error	% Error	S5	Error	% Error	S6	Error	% Error
Stem Biomass (kg ha^{-1})									
06 Cullison	1672	-580	-25.8%	1549	-703	-31.2%	2079	-173	-7.7%
06 Moscow	1883	717	61.5%	1662	496	42.5%	1838	672	57.6%
06 Partridge	1127	309	37.8%	1073	255	31.2%	1373	555	67.8%
RMSE		562			518			513	
Avg			24.5%			14.2%			39.3%
Reproductive Biomass (kg ha^{-1})									
06 Cullison	4035	-3013	-42.7%	4021	-3027	-42.9%	4697	-2351	-33.4%
06 Moscow	3408	-1511	-30.7%	3621	-1298	-26.4%	3310	-1609	-32.7%
06 Partridge	2329	-138	-5.6%	2288	-179	-7.3%	2740	273	11.1%
RMSE		1948			1904			1652	
Avg			-26.4%			-25.5%			-18.3%
Total Biomass (kg ha^{-1})									
06 Cullison	5707	-3593	-38.6%	5570	-3730	-40.1%	6776	-2524	-27.1%
06 Moscow	5291	-794	-13.0%	5283	-802	-13.2%	5148	-937	-15.4%
06 Partridge	3456	172	5.2%	3362	78	2.4%	4113	829	25.2%
RMSE		2127			2203			1626	
Avg			-15.5%			-17.0%			-5.8%

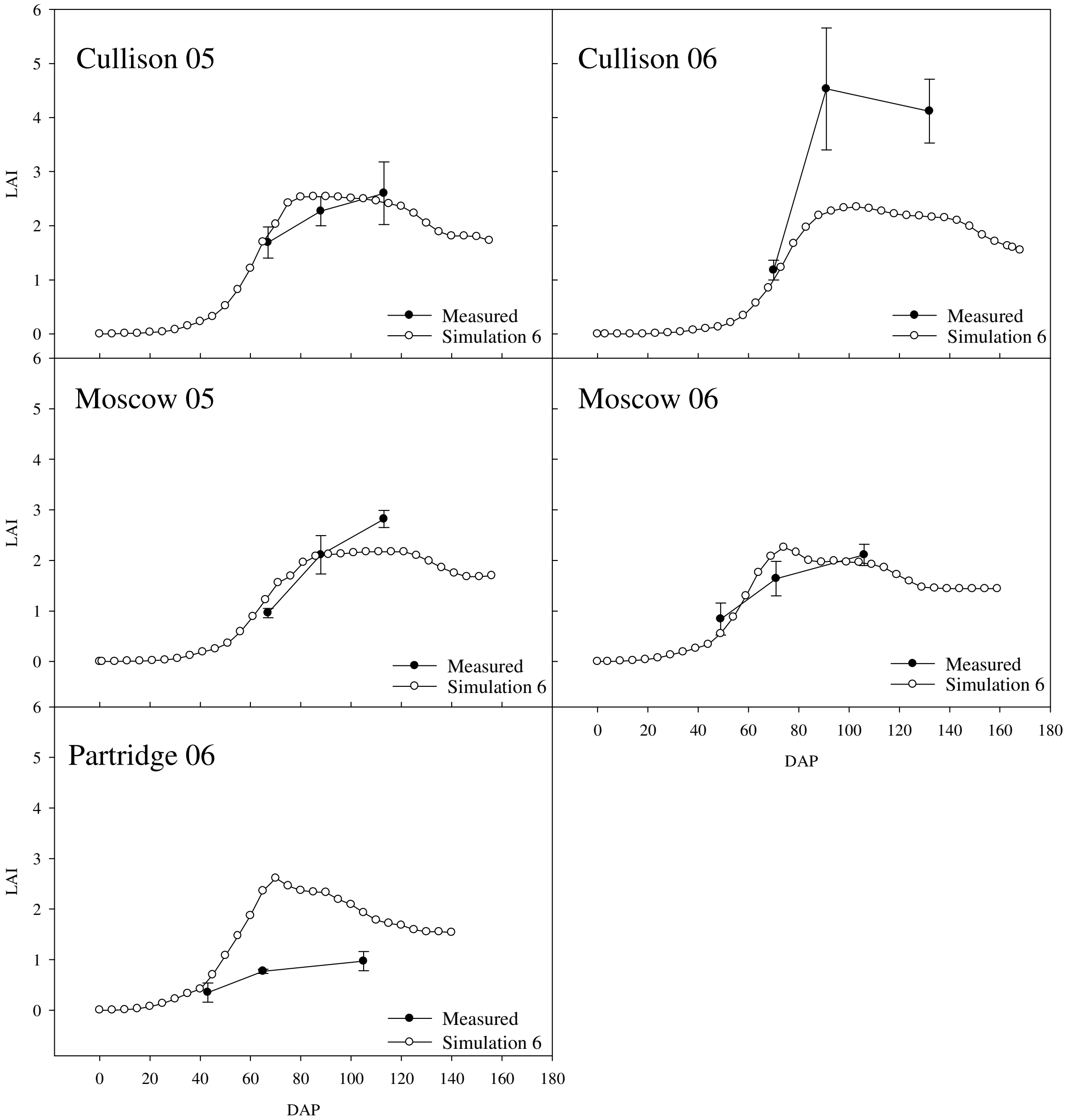


Figure 3.31 Measured and simulated cotton LAI for the five location-years in Kansas.

consistently over predicted at Partridge. Peak simulated LAI occurred earlier in the season than observed everywhere except Cullison in 2006 (Figure 3.31). Simulated LAI, measured during boll development, was predicted best in S6 at Cullison in 2005 and Moscow in 2005, which had errors of 9.5 and -1.4%. The errors for simulated LAI at

Cullison in 2006, Moscow in 2006, and Partridge were -49.9, 29.9, and 99.0% respectively (Tables 3.21 and 3.22).

Discussion

Overall, the model adequately simulated yield and boll number. However, it underestimated the above average yields and boll numbers at the two irrigated locations in 2006. The model adequately simulated total biomass, but like the other two models it did not partition biomass correctly. Overall, LAI simulations were reasonable, but the model did not always simulate the timing and value of peak LAI correctly.

The RMSE for simulated yield was very close to that obtained by Guerra et al. (2006). However, the RMSEs for simulated biomass portioned to the various parts were higher than theirs. Overall, CROPGRO-Cotton simulated yields in Kansas, but further calibration of the model is still needed. Also, clarification is needed from the developers on exactly what some of the outputs are and how they are determined.

Conclusions

Calibration of the CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton models improved model performance. Of the three models, CROPGRO-Cotton performed the best. The models did a reasonable job predicting yield; however, there seems to be problems with the way yield is obtained through yield component simulation. Specifically, the CERES-Maize and CERES-Sorghum models could not simulate kernel number and ear or head number per plant. Modifications to the cultivar and ecotype coefficients had no affect on ear or head number simulations and the only way to overcome this deficiency was to set plant population inputs to match the measured ear or head number. The CERES-Sorghum did not compensate well for the effects of tillering and CERES-Maize did not do simulate double ear or barren plants. No real difference was seen in yield simulation between irrigated or dryland environments, with the models under predicting yield in some and over predicting in others. So with the models under predicting yields in some of the irrigated environments, where water stress should not have been an issue, the model may be over compensating for heat stress.

Overall the models adequately simulated total biomass during the season at the different locations. However, biomass partioning between leaf, stem, and reproductive parts was highly variable. Many times the models would simulate total biomass close to measured values but for the wrong reasons, with partioning to some parts being over predicted and under predict partioning to others. Leaf area simulations by the models was highly variable, with simulated peak LAI often lower and occurring earlier in the season than the measured values.

Our model calibration for the most part improved model performance, however, further calibration should be pursued, especially for CERES-Maize and CERES-Sorghum. These two are not capable of correctly simulateing kernel number and ear or head numbers correctly. Further work is needed for the three models on partioning of biomass into the different plant parts and on LAI simulation.

A potential source of error in our simulations may stem from the soil files which we created. Due to several constraints many of the parameters needed to build the soils files were not measured in the field but were taken from the NRCS characterization database for the corresponding soil type. These values may not accurately match those which actually occur in the fields. Also, due to constraints in logistics and distance, we were not able to make multiple collections of data on crop phenology or have more sampling dates at many of our research sites to better calibrate the models. Another possible source of error could be attributed to the fact that cultivars varied across most of the location-years for the three crops which made calibration of individual cultivars for all location-years difficult.

At present, the models would not be a very useful tool for most cropping systems research. The models had too much variability across the individual location-years to be able to accurately study the effects of changes in management practices at a specific local. Also, due to problems with yield components, biomass partioning, and LAI simulation, the models would not be very reliable to predict the impact that changes in management practices would have on specific plant components. Also, to truly evaluate the models ability so simulate crop rotation effects caused by the inclusion of different crops into a system would require data from long-term crop rotations studies conducted in the field. Since this is not very feasible, researchers will have to assume that accurate calibration of the individual models will allow for accurate cropping system rotation studies. However, the models simulate yield reasonably well and could be fairly reliable for studying broader concepts such as large changes in the amount of irrigation each season on average yield for a region over many years. The models ability to accurately predict water use by the different crops was not examined, so using the models to study the effects of different crops in rotation on the cropping systems overall water use may or may not be reliable.

CHAPTER VI

SYSTEMS SIMULATION

Introduction

The High Plains aquifer is one of the largest fresh water aquifer systems in the world and underlies 44.9-million hectares of the Great Plains. Of the 44.9-million hectares, the majority is cropland of which approximately 23 percent is irrigated, accounting for 94 percent of the total ground-water use on the High Plains. An estimated 1.9 million hectare meter of water is withdrawn for irrigation each year (Waskom et al., 2006). Irrigated cropping systems are a major part of crop production in the central Great Plains, specifically western Kansas. In 2002, there was approximately 1.1 million hectares of irrigated cropland in Kansas with almost 50 percent of the irrigated cropland in corn (NASS, 2004).

Cropping systems research to prolong the life of the aquifer has been mainly focused around the use of more efficient irrigation methods, irrigation timing, or the effects of limited versus full irrigation. Limited research has been done, however, on improving cropping systems through the inclusion of different crops, especially drought tolerant crops like grain sorghum and cotton, into traditional crop rotations as an effective tool to prolonging the life of the aquifer.

Crop models pose distinct advantages for use in scientific research. Traditional in-field research requires significant investments of time, labor, money, and other resources. Cropping systems research usually requires long-term experiments to take into account variations in yearly climatic conditions, such as temperature and precipitation. Crop models, once calibrated, allow researchers to simulate multiple years of experiments, utilizing historical weather data, in a matter of hours. The objective of this research was to study the simulated effects of different irrigation amounts and initial soil water contents on corn, cotton, and grain sorghum.

Materials and Methods

Simulations were conducted using CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton to evaluate the effects of irrigation amounts and initial soil moisture levels in these crops. Simulations were conducted with a Crete (Fine, smectitic, mesic Pachic Argiustoll) soil, with a loam surface texture, and a depth of 183 cm. Weather data for the simulations was from Garden City, KS from 1961 to 1999.

Three treatments for the soil initial water content were established at 100, 75, and 50% plant available water, measurement dates were set equal to the respective planting dates for each crop. The 100% profile had volumetric water contents of 0.194, 0.226, 0.32, 0.278, 0.296, 0.273, 0.278, and 0.272 cm^3 for base layer depths of 18, 28, 38, 61, 71, 97, 122, and 152 cm, respectively. Volumetric water contents, for the same base layer depths as above, of 0.171, 0.207, 0.3, 0.263, 0.267, 0.242, 0.242, and 0.237 cm^3 and 0.148, 0.188, 0.28, 0.248, 0.238, 0.212, 0.206, and 0.202 cm^3 were used for the 75 and 50 percent treatments. These profile values were calculated by the XBuild function in DSSAT.

Irrigation amounts of 36, 25, 18, and 0 mm were used. Irrigation events started on 14, June and occurred every seven days, ending on 23, August. Irrigation amounts were designed to provide approximately 5, 3.75, 2.5, and 0 mm d^{-1} to evaluate differences among full and limited irrigation and dryland scenarios.

Simulated planting dates were 16, April, 23, May, and 30, May with emergence dates seven days later for corn, cotton, and grain sorghum, respectively. Plant densities at emergence were 6.7, 9.5, and 15.0 plants m^{-2} for the corn, cotton, and grain sorghum, respectively. Planting depths were 5 cm for corn and grain sorghum and 3 cm for cotton and row spacing was 76 cm for all three crops. Nitrogen and symbiosis were turned to no and unlimited N in the simulation options, so that N was not a yield limiting factor. All simulations were started on the same day as the planting dates for the respective crops with initial soil conditions as reported. The cultivars used were those created through model calibration, as described in chapter three. The coefficient settings for the three models can be found in the appendix.

The simulation output was evaluated for each crop based on yield, evapotranspiration (ET), water use efficiency (WUE), available soil water at maturity, and gross income per hectare. Yield, ET, and available soil water at maturity were obtained from the model output, except yield for cotton which was determined by taking the output for reproductive biomass times 0.27. Water use efficiency was determined by dividing yield by ET. Two gross incomes per hectare were calculated for the corn using \$0.12 kg^{-1}, which is the price given in Farm Management Guide (Dumler, T.J. and C.R. Thompson, 2006a), and \$0.16 kg^{-1} which better represents the current grain markets. Gross income per hectare for grain sorghum was calculated using \$0.10 kg^{-1}, price used in the Farm Management Guide (Dumler, T.J. and C.R. Thompson, 2006b), and \$0.15 kg^{-1}, which represents current markets. Cotton gross income per hectare was calculated using \$1.19 kg^{-1}, the current market price. Results were analyzed with SAS v9.1 using PROC GLM with years as replications as cited by Baumhardt (200).

Results and Discussion

No significant interactions were observed between the irrigation rate and initial soil water content treatments for any of the crops simulated (Tables 4.1, 4.2, and 4.3). Both irrigation and initial soil water content were significant, for almost all six variables, for both the corn and grain sorghum simulations. The only exception was in grain sorghum where available soil water at maturity was not significant for the initial soil water content treatment. For cotton, irrigation rate was significant for all five variables; however, initial soil water content was only significant for ET.

Corn yield, ET, WUE, and gross income all decreased as irrigation rates declined (Table 4.4). The greatest decrease in values occurred when no irrigation was applied. Full irrigation provided the highest corn yields and gross incomes. Limited irrigation, however, did not cause a major decrease in yield and gross income and would still result in higher yields and income than dryland. No difference were observed in any of the variables between the 100 and 75% initial soil water contents however; a decrease was observed in all variables at the 50% initial soil water content (Table 4.5).

Table 4.1 Analysis of variance results for corn simulations.

Source	DF	Mean Square	F Value	Pr>F
Yield (kg ha^{-1})				
Irrigation	3	2 488 127 424.00	441.94	<.0001
Initial Soil Water	2	48 533 691.00	8.62	0.0002
Irrigation*Initial Soil Water	6	1 696 799.00	0.30	0.9361
Error	456	5 630 017.00		
Evapotranspiration (mm)				
Irrigation	3	1 030 039.80	414.24	<.0001
Initial Soil Water	2	30 819.39	12.39	<.0001
Irrigation*Initial Soil Water	6	1066.22	0.43	0.8598
Error	456	2486.59		
Water Use Efficiency (kg mm^{-1})				
Irrigation	3	4790.28	339.81	<.0001
Initial Soil Water	2	62.86	4.46	0.0121
Irrigation*Initial Soil Water	6	9.26	0.66	0.6844
Error	456	14.10		
Available Soil Water at Maturity (mm)				
Irrigation	3	181 304.73	191.00	<.0001
Initial Soil Water	2	10 469.44	11.03	<.0001
Irrigation*Initial Soil Water	6	49.08	0.05	0.9994
Error	456	949.23		
Gross Income at \$0.12 (\$ ha^{-1})				
Irrigation	3	34 560 850.70	441.94	<.0001
Initial Soil Water	2	674 145.90	8.62	0.0002
Irrigation*Initial Soil Water	6	23 568.70	0.30	0.9361
Error	456	78 202.70		
Gross Income at \$0.16 (\$ ha^{-1})				
Irrigation	3	61 441 505.90	441.94	<.0001
Initial Soil Water	2	1 198 491.00	8.62	0.0002
Irrigation*Initial Soil Water	6	41 900.20	0.30	0.9361
Error	456	139 027.10		

Table 4.2 Analysis of variance results for grain sorghum simulations.

Source	DF	Mean Square	F Value	Pr>F
Yield (kg ha^{-1})				
Irrigation	3	767 865 201.00	358.99	<.0001
Initial Soil Water	2	13 628 467.00	6.37	0.0019
Irrigation*Initial Soil Water	6	1 894 591.00	0.89	0.5051
Error	456	2 138 958.00		
Evapotranspiration (mm)				
Irrigation	3	1 724 108.88	520.26	<.0001
Initial Soil Water	2	29 396.96	8.87	0.0002
Irrigation*Initial Soil Water	6	3936.23	1.19	0.3115
Error	456	3313.92		
Water Use Efficiency (kg mm^{-1})				
Irrigation	3	661.95	129.96	<.0001
Initial Soil Water	2	22.39	4.40	0.0129
Irrigation*Initial Soil Water	6	7.80	1.53	0.1657
Error	456	5.09		
Available Soil Water at Maturity (mm)				
Irrigation	3	15 912.38	18.25	<.0001
Initial Soil Water	2	1465.65	1.68	0.1873
Irrigation*Initial Soil Water	6	129.00	0.15	0.9894
Error	456	871.78		
Gross Income at \$0.10 (\$ ha^{-1})				
Irrigation	3	8 322 342.98	358.99	<.0001
Initial Soil Water	2	147 706.18	6.37	0.0019
Irrigation*Initial Soil Water	6	20 534.07	0.89	0.5051
Error	456	23 182.69		
Gross Income at \$0.15 (\$ ha^{-1})				
Irrigation	3	16 665 442.26	358.99	<.0001
Initial Soil Water	2	295 786.79	6.37	0.0019
Irrigation*Initial Soil Water	6	41 119.29	0.89	0.5051
Error	456	46 423.02		

Table 4.3 Analysis of variance results for cotton simulations.

Source	DF	Mean Square	F Value	Pr>F
Yield (kg ha^{-1})				
Irrigation	3	8 628 556.34	171.30	<.0001
Initial Soil Water	2	96 704.47	1.92	0.1478
Irrigation*Initial Soil Water	6	38 407.83	0.76	0.5998
Error	456	50 371.91		
Evapotranspiration (mm)				
Irrigation	3	749 107.47	377.52	<.0001
Initial Soil Water	2	9824.01	4.95	0.0075
Irrigation*Initial Soil Water	6	3134.76	1.58	0.1512
Error	456	1984.27		
Water Use Efficiency (kg mm^{-1})				
Irrigation	3	8.39	45.37	<.0001
Initial Soil Water	2	0.12	0.66	0.515
Irrigation*Initial Soil Water	6	0.10	0.54	0.7788
Error	456	0.19		
Available Soil Water at Maturity (mm)				
Irrigation	3	11 453.67	18.22	<.0001
Initial Soil Water	2	4.36	0.01	0.9931
Irrigation*Initial Soil Water	6	6.63	0.01	1
Error	456	628.49		
Gross Income ($ ha^{-1})				
Irrigation	3	12 177 861.93	171.30	<.0001
Initial Soil Water	2	136 482.67	1.92	0.1478
Irrigation*Initial Soil Water	6	54 206.91	0.76	0.5997
Error	456	71 092.12		

Table 4.4 Means for corn simulations for the four irrigation amounts.

Irrigation Treatment (mm d^{-1})	Mean					
	Yield (kg ha^{-1})	Evapotranspiration (mm)	Water Use Efficiency (kg mm^{-1})	Available Water at Maturity (mm)	Gross Income at $0.12 ($ ha^{-1})	Gross Income at $0.16 ($ ha^{-1})
5	15 484 a[†]	511.4 a	30.3 a	143.4 a	1824.87 a	2433.16 a
3.75	14 057 b	488.2 b	28.7 b	98.1 b	1656.66 b	2208.88 b
2.5	11 896 c	452.6 c	26.0 c	73.6 c	1402.08 c	1869.43 c
0	5074 d	302.8 d	16.0 d	51.7 d	597.95 d	797.26 d

[†] Means followed by the different letters in the same column are different at the 0.05 probability level

Table 4.5 Means for corn simulations for the three initial soil water contents.

Soil Water Treatment (%)	Mean					
	Yield (kg ha^{-1})	Evapotranspiration (mm)	Water Use Efficiency (kg mm^{-1})	Available Water at Maturity (mm)	Gross Income at \$0.12 (\$ ha^{-1})	Gross Income at \$0.16 (\$ ha^{-1})
100	12 102 a[†]	451.06 a	25.73 a	98.98 a	1426.29 a	1901.72 a
75	11 768 a	441.74 a	25.43 a	93.28 a	1386.90 a	1849.20 a
50	11 013 b	423.43 b	24.51 b	82.83 b	1297.97 b	1730.62 b

[†] Means followed by the different letters in the same column are different at the 0.05 probability level

In the grain sorghum simulations yield, ET, WUE, and gross incomes all decreased as irrigation amounts decreased (Table 4.6). The largest decrease occurred when no irrigation was applied. Just like in corn, there was a decrease between fully irrigated grain sorghum and limited irrigated grain sorghum while limited irrigation was better than dryland. A decrease in all the variables was seen at the 50% initial soil water content, but no differences were seen between the 100 and 75% soil water contents (Table 4.7).

Table 4.6 Means for grain sorghum simulations for the four irrigation amounts.

Irrigation Treatment (mm d^{-1})	Mean					
	Yield (kg ha^{-1})	Evapotranspiration (mm)	Water Use Efficiency (kg mm^{-1})	Available Water at Maturity (mm)	Gross Income at \$0.10 (\$ ha^{-1})	Gross Income at \$0.15 (\$ ha^{-1})
5	8970 a[†]	561.67 a	15.93 a	58.97 a	933.85 a	1321.48 a
3.75	8004 b	527.75 b	15.07 b	41.11 b	833.25 b	1179.13 b
2.5	6550 c	479.74 c	13.46 c	40.56 b	681.89 c	964.94 c
0	3120 d	289.76 d	10.53 d	31.02 c	324.77 d	459.58 d

[†] Means followed by the different letters in the same column are different at the 0.05 probability level

Table 4.7 Means for grain sorghum simulations for the three initial soil water contents.

Soil Water Treatment (%)	Mean					
	Yield (kg ha^{-1})	Evapotranspiration (mm)	Water Use Efficiency (kg mm^{-1})	Available Water at Maturity (mm)	Gross Income at $0.10 ($ ha^{-1})	Gross Income at $0.15 ($ ha^{-1})
100	6902 a†	476.23 a	14.05 a	45.48 a	718.55 a	1016.81 a
75	6749 a	468.42 a	13.88 a	43.74 a	702.66 a	994.33 a
50	6331 b	449.53 b	13.32 b	39.52 a	659.11 b	932.71 b

†Means followed by the different letters in the same column are different at the 0.05 probability level

In the cotton simulations decreasing irrigation amounts resulted in decreases in ET. Yield and gross income decreased from 3.75 to 2.5 mm d^{-1} and from 2.5 to 0 mm d^{-1} but were not different between 5 and 3.75 mm d^{-1}. Water use efficiency was different from 2.5 to 0 mm d^{-1} and from 5 to 2.5 mm d^{-1}, but no difference was seen between 5 and 3.75 mm d^{-1} and 3.75 and 2.5 mm d^{-1} (Table 4.8). With no difference in yield or gross income between the 5.0 and 3.75 mm d^{-1} irrigation rates, this suggests that irrigated cotton could be grown with less irrigation water than corn or grain sorghum. However, there is still a fairly large difference between limited irrigation and dryland cotton. The only difference between the initial soil water contents for the cotton simulations was for ET between the 75 and 50% soil water contents (Table 4.9).

Table 4.8 Means for cotton simulations for the four irrigation amounts.

Irrigation Treatment (mm d^{-1})	Mean				
	Yield (kg ha^{-1})	Evapotranspiration (mm)	Water Use Efficiency (kg mm^{-1})	Available Water at Maturity (mm)	Gross Income ($ ha^{-1})
5	1216 a†	521.43 a	2.33 a	30.93 a	1444.46 a
3.75	1166 a	505.89 b	2.31 a b	25.83 a	1385.44 a
2.5	1067 b	483.56 c	2.21 b	18.82 b	1267.70 b
0	621 c	346.64 d	1.76 c	8.08 c	737.59 c

†Means followed by the different letters in the same column are different at the 0.05 probability level

Table 4.9 Means for cotton simulations for the three initial soil water contents.

Soil Water Treatment (%)	Mean				
	Yield (kg ha^{-1})	Evapotranspiration (mm)	Water Use Efficiency (kg mm^{-1})	Available Water at Maturity (mm)	Gross Income (\$ ha^{-1})
100	1038 a[†]	470.89 a	2.18 a	21.04 a	1232.71 a
75	1025 a	466.72 a	2.16 a	20.98 a	1217.97 a
50	990 a	455.54 b	2.12 a	20.72 a	1175.72 a

[†] Means followed by the different letters in the same column are different at the 0.05 probability level

Discussion

Of the three crops simulated, corn had the highest yield, WUE, available water at maturity, and gross income, at both prices, and the lowest ET. Grain sorghum had the highest ET of the three crops and the lowest gross income, at both prices. Cotton had the lowest yield, WUE, and available water at maturity of the three. All the variables were affected more by the irrigation rates than the initial soil water contents. Cotton showed the least response to irrigation rates and initial soil water content of the three crops

Corn had higher gross incomes per hectare at the average and the higher current market price than the other two crops, for the three irrigation rates. However, dryland corn had a lower gross income than cotton at the average price, but at the current market price it was slightly higher. Cotton had the next highest gross income of the three. Grain sorghum had the lowest gross income, but only slightly lower at the higher current market price than that of cotton.

Corn had the highest available soil water amounts at maturity in all the treatments of the three crops, with cotton having the lowest. Cotton and grain sorghum are considered to be more drought tolerant than corn and thus you would think that there would mostly likely be more water left at the end of the growing season, however this is not shown in the simulations. A possible reason for this is that since grain sorghum and cotton, especially, have much longer growing seasons than corn, they may use more total water. Based on the simulations, corn would be a better crop in rotation, since it leaves more available water at the end of the season for the next crop than grain sorghum or cotton.

Simulated corn yields were higher for the irrigation rates and slightly lower for the dryland than those actually measured by Norwood and Dumler (2002) in a limited irrigation study at Garden City, KS. They had average yields over the three year study ranging from approximately 10000 kg ha^{-1}, for the highest irrigation rate, to 6000 kg ha^{-1}, for the dryland. Simulated full irrigation sorghum yields were much higher than those measured by Norwood (1995) in a limited irrigation cropping systems study conducted at Garden City. However, simulated dryland yields were generally lower than those measured. Norwood had measured irrigated yields around 5400 kg ha^{-1} and average dryland yields ranging from 5700 to 2100 kg ha^{-1}.

Conclusions

Yield declined as irrigation amounts declined for all three crops as did ET, WUE, available water at maturity, and gross income. However the only differences seen in initial soil water contents were at the 50% of a full profile treatment. Of the three crops, cotton responded the best to decreasing irrigation rates. Cotton simulations showed no difference between the full irrigation amount, 5 mm d^{-1}, and the first limited irrigation amount, 3.75 mm d^{-1}. So irrigated cotton, essentially, could still be grown under full irrigation conditions while using less water than fully irrigated corn or grain sorghum. Cotton also showed it was not really affected by initial soil water content with no differences simulated between any of the three levels, except for ET at 50%. Cotton also showed the smallest drop off in yield and gross income from irrigated conditions to dryland of the three crops.

Corn had the highest gross income per hectare of the three crops at both prices for the three irrigation amounts. However, the cotton had a higher gross income for the dryland scenario. Grain sorghum had the lowest gross income at both prices of the three crops at all of the irrigation amounts.

While the simulations show that corn does the best, especially when looking at gross income, cotton has the potential to save water. The simulations showed that cotton could be grown at lower irrigation amounts than either corn or grain sorghum with no decrease in yield or gross income. If producers are forced to go to more limited irrigation practices, especially in western Kansas, cotton could be a big part of these cropping systems. Also, cropping systems that include cotton have the potential to reduce overall irrigation demand on the Ogallala aquifer, therefore potentially prolonging the life of the aquifer.

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APPENDIX

Table A1. Final cultivar coefficient settings for CERES-Maize after calibration.

Coefficient	Definition	Setting
ECO#	Ecotype code for this cultivar, points to the Ecotype in the ECO file	IB0001
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod.	220.0
P2	Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours).	0.520
P5	Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8°C).	780.0
G2	Maximum possible number of kernels per plant.	1100
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg day^{-1}).	10.00
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.	38.90

Table A2. Final ecotype and cultivar coefficient settings for CERES-Sorghum after calibration.

Coefficient	Definition	Setting
TBASE	Base temperature below which no development occurs, °C	8.0
TOPT	Temperature at which maximum development rate occurs during vegetative stages, °C	34.0
ROPT	Temperature at which maximum development rate occurs for reproductive stages, °C	34.0
DJTI	Minimum days from end of juvenile stage to tassel initiation if the cultivar is not photoperiod sensitive, days	102
GDDE	Growing degree days per cm seed depth required for emergence, GDD cm^{-1}	6.0
RUE	Radiation use efficiency, g plant dry matter MJ PAR^{-1}	3.5
KCAN	Canopy light extinction coefficient for daily PAR	0.85
P3		465
P4		234
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod.	435
P2O	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values higher than P20, the rate of development is reduced.	12.50
P2R	Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P20.	20.0
P5	Thermal time (degree days above a base temperature of 8°C) from beginning of grain filling (3-4 days after flowering) to physiological maturity.	540.0
G1	Scaler for relative leaf size.	20.0
G2	Scaler for partitioning of assimilates to the panicle (head).	8.0
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.	49.00

Table A3. Final ecotype coefficient settings for CROPGRO-Cotton after calibration.

Coefficient	Definition	Setting
MG	Maturity group number for this ecotype, such as maturity group in soybean	02
TM	Indicator of temperature adaptation	01
THVAR	Minimum rate of reproductive development under short days and optimal temperature	0.0
PL-EM	Time between planting and emergence (thermal days)	4.0
EM-V1	Time required from emergence to first true leaf, thermal days	4.0
V1-JU	Time required from first true leaf to end of juvenile phase, thermal days	0.0
JU-R0	Time required for floral induction, equal to the minimum number of days for floral induction under optimal temperature and daylengths, photothermal days	0.0
PM09	Proportion of time between first seed and physiological maturity that the last seed can be formed	0.90
LNGSH	Time required for growth of individual shells (photothermal days)	6.0
R7-R8	Time between physiological and harvest maturity (days)	10.0
FL-VS	Time from first flower to last leaf on main stem (photothermal days)	75.00
TRIFL	Rate of appearance of leaves on the mainstem (leaves per thermal day)	0.20
RWDTH	Relative width of this ecotype in comparison to the standard width per node (YVSWH) defined in the species file (*.SPE)	1.00
RHGHT	Relative height of this ecotype in comparison to the standard height per node (YVSHT) defined in the species file (*.SPE)	1.00
THRSH	The maximum ratio of (seed/(seed+shell)) at maturity. Causes seed to stop growing as their dry weights increase until shells are filled in a cohort. (Threshing percentage).	74.0
SDPRO	Fraction protein in seeds (g(protein) g^{-1}(seed))	0.153
SDLIP	Fraction oil in seeds (g(oil) g^{-1}(seed))	0.120
R1PPO	Increase in daylength sensitivity after R1 (CSDVAR and CLDVAR both decrease with the same amount) (h)	0.001
OPTBI	Minimum daily temperature above which there is no effect on slowing normal development toward flowering (°C)	20.0
SLOBI	Slope of relationship reducing progress toward flowering if TMIN for the day is less than OPTBI	0.001

Table A4. Final cultivar coefficient settings for CROPGRO-Cotton after calibration.

Coefficient	Definition	Setting
CSDL	Critical Short Day Length below which reproductive development progresses with no daylength effect (for shortday plants) (hour)	23.00
PPSEN	Slope of the relative response of development to photoperiod with time (positive for shortday plants) (1 hour^{-1})	0.01
EM-FL	Time between plant emergence and flower appearance (photothermal days)	30.0
FL-SH	Time between first flower and first pod (photothermal days)	12.0
FL-SD	Time between first flower and first seed (photothermal days)	17.0
SD-PM	Time between first seed and physiological maturity (photothermal days)	45.00
FL-LF	Time between first flower and end of leaf expansion (photothermal days)	75.00
LFMAX	Maximum leaf photosynthesis rate at 30 C, 350 vpm CO^2, and high light (mg CO^2 m^2-s^{-1})	1.10
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	170
SIZLF	Maximum size of full leaf (three leaflets) (cm^2)	300.0
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.80
WTPSD	Maximum weight per seed (g)	0.180
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	35.0
SDPDV	Average seed per pod under standard growing conditions (#/pod)	27.00
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	9.0

Table A.5 Specific management data for the research location sites in Kansas in 2005.

Location	Crop	Date	Activity
Cullison	Corn	19-Apr	8 gal/a High NRGN, 1 qt/a Micro 500, 4.5 gal/a 9-24-3 starter
		28-May	0.5 oz/a AIM EW, 16 oz/ac Atrazine, 2 qt/a Bicep II Magnum
			115 units/a actual N sidedress
			10 gal/a 28-0-0 with herbicide
			10 gal/a High NRGN threw pivot
			5 oz/a Capture
Cullison	Cotton	20-May	8 gal/a High NRGN, 1 qt/a Micro 500, 4.5 gal/a 9-24-3 starter
		18-Jun	4 oz/a Acephate 90
		30-Jun	4 oz/a Acephate 90
			10 gal/a High NRGN, 1 gal/a SureK threw pivot
			Glyphosate
			Glyphosate
			1 qt/a Caperol & Direx 4L
			4 oz/a MEP 42
			6 oz/a MEP 42
			2 pt/a Prep, 1 pt/a Def
Moscow	Corn	13-Mar	192 lb/a 82-0-0, 9.4 gal/a 10-34-0 preplant strip till
		26-Apr	40 oz/a glyphosate, 4 oz/a 2,4-D
		19-May	32 oz/a glyphosate, 40 oz/a Atrazine 4L, 3 oz/a 2,4-D
			30 lb/a 32-0-0 threw pivot
Moscow	Cotton	16-Mar	30 lb/a 82-0-0, 4.6 gal/a 10-34-0 preplant strip till
		20-Jun	26 oz/a Roundup Max, 4 oz/a Acephate
		25-Jun	11 oz/a Omax, 16 oz/a Dual Magnum
		09-Jul	1.6 oz/a Baythroid, 1 oz/a PGR IV Plus, 8 oz/a Mepiquat Extra
		25-Jul	20 oz/a glyphosate
		20-Aug	16 oz/a Mepiquat Extra
		07-Oct	36 oz/a Super Boll
Preston	Grain Sorghum		

Table A.6 Specific management data for the research location sites in Kansas in 2006.

Location	Crop	Date	Activity
Cullison	Corn	05-Apr	1 lb/a Atrazine, 0.5 lb/a 2,4-D
			10 gal/a High NRGN, 3 gal/a 9-24-3, 1 qt/a
		24-Apr	Micro 500 starter
		02-Jun	2 oz/a Distinct, 1 lb/a Atrazine
			6 gal/a High NRGN
			100 lb/a N sidedress
Cullison	Cotton	08-Apr	0.5 lb/a 2,4-D, 1 oz/a Baur
			10 gal/a High NRGN, 3 gal/a 9-24-3, 1 qt/a
		03-May	Micro 500 starter
		24-May	32 oz/a glyphosate
		30-May	4 oz/a Orthene
		07-Jun	32 oz/a glyphosate, 6 oz/a Orthene
		29-Jun	2.3 oz/a Methachlore
		06-Jul	75 lb/a N sidedress
		20-Jul	0.15 oz/a Envoke, 12 oz/a Mepiquat
		10-Oct	2.5 pt/a Prep
Manhattan	Corn	06-Mar	30 gal/a 28-0-0 preplant
		19-Apr	35 lb/a P2O5 at planting
		21-Apr	32 oz/a RoundUp and Bicep II
		02-Jun	100 lb/a 46-0-0 topdress
Manhattan	Grain Sorghum	06-Mar	30 gal/a 28-0-0 preplant
			32 oz/a RoundUp, 1.7 pt/a Dual II Magnum,
		02-Jun	2.6 lb/a Milo Guard
Moscow	Corn	26-Jan	50 lb/a N, 25 lb/a P preplant strip till
		26-Apr	10 gal/a 32-0-0 starter
		03-May	32 oz/a Roundup, 2 oz/a 2,4-D, 2 oz/a Banvel
		08-Jun	32 oz/a Aatrex, 3.5 oz/a Distinct
		11-Jun	30 gal/a 32-0-0 topdress
Moscow	Cotton	23-Feb	50 lb/a N, 35 lb/a P preplant strip till
		22-May	32 oz/a glyphosate, 0.5 oz/a Distinct
		10-Jun	40 oz/a glyphosate, 16 oz/a Arrow
		01-Jul	28 oz/a glyphosate, 3.5 oz/a Mepiquat Chloride
		19-Jul	32 oz/a glyphosate, 7 oz/a Mepiquat Chloride
		11-Aug	10.8 oz/a Mepiquat Chloride
		18-Aug	2.8 oz/a Mustang Max
		01-Sep	32 oz/a glyphosate
		10-Oct	2 pt/a Boll Opener, 0.75 oz/a ET 2.5% EC
Partridge	Corn	20-Apr	100 lb/a N topdress
Partridge	Cotton	20-Apr	100 lb/a N topdress
Partridge	Grain Sorghum	20-Apr	100 lb/a N topdress

Table A.7 Irrigation dates and amounts for the research location sites in Kansas in 2005.

Location	Crop	Date	Amount (mm)
Cullison	Corn	24-Jun	20.3
		26-Jun	20.3
		28-Jun	20.3
		01-Jul	20.3
		10-Jul	20.3
		15-Jul	20.3
		17-Jul	20.3
		21-Jul	20.3
		23-Jul	20.3
		25-Jul	20.3
		29-Jul	20.3
		01-Aug	20.3
		08-Aug	20.3
Cullison	Cotton	18-Jul	12.7
		20-Jul	12.7
		25-Jul	19.1
		29-Jul	12.7
		01-Aug	25.4
		03-Aug	19.1
Moscow	Corn	18-Jun	25.4
		25-Jun	20.3
		26-Jun	25.4
		03-Jul	20.3
		03-Jul	25.4
		10-Jul	20.3
		11-Jul	25.4
		18-Jul	20.3
		19-Jul	25.4
		27-Jul	20.3
		28-Jul	25.4
		03-Aug	20.3
		08-Aug	25.4
		13-Aug	20.3
		14-Aug	25.4
		20-Aug	20.3
		21-Aug	25.4
Moscow	Cotton	none	
Preston	Grain Sorghum	14-Jul	12.7
		25-Jul	12.7
		02-Aug	12.7
		04-Aug	25.4
		09-Aug	12.7
		31-Aug	12.7
		03-Sep	12.7
		09-Sep	12.7
		12-Sep	12.7
		14-Sep	12.7
		21-Sep	12.7
		26-Sep	12.7

Table A.8 Irrigation dates and amounts for the research location sites in Kansas in 2006.

Location	Crop	Date	Amount (mm)
Cullison	Corn	10-May	20.3
		30-May	20.3
		04-Jun	20.3
		09-Jun	20.3
		17-Jun	20.3
		28-Jun	20.3
		01-Jul	20.3
		05-Jul	20.3
		10-Jul	20.3
		13-Jul	20.3
		15-Jul	20.3
		17-Jul	20.3
		20-Jul	20.3
		23-Jul	20.3
		25-Jul	20.3
		28-Jul	20.3
		01-Aug	20.3
		08-Aug	20.3
Cullison	Cotton	09-Jun	12.7
		03-Jul	19.1
		12-Jul	19.1
		14-Jul	19.1
		16-Jul	19.1
		22-Jul	19.1
		26-Jul	19.1
		11-Aug	19.1
		17-Aug	19.1
Moscow	Corn	28-May	19.1
		31-May	19.1
		12-Jun	19.1
		16-Jun	19.1
		20-Jun	19.1
		23-Jun	19.1
		26-Jun	19.1
		30-Jun	19.1
		03-Jul	12.7
		05-Jul	19.1
		08-Jul	19.1
		11-Jul	19.1
		14-Jul	12.7
		16-Jul	19.1
		19-Jul	12.7
		21-Jul	19.1
		24-Jul	19.1
		04-Aug	19.1
		07-Aug	19.1
Moscow	Cotton	10-May	63.5
		10-Jul	20.3
		01-Aug	20.3

Table A.9 Climatic conditions for research location sites in Kansas in 2005.

Location and Month	Temperature				Precipitation	
	Average Max.	Average Min.	Daily Average	Departure from Normal	Total	Departure from Normal
	°C				cm	
Cullison						
April	19.6	5.6	12.8	-0.6	4.80	-2.13
May	25.3	11.9	18.5	0.1	7.39	-2.21
June	30.5	17.0	23.8	-0.1	14.45	4.55
July	32.5	18.6	25.5	-1.2	8.92	0.48
August	31.3	18.5	24.5	-1.6	14.00	6.48
September	30.0	15.3	22.6	1.1	1.42	-5.03
October	22.1	7.6	14.4	-0.7	7.29	1.57
November	17.1	0.2	8.2	1.3	0.79	-2.69
Moscow						
April	21.0	3.6	12.3	0.3	1.88	-2.31
May	24.6	9.4	17.0	-0.3	8.43	0.84
June	30.6	15.2	22.9	-0.3	2.74	-4.50
July	33.5	16.8	25.2	-0.7	4.70	-2.06
August	31.6	16.7	24.1	-0.6	10.46	5.23
September	29.9	14.2	22.1	2.2	8.03	3.84
October	22.3	5.9	14.1	0.8	7.77	4.78
November	17.0	-1.7	7.7	2.1	0.61	-1.57
Preston						
April	19.0	5.0	12.0	-1.3	4.50	-2.44
May	25.0	11.5	18.2	-0.2	5.94	-3.66
June	30.3	17.4	23.9	-0.1	12.67	2.77
July	33.2	18.1	25.6	-1.1	13.06	4.62
August	32.2	18.7	25.4	-0.6	20.32	12.80
September	30.3	14.6	22.4	0.9	6.63	0.18
October	21.8	7.0	14.4	-0.7	4.88	-0.84
November	16.6	0.0	8.3	1.5	1.17	-2.31

Table A.10 Climatic conditions for the research location sites in Kansas in 2006.

Location and Month	Temperature				Precipitation	
	Average Max.	Average Min.	Daily Average	Departure from Normal	Total	Departure from Normal
	°C				cm	
Cullison						
April	24.7	6.9	15.8	2.4	4.62	-2.31
May	26.5	12.3	19.4	0.9	10.44	0.84
June	32.7	17.1	24.9	1.0	8.61	-1.30
July	35.1	20.0	27.6	0.9	7.37	-1.07
August	31.7	19.7	25.7	-0.4	8.08	0.56
September	26.0	10.9	18.5	-3.0	2.06	-4.39
October	20.1	6.7	13.4	-1.7	6.68	0.97
November	14.3	0.3	7.3	0.5	0.43	-3.05
Manhattan						
April	22.7	7.3	15.0	2.2	7.01	-0.79
May	25.2	11.9	18.5	0.2	7.32	-5.59
June	31.0	16.8	23.9	0.2	3.68	-9.60
July	33.8	20.6	27.2	0.6	9.42	-0.99
August	32.5	19.5	26.0	0.5	28.30	19.99
September	24.3	10.8	17.5	-2.9	5.05	-4.27
October	19.0	5.7	12.3	-1.6	6.38	-0.66
November	13.8	-0.4	6.7	0.9	0.18	-5.16
Moscow						
April	24.4	5.7	15.0	3.0	0.71	-3.48
May	27.6	11.3	19.4	2.1	4.22	-3.38
June	33.2	16.0	24.6	1.4	5.31	-1.93
July	34.2	18.5	26.3	0.5	6.12	-0.64
August	31.1	17.9	24.5	-0.1	9.73	4.50
September	25.2	10.6	17.9	-2.0	2.06	-2.13
October	21.3	5.1	13.2	-0.2	4.37	1.37
November	14.3	-2.9	5.7	0.1	0.00	-2.18

Table A.10 (continued)

Location and Month	Temperature				Precipitation	
	Average Max.	Average Min.	Daily Average	Departure from Normal	Total	Departure from Normal
	°C				cm	
Partridge						
April	24.3	7.9	16.1	4.1	4.42	-2.77
May	25.8	12.7	19.3	1.7	7.26	-3.81
June	32.3	17.2	24.7	1.2	9.32	-0.76
July	35.6	20.4	28.0	1.4	6.50	-2.90
August	33.2	20.5	26.8	1.2	6.73	-0.81
September	26.5	11.5	19.0	-1.8	4.57	-3.10
October	20.2	7.0	13.6	-0.2	3.71	-2.46
November	15.1	-0.5	7.3	1.5	0.00	-3.96

Table A.11 Measured plant data at the research location sites in Kansas in 2005.

Location	Crop	Sampling Date (DAP)	Growth Stage	Height Avg (cm)	Height Std (cm)	Nodes Avg	Nodes Std
Cullison	Corn	62	11-12 leaf				
		79	R1-R2				
		98	R3-R4				
		144	R6				
Cullison	Cotton	67		50-55		13-15	
		88		70-87		18.5	1
		113		69.78	13.94	19.03	3.2
Moscow	Corn	66	10 leaf				
		81	13-15 leaf				
		100	R3				
		146	R8				
Moscow	Cotton	67					
		88		60-74			
		113		74.69		3.43	
Preston	Grain Sorghum	67		122.25	5.12		
		94	9				

Table A.12 Measured plant data at the research location sites in Kansas in 2006.

Location	Crop	Sampling Date (DAP)	Growth Stage	Height Avg (cm)	Height Std (cm)	Node # Avg	Node # Std
Cullison	Corn	50	V10			12-13	
		79	R2	239-247		20	
		100	R5				
		140	R6				
Cullison	Cotton	70		45.15	3.21	16.15	0.69
		91		80.32	7.72	19.74	2.64
		132		85.16	6.74	22.21	2.42
Manhattan	Corn	42	V6-7				
		51	V9-10				
		57	V11-12	95-105		14-15	
		64	V13-14			17	
		71	V16-17	130-170		19	
		79	VT-R1	200-230		22	
		86	R2	225-250			
		96	R3-R4				
		103	R4-5				
		110	R5				
		125	R6				
Manhattan	Grain Sorghum	24	4-6 leaf				
		32	7-9 leaf	23-38			
		39	10-11 leaf	45-65			
		49	Flag leaf-Boot	55-65			
		56	Heading-Anthesis	85-110			
		63	Anthesis-Milk	90-110			
		72	Milk-Dough	85-100			
		78	Dough				
		85	Hard Dough				
Moscow	Corn	49	V9			11-12	
		76	R1	235		20	
		98	R4				
		133	R6				
Moscow	Cotton	49		33.81	4.6	11.03	1.47
		71		58.39	9.11	14.33	2.19
		106		61.16	8.36	16.71	1.85
Partridge	Corn	60	V11-12	115-120			
		89	R3	232			
		111	R4-R5				
Partridge	Cotton	43		26.68	6.83	8.54	1.73
		65		41.91	10.82	11.27	2.49
		105		47.79	8.46	13.29	1.73
Partridge	Grain Sorghum	43	11-12 leaf	55-65			
		65	Boot-Anthesis	75-90			
		105	Harvested				

Table A.13 Measured leaf area data at the research location sites in Kansas in 2005.

Location	Crop	Sampling Date (DAP)	SLA Avg (cm^2 g^{-1})	SLA Std (cm^2 g^{-1})	LAI Avg	LAI Std
Cullison	Corn	62	180.41	17.80	5.36	0.65
		79	168.65	9.97	5.80	0.51
		98	159.53	6.19	6.14	0.45
Cullison	Cotton	67	212.88	7.59	1.69	0.29
		88	145.03	9.65	2.27	0.27
		113	153.03	5.66	2.60	0.58
Moscow	Corn	66	163.97	16.20	3.09	0.32
		81	164.88	5.23	2.62	1.98
		100	145.23	8.91	5.11	0.35
Moscow	Cotton	67	137.10	15.36	0.96	0.09
		88	134.24	30.31	2.11	0.38
		113	150.95	11.99	2.82	0.17
Preston	Grain Sorghum	67	184.25	6.41	3.49	0.49

Table A.14 Measured leaf area data at the research location sites in Kansas in 2006.

Location	Crop	Sampling Date (DAP)	SLA Avg ($cm^2 g^{-1}$)	SLA Std ($cm^2 g^{-1}$)	LAI Avg	LAI Std
Cullison	Corn	50	206.19	6.86	1.51	0.32
		79	151.24	5.71	3.83	0.67
		100	151.14	8.52	3.61	0.55
Cullison	Cotton	70	138.13	6.40	1.18	0.18
		91	175.68	9.49	4.53	1.13
		132	168.06	8.03	4.12	0.59
Manhattan	Corn	42	174.92	8.91	0.40	0.14
		51	215.00	3.96	1.60	0.18
		57	191.50	8.88	2.40	0.31
		64	174.50	7.14	3.50	0.14
		71	162.50	7.07	4.00	0.44
		79	166.20	11.69	3.80	0.27
		86	159.75	5.24	4.40	0.35
		96	159.49	9.78	4.10	0.40
		103	126.59	4.22	3.30	0.18
		110	147.78	6.82	2.20	0.26
Manhattan	Grain Sorghum	24	207.26	14.07	0.09	0.04
		32	247.24	11.10	0.45	0.09
		39	283.42	3.28	1.58	0.00
		49	213.24	10.69	2.87	0.85
		56	192.08	9.44	3.22	0.48
		63	195.84	8.66	3.34	0.72
		72	189.21	7.93	2.75	0.35
		78	184.59	5.36	2.72	0.26
		85	178.81	6.35	2.74	0.35
		94			2.50	0.25
Moscow	Corn	49	201.42	8.59	1.57	0.55
		76	173.70	6.38	4.68	1.34
		98	166.47	14.59	4.26	0.48
Moscow	Cotton	49	171.18	55.15	0.84	0.32
		71	136.99	5.28	1.64	0.34
		106	149.18	9.53	2.11	0.21
Partridge	Corn	60	186.82	5.97	2.85	0.45
		89	155.49	9.90	3.16	0.78
Partridge	Cotton	43	112.42	7.12	0.35	0.19
		65	141.65	5.27	0.77	0.04
		105	132.33	3.66	0.97	0.19
Partridge	Grain Sorghum	43	195.27	9.22	2.47	0.16
		65	147.84	0.77	3.31	0.07
		105	118.94	4.62	2.16	0.23

Table A.15 Measured biomass data at the research location sites in Kansas in 2005.

Location	Crop	Sampling Date (DAP)	Biomass (kg ha^{-1})							
			Leaf Avg	Leaf Std	Stalks Avg	Stalks Std	Reproductive Avg	Reproductive Std	Total Avg	Total Std
Cullison	Corn	62	2982.7	348.2	2530.2	457.3			5512.9	793.7
		79	3444.5	332.1	6357.0	382.8	1219.2	232.1	11 020.6	896.2
		98	3849.1	293.1	7281.1	641.2	8357.2	956.4	19 487.4	1732.2
		144	4569.1	430.4	5492.9	961.2	16 617.9	83.7	26 679.9	1390.6
Cullison	Cotton	67	793.2	112.3	679.0	88.0	152.3	20.3	1624.4	214.8
		88	1560.8	88.4	1637.6	81.7	1524.4	365.1	4722.7	409.3
		113	1711.4	434.2	2022.5	554.2	3464.5	1063.7	7198.4	2046.9
Moscow	Corn	66	1900.4	273.5	1307.8	162.8			3208.2	432.8
		81	3291.9	125.6	4497.2	147.9			7789.1	255.8
		100	3523.6	177.5	5884.4	463.9	4244.2	400.0	13 652.2	473.7
		146	3192.4	295.3	4551.4	762.6	15 959.6	2314.7	23 703.4	3060.5
Moscow	Cotton	67	710.2	102.1	588.7	88.8	87.9	35.3	1386.8	219.1
		88	1594.3	157.3	718.7	136.4	1796.1	113.5	4109.0	393.4
		113	1877.8	222.9	2311.0	207.7	2377.6	490.8	6566.4	909.2
Preston	Grain Sorghum	67	1891.9	262.9	4413.6	708.7	1374.4	210.8	7679.8	1075.9
		94	1817.7	128.2	2822.9	175.1	8096.0	728.6	12 736.6	1020.9

Table A.16 Measured biomass data at the research location sites in Kansas in 2006.

Location	Crop	Sampling Date (DAP)	Biomass (kg ha^{-1})							
			Leaf Avg	Leaf Std	Stalks Avg	Stalks Std	Reproductive Avg	Reproductive Std	Total Avg	Total Std
Cullison	Corn	50	962.5	174.6	603.2	159.1			1565.7	323.3
		79	2530.5	425.2	5336.1	1200.3	2684.8	570.0	10 551.3	1604.5
		100	2377.9	246.7	4570.1	353.0	10 077.1	219.5	17 025.1	765.1
		140	1929.3	266.4	3829.4	429.1	14 467.4	2289.4	20 226.1	2925.0
Cullison	Cotton	70	872.9	110.9	681.3	80.1	98.0	15.3	1652.2	205.1
		91	2561.5	520.4	2643.3	710.2	1396.7	255.2	6601.5	1322.1
		132	2458.7	433.6	3422.6	545.8	7360.6	1239.5	13 241.9	2080.1
		202			2252.1	382.1	7047.8	787.4	9299.9	1129.4
Manhattan	Corn	42	254.3	87.8	154.2	66.4			408.6	153.2
		51	746.9	84.5	641.6	79.1			1388.5	163.1
		57	1253.6	201.6	1201.1	242.3			2454.7	443.1
		64	2033.7	152.2	3974.5	646.4			6008.1	703.4
		71	2449.5	232.3	3425.1	641.9	167.0	33.4	6041.6	891.2
		79	2296.5	180.5	6624.8	812.6	1007.8	155.1	9929.1	1115.8
		86	2734.3	176.9	4710.9	285.5	1935.5	242.3	9380.7	562.9
		96	2583.4	391.2	4684.6	750.7	4562.9	1046.5	11 830.9	2178.6
		103	2613.2	189.4	5026.3	724.0	7852.5	1335.7	15 491.9	2170.7
		110	1512.2	114.8	3559.3	233.7	6796.4	600.9	11 867.9	868.7
		125	2723.2	30.5	4376.1	437.4	7927.9	1184.3	15 027.2	1622.9
Manhattan	Grain Sorghum	24	45.3	15.8	24.3	10.2			69.6	26.0
		32	182.5	46.4	105.0	35.3			287.5	81.7
		39	558.5	6.5	411.5	47.3			970.1	40.8
		49	1355.3	466.9	1430.2	736.1	116.2	164.3	2901.7	1367.3
		56	1671.7	168.0	3312.5	485.5	1287.1	78.9	6271.3	732.4
		63	1699.9	293.3	3363.7	695.2	1579.2	486.4	6642.8	1474.9
		72	1453.1	124.4	3036.2	425.1	3401.8	223.7	7891.2	325.8
		78	1469.5	99.3	2763.8	307.2	4917.3	130.0	9150.7	276.6
		85	1529.9	142.0	2550.5	427.0	6587.0	254.3	10 667.5	30.6
		94	1468.2	91.9	2667.4	172.7	6995.3	480.8	11 130.9	561.6
		113	1583.1	193.1	3268.6	451.1	6157.1	257.1	11 008.8	387.1

Table A.16 (continued)

Location	Crop	Sampling Date (DAP)	Biomass (kg ha^{-1})							
			Leaf Avg	Leaf Std	Stalks Avg	Stalks Std	Reproductive Avg	Reproductive Std	Total Avg	Total Std
Moscow	Corn	49	1016.3	239.1	644.9	139.0			1661.2	377.8
		76	2689.7	755.8	4132.3	1310.2	757.1	171.9	7579.1	2234.4
		98	2589.3	455.0	5015.8	1027.3	6979.9	2299.7	14 584.9	3737.7
		133	2508.9	314.7	3542.9	391.4	10165.4	3279.5	16 217.2	3786.5
Moscow	Cotton	49	483.1	47.4	317.0	56.7	18.0	4.7	818.1	96.5
		71	1201.1	275.0	1433.4	230.1	492.6	131.3	3127.1	629.9
		106	1416.7	166.6	1642.5	223.9	3253.8	282.2	6313.0	623.9
		180			1166.0	219.9	4918.9	693.3	6084.9	611.1
Partridge	Corn	60	1526.7	234.3	1529.3	340.5			3055.9	559.7
		89	2018.0	409.0	4047.0	670.4	395.6	101.8	6460.6	1158.0
		111	2161.6	102.0	4541.4	399.2	988.0	69.2	7691.0	498.3
		151	1394.5	233.8	4004.6	408.4	2012.8	1151.1	7411.8	1195.3
Partridge	Cotton	43	304.5	146.7	207.4	128.1	5.3		514.6	278.5
		65	541.5	4.6	592.7	30.6	93.9	8.4	1228.0	34.3
		105	735.1	120.7	984.5	124.4	1792.5	192.1	3512.1	437.2
		175			817.8	211.6	2466.5	50.1	3284.3	261.8
Partridge	Grain Sorghum	43	1270.0	143.9	833.6	144.8			2103.6	288.7
		65	2241.4	34.3	2684.4	94.7	486.3	142.0	5412.2	13.0
		105	1823.3	263.6	3556.7	416.8	4798.5	249.7	10 178.5	930.1

Table A.17 Measured corn yield and yield component data for the research location sites in Kansas in 2005 and 2006.

Location	Year	Sampling Date (DAP)	Yield Avg* (kg ha^{-1})	Yield Std (kg ha^{-1})	Ear # Avg (ears m^{-2})	Ear # Std (ears m^{-2})	Kernel # Avg (kernels m^{-2})	Kernel # Std (kernels m^{-2})	Kernel Wtg (mg kernel^{-1})
Cullison	2005	144	15360.6	2381.5	6.7	0.45	4620.9	449.2	287.3
Moscow	2005	146	13632.2	921.4	7.0	0.48	3357.0	898.1	306.0
Cullison	2006	140	15468.4	448.1	8.9	0.14	4337.2	67.2	308.8
Manhattan	2006	125	6532.2	473.7	7.6	0.42	3549.4	478.4	160.5
Moscow	2006	133	10027.8	3315.7	9.8	0.76	4033.6	1091.6	214.9
Partridge	2006	151	1662.1	834.5	3.9	0.86	956.1	476.9	149.8

*Yield is standardized at 15.5% moisture.

Table A.18 Measured grain sorghum yield and yield component data for the research location sites in Kansas in 2005 and 2006.

Location	Year	Sampling Date (DAP)	Yield Avg* (kg ha^{-1})	Yield Std (kg ha^{-1})	Head # Avg (heads m^{-2})	Head # Std (heads m^{-2})	Kernel # Avg (kernels m^{-2})	Kernel # Std (kernels m^{-2})	Kernel Wtg (mg kernel^{-1})
Preston	2005	94	6601.9	215.3	14.9	0.86	25010.8	926.1	23.5
Manhattan	2006	113	5270.7	32.2	19.0	2.78	19923.1	1138.4	23.6
Partridge	2006	105	4818.8	69.5	9.8	0.93	17307.5	96.5	24.8

*Yield is standardized at 12.5% moisture.

Table A.19 Measured cotton yield and yield component data for the research location sites in Kansas in 2005 and 2006.

Location	Year	Sampling Date (DAP)	Yield Avg (kg ha^{-1})	Yield Std (kg ha^{-1})	Boll # Avg (bolls m^{-2})	Boll # Std (bolls m^{-2})
Cullison	2005	182	1214.9	159.6	66.3	4.5
Moscow	2005	182	1225.3	95.1	67.8	6.2
Cullison	2006	202	1934.3	94.2	97.1	8.7
Moscow	2006	180	1747.0	111.9	114.2	17.9
Partridge	2006	175	713.5	101.5	45.4	8.8

Table A.20 Soil testing results for the research location sites in Kansas in 2005 and 2006.

Location	Crop	pH	Buffer pH (SMP)	Bray-1 P (ppm)	K (ppm)	NO3-N (ppm)	Organic Matter (%)
2005							
Cullison	Corn	5.5	6.6	50	363	16.3	1.7
Cullison	Cotton	5.3	6.7	25	253	11.1	1.5
Moscow	Corn	7.3		19	581	8.7	1.9
Moscow	Cotton	6.7		33	808	17.7	2.2
Preston	Grain Sorghum	6.2	7.2	45	222	1.5	1.5
2006							
Cullison	Corn	5.9	7.0	21	232	20.2	1.3
Cullison	Cotton	5.1	6.7	62	340		
Manhattan	Corn	6.4	6.7	37	295	23.4	2.2
Manhattan	Grain Sorghum	6.2	6.7	35	288	23.1	2.6
Moscow	Corn	7.9		22	674	11.7	1.8
Moscow	Cotton	7.2		9	492		
Partridge	Corn	5.4	6.3	38	296	4.2	1.1

Table A.21 Beginning soil core data for the research location sites in Kansas in 2005.

Location	Crop	Depth	Gravimetric Water Content (g)	Volumetric Water Content (cm3)	Texture			NO3 N (ppm)
					% Sand	% Silt	% Clay	
Cullison	Corn	0-6"	0.14	0.23	59	27	15	9.5
		6-12"	0.16	0.29	70	13	18	5.1
		1-2'	0.14	0.26	57	21	23	6.1
		2-3'	0.13	0.23	56	27	18	5.9
		3-4'	0.11	0.18	49	32	19	5.6
		4-5'	0.07	0.12	45	37	19	5.7
		5-6'	0.08	0.14	49	35	17	9.9
Cullison	Cotton	0-6"	0.13	0.22	61	28	11	8.4
		6-12"	0.16	0.27	55	30	16	5.7
		1-2'	0.17	0.30	53	30	17	5.2
		2-3'	0.16	0.28	47	30	24	4.8
		3-4'	0.13	0.21	57	23	21	4.6
		4-5'	0.15	0.26	44	32	24	3.8
		5-6'	0.16	0.26	29	40	32	4.5
Moscow	Corn	0-6"	0.16	0.23	50	36	15	4.8
		6-12"	0.19	0.27	51	28	21	3.6
		1-2'	0.21	0.28	37	41	22	2.8
		2-3'	0.21	0.28	19	58	24	2.4
		3-4'	0.19	0.26	22	59	20	4.0
		4-5'	0.19	0.26	27	58	16	8.7
		5-6'	0.16	0.24	32	56	13	7.6
Moscow	Cotton	0-6"	0.19	0.29	25	45	31	15.4
		6-12"	0.20	0.35	18	46	37	11.3
		1-2'	0.18	0.31	17	47	37	10.9
		2-3'	0.19	0.28	21	51	29	8.4
		3-4'	0.18	0.27	19	54	28	5.0
		4-5'	0.19	0.26	20	54	27	4.9
		5-6'	0.17	0.24	25	50	26	9.5
Preston	Grain Sorghum	0-6"	0.13	0.20	86	9	5	5.2
		6-12"	0.12	0.22	84	6	11	3.9
		1-2'	0.15	0.26	73	12	16	2.6
		2-3'	0.15	0.28	48	26	27	1.8
		3-4'	0.14	0.26	41	31	29	3.4
		4-5'	0.13	0.24	47	25	28	2.0
		5-6'	0.12	0.23	52	22	26	5.7

Table A.22 Beginning soil core data for the research location sites in Kansas in 2006.

Location	Crop	Depth	Gravimetric Water Content (g)	Volumetric Water Content (cm^3)	Bulk Density (g cm^{-3})
Cullison	Corn	0-6"	0.14	0.23	1.66
		6-12"	0.16	0.26	1.66
		1-2'	0.14	0.24	1.77
		2-3'	0.07	0.14	1.83
		3-4'	0.09	0.16	1.82
		4-5'	0.16	0.29	1.87
		5-6'	0.19	0.29	1.55
Cullison	Cotton	0-6"	0.16	0.28	1.70
		6-12"	0.19	0.32	1.71
		1-2'	0.19	0.34	1.84
		2-3'	0.17	0.30	1.79
		3-4'	0.12	0.20	1.68
		4-5'	0.09	0.16	1.71
		5-6'	0.10	0.18	1.80
Manhattan	Corn	0-6"	0.20	0.30	1.45
		6-12"	0.25	0.40	1.60
		1-2'	0.26	0.42	1.62
		2-3'	0.24	0.40	1.68
		3-4'	0.23	0.36	1.57
		4-5'	0.22	0.36	1.65
		5-6'	0.21	0.34	1.63
Manhattan	Grain Sorghum	0-6"	0.20	0.27	1.36
		6-12"	0.26	0.38	1.43
		1-2'	0.26	0.41	1.55
		2-3'	0.25	0.39	1.58
		3-4'	0.25	0.38	1.53
		4-5'	0.24	0.36	1.51
		5-6'	0.23	0.40	1.73
Moscow	Corn	0-6"	0.20	0.31	1.55
		6-12"	0.23	0.36	1.57
		1-2'	0.21	0.32	1.57
		2-3'	0.15	0.23	1.53
		3-4'	0.13	0.18	1.41
		4-5'	0.13	0.20	1.47
		5-6'	0.16	0.27	1.68
Moscow	Cotton	0-6"	0.18	0.32	1.77
		6-12"	0.20	0.36	1.76
		1-2'	0.19	0.32	1.64
		2-3'	0.21	0.33	1.59
		3-4'	0.23	0.36	1.60
		4-5'	0.22	0.36	1.61
		5-6'	0.24	0.45	1.85
Partridge	Corn	0-6"	0.14	0.25	1.72
		6-12"	0.16	0.29	1.86
		1-2'	0.17	0.28	1.65
		2-3'	0.20	0.37	1.80
		3-4'	0.20	0.38	1.90
		4-5'	0.21	0.40	1.93
		5-6'	0.21	0.49	

Table A.23 Final soil core data for the research location sites in Kansas in 2005.

Location	Crop	Depth	Gravimetric Water Content (g)	Volumetric Water Content (cm3)
Cullison	Corn	0-6"	0.13	0.22
		6-12"	0.16	0.28
		1-2'	0.12	0.22
		2-3'	0.08	0.15
		3-4'	0.09	0.15
		4-5'	0.09	0.15
		5-6'	0.09	0.14
Cullison	Cotton	0-6"	0.08	0.13
		6-12"	0.07	0.13
		1-2'	0.08	0.14
		2-3'	0.07	0.13
		3-4'	0.10	0.16
		4-5'	0.10	0.18
		5-6'	0.14	0.23
Moscow	Corn	0-6"	0.16	0.23
		6-12"	0.18	0.26
		1-2'	0.21	0.28
		2-3'	0.20	0.26
Moscow	Cotton	0-6"	0.19	0.28
		6-12"	0.20	0.34
		1-2'	0.14	0.23
		2-3'	0.11	0.17
		3-4'	0.10	0.15

Table A.24 Characterization for Crete soil used to build the soil file used in the systems simulations.

Depth (cm)	Clay (%)	Silt (%)	Organic Carbon (%)	pH (in water)	CEC (cmol kg^{-1})	Lower Limit	Drained Upper Limit	Saturation	Bulk Density (g cm^{-3})	Root Growth Factor	Other	
18	26.7	57.0	1.2	5.9	18.1	0.102	0.194	0.407	1.32	0.5	Slope	3%
28	37.7	49.5	1.2	6.9	23.7	0.149	0.226	0.402	1.40	0.5	Runoff Potential	Moderately High
38	36.6	51.3	1.0	7.3	21.9	0.240	0.320	0.401	1.41	0.5	Fertility Factor	1
61	30.9	54.2	0.5	7.5	17.7	0.219	0.278	0.405	1.43	0.2	Color	Brown
71	27.9	57.2	0.5	7.6	17.3	0.180	0.296	0.405	1.40	0.2	Drainage	Well
97	25.8	59.4	0.5	8.0	16.6	0.150	0.273	0.404	1.44	0.2	Runoff Curve Number	84
122	27.1	59.8	0.5	8.2	16.3	0.134	0.278	0.402	1.40	0.2	Albedo	0.13
152	27.1	59.8	0.5	8.2	16.3	0.131	0.272	0.402	1.40	0.2	Drainage Rate	0.6