INCORPORATION OF PIVOT MONITORING EQUIPMENT TO MODEL IRRIGATED COTTON AT LANDSCAPE-SCALE

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Abstract

Advances in computer speed, industry IT core capabilities, and available soil and weather information have resulted in a demand for "*cropping system models*" that address in detail the spatial and temporal water, energy and carbon balance of the system at a landscape scale. Many of these models have been upgraded from column, i.e., two dimensions to distributed or three-dimensional models associated with GIS systems, and supporting the use of readily accessible grid based data, i.e., elevation and soil survey. These GIS linked models are thus tools that can be used to manage agronomic inputs in a cotton system. Furthermore, increased adoption of pivot monitoring systems, which provide continuous position and flow measurements of irrigation water, is providing yet another temporal and spatial dataset that improves the accuracy of water balance modeling irrigated cotton systems. Since pivot irrigation equipment can take several days to complete a circuit around the field, accurate representation of the spatial and temporal dynamics of irrigation input is needed to adequately model the cotton system. One subject of a project among researchers from Texas Tech University, USDA-ARS (Bushland and Lubbock, TX) and the University of Wisconsin-Madison, that will combine the Precision Agricultural-Landscape Modeling System and COTTON2K models, will be to evaluate the effect of using pivot flow and position data in irrigated cotton system simulations. Initial modeling efforts using spatially and temporally representative irrigation input data produced output with a 20% lower root mean squared deviation from measured values, when contrasted with blanket irrigation input.

Introduction

There is an increasing demand, in both agricultural research and agribusiness communities, for "*cropping system models*" that address the water, energy, and carbon balance of the system across the landscape at a detailed level of spatial and temporal resolution. Advances in computer speed, industry information technology capabilities, and available soil, geographic, and weather information have resulted in renewed interest in existing mechanistic models, many of which were developed decades ago. The abilities of these models, when developed, were well ahead of the computational resources of the time, and many have been upgraded from column models, or combined with other models, to produce distributed four-dimensional models associated with geographic information systems (GIS). These GIS linked models are tools that can be used to postulate, evaluate, and/or manage agronomic inputs within the target cropping systems.

Landscape-scale models that simulate mass and energy balance on a detailed spatial and temporal resolution require considerable amounts of similarly detailed input data to form the underlying structure of the model. Such data has become increasingly available. Examples are GIS compatible soil survey and aerial photography datasets from the U.S. Department of Agriculture – Natural Resources Conservation Service and digital elevation model datasets from the U.S. Geological Survey. Use of these free datasets, with some level of expert local knowledge provides adequate detail for the three-dimensional representation of a field or group of fields. This representation of the landscape, in combination with routinely available weather data and records of agronomic management activities, can provide the necessary input for modeling a rainfed or dryland cropping system at a large scale with detailed resolution.

To support the modeling of a pivot irrigated cropping system further information will be needed. Since pivot irrigation equipment can take several days to complete a cycle around the field, the temporal and spatial variability of physical balance dynamics is magnified. Accurate data concerning the position and flow of the pivot equipment is also becoming increasingly available, through the adoption of pivot monitoring equipment. Use of accurate flow and position data, in models that can accept this level of detailed input, should increase the accuracy of pivot irrigated cropping system simulations. One subject of a project consisting of researchers from Texas Tech University, USDA-ARS (Bushland and Lubbock, TX) and the University of Wisconsin-Madison (Booker et al., 2009), that will combine the Precision Agricultural-Landscape Modeling System (PALMS) and COTTON2K models, will be to evaluate the effect of using pivot flow and position data in irrigated cotton system simulations. The combination of PALMS and COTTON2K will support the simulation of center-pivot irrigated cotton across the landscape at a very detailed temporal and spatial resolution, and thus provide a tool for the evaluation of management practices that help improve cotton crop economics under limited water resource conditions.

Models

The PALMS model is a hydrologic model that is designed to perform at landscape-scale and represent spatial and temporal variability discussed above. It was developed to address several specific limitations identified by the developers during a review of numerous surface water models; details of this review and the model development are presented by Molling et al. (2005). The model has been extensively tested in the Midwest to model surface and subsurface hydrology, plant soil relationships, and calculate erosion and runoff in corn and soybean cropping systems (Morgan, 2003; Bonilla, 2007; Bonilla, 2007). The model has recently been applied, calibrated, and tested in dryland cotton systems in the Southern High Plains of Texas (SHP); however, efforts were limited by the fact that the model does not yet have a cotton growth simulation component (Nelson, 2010).

The PALMS model, developed by personnel at the University of Wisconsin-Madison, is an amalgamation of governing equations from the CASC2D model developed by Julien et al. (1995) and a version of the IBIS (Integrated Biosphere Simulator) model developed by Foley et al. (1996), modified by Kucharik and Brye (2003) to specifically address agricultural cropping systems and published under the name of AgroIBIS.

The CASC2D model simulates infiltration using the Green and Ampt equations and surface water flow using two-dimensional, diffusive wave runoff equations. The model was originally tested for grid sizes of 300 – 600 feet (100 – 200 m), but was considered valid at smaller grid sizes if detailed elevation and soil texture data were available (Julien et al., 1995). In PALMS, the governing equations in CASC2D are modified by adding a stability factor that provides stable solutions when slopes are close to zero; this allows the equations to accommodate closed depression ponding (Molling et al., 2005).

The IBIS model is designed to simulate biophysical water, carbon, and energy flux between the root zone (soil), plant canopy, and atmosphere within natural vegetation communities at large regional- to continental-scales (Foley, 1996). The AgroIBIS model modified the governing equations in IBIS so that the model was applicable to managed vegetation communities and was useable at much smaller regional- to field-scales (Kucharik, 2003 and Kucharik and Byre, 2003). The PALMS model simulates spatially distributed biophysical processes and fluxes at the field- or landscape-scale, on 15 to 60 foot (5 to 20 m) horizontal grid spacing, within 26 soil layers down to 18 feet (5 m), and at 15 minute time steps. This equates, over a quarter section field, to around 17+ million 'location by time step' discretizations within the model's domain during each model day.

In order to manage this large volume of data and calculations, PALMS uses Unidata's netCDF file format for input and output. The use of netCDF format seems to be fairly unique within the agricultural research community. This binary, multi-dimensional format developed and used by the atmospheric science community (Unidata, 2010). It supports the efficient representation of three-dimensional spaces, like that of the soil across a landscape or field, at each time step. The format is supported by commonly used software, such as ArcGIS, R, and Matlab, and there is an extensive group of user produced tools and support forums available on the internet (Unidata, 2010).

The model COTTON2K is a likely candidate to be coupled with PALMS in order to allow the modeling of irrigated cotton systems on the SHP. COTTON2K is based on the cotton model GOSSYM-COMAX developed by USDA-Agricultural Research Service (USDA-ARS), but was developed specifically to improve the calculation of water, energy, and carbon balance for irrigated cotton grown in arid and semi-arid regions (Marani, 2004). The COTTON2K model has been shown to outperform its parent model, GOSSYM-COMAX, when applied to irrigated cotton systems of the SHP (Clouse, 2006).

The COTTON2K model is a refinement of the USDA-ARS model GOSSYM/COMAX. COTTON2K uses the governing equations of GOSSYM/COMAX, but specifically differs in its use of weather data (Marani, 2004). The model uses the same daily weather data that GOSSYM/COMAX uses, but calculates hourly weather values according to equations developed by Ephrath et al. (1996). Hourly weather values are then used to calculate water and energy balances hourly; allowing the model to more closely represent arid and semi-arid conditions. The use of an hourly time step improves the model's ability to calculate water balance under these conditions. Ephrath et al. (1996) stated:

> *"Most physiological processes, such as photosynthesis enzymatic activity, respiration, transpiration, translocation and absorption of nutrients, respond instantaneously to weather variables, so that daily totals or means of the required weather data are not sufficient."*

They went on in the article to discuss that deviations created by using daily weather data time steps, rather than shorter time steps, was "particularly" important when hourly data followed nonlinear diurnal patterns or where interactions of weather parameters were important in calculation of energy or water balances, i.e., nonlinear diurnal wind speed patterns and/or interactions of wind speed and solar irradiation driving evapotranspiration.

The COTTON2K model is similar in overall function to AgroIBIS, i.e., it is a biophysical model based on mechanistic equations for calculating mass and energy flux within the soil, canopy, and atmosphere domain and is specifically intended for managed agricultural systems. Like IBIS and AgroIBIS, COTTON2K was designed as a column model and is generally run to represent an entire field or individual area of a field, using average input and parameter values for the modeled area. The model can be run for several areas (represented as different soil profiles) within a field, but does not address interactions between these areas.

The combined model, i.e., PALMS with COTTON2K embedded as a cotton crop growth model, is currently in the final 'debugging' stage of development. Once the model is debugged, then testing on historical research station data from sites with contrasting soil series, Amarillo sandy loam and Pullman clay loam, will begin. Initial development will be followed by testing and evaluation of the model under production conditions on two producer fields with the same contrasting soil series. The modeling results exhibited here use the existing PALMS model with the soybean growth model utilized to represent the cotton crop; allowing preliminary contrasts between different strategies of pivot irrigation input for the modeling efforts to be evaluated. The objective of this manuscript and the associated presentation during the 2011 Beltwide Cotton Conferences is to introduce the project's efforts and exhibit modeling results using temporally and spatially representative irrigation input files.

Materials and Methods

The field site is located northeast of Littlefield, TX (latitude 33.9519, longitude -102.2735). This field was chosen due to its variability in soil series and elevation (Figure 1). Elevation ranges from ~ 3,563 feet at a knoll on the western side of the field to 3,537 feet in the bottom of a playa at the north edge of the field. The northern two thirds of the field are mapped as a combination of Amarillo fine sandy loam and loamy fine sand (Fine-loamy, mixed, superactive, thermic Aridic Paleustalfs). The northern third of the field, grading down slope into the playa area, is mapped as Berda loam (Fine-loamy, mixed, superactive, thermic Aridic Haplustepts) transitioning into Gomez loamy fine sand (Fine-loamy, mixed, superactive, thermic Aridic Haplustepts).

The field was planted flat, i.e., with no beds or furrows, to sorghum (*Sorghum bicolor*) in 2009 with the stubble being retained after harvest. The 2010 cotton seedbed was prepared by strip tillage, thus retaining most of the previous crops residue. Cotton (*Gossypium spp.*) was planted on 11 May 2010. Irrigation was initiated on the 24 July and the pivot applied an average of three quarters of an inch of irrigation (19 mm), to alternate rows, per 4 ½ day cycle. Total irrigation applied to the field, between 24 July 2010 and 16 September 2010 was 8.7 inches (220 mm).

Soil water potential was measured at 15 minute intervals throughout the growing season using a Watermark© (Spectrum Technologies, Inc., 2010) granular matrix sensor. This sensor was installed at an 18° angle, with the center of the sensor being placed at 6 inches below the soil surface. Soil water potential data from the Watermark sensor was translated to volumetric water content using the function published by Campbell (1974), the same function used in the PALMS model. The function, which relates the soil water potential with volumetric water content, is $\mathbf{\Psi = \Psi_e (\theta/\theta_s)^{-b}}$ where Ψ is the soil water potential, Ψ_e is the air entry potential, θ is the volumetric soil water content, θ_s is the saturated volumetric water content, and the b parameter is a curve fitting constant.

Soil survey information from USDA-NRCS

Soil Types:
AfA - Amarillo fine sandy loam, 0-1% slope
AfB - Amarillo fine sandy loam, 1-3% slope
AmB - Amarillo loamy fine sand, 1-3% slope
BeC - Berda fine sandy loam, 3-5% slope
Pn - Gomez loamy fine sand

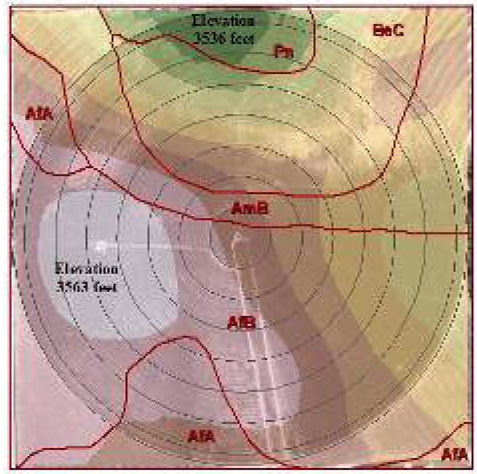

Figure 1. Aerial photo of field site with an overlay of relative elevation (3.4 foot contour lines) and soil mapping units (USDA, 2010; USGS, 2010).

Movement and flow pressure of the center-pivot irrigation equipment was monitored using a SmartField Pivot Scout© equipment (Smartfield, 2010), that consisted of a global positioning system and a pressure transducer connected to a data logger. The monitoring equipment was installed on the third tower of the center-pivot, 575 feet (175 m) from the center point. The monitoring equipment produced reliable pressure data during the irrigation season, but failed to provide useable position and angle data. The position of the pivot was therefore inferred from data provided by five soil moisture sensors (Watermark©, granular matrix sensors) installed at 6 inches below the surface of the soil at various angles from the pivot center, 109°, 68°, 358°, 338°, and 221°. The pivot was assumed to be at the respective angle of the sensor, and the time was noted, when the sensor first indicated an increase in soil water content. Pivot movement between the respective angles was linearly interpolated. This data was further verified using pictures taken by a time-lapse camera installed at the center of the pivot and aimed towards the north. The camera provided episodic photographic evidence of the pivot position, which was used to check the linearly interpolated position calculated from the soil moisture sensor data. Combination of the interpolated angle data and the pressure data from the pivot monitoring equipment allowed a file containing hourly pivot angle and pressure to be constructed.

The pressure and angle information was then used to create hourly raster files in which each grid point was assigned irrigation or no irrigation; examples are shown in Figure 2. Each 33 by 33 foot grid cell was assigned 0.75 inches of irrigation if:

1. it was within the radius of the pivot irrigation equipment,
2. it was within the angle traveled by the pivot during the respective hour, and
3. irrigation was being applied (i.e., indicated by the equipment pressure being at operating levels).

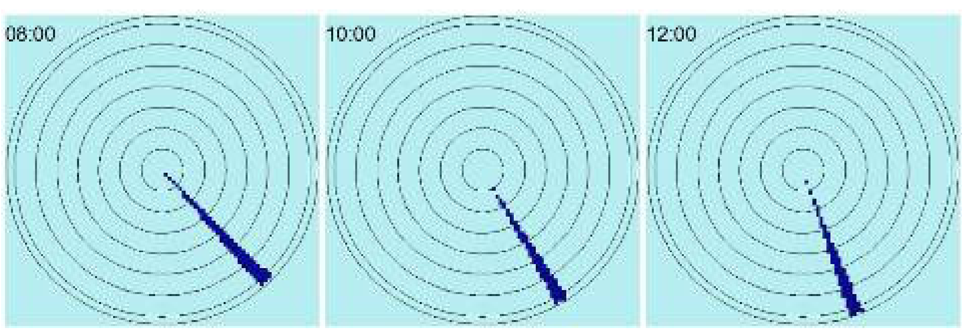

Figure 2. Examples of spatially and temporally representative irrigation input files; grid points receiving irrigation are shown in dark blue.

The flow rate of the irrigation equipment, in inches, was calculated using timed volumetric measurements (a five gallon bucket and a stopwatch) at several positions in the field on several different dates during the irrigation period. Results indicated that flow rates were in agreement with the published values for the pressure regulators and nozzle package installed by the producer and the speed of the pivot.

The PALMS model was run for the time period of 06 May 2010 through 30 September 2010; once with spatially and temporally representative irrigation input and once with blanket application of the irrigation. Blanket irrigation applications were added in the model during the first hour of the day closest to the middle of each 4 ½ day irrigation cycle. Simulated volumetric soil water content data from the 5.5 to 7.1 inch depth layer for model days 01 August 2010 through 31 August 2010 was extracted from both runs of the model for comparison with measured soil water data.

Results and Discussion

The PALMS model provides output for more than 70 variables at each time by space discretization location within the domain of the model. Figures 3a – 3c exhibit simulated values of volumetric soil water content in the 5.5 to 7.1 inch depth layer, over the entire area of the irrigated field and dryland corners, at 7:00 p.m., on three separate days during August 2010. Data are from the model run using spatially and temporally representative irrigation input. These figures provide examples of the extreme variability in water content over space and time that is associated with center pivot irrigation equipment.

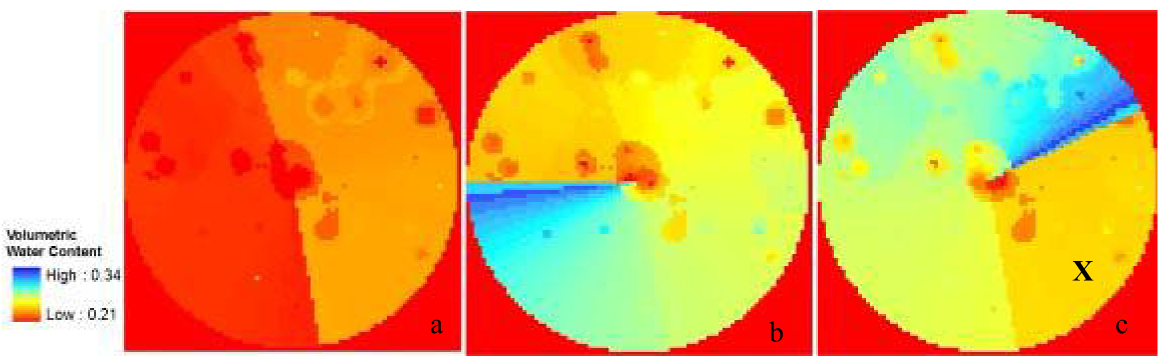

Figure 3. Simulated volumetric soil water content values produced using spatially and temporally representative irrigation input. Shown are soil water content data in the 5.5 to 7.1 inch depth layer, at 7:00 p.m., on days 01, 12, and 22 August 2010.

In Figure 3a, 01 August 2010, it can be seen that the eastern side of the field is wetter than the western side. This is due to an irrigation cycle during late July that began in the northern part of the field and ended at a turnrow in the southern part of the field. Figure 3a presents volumetric soil water content before irrigation was continued in August. The field at this time was fairly dry, as indicated by the red and orange colors.

Figure 3b represents soil water content on 12 August 2010; two cycles of irrigation and 0.5 inches of rain have been added to the water balance of the field since the snapshot shown in Figure 3a. A strong gradient of water content values is evident from where the pivot is irrigating and values are high, around the field counter-clockwise to just in front of the pivot, where values are much lower due to 4 ½ days of evapotranspiration.

Figure 3c represents volumetric soil water content on 22 August 2010. The strong gradient is again noticeable. Another point of interest is that the contrast in the southern part of the field from the July irrigations is still noticeable, even after ~ 3 inches of irrigation and 1.5 inches of rain. The patterns of soil water content exhibited in Figure 3 highlight the extreme amount of spatial and temporal variability in water balance dynamics created by the process of center pivot irrigation, and demonstrate the importance of modeling center pivot irrigated cropping systems at the field scale and at a detailed resolution. The location marked on Figure 3c (**X**) is where detailed data were extracted from the model output in order to contrast measured water content with simulated values from both runs of the model.

Figure 4 focuses on the temporal comparison of measured and simulated water content data for one location in the field, at the 5.5 to 7.1 inch depth layer, spanning the month of August 2010. Measured soil water content data are shown as the continuous red line, model output data using representative irrigation input are shown as blue points, and model output data using blanket irrigation input are shown as green triangles. Comparison of the measured data and the representative irrigation input model run shows close agreement in the timing of local maximum and minimum water contents throughout the month. This is as expected, since irrigation input for the model run is temporally representative. Conversely, output from the blanket irrigation model run shows a temporal offset. The absolute differences between the simulated and measured values are likely related to the model using soybean rather than cotton crop growth parameters; this agreement should be improved once COTTON2K is merged with PALMS. The data in Figure 4 illustrates two other, subtler, differences between the output from the two model runs.

Output from the two model runs (Figure 4) reveal differences in the simulated dynamics of soil water content as impacted by irrigation. Looking at the water content local maxima near the dates of 11, 15, 23, and 27 of August it can be seen that the local maxima associated with the blanket irrigation model run are slightly higher than the corresponding peaks associated with the representative irrigation model run. Additionally, following the data to the corresponding local minima it can be seen that the blanket irrigation model output does not go as low as the representative irrigation model output. Discrepancies at the local maxima and minima indicate that the blanket irrigation model run is over estimating the efficacy of the irrigation input. A result that is likely due to the blanket irrigation being applied in the model during a diurnal period of low evapotranspiration demand. Biases introduced when using blanket irrigation input could lead to over estimation of irrigation water percolation to lower profile depths associated with the maxima and under estimation of water stress associated with the minima.

Output from the two model runs (Figure 4) also reveals differences in the simulated dynamics of water content as impacted by the interaction of irrigation and rainfall. Evaluating the local maxima near the dates of 06 and 17 of August it can be seen that the simulated maximum from the representative irrigation model run is higher than that from the blanket irrigation model run. On these dates the field received rain and this specific location received irrigation; by chance the rain and irrigation occurred at the same general time at the subject location. This difference demonstrates that the blanket irrigation input strategy is missing an important interaction between rainfall and irrigation, when occurring in close temporal proximity. Bias introduced through the use of blanket irrigation input could result in under estimation of runoff and percolation into the lower depths of the profile.

Analysis of the data presented in Figure 4 produces a root mean squared deviation from the measured data of 0.019 for the representative irrigation input and 0.023 for the blanket irrigation input, a relative difference of ~ 21%. The offsets and biases discussed could be remedied for this location by changing the blanket irrigation input time. However, this would change the dynamics for other parts of the field. Since the object of the project is to model pivot irrigated cotton system dynamics over the entire field at a detailed resolution, the data presented in Figures 3 and 4 demonstrate that spatially and temporally representative irrigation input is important to increasing the accuracy of the model.

Summary

Advances in information technology resources are increasing the interest, in agricultural research and agribusiness, for cropping system models that address the water, energy, and carbon balance of the system across the landscape at a detailed level of spatial and temporal resolution. An increase in publicly available (free) GIS data, such as soil survey and elevation, is providing the detailed structure necessary to support the use of such models. Data from center pivot irrigation monitoring equipment, that provide continuous position and flow measurements and are becoming increasingly popular, can provide yet another important data layer and should increase the accuracy of the models.

The PALMS model allows for spatially and temporally representative irrigation data and accounts for important surface and subsurface water linkages across the field or landscape being modeled. Since pivot irrigation equipment can take several days to complete a circuit around a field, surface and subsurface water routing are important to the accurate representation of the spatial and temporal dynamics of water balance and are necessary to adequately model the cotton system. When contrasted with blanket irrigation model input, the use of temporally and spatially representative irrigation input has shown promise for the improvement of modeling efforts; in this example RMSD between measured and modeled volumetric soil water content was reduced by more than 20%. Detailed irrigation input data are necessary for more accurate field-scale simulation of energy and mass balances at detailed resolutions.

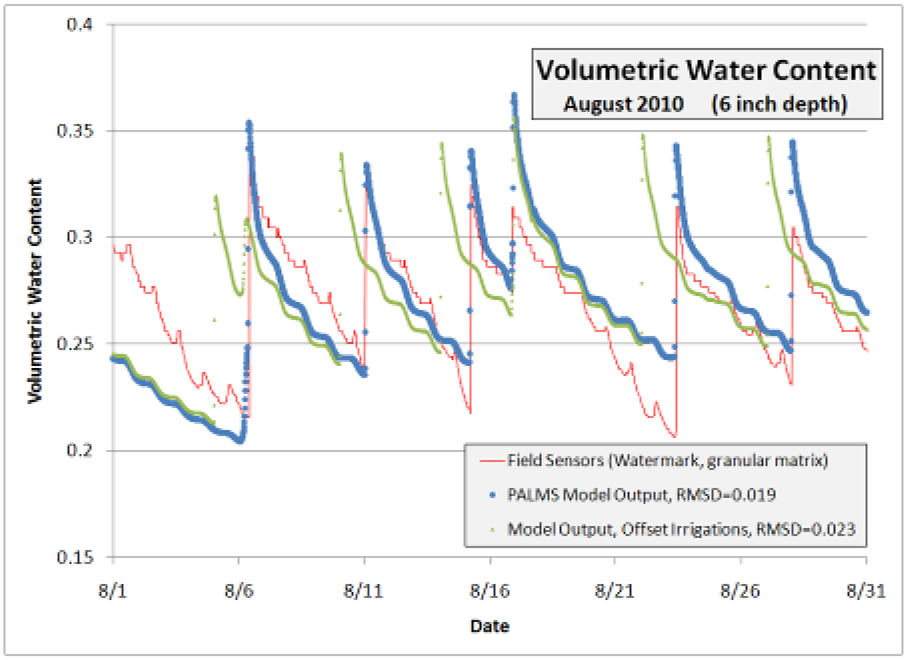

Figure 4. Comparison of measured and simulated volumetric soil water content at one specific location in the field, during the month of August 2010.

The PALMS model currently provides an efficient tool to address field-scale dynamics at a detailed level of resolution. The current version of the model can be used for corn and soybean systems; however, efforts to combine the PALMS model with COTTON2K will support future modeling of cotton systems. Such a tool would be capable of utilizing increasingly common soil, elevation, weather, and irrigation data to improve crop management decisions made by consultant and producer teams. The combined model would be capable of calculating soil water balance, within the context of crop water requirements; thus providing improved understanding of effective rainfall throughout the season and soil water storage compared to remaining crop water requirements at the end of the season.

The model could also provide better estimates of runoff and irrigation return flow at landscape-scale and increase the precision of localized groundwater models developed for environmental permitting, compliance demonstration, and remediation planning. Additionally, the model could be used to simulate and analyze previous and future agricultural research findings; reducing the reliance on and maximizing the effectiveness of costly and time consuming field research. High resolution, landscape-scale modeling could also be instrumental in the evaluation of previous and future research findings under future climate variability scenarios, such as predicted future precipitation intensity changes.

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