Comparison of field level and regional actual ETc values developed from remote sensing and dual crop coefficient procedure

Daniel J. Howes, Ph.D., P.E.

Assistant Professor, Irrigation Training and Research Center, BioResource and Agricultural Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407, 805-756-2434. djhowes@calpoly.edu.

Lucas Hoffman, EIT

Irrigation Support Engineer, Irrigation Training and Research Center, California Polytechnic State Univ. San Luis Obispo, CA 93407. ljhoffma@calpoly.edu.

Franklin Gaudi, CID

Assistant Professor, Irrigation Training and Research Center, BioResource and Agricultural Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407. fgaudi@calpoly.edu.

Abstract. *Crop evapotranspiration (ETc) estimates are important for regional water planning as well as irrigation scheduling. Traditional ETc computations utilize published crop coefficients (basal) that are adjusted on a daily basis depending on soil water availability (i.e., dual crop coefficient method). Recent advancements include using remote sensing data such as LandSAT combined with a surface energy balance algorithm (METRIC), allowing crop evapotranspiration to be computed for each pixel throughout images taken during the season. There are limitations and advantages for both methods. Comparisons of soil water balance evapotranspiration values to METRIC values for two scenarios in different regions of California have been made. The comparisons show that when averaged either spatially or temporally, values estimated from the methods show a good relationship. However, there can be significant variability between the two methods when looking at instantaneous values (for a specific day that the LandSAT image was taken). The cause for this can be attributed to the inputs into the dual crop coefficient model. Both methods have advantages and disadvantages. If the user has good input information, both methods can provide accurate evapotranspiration estimates. Work is currently underway to leverage advantages from both methods by coupling them together.*

Keywords. *Evapotranspiration, irrigation scheduling, remote sensing, satellite, FAO 56, crop coefficients*

Background

The need for accurate evapotranspiration estimation cannot be understated. Evapotranspiration estimates are used for irrigation system design, irrigation scheduling, regional water management, and long-term water planning. Underestimating evapotranspiration can lead to poor yields because of insufficient irrigation or under-designed irrigation systems. Overestimating evapotranspiration will lead to excessive water losses (i.e., deep percolation) caused by over-application or unnecessary system cost when the irrigation system has been overdesigned.

Crop evapotranspiration (ETc) is the combination of evaporation from the plant and soil surfaces and transpiration of water from the plant tissue into the atmosphere. Transpiration and evaporation consist of vaporization of water from a liquid state. Since both processes occur simultaneously it is difficult to differentiate the two processes (Allen et al. 1998). In situations where there is healthy vegetative cover, transpiration will be the dominate process over the longer term (Burt et al. 2002). Obviously, in situations with minimal vegetation, evaporation from the soil will dominate.

ETc is driven by energy supply (solar radiation, temperature, etc.), vapor pressure gradient, wind, plant characteristics, cultivation practices, etc. (Allen et al. 1998). Direct field measurement of ETc is impossible on a large scale because of the wide variety of elements that influence ETc. The most effective tool, a weighing lysimeter, is utilized for research purposes only. Other technology used by researchers includes eddy covariance and Bowen Ratio sensors, which measure energy fluxes to estimate ETc.

Because of the difficulty of directly measuring evapotranspiration on a field or regional scale, a procedure has been used whereby ETc is estimated empirically using a reference crop evapotranspiration computed based on weather parameters and a crop coefficient that accounts for crop type. The reference evapotranspiration is computed based on a reference crop, typically either alfalfa or grass assuming the reference crop is well watered and there is no surface wetting (the reference evapotranspiration does not account for evaporation). In California, grass is the primary reference crop and grass reference evapotranspiration is denoted as ETo, where the subscript “o” indicates grass reference. ETc is then computed as:

$$ETc = ETo \times Kc \qquad \text{Eq. 1}$$

Where, Kc is the crop coefficient. Traditionally, Kc values were computed based on measured ETc and ETo as Kc = ETc/ETo. In most cases the Kc values are provided for three plant growth stages: initial, middle, and end. The length of each stage can be obtained from regional tables or computed using degree days (Allen et al. 1998). The ETc values are measured in research settings using weighing lysimeters or other methods. ETo values are computed by measuring relative humidity, incoming solar radiation, temperature, and wind speed at a properly sited, nearby weather station (Allen et al. 2005).

While the single crop coefficient method continues to be widely used, the transferability of Kc values is limited. These values are driven by assumed irrigation scheduling and cultural practices, which may differ in actual applications. Regional variability in weather conditions will also impact the transferability of Kc values (Allen et al. 1998).

In order to increase the transferability of the crop coefficient method, a more intensive approach of computing ETc was developed called the dual-crop coefficient method (Allen et al. 1998), which is based on a basal crop coefficient (Kcb). Kcb values have been derived in a similar fashion as Kc values, except that when the ETc is measured, care is taken so that there is minimal evaporation from the soil or plant surface and the crop being examined is well watered (i.e., no water stress). Therefore, multiplying Kcb and ETo results in a “potential” transpiration rate. Utilizing a daily soil water balance model, the cropping system is examined on a day-to-day basis with inputs including planting and harvest dates, growth stages, irrigation schedules, soil types, and cultural practices that may influence ETc.

The dual-crop coefficient method has been a significant improvement over the more traditional single crop coefficient approach. Basal crop coefficients are truly transferable as long as they were correctly developed. Most importantly, adjustments are made to the Kcb (and thus the ETc) to account for increased evaporation if the soil and plant are wet, or decreased transpiration if the soil moisture in the root zone is below a certain threshold (accounts for water stress). However, the dual crop coefficient method is more time consuming to implement compared to the single crop coefficient method, because the daily soil water balance must be examined. A dual crop coefficient daily soil water balance model requires very good input information, typically gathered through local grower interviews, to compute ETc accurately.

In the 1990’s, a procedure was developed to use remote sensing data from satellite images (such as LandSAT) to directly compute actual evapotranspiration (Bastiaanssen et al. 2005). Using the thermal image available from special remote sensing technology, actual evapotranspiration can be estimated using a surface energy balance. While there are several methods available to compute actual evapotranspiration from remotely sensed data, the methodology behind METRIC (Mapping Evapotranspiration at High Resolution with Internal Calibration) has been designed for agricultural crop evapotranspiration estimation (Allen et al. 2007). The advantage of METRIC lies in the sensible heat flux computation, which is based on internal calibration. Unlike other energy balance methods, the internal calibration for METRIC is based on the selection of hot and cold pixels within agricultural fields. In addition, the interpolation of ETc between image dates is based on reference evapotranspiration (Gowda et al. 2008). Grass reference ETo is used for the Irrigation Training and Research Center (ITRC)’s modified version of METRIC, which is typically available throughout the western US on an hourly and daily basis.

There are distinct advantages and disadvantages to each of the methods described for estimating actual evapotranspiration. The single crop coefficient method is simple to implement but could result in inaccuracies due to actual weather conditions, limited transferability of published Kc values, variable cultural practices and irrigation scheduling, and different irrigation methods (flood, sprinkler, or drip/micro). The dual crop coefficient method is a significant improvement since the temporal resolution is improved with a daily time-step and corrections to ETc based on soil water content each day. However, this method continues to rely on inputs regarding planting and harvest dates, crop growth stages, and irrigation dates which will influence results. Both methods have limited spatial resolution since these are typically evaluated 1-dimensionally for an “average” condition.

The improved spatial resolution using METRIC with LandSAT provides a significant advantage over the other more traditional crop coefficient approaches. Influences such as crop stress, non-uniformity of vegetation, actual vegetative cover, etc. are accounted for in the images. Using LandSAT with thermal sharpening or aerial imagery, the resolution is high (≤30 meters) and a large region can be evaluated from a single image (LandSAT 5 image is approximately 170 kilometers x 170 kilometers). However, there is limited temporal resolution; the LandSAT satellites acquire images on a 16-day interval and if there is cloud cover, the available images are less frequent. The METRIC process requires approximately one man-day to process a single image when thermal sharpening is implemented, which is costly for long-term ETc evaluations.

The purpose of this study was to compare the results from METRIC and the more traditional dual-crop coefficient soil water balance model. Two scenarios were examined: the first was a large farming operation near Palmdale, CA (approximately 2,050 acres) and the second was applied to a large regional analysis of an irrigation district in the Central Valley of California (approximately 45,000 acres). For the farming operation, detailed information on planting/harvest dates, irrigation dates, volumes, and cultural practices are recorded daily, which makes it an excellent study area. The irrigation district evaluation utilized approximately 15 grower interviews to conduct the modeling. It is hypothesized that while both scenarios used the same methodology to compute ETc, the ETc will be more closely aligned between METRIC and the dual-crop coefficient method for the farming operation because of the quality of model input data. For both scenarios it is expected that the main differences between ETc values from the different methods will be found during the initial and developmental periods since these are the most difficult to estimate for the model.

Procedure

Two scenarios were examined to compare the dual-crop coefficient method with ITRC METRIC results: large farm operation and irrigation district. The comparison procedures for each scenario will be discussed in this section.

Farming Operation

Palmdale WRP agricultural site (Figure 1) contains 27 center pivots of varying sizes. The two crops grown throughout the 2,050-acre agricultural site are alfalfa and winter small grain mix (mixture of barley, oats, and wheat). A detailed description of the pivots and their operations can be found in Howes et al. (2007) and Gaudi et al. (2007). Data on cultural practices including volume of irrigation water applied, harvests, and planting have been collected on a daily basis for each center pivot throughout the study period. Weather data and center pivot flow are incorporated into the dual crop coefficient soil water balance model utilizing the FAO 56 methodology (Allen et al. 1998). This information is used to predict irrigation schedules and track water destinations.

Figure 1. Palmdale WRP Agricultural Site (AS)

Years 2007 and 2010 were selected for this evaluation because there was deliberate water stress in a number of center pivots during the spring and early summer of 2007. Since this farming operation relies on treated wastewater, it is difficult to match supply and ETc demands.

The goal of the operation is to utilize the treated effluent on a day-to-day basis. Therefore, the ag operation would plant crops in more pivots than there may be water for in the late spring and early summer and intentionally under-irrigate the pivots until the winter grains could be harvested. This would ensure sufficient area to use effluent during the winter when ETc is very low. During the summer when ETc is high the amount of acreage with a crop is reduced from 2,050 to approximately 900 acres (primarily alfalfa). In 2010, storage reservoirs became operational and there was no need to plant excess acreage. Therefore, starting in 2010, irrigations could be scheduled to meet ETc and distribution uniformity and minimize water stress.

A total of eleven LandSAT 5 images were examined in this study: seven from 2007 and four from 2010. Each image was processed using METRIC to compute instantaneous and daily ETc and the Kc. The image acquisition dates are shown in Table 1. Dates early in the year were selected since the winter grain crops were in the field and water stress (for 2007) was occurring towards late spring and early winter.

Table 1. LandSAT 5 Image acquisition dates for the Palmdale AS METRIC evaluation.

2007	2010
1/21/2007	3/18/2010
2/6/2007	4/19/2010
3/10/2007	5/5/2010
4/27/2007	6/22/2010
5/13/2007	
6/14/2007	
6/30/2007	

The ITRC METRIC procedure produces an image of instantaneous actual evapotranspiration at the time of image acquisition. By dividing this instantaneous ETc by the grass reference evapotranspiration (ETo) at the time of image acquisition, the crop coefficient (Kc) can be computed for each pixel. The Kc values within each Palmdale AS center pivot were extracted and compared to the predicted Kc values from the dual crop coefficient soil water balance model for that day.

Irrigation District

An evaluation of monthly crop evapotranspiration (ETc) values was conducted for a specific region along the west side of the San Joaquin Valley. ITRC had previously conducted long term water balance evaluations in this region and a specific irrigation district that has detailed crop information in GIS was selected for this ETc evaluation for a single year (2007). Primary crops in this region are alfalfa, cotton, corn, winter grains (for hay, silage, or grain), and tomatoes.

ETc values from three sources were compared:

1. DWR C2VSIM
2. Dual crop coefficient soil water balance (a.k.a. ITRC FAO 56 Model) values were previously developed as part of a water balance for the irrigation district. These ETc values have been corrected for bare spots and decreased vigor.
3. ITRC METRIC was utilized to estimate the ETc from the LandSAT 5 images taken in spring, summer, and fall, to compute actual ETc on the specific days the images were acquired.

The California Department of Water Resources (DWR) has developed a model called the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM). The monthly DWR C2VSIM ETc values for crops within the region of interest were extracted from the model and used in the comparison.

The daily soil water balance model was used to compute daily adjusted Kc and ETc based on typical cropping scenarios within the region. Grower interviews were conducted to provide inputs into the model including average planting and harvest dates, typical irrigation frequencies, irrigation methods, and cultural practices that could influence crop evapotranspiration. Digital NRCS soils maps were used to provide input information on soils in the region.

Three images were process using the ITRC modified METRIC procedure. The dates of these images were April 25, 2007, July 30, 2007, and October 5, 2007 to represent ETc from spring, summer, and fall. The instantaneous ETc was computed for each image and the Kc was computed using quality controlled and corrected ETo data from CIMIS Station #56 located near Los Banos, California.

The comparison was conducted on a monthly basis. The Kc computed on the image days was used to estimate the monthly ETc. Using the GIS field boundaries within the area of interest, the Kc values were averaged within each field boundary by crop type. For example, if there were 50 fields of cotton, the Kc's within the field boundaries identified by cotton were averaged into a single, average cotton Kc for that image date. Since the image dates were near the beginning or end of the months, that same Kc for each crop was used for two adjacent months:

- April 25, 2007 – (Kc used for April and May)
- July 30, 2007 – (Kc used for July and August)
- October 5, 2007 – (Kc used for September and October)

The estimated METRIC Kc values for the 6 months were multiplied by the monthly ETo to estimate the monthly ETc in this comparison.

Results

Farming Operation

Figures 2 and 3 show comparisons of crop coefficients (Kc) from the daily dual crop coefficient model and METRIC for 2007 and 2010, respectively. The center pivots were selected to show different crop types and scenarios. In Figure 2, Pivots 3, 4, and 5 are alfalfa hay with cutting during the summer approximately every 30 days. In this area seven to eight cuttings per year are typical. Pivot 6 has winter grain hay planted in late November 2006 and harvested in late April with sudan (a summer forage) planted in mid-June 2007. Sudan is harvested (cut and baled) approximately three times during the summer. Pivots 18 and 21 have winter grain hay that is harvested in early April and allowed to re-grow for a second harvest in early June. The second harvest of grain hay typically has a lower yield than the first.

The dual crop coefficient Kc (labeled "Kc") in the figures is the adjusted Kc accounting for (i) additional evaporation when the soil and plant are wet from rainfall/irrigation and (ii) crop stress when the soil moisture drops below a threshold level. The basal Kc is shown as a reference. When the soil and plant surfaces are wet the evaporation increases, as indicated by the "Kc" above the Basal Kc in the figures. When the soil moisture in the root zone drops below a threshold (typically 55-60% of available water has been depleted for these crops and soil types), the “Kc” drops below the Basal Kc curve. Water stress results in the plants having less ETc, as indicated by the Kc value dropping below the Basal Kc curve.

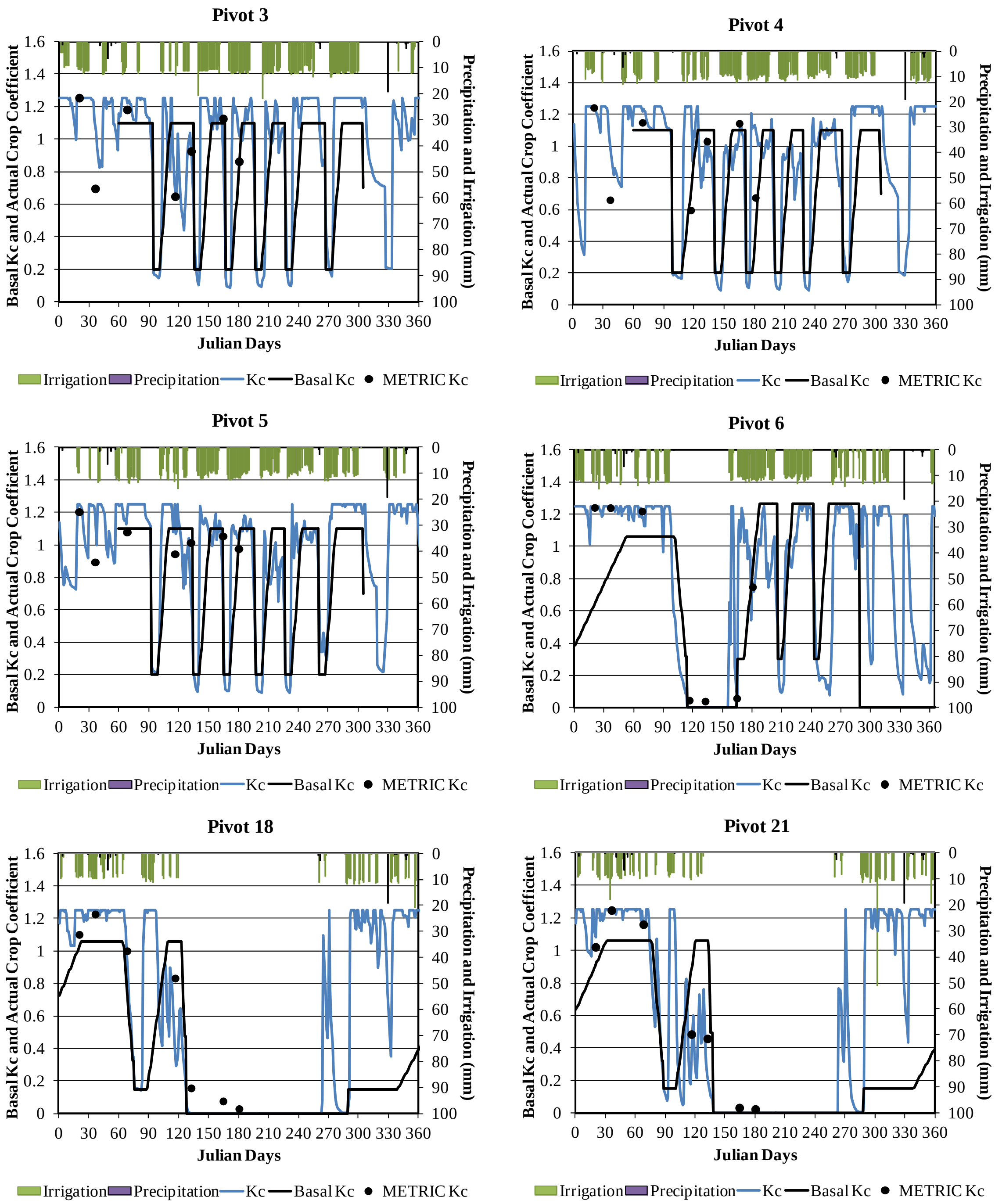

Figure 2. Comparison of daily adjusted Kc values (Kc) and METRIC Kc values for the image dates for select center pivots in 2007.

Figure 3 shows the comparison of the soil water balance Kc values and METRIC Kc values for several cropping scenarios. Alfalfa is shown in Pivots 2 and 11, two cuttings of winter grain hay in Pivots 14 and 17, single cut grain hay in Pivot 23, and single cut grain hay followed by a fall planting of new alfalfa in Pivot 5.

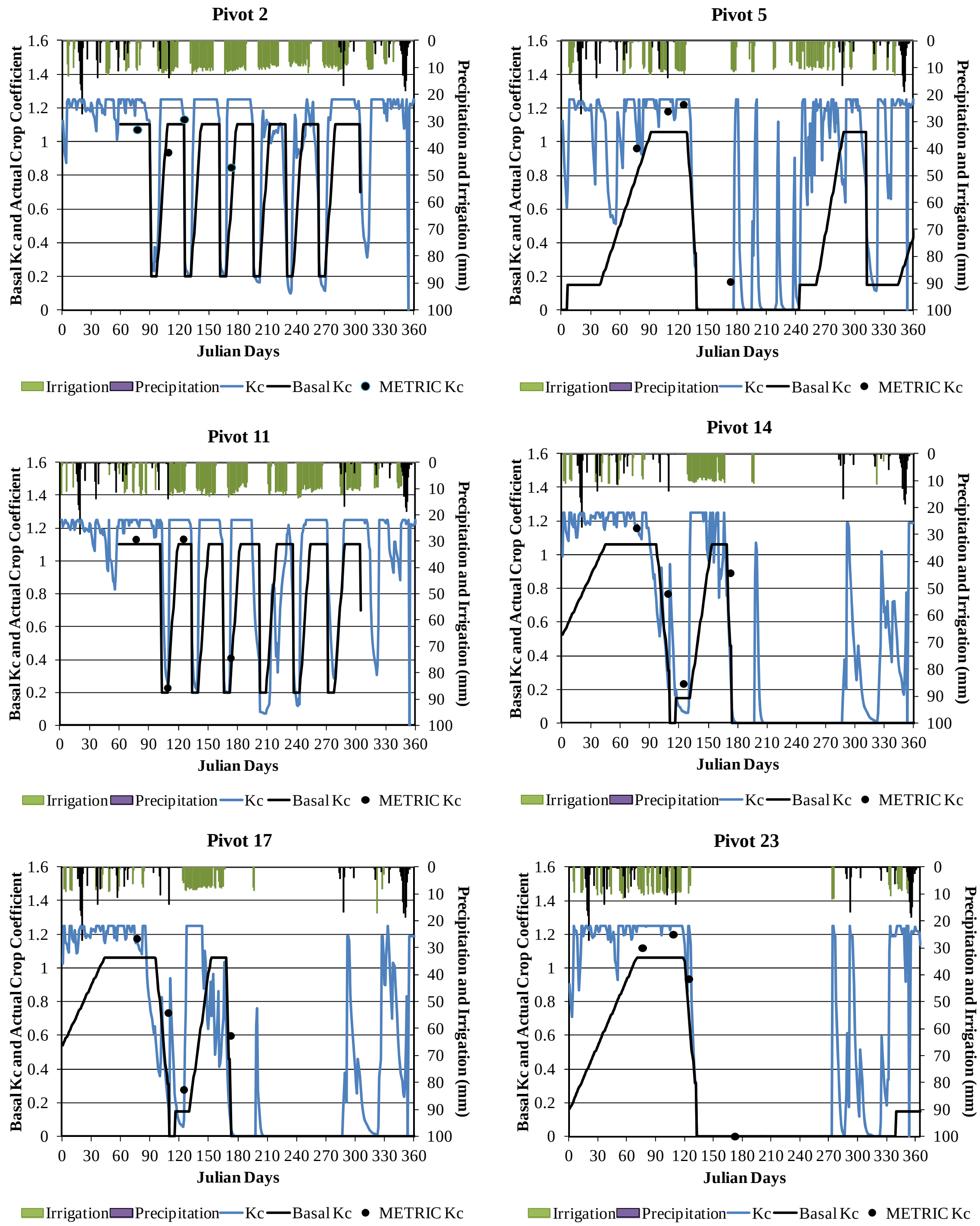

Figure 3. Comparison of daily adjusted Kc values (Kc) and METRIC Kc values for the image dates for select center pivots in 2010.

Figure 4 shows the comparison of modeled and METRIC Kc (field averaged) values for each field on each individual image date. The linear regression equation and r-squared value is shown. The METRIC Kc is can be considered the actual Kc and the figure indicates how well the modeled Kc's matched.

There is a significant amount of variability between the two Kc sources, more than might be expected when examining Figures 2 and 3. There are several issues that can contribute the variability. Through examination of some of the most significant outliers, one of the main issues is the way input information was recorded and entered into the dual crop coefficient model. For example, harvest dates are assumed in the model to have completely occurred by the date that was entered. However, in many cases the harvest may take multiple days or did not start until later in the afternoon. In this case the model shows a significantly lower Kc than METRIC. Similarly, the field is assumed to be irrigated entirely by the time the irrigation occurs. However, this is not always the case. Depending on pivot speed, only half or less of a pivot may be irrigated each day and therefore the METRIC Kc averaged over the entire pivot is lower than the model shows.

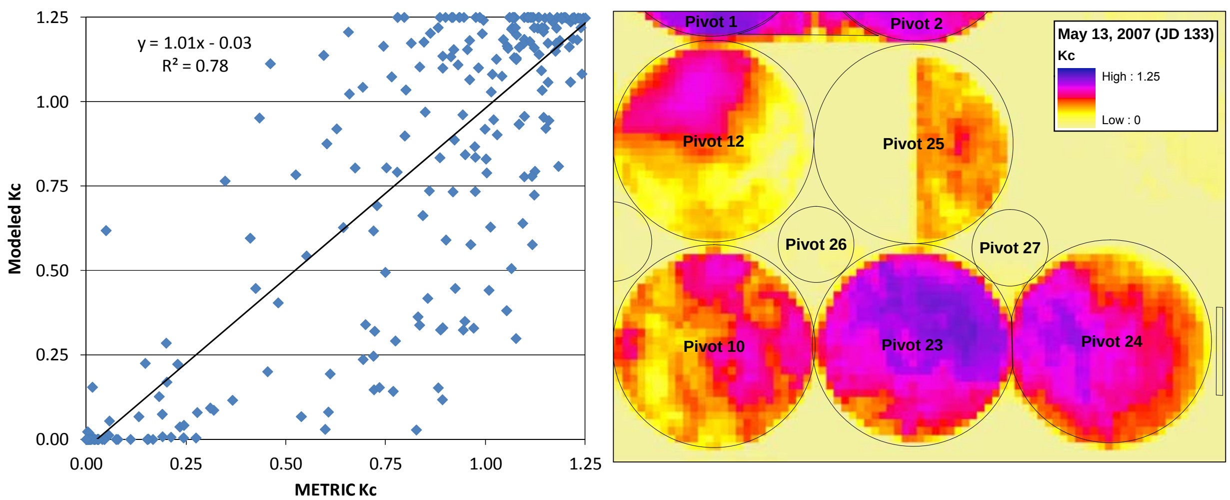

Figure 4. Comparison of METRIC and dual crop coefficient modeled Kc values (left). Example of variability in Kc values throughout evaluated fields (right).

Some examples of variability in actual field conditions are shown in the image on the right side of Figure 4. Pivots 12 and 25 were in transition at the time the image was acquired. The dual crop coefficient model assumes no transition and that practices occur immediately. Half of Pivot 25 had been harvested previously and Pivot 12 is being irrigated (after the alfalfa was harvested) at the time of image acquisition. The darker colors indicate higher Kc values.

In an attempt to minimize the daily variability, a general comparison of the modeled adjusted and METRIC Kc values was developed and is shown in Figure 5. Figure 5 (right) shows the monthly average Kc over all of the fields by month, compared for both methods during 2007. The METRIC Kc values were extracted from within the field boundaries and averaged over the entire farm. The month associated with a particular Kc value was assumed to be the month in which the image was acquired. Figure 5 (left) shows the monthly averaged Kc for each of the 27 fields. The METRIC Kc values were interpolated between image dates and a monthly average was developed.

For both figures, the dual crop coefficient model ETc was summed over the day of the month and divided by the monthly ETo to develop the monthly average Kc. From the comparison shown in Figure 5, the relationship significantly improved as would be expected when day-to-day variation is minimized. There is a slight tendency for the model to overestimate Kc compared to METRIC. That is not unexpected since METRIC accounts for actual field conditions such as bare spots, non-uniformity in planting, pest damage, decreased vegetative vigor, etc.

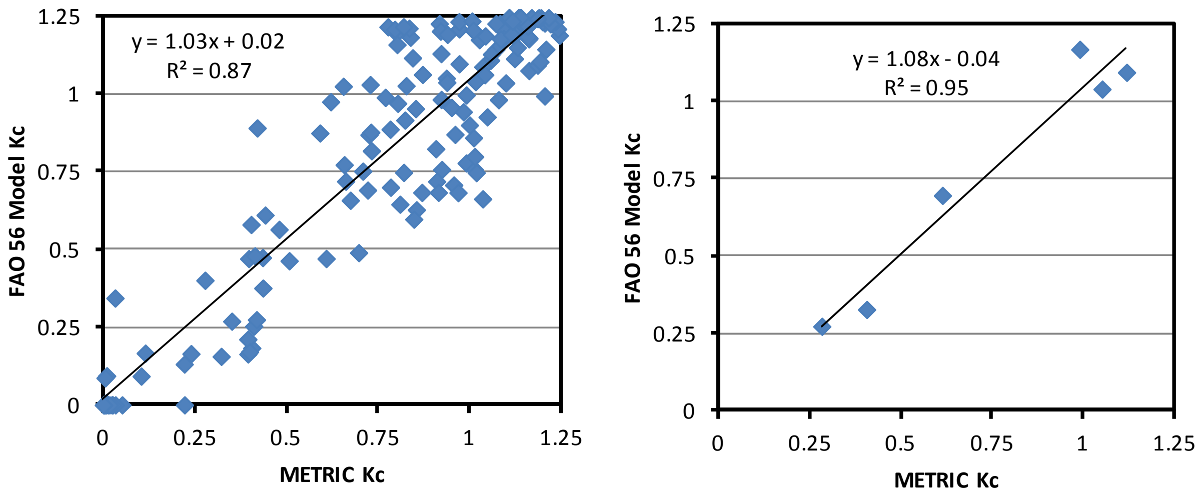

Figure 5. Monthly average Kc by field and month (left) and monthly Average Kc comparison with Kc values averaged over all of the fields (right).

A critical point that can be taken from this evaluation is that modeling results must be examined with care, especially when modeling small areas such as single fields. It is important that correct input data be incorporated into the model at any scale. However, small discrepancies in planting/harvest dates, irrigations application dates, etc. will tend to be averaged out over larger areas of investigation (i.e., more fields in the area of interest).

Irrigation District

The results shown in Figure 6 compare the monthly ETc depth from the three sources. The notations on the legend indicate the source: “DWR” is the C2VSIM values, “ITRC Model” is the FAO 56 based dual crop coefficient model, and “METRIC” is the ITRC modified METRIC remote sensing procedure. Four of the major crops in the region are compared: alfalfa, cotton, winter grain, and tomatoes.

While there were only three images processed for the METRIC evaluation, since the images were near the end or beginning of the month it was assumed that the Kc would be applicable for both months. Utilizing a single Kc for two consecutive months is not the most accurate procedure; however, for this evaluation it provides an interesting comparison. This is especially true for the spring Kc value since the Kc should be higher in May than in April for summer crops even though the image was taken at the end of April. Conversely, the Kc should decrease in May for winter grains (small grains) as the season progresses towards harvest.

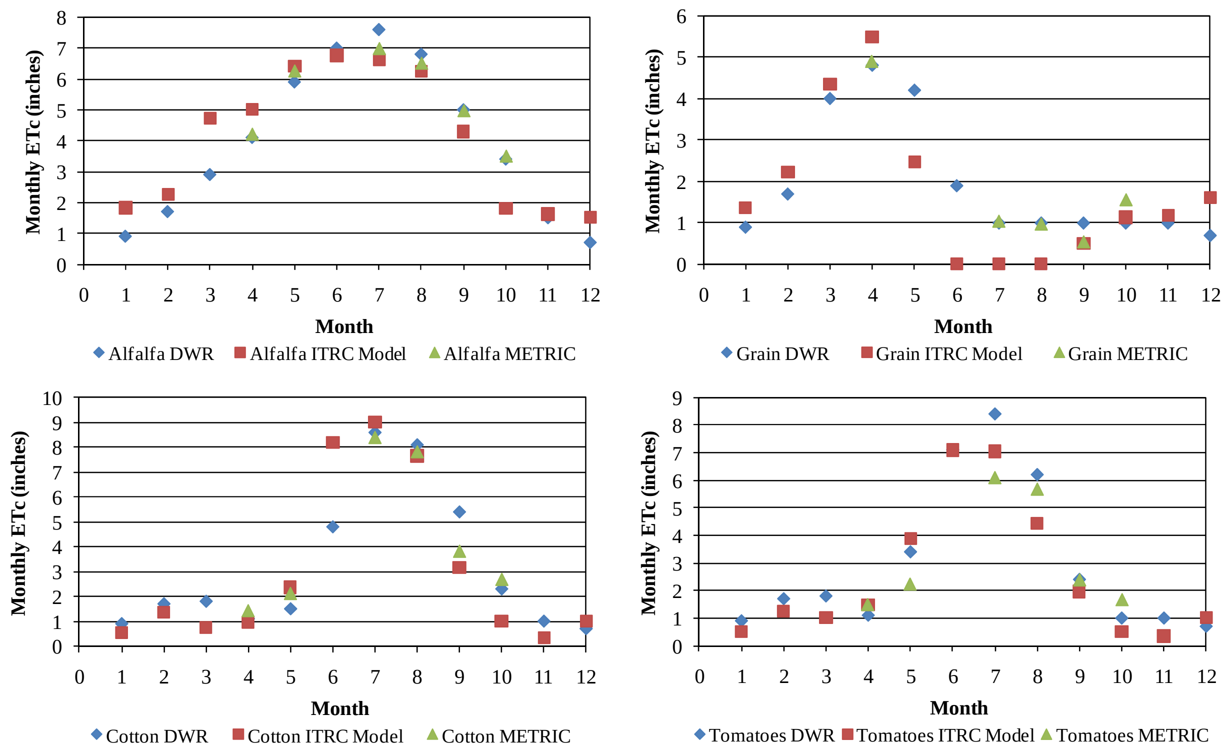

Figure 6. 2007 ETc Comparison between ITRC FAO 56 Modeled ETc, DWR C2VSIM ETc, and ITRC METRIC ETc for alfalfa, small grains, cotton, and tomatoes for the west side of the San Joaquin Valley.

The METRIC ETc values were averaged over multiple fields within the irrigation district. As with the farming operation scenario, this averaging eliminates much of the noise that would occur if only one field was examined. This is especially true for alfalfa, which has approximately 7 cuttings per year. For images taken after March and before November, a number of alfalfa fields will have been harvested. Averaging multiple fields accounts for alfalfa at different stages of development.

Overall the monthly ETc values from all methods seem to match well. One issue is related to summer ETc for grain. The ITRC model shows an ETc of zero while the others show approximately 1 inch of ETc per month (June and July). One likely reason that METRIC showed some ETc, even though the soil was supposedly bare, is that there were errors in the classification of the GIS field boundaries for the grain category. For example, if some of the fields had grain that was followed by summer corn or sudan, those fields would show some ETc but not from the winter grain. That would lead to some fields showing high ETc but once all fields classified as “grain” were averaged, the ETc would be only 1 inch per month. The ITRC model assumed grain hay that was harvested in early May and not allowed to re-grow and therefore once the soil moisture was depleted there was no longer ETc.

Conclusion

There has been a significant amount of research on ETc estimation over the past century. Recent developments in computing actual ETc using remote sensing have improved the accuracy and spatial resolution. However, the procedures are time consuming, images are limited temporally, and the process requires oversight by someone with detailed knowledge of cropping systems, irrigation, and plant water use. It is also difficult to forecast future needs using historical images without some type of forecasting algorithm (ITRC has a forecasting algorithm in the dual crop coefficient model to estimate future irrigation requirements).

Computer modeling using a daily soil water balance is less time consuming but the modeler must have knowledge of the systems and plant water use as well as detailed input information for the model. This procedure has spatial limitations since it is unreasonable to simulate every possible cropping scenario within a region or even a field that has spatial variability.

The results from the farming operation study are important for understanding some of the limitations from both methods. The METRIC has temporal limitation since the images are available at most every 16 days and the ETc is really a snapshot during the day. If a field is being irrigated or harvested the Kc values could be skewed between image acquisition dates.

The model also has limitations since vegetative non-uniformity is difficult to take into account. In addition, accurate input information is required for modeling to be successful. One advantage of the daily model is that if a harvest or planting date is off by several days, the overall error is not very significant on a monthly or annual basis as indicated in the comparison of average monthly values.

Looking at spatially and temporally averaged ETc and Kc values, the METRIC and dual crop coefficient modeled outputs (both with very good input information) match up well even though the daily comparison showed significant variability. Again, this variability is due to cultural practices and spatial variability that were not accounted for in the modeling.

From the results of this study several conclusions can be drawn:

- For a day-to-day irrigation schedule, using weather-based dual crop coefficient modeling is advantageous since it will most likely not underestimate the amount off irrigation required.
- The dual crop coefficient modeling should be checked periodically using independent verification such as METRIC. This will also provide the user with the spatial variability in ETc throughout each field, which can provide important management information.
- For regional water assessments METRIC provides accurate ETc estimates regardless of the accuracy of crop type acreage accounting. There is really no way to differentiate the ETc from irrigation water or precipitation, however, and timeframes over 3-4 years can be cost prohibitive.
- For long-term regional water use assessments, combining METRIC with the dual crop coefficient modeling has been successfully implemented by ITRC. METRIC provides a check on planting and harvest dates, overall vegetative health, and other important inputs that are used for modeling. The model provides the ability to cost-effectively examine long-term ETc. In addition, the ITRC dual crop coefficient model can separate the ETc from irrigation water and precipitation, which is needed for proper irrigation efficiency computations.

Future work that will benefit this evaluation is use METRIC to compute actual ET for LandSAT images during the remainder of 2007 and 2010. This will allow for more accurate interpolation of ETc between image dates and provide an annual ETc estimate on a field by field basis which can be compared against the dual crop coefficient model. Coupling the two methods has been successfully implemented on a recent project (not shown) however more work is necessary to quantify the accuracy improvements.

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