SPATIAL VARIABILITY IN EVAPOTRANSPIRATION RELATED TO IRRIGATION SYSTEM DISTRIBUTION UNIFORMITY

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ABSTRACT

Understanding the causes of variable ET in a field is critical for maximizing yield on a per-acre basis as well as for proper irrigation scheduling and regional water management. Since 2004, the ITRC has provided technical irrigation support and management for over 2,000 acres of center pivot irrigated forage crops being supplied by reclaimed water near Palmdale, California. Irrigation scheduling is conducted using a daily soil water balance dual crop coefficient approach. Detailed records on planting and harvest dates, daily water applications, pivot run speeds, and annual distribution uniformity evaluations are maintained along with daily reference evapotranspiration data from a station on site. Since accurate records on pivot distribution uniformity are available, and most of the pivots were under moderate deficit irrigation in one of the years analyzed, a portion of the spatial variability in ETc can be attributed (quantifiably) to this non-uniformity in irrigation distribution. During 2010, the same fields were fully irrigated (no water stress) during the evaluation period because a reservoir was constructed on site. The variability in ETc during the non-water stressed conditions can be attributed to causes other than irrigation DU. Comparing the uniformity of evapotranspiration from the same fields, with the same crops, under both water stressed conditions, the uniformity of evapotranspiration due to irrigation system DU (ET_U_{DU}) was quantified. The results indicate that under moderate water stressed conditions, the ET_U_{DU} contributes approximately 55% to the overall non-uniformity of evapotranspiration in a field.

INTRODUCTION

Farmers throughout California strive to achieve a uniform crop yield. As costs for farm input such as water, fuel, fertilizers, and labor increase, optimizing yields is of the utmost importance to remain profitable. While most discussion of crop yield addresses an average yield-per-area basis (such as tons per acre) over an entire parcel, at the field scale there will be spatial distribution of yields over the entire area. This means that in some areas there is significantly more or less yield per area than the average. The goal of farming operations that are trying to maximize harvested tonnage is to achieve the maximum potential yield over the entire field. Other farming operations, such as quality wine grapes, try to match the quality at the average point in the field. In either case,

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spatial uniformity of the crop is becoming more imperative as agriculture is shifting towards the “more crop per drop” concept.

There are a number of factors that can impact spatial distribution of crop yield within a field, including: different soil types, salinity, fertilizer availability, soil compaction, and irrigation distribution uniformity (DU). Under different scenarios some of these factors will impact yield distribution more than others. For example, under well-watered conditions (“perfect” irrigation scheduling) one would expect to see minimal impact on yield due to how uniformly the water was applied across the field.

Under deficit irrigation the effects of irrigation distribution uniformity could have a significant impact on yield distribution. Deficit irrigation is used more and more in California to improve the quality of harvested crops (wine grapes and processing tomatoes) and during drought years when farmers simply do not have enough supply to achieve optimal crop evapotranspiration rates over the entire field.

***Problem/Issue* –** There has been limited research on the actual impact of specific factors on crop yield uniformity at the field scale. Therefore, farmers are lacking information on where specific investments can be made to improve uniformity of yield.

In this study, an intensely managed medium-scale farming operation was examined. Irrigation and agronomic management data was gathered and used as input into a daily soil water balance using the FAO 56 dual crop coefficient soil water balance method (Allen et al. 1998). The agricultural site is owned and operated by County Sanitation District No. 20 of Los Angeles County (LACSD), Palmdale Water Reclamation Plant (WRP), which since the early 2000’s has reused treated effluent to irrigate forage crops using center pivots near Palmdale, CA. The Irrigation Training and Research Center (ITRC) at California Polytechnic State University (Cal Poly), San Luis Obispo provided technical assistance for agricultural and irrigation operations to the agricultural site from 2004 through 2012.

The factors that make the location of this project suitable for data collection and analysis are:

1) Daily water applications on a field-by-field basis are known.
2) Planting and harvest dates are known to the day as well as harvested yield.
3) The irrigation distribution uniformity (measure of how uniformly irrigation water is applied, discussed in Burt et al. (1997)) of each of the center pivots is evaluated on a 1-2 year basis at the Palmdale WRP agricultural site.
4) There is a known level of water stress because of deficit irrigation during several years (2006-2009) on forage crops from spring to early summer because of a lack of water availability during those periods.
5) For those same alfalfa pivots, in 2010 there was no deficit irrigation during this same time frame.

The goal of this study is to differentiate the impact of irrigation DU on the spatial distribution of evapotranspiration from the impacts of other factors. A logical assumption is that the spatial variability of evapotranspiration is directly related to the spatial variability of yield at least within individual fields. With this assumption, the first objective of this study was to determine if spatial variability of evapotranspiration could be measured directly using LandSAT images processed with METRIC^{TM} (Mapping EvapoTranspiration at High Resolution with Internal Calibration). The second objective was to use the measured spatial distribution of evapotranspiration to compute values for actual uniformity of evapotranspiration due to DU (ET_U_{DU}). This value was then compared to $ET\_U_{DUpredicted}$ calculated using a soil water balance model.

METHODOLOGY

Palmdale WRP agricultural site (Figure 1) contains 27 center pivots of varying sizes. Eight center pivots were planted in alfalfa from 2007 through 2010. A detailed description of the pivots and their operations can be found in Howes et al. (2007) and Gaudi et al. (2007). Data is collected on a daily basis for each center pivot. Weather data and center pivot flow are incorporated into a soil water balance model utilizing the FAO 56 dual crop coefficient (grass reference) methodology (Allen et al. 1998). This information is used to predict irrigation schedules and track water destinations. Figure 2 shows outputs of actual crop coefficients from the soil water balance in a single alfalfa field in 2007 where water stress occurred and in 2010 with no water stress.

Figure 1. Palmdale WRP Agricultural Site (AS)

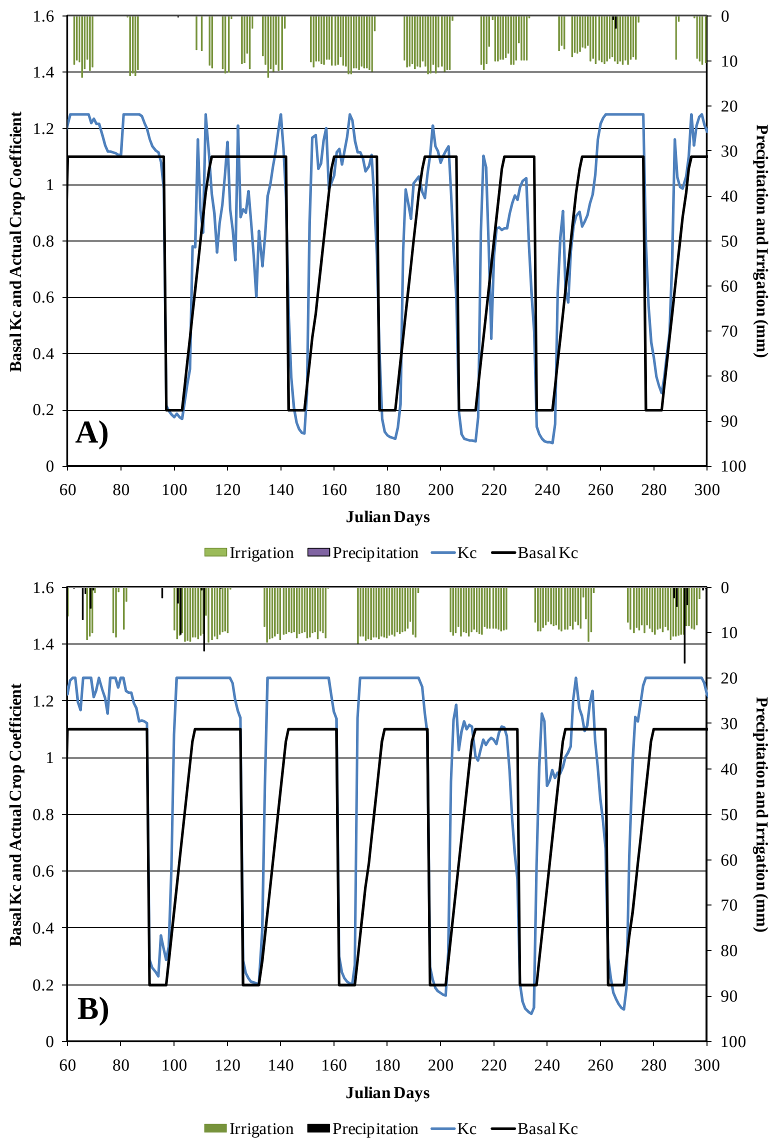

Figure 2. Actual and basal crop coefficient (Kc and Basal Kc respectively) curves for alfalfa in the same center pivot at Palmdale WRP Agricultural Sites (A) in 2007 prior to reservoir installation and (B) in 2010 with operational reservoirs.

The deficit irrigation occurring on the fields from late spring through the summer of 2007 caused plant stress as shown in the crop coefficient curve in Figures 2A. Since the installation of reservoirs at the end of 2009, effluent is held in the reservoirs for irrigation in the spring and early summer, reducing the deficit irrigation (Figure 2B).

A total of four LandSAT 5 images were examined in this study: two from 2007 and two from 2010. The image dates of 4/27/2007, 5/13/2007, 4/19/2010, and 5/5/2010 were used. These image dates were selected because on those dates, moderate water stress was occurring during 2007 and no water stress was occurring in 2010 in the majority of the fields. Each image was processed using METRIC to compute instantaneous and daily ETc and the Kc.

METRIC is an algorithm developed by Dr. Richard Allen from the University of Idaho, in which evapotranspiration is computed from LandSAT data. LandSAT satellites have a 30 m × 30 m resolution for non-thermal bands and 120 m × 120 m resolution for the thermal bands (Courault et al. 2005). While there are several methods available to compute evapotranspiration from LandSAT data, the methodology behind METRIC, specifically within the sensible heat flux computation, has been designed for agricultural crop evapotranspiration estimation (Allen et al. 2007). For this project, the absolute evapotranspiration is not as important as the relative evapotranspiration rates throughout a field. The ITRC has made several modifications to the original METRIC algorithm to enhance usability and decrease processing time. These include developing a semi-automated calibration procedure and converting from an alfalfa-based reference evapotranspiration system to a grass-based reference, which is more applicable for California.

METRIC is based on the surface energy balance equation:

$$LE = Rn - G - H \tag{1}$$

where *LE* is the latent heat flux, *Rn* is net radiation at the surface, *G* is the soil heat flux, and *H* is the sensible heat flux into the air. *LE* is converted into ETc at the time the image was taken as depth per unit time (typically mm/hour). Each component of the surface energy balance requires numerous computations. The current model is fully described in Allen et al. (2007) and Allen et al. (2010).

The required information for METRIC includes LandSAT images, raster land use maps, digital elevation models, and hourly corrected weather data from a nearby station. Utilizing image processing software ERDAS Imagine (Earth Resource Data Analysis System, Atlanta, GA), Microsoft Excel, and ArcGIS 9 (ESRI, Redlands, CA), the inputs are processed and the model computes the instantaneous ETc for each pixel within a LandSAT image. The primary models for each component of Eq. 1 are built in ERDAS Imagine. The spreadsheet program is used to compute and store parameters that are needed as inputs into ERDAS. ArcGIS is used for thermal sharpening (Trezza et al. 2008) and to create image outputs.

Irrigation system distribution uniformity was the focus of this evaluation. A full discussion on the subject can be found in Burt et al. (1997). This discussion will focus on how the distribution uniformity can impact evapotranspiration distribution and why the evapotranspiration variability due to irrigation application uniformity will only be apparent during water stress periods. Figure 3 shows water destination diagrams for two scenarios: (A) perfect irrigation scheduling with no water stress, and (B) under-irrigation of approximately 50% of the field. The sloping line on the bottom of each figure is a function of the distribution uniformity. The depth of portions of the field receiving at least this amount of water has been sorted from the maximum depth on the left to the minimum depth applied in the field on the right. In order to refill the root zone and thus meet potential evapotranspiration demands, water must be applied so that the depletion (SMD) in the lowest point (actually average of the lowest quarter of the field) is met.

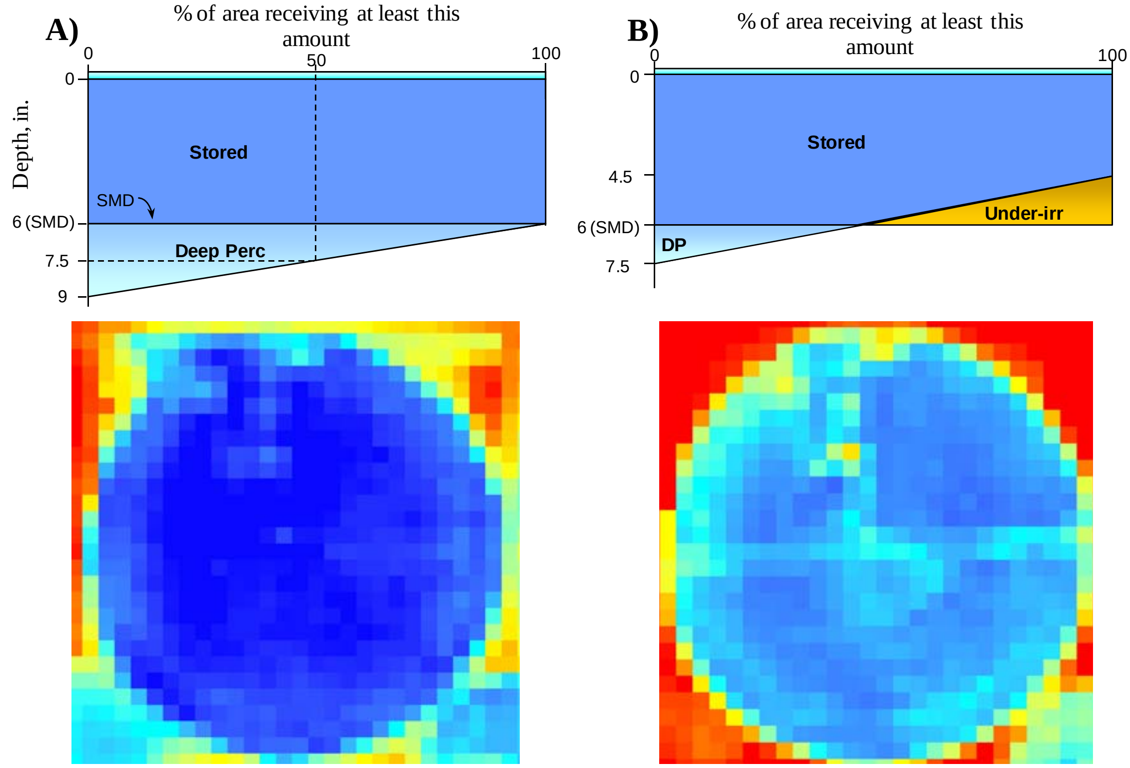

Figure 3. Water destination diagrams (top) showing the effects of distribution uniformity on applied water under (A) perfect irrigation scheduling and (B) under-irrigation of 50% of the field. METRIC images (bottom) for the same field under similar water stress conditions as shown in the water destination diagrams above (blue = high ETc and red = low ETc).

Figure 3A shows a well-watered condition where full potential evapotranspiration demands would be met throughout the field. In this case, there should be no spatial evapotranspiration non-uniformity due to irrigation distribution uniformity throughout the field. The METRIC processed image below the destination diagram indicates high evapotranspiration uniformity, although not perfect. In any field there is some non-uniformity in evapotranspiration due to other factors (ET_U_{Other}), which is the non-uniformity apparent in Figure 3A. Figure 3B shows some under-irrigation on the same parcel. In this case approximately 50% of the field should be at full potential evapotranspiration and the remaining 50% will have declining evapotranspiration rates. The METRIC image below the water destination diagram, Figure 3B, shows significantly more non-uniformity in evapotranspiration than the non-water stressed condition (Figure 3A). In this water stressed situation, METRIC shows significant evapotranspiration non-uniformity well beyond ET_U_{Other}.

Measured Evapotranspiration Uniformity from METRIC

The actual computation of ET_U_{Total} and ET_U_{Other} involved extracting the evapotranspiration on a pixel-by-pixel basis throughout the field. For each field in each year, the standard deviation and the mean of pixel values was used to compute the coefficient of variation (CV). A requirement for ET_U_{Other} is that the field not be under water stress, otherwise the irrigation system DU might influence the values. The non-water stressed condition was check for the 2010 image dates using the FAO 56 soil water balance model which is discussed in more detail in the next section. The model was run under two different conditions. Since the gross applied water is measured daily for each field, the model was run examining the average point in the field and the lowest quarter point in the field. Water stress is likely occurring if the ETc did not match at the average point and the lowest quarter point in the field. If this was the case the fields were removed from the analysis.

The uniformity of evapotranspiration within a field is estimated from these standard statistics similar to the irrigation distribution uniformity described in Burt et al. (1997) as:

$$ET\_U_{*} = 1 - 1.27 * CV \tag{2}$$

Once ET_U_{Total} and ET_U_{Other} were computed using the METRIC images, ET_U_{DU} was then directly computed similar to a statistical procedure for defining global irrigation distribution uniformity (Burt et al. 1997). The relationship between ET_U_{Total}, ET_U_{DU} and ET_U_{Other} exists as:

$$ET\_U_{Total} = [1 - \sqrt{(1 - ET\_U_{DU})^2 + (1 - ET\_U_{Other})^2}] \tag{3}$$

ET_U_{DU} is found on a field-by-field basis by rearranging Eq. 3. The resulting ET_U_{DU} is the <u>measured</u> uniformity of evapotranspiration due to irrigation distribution uniformity from the fields in 2007.

Predicted ET_U_{DU} based on Irrigation System DU

For each field in 2007, the FAO 56 soil water balance model and the measured irrigation distribution uniformities were used to <u>predict</u> the ET_U_{DU} (the predicted uniformity is termed $ET\_U_{DUpredicted}$). The FAO 56 soil water balance model was developed by ITRC as an irrigation scheduling tool for the Palmdale WRP. Each center pivot is tracked individually. Inputs into the model include irrigation system DU, planting dates, predicted and actual harvest dates, daily flows to each pivot, daily grass reference evapotranspiration, wind speed, temperature, and relative humidity, as well as soil and crop growing stage length information.

The soil water balance model is a one-dimensional model, meaning that it examines the evapotranspiration of the crop at a single point in a field. The irrigation scheduling program is set up to examine the average point in the field. The irrigation system DU is used to estimate the amount of deep percolation during irrigation events as shown graphically in Figure 3.

The $ET\_U_{DUpredicted}$ was computed based on the crop coefficient at the average point in the field. The model was modified to examine the point in the field receiving the average of the lowest quarter (in a water destination diagram such as the ones shown in Figure 3, this would be the 87.5% point along the horizontal axis). Under a non-water stressed condition, the K_c at the lowest quarter, K_{c_lq} should be equal to the Kc at the average point (ET_{c_avg}). Using linear interpolation and extrapolation between the K_{c_lq} and the K_{c_avg}, the Kc values at 40 points throughout the field were determined. The maximum crop coefficient for the extrapolated Kc values was taken as 1.25 (using grass reference ET_o, K_c = 1.25 is a reasonable maximum crop coefficient value). Figure 4 shows some examples of crop coefficients at different points in the field. The portion of the field on the horizontal axis is consistent with that shown in Figure 3 for a reference (meaning 0% receives the most water and 100% the least).

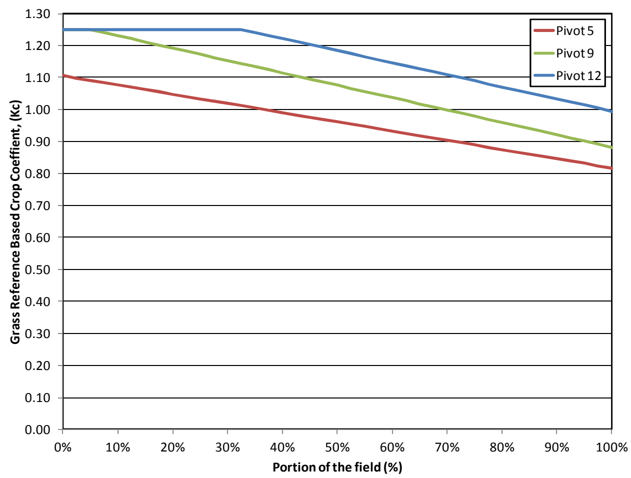

Figure 4. Example of crop coefficients estimated at different point within a field under different water stress conditions.

$ET\_U_{DUpredicted}$ was computed using Eq. 2 by computing the mean, standard deviation, and coefficient of variation (CV) from the interpolated and extrapolated value for each field in the analysis. Percent error was used to examine and compare the $ET\_U_{DUpredicted}$ and the measured ET_U_{DU} for each of the fields examined (2007).

The final evaluation examined the relative significance of ET_U_{DU} compared to ET_U_{Other} on the total evapotranspiration non-uniformity. Looking at Eq. 3, each of the components contributes some amount to the ET_U_{Total}. The following equation was used to compute the percentage that each component contributed to ET_U_{Total}:

$$\%\ Contribution = \frac{1 - ET\_U_*}{(1 - ET_{U_{Other}}) + (1 - ET_{U_{DU}})} \times 100 \quad (4)$$

Where, ET_U_* is one of the two components of ET_U_{Total}. The result of this will indicate the overall importance of each factor on evapotranspiration and thus crop yield for these forage crops under water stressed conditions.

RESULTS AND DISCUSSION

Once the LandSAT 5 images were processed using METRIC, the fields were examined to determine which ones could be selected for analysis. Because of variable harvest timing, not all center pivot fields could be examined for both years in both months. In some cases the forage crops had been harvested just prior to the image date so those were abandoned. In total, 18 fields were examined, three of which were examined in both April and May (Pivots 1, 5, and 11 are used for both April and May). Table 1 shows the image date, field, crop type, field acreage, and measured DU from 2007.

Table 1. Crop type, irrigated acreage, and measured irrigation system distribution uniformity for the fields (center pivots) used in this evaluation.

Month	Field	Crop Type	Irrigated Acres	2007 Measured Irr. System DU
April	Pivot 1	Alfalfa	127.20	0.87
	Pivot 5	Alfalfa	121.50	0.85
	Pivot 7	Alfalfa	115.80	0.88
	Pivot 10	Winter forage	125.10	0.85
	Pivot 11	Alfalfa	121.50	0.85
	Pivot 12	Alfalfa	121.30	0.84
	Pivot 13	Winter forage	19.30	0.89
	Pivot 23	Winter forage	125.00	0.80
	Pivot 24	Winter forage	130.20	0.84
	Pivot 25	Winter forage	128.30	0.87
	Pivot 26	Winter forage	18.80	0.84
	Pivot 27	Winter forage	18.80	0.85
May	Pivot 1	Alfalfa	127.20	0.87
	Pivot 2	Alfalfa	127.20	0.83
	Pivot 3	Alfalfa	22.10	0.85
	Pivot 5	Alfalfa	121.50	0.85
	Pivot 9	Alfalfa	125.10	0.82
	Pivot 11	Alfalfa	121.50	0.85

Figure 5 shows the ET_U_{Total} and ET_U_{Other} from the fields analyzed. In order for this analysis to be effective, the ET_U_{Other} must be greater than the ET_U_{Total}. The average ET_U_{Total} and ET_U_{Other} over the analysis area were 0.86 and 0.91, respectively. In all cases the ET_U_{Other} was greater than the ET_U_{Total}, which indicates that in fact evapotranspiration uniformity is impacted by the irrigation system DU during water stress. In addition, ET_U_{DU} can be quantified using the values shown in Figure 5 and Eq. 3.

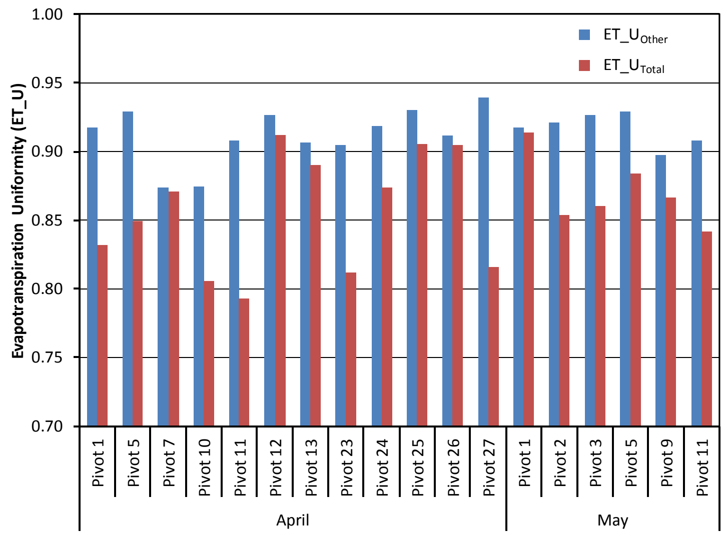

Figure 5. ET_U_{Total} (2007 images) and ET_U_{Other} (2010 images) from individual fields computed from LandSAT images taken in April and May of each year.

Using the values from Figure 5, measured ET_U_{DU} was computed using Eq. 3 under the 2007 water stress conditions. The irrigation system DU and the values from the FAO 56 soil water balance model were used to compute the $ET\_U_{DUpredicted}$. The overall average $ET\_U_{DUmeasured}$ and $ET\_U_{DUpredicted}$ were 0.90 and 0.89, respectively, resulting in an average error of approximately one percentage point.

The comparison of the measured and predicted on a field-by-field basis is shown in Figure 6. The average percent error ((predicted – measured)/measured) is also shown for each field on the right axis. The percent error ranged from a +8.7% to a -8.9% over the evaluation area. The fact that percentage errors are within a +/-10% are encouraging and indicate that in fact ET_U_{DU} is reasonably predictable.

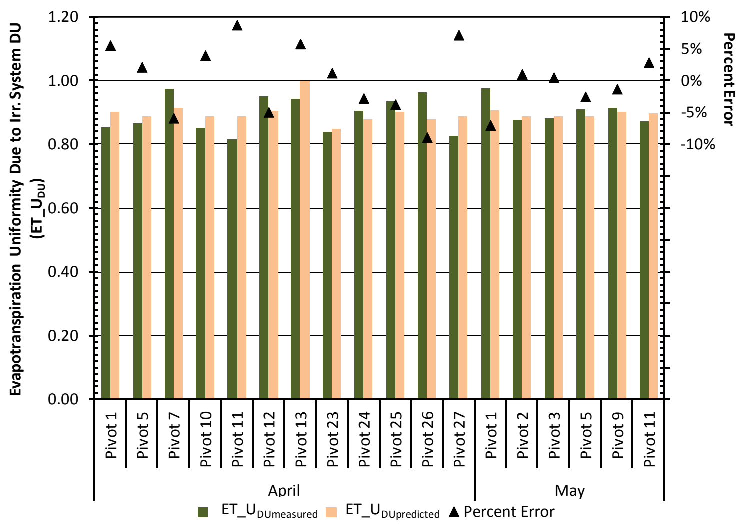

Figure 6. Comparison of ET_U_{DU} measured and predicted and the percent error for each field evaluated.

Figure 7 shows the percent error in predicted ET_U$_{DU}$ compared to the field averaged measured METRIC Kc's (Figure 7-top) and the center pivot DU (Figure 7-bottom). There does not seem to be any relationship between the center pivot DU and percent error; however, the range of DUs is limited in this evaluation (between 0.8-0.9). The predicted ET_U$_{DUpredicted}$ seems to be underestimating the ET_U$_{DUmeasured}$ with higher crop coefficients (likely less stress). However, there is not enough information to state this conclusively.

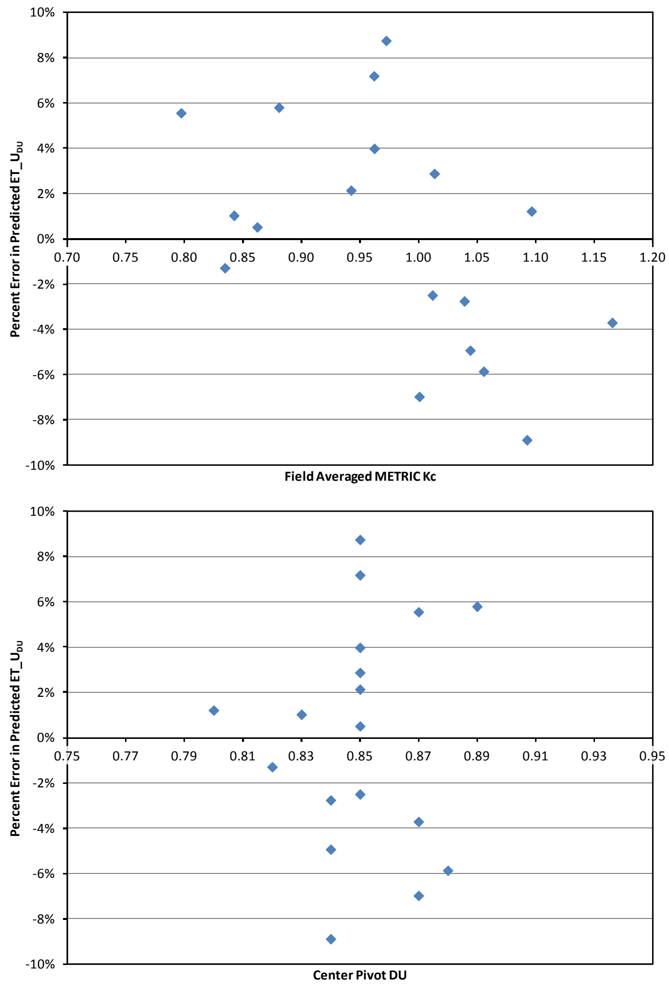

Figure 7. Percent error in predicted ET_U compared to the average measured METRIC Kc (top) and center pivot DU (bottom).

The importance of quantifying ET_U$_{DU}$ is in understanding its significance related to the overall uniformity in crop evapotranspiration and the impact on yield. The average ET_U$_{Total}$, ET_U$_{Other,}$ and ET_U$_{DU}$ averaged over the entire field was 0.91, 0.86, and 0.89, respectively. Using Equation 4, the percent contribution from irrigation system DU and other factors on the non-uniformity of evapotranspiration is approximately 55% and 45%, respectively. This means that under water stressed conditions, irrigation system DU will contribute 55% to the non-uniformity of evapotranspiration in a field. Since vegetative crops, such as the winter forage and alfalfa examined here, typically have yields that are directly proportional to the evapotranspiration, the irrigation system DU will have a significant impact on yield.

IMPACT

This study was conducted to assist farmers and irrigation designers with understanding the level of importance for one key factor: irrigation system distribution uniformity. An example of the potential economic impacts from this study is examining LACSD's Center Pivot 9 in Palmdale, CA. The existing center pivot distribution uniformity for that field in that season was 0.82, and the actual annual average yield over the field was 11.1 tons per acre. Utilizing the relative yield to relative evapotranspiration rate for alfalfa from FAO Water Development and Management Unit (Doorenbos and Kassam 1979), the yield can be predicted for the portion of the field receiving the most water (12.9 tons per acre) and the portion of the field receiving the least water (9.2 tons per acre).

If investments were made to increase the distribution uniformity to 0.89 (the highest Pivot DU of any pivot at in the 2007 evaluation), the annual average yield over the field increases by approximately 0.5 tons per acre. With prices of alfalfa at $180 to $200 per ton in 2010 (USDA 2010), the improved DU results in an increase in gross per-acre income of $90 to $100 per acre. For this field, which is 125 acres, this translates to an increased gross income of $12,500 per year by improving the distribution uniformity (current alfalfa prices in California are $250 per ton for average quality, which would lead to even higher potential increase in gross income). For center pivots it is reasonably simple to achieve a distribution uniformity of 0.85 to 0.89 by cleaning the spray nozzles (estimated cost $400 for this pivot), completely changing the sprinkler package (estimated cost $3,000 for this pivot), <u>or</u> adding pressure regulators at each drop (estimated cost $3,500 for this pivot). These costs have been estimated using actual costs from similar tasks that were completed recently in Palmdale, CA.

CONCLUSION

Utilizing LandSAT images with the METRIC algorithm, this study examined the spatial variability in ETc for forage crops (alfalfa and winter forage) being irrigated with center pivot irrigation under water stressed and non-water stressed situations. Under non-water stressed conditions, the spatial variability in ETc can be attributed to causes other than irrigation distribution uniformity. Under water stressed conditions the METRIC images processed showed that there is additional variability in evapotranspiration through the same fields. Comparing the uniformity of evapotranspiration from the same fields, with the same crops, under both conditions the uniformity of evapotranspiration due to irrigation system DU (ET_U_{DU}) was quantified. The results indicate that under moderate water stressed conditions, the ET_U_{DU} can contribute approximately 55% to the overall non-uniformity of evapotranspiration in a field. Since ETc is directly related to yield for vegetative crops such as alfalfa and winter forage, improving the irrigation system uniformity can improve crop yield under water deficit conditions.

Future work is planned to examine additional image dates to increase the confidence of the results. Additional work will be conducted to examine the components of non-uniformity due to "Other" causes such as variability in soil types, salinity, etc.

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