DEVELOPING CORN REGIONAL CROP COEFFICIENTS USING A SATELLITE–BASED ENERGY BALANCE MODEL (RESET) IN THE SOUTH PLATTE RIVER AREA OF COLORADO

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ABSTRACT

Accurate estimates of evapotranspiration for agricultural crops are essential for water resources management and for crop production. Traditional methods for estimating crop evapotranspiration are based on weather based reference evapotranspiration estimates multiplied by a crop coefficient (Kc). The crop coefficient varies based on crop type and growth stage and optimum growing conditions are assumed in this approach. Satellite based energy balance models can directly measure actual ET in fields and these measurements can be used to develop crop coefficients for different crops for a particular region. In this study a surface energy balance model (ReSET) is used to measure actual ET for corn fields in the South Plate River Basin of Colorado. The study covers four growing seasons (2001, 2004, 2005 and 2006). A total of 79 Landsat 5 and 7 images were used for the four years using two satellite paths 33/32 and 32/32.

INTRODUCTION

Remote sensing algorithms that use satellite imagery have been widely used to estimate evapotranspiration (ET). These algorithms are called surface energy balance models and most of them were developed in the last decade (Kustas and Norman 1996; Bastiaanssen et al. 1998a,b; Timmermans et al. 2004; Nagler et al. 2005; Allen et al. 2007a,b). These models use satellite imagery such as Landsat, AVHRR, ASTER, and MODIS to estimate ET (Nishida et al. 2003). The models estimate the actual ET occurring in the fields, which takes into account the cumulative impact on ET of all ground factors such as water stress, soil salinity, pest infestations, hail damage, agronomic practices, etc. The models cannot determine the impact of each factor but the combined impact of all ground factors. Remote sensing of ET provides an "actual" estimate of ET versus more traditional ET methods which calculate a reference crop ET and then apply crop coefficients to estimate the ET for different crops under optimum conditions. Of the traditional approaches for calculating crop ET, weather based reference ET is the most commonly used along with

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crop coefficient (Kc) curves to estimate water demand for different crops. Crop coefficient curves presented in the literature by Doorenbos and Pruitt (1977), Wright (1981, 1982 and 1995) and Allen et al. (1998) are based on point measurements and assume optimum cultivating conditions (management, irrigation, etc). Such assumptions do not apply for many fields since irrigation type and adequacy differs from field to field as well as soil type. Presence of soil salinity and fertilizers application can also vary significantly between fields that have the same crop. A regional based crop coefficient approach is proposed in this research that takes into account the spatial and temporal variability in crop conditions in an area, which can be accomplished using surface energy balance models using satellite imagery. Surface energy balance models measure actual ET in the fields which aggregates all temporal and spatial variability. This actual measured ET is then used with weather based reference ET to develop crop coefficient curves that are tailored to each crop type and to each region. These regional crop coefficient curves can be used to determine crop water requirements for a particular region. The ReSET (Elhaddad et al., 2008) surface energy balance model is used in this research to determine the "actual" ET.

METHODOLOGY

The study area is an agricultural area covering a portion of the South Platte river basin in northwest Colorado. This region has a semi-arid climate with irrigation water resources in the area mainly from the South Platte River or from ground water. The main crops cultivated in the area are corn, alfalfa, small grains, dry beans and sugar beets. The study area falls on two Landsat paths 32/32 and 33/32. In this study crop coefficients for grain corn were developed; the study area starts on the west at the town of Wiggins and extends north east to the town of Ovid as shown in Figure 1.

The data used in the ReSET model includes a digital elevation map for the area, hourly and daily reference ET grids from five weather stations in the area (Crook, Ovid, Sterling, Brush and Wiggins) and finally Landsat 5 and 7 images collected at 11:20 am (during the growing season – daylight savings time). The study covered the growing season for corn (May to October) for four years (2001, 2004, 2005 and 2006) for Landsat paths 32/32 and 33/32. Landsat images are available every 16 days for each path which makes it possible to collect almost 4 images from the two satellites (Landsat 5 and 7) per month. However, the number of usable images per month is less than four since the ReSET model can only use cloud free images, therefore the number of usable images varies depending on the cloud cover. The Landsat 7 imagery for the 2001 year was useable since it did not have the stripping problem of blank strips with no data that started in 2003. The Landsat 7 images from years 2004, 2005 and 2006 had the stripping problem and the areas covered by the strips were masked with values of no data, which allowed the remainder of the image to be use in the Kc calculations.

A total number of seventy nine Landsat images were used to develop the corn Kc curve with an average of four images per month and twenty images per growing season. An initial set of corn fields were identified based on a crop classification map developed by the Northern Colorado Water Conservancy District (NCWCD) for each growing season. Those sets of fields had to be filtered to eliminate fields that might have been misclassified, partially cultivated, fields that were abandoned during the growing season and/or fields that were harvest for silage (since they are harvest earlier than grain corn). The objective of the filtering procedure is not to select ideal grain corn fields but to select grain corn fields growing under typical and variable conditions for an entire corn grain season.

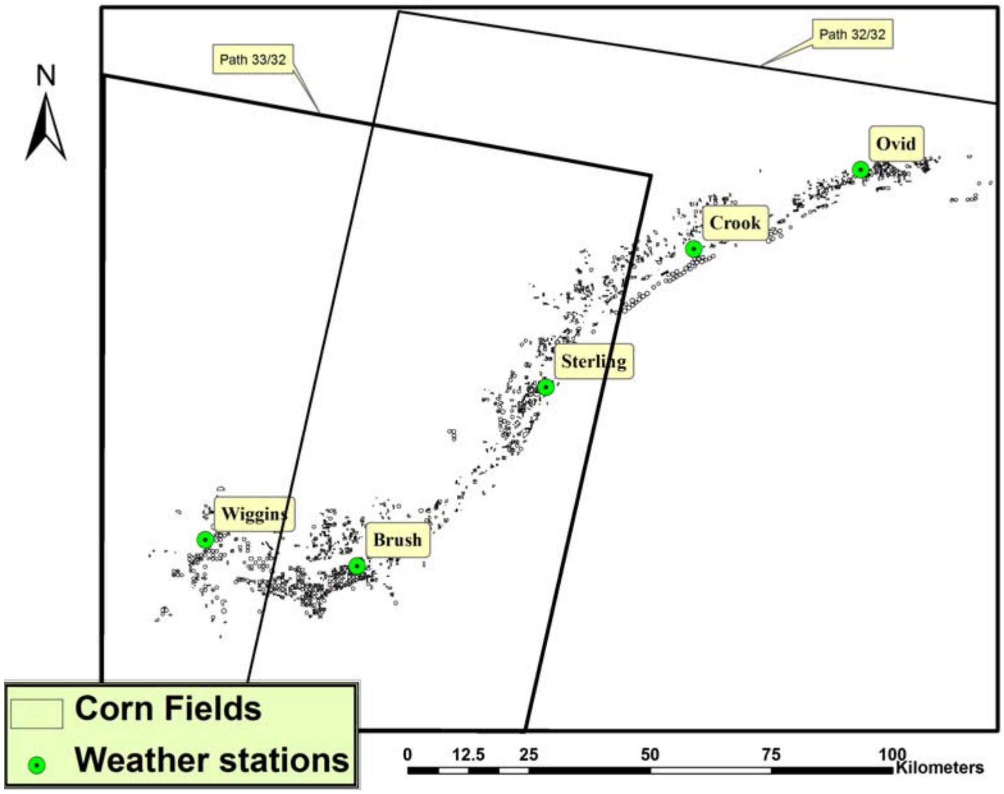

Figure 1. Study Area

Filtering Procedure for Fields

1. ***Using Consecutive Values of NDVI:*** Knowing the mean Normalized Difference Vegetation Index (NDVI) value for each field for several consecutive dates (this value is expected to increase throughout the season), if a different behavior is detected (NDVI decreases during the middle of the season) this indicates that the crop is either not corn, silage corn, or corn that was grown under abnormal growing conditions (drought, hail damage, pests) and therefore these fields were removed from the dataset. An example is shown in Figure 2, which is a false color infrared image where red represents actively growing crops and fields classified as corn by NCWCD are shown with an outline. The left image was taken in July 14, 2006 and clearly shows an actively growing crop in the two center pivots inside the black circle in the middle of the image. The right image was taken on July 30, 2006 and shows the same fields but with very light color that indicates a drop in vegetation density.

These fields were excluded because they were probably not corn or corn that was harvest very early as silage corn.

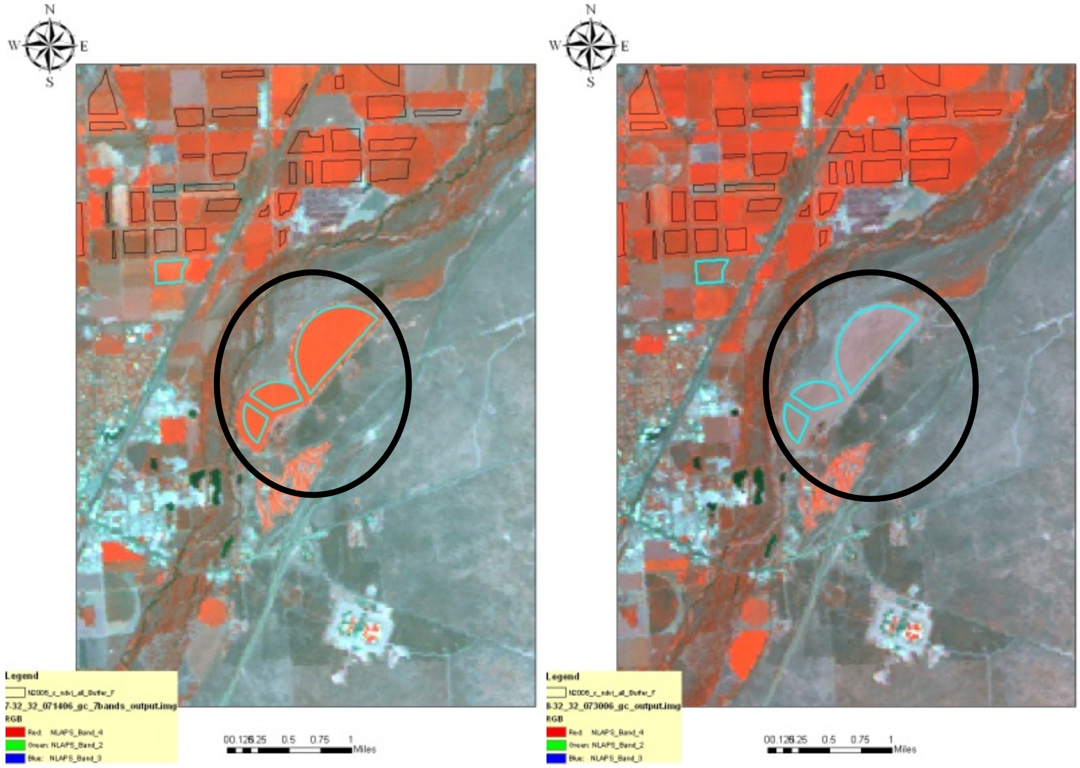

Figure 2. Fields probably misclassified as corn. Left image was taken on 7/14/06 and right image was taken on 7/30/06.

2. ***High NDVI Standard Deviation:*** Fields with high NDVI standard deviation indicate a large spatial variation in the field which could be because the field is partially cultivated as seen in Figure 3 or the field has areas with high salinity, partially irrigated, pests, etc. These are not good fields for use in generating Kc values for corn since they will cause an underestimation of the Kc values. Fields with high NDVI standard deviation (higher than 0.1) were removed from the analysis.

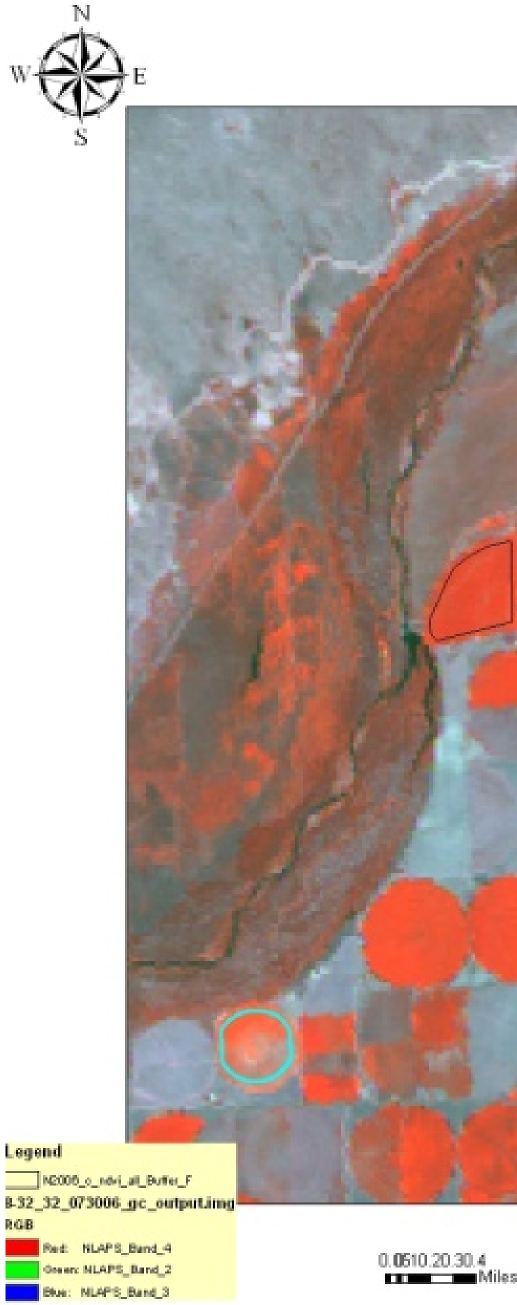

Figure 3. Fields classified as corn but partially cultivated.

3. ***Using NDVI Values to Single Out Non-corn Fields***: The last check to ensure that the selected fields are all corn fields is a NDVI value check at early, mid and late season. Corn fields should have low NDVI values during the early part of the growing season (May-June) since they should have little vegetation at that time and therefore a low NDVI value (0.1 to 0.5). Fields with high NDVI values during the early part of the season such as those shown in Figure 4 from a satellite image taken on 4/16/2006 should be excluded. Those fields are either not corn, corn that was planted very early,

or another crop and therefore would introduce some error when calculating Kc for the majority of corn fields, a mid season check on the NDVI values around late July is done to exclude fields with low NDVI values (less than 0.7) in July since fields with corn in good conditions should have NDVI values from 0.7 to 0.8. Any fields with low NDVI during this time should be excluded. For the late season NDVI values should not exceed 0.5 for corn fields, fields with higher values should be excluded.

Figure 4. Non corn fields or fields with corn planted very early since it is actively growing on 4/16/2006.

4. ***Cloud Masking***: Creating a subset of the fields that are cloud free on ALL dates may reduce the number of fields too much. Therefore, sets of fields for each image date are created so that the maximum number of fields is used for each image date. To do this the shapefile containing the corn fields with the correct range of NDVI values and NDVI standard deviation values are used as the starting set. This set stays the same on dates with no clouds; for dates with cloud cover a shapefile excluding the fields under cloudy areas is created.

Fields that passed all these filtering procedures are considered representative full season grain corn fields for the range of growing conditions and can be used to calculate Kc for grain corn. Before the application of the filtering procedure, all fields were buffered with a 60 m inward buffer to minimize the thermal pixel contamination at the borders of the fields caused by the areas surrounding the fields. After the buffer is applied, the fields with areas less than 28,328 m^2 (7 acres) were excluded from the set for being too small compared to the thermal pixel size. The maximum pixel size (thermal pixels) in the imagery used (Landsat 5) is 120 m by 120 m which represents an area of 14,400 m^2, to ensure that the smallest field used contains at least two thermal pixels, the area of 28,800 m^2 was used. The mean value of the hourly ET estimated by the ReSET model from all pixels within the boundary of each field is assigned as a single value for each field. This value is divided by the spatially corresponding gridded weather station hourly reference ET to develop a Kc value for that field. A mean value of the Kc for all fields is then used to represent the corn Kc for that date. The Kc developed from each date was then combined to create a corn Kc curve for the whole growing season for each year. A final cumulative Kc curve for the four years (2001, 2004, 2005 and 2006) for the study area was developed.

The interpolated spatial grid of hourly weather station reference ET from all five weather stations was generated for each of the Landsat image dates. The reference ET for each field was extracted from these grids based on the location of each field. This process allocates reference ET based on the spatial location of each field rather than using a point value from one or more weather stations for all fields which could cause either an overestimation or underestimation of the reference ET because of spatial variability in weather conditions.

RESULTS AND DISCUSSION

The ResET model was used to estimate hourly ET (Fig 5b) from Landsat 5, 7 images (Fig 5a), a shapefile of corn fields (Fig 6) was buffered and fields smaller than 28,328 m^2 (7 acres) were excluded (Fig 7) to avoid thermal pixel contamination.

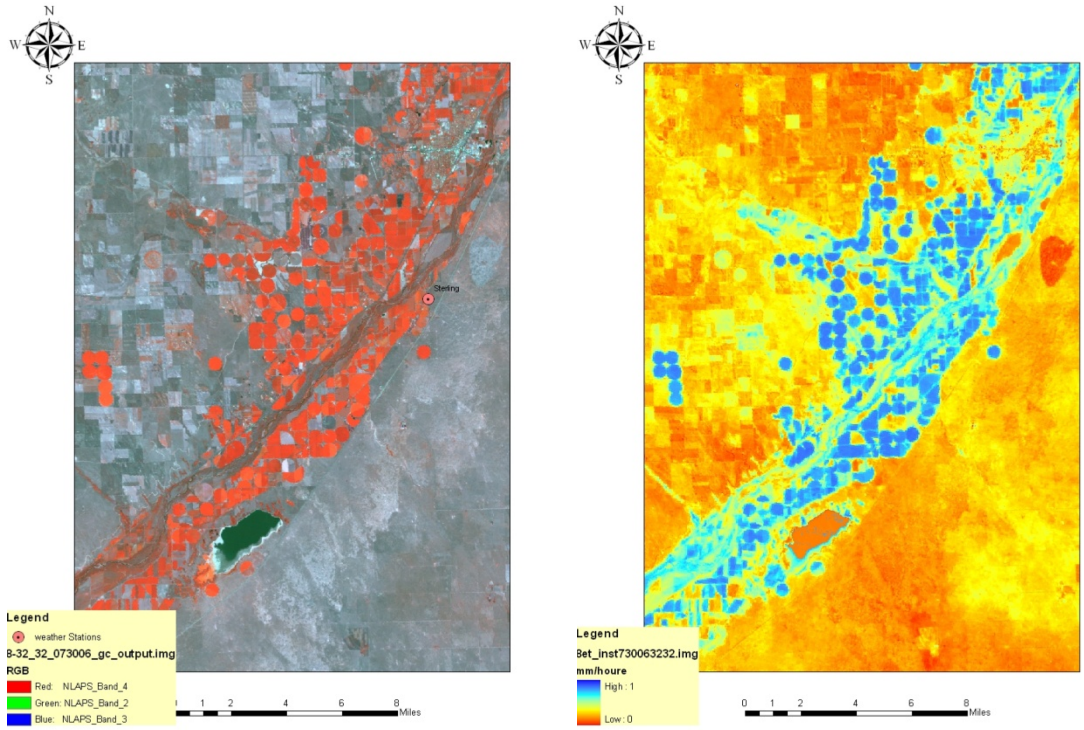

Figure 5. a) Landsat image on 7/30/2006 b) Hourly ReSET ET 7/30/2006

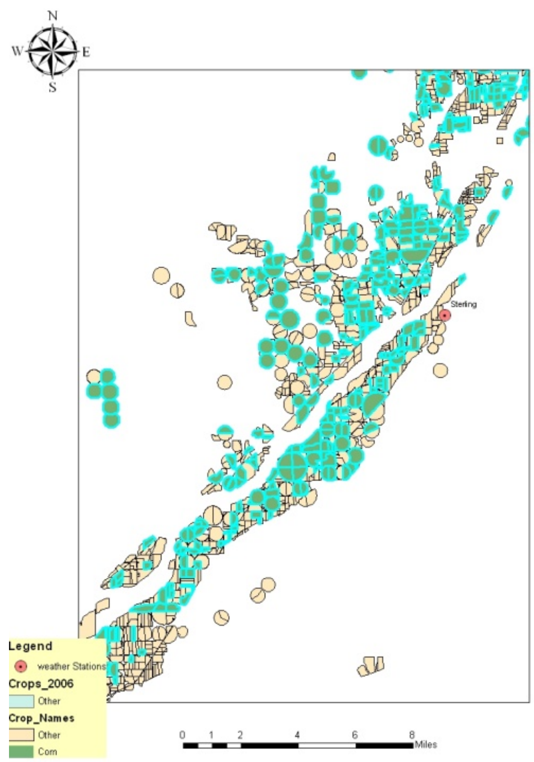

Figure 6. Corn fields

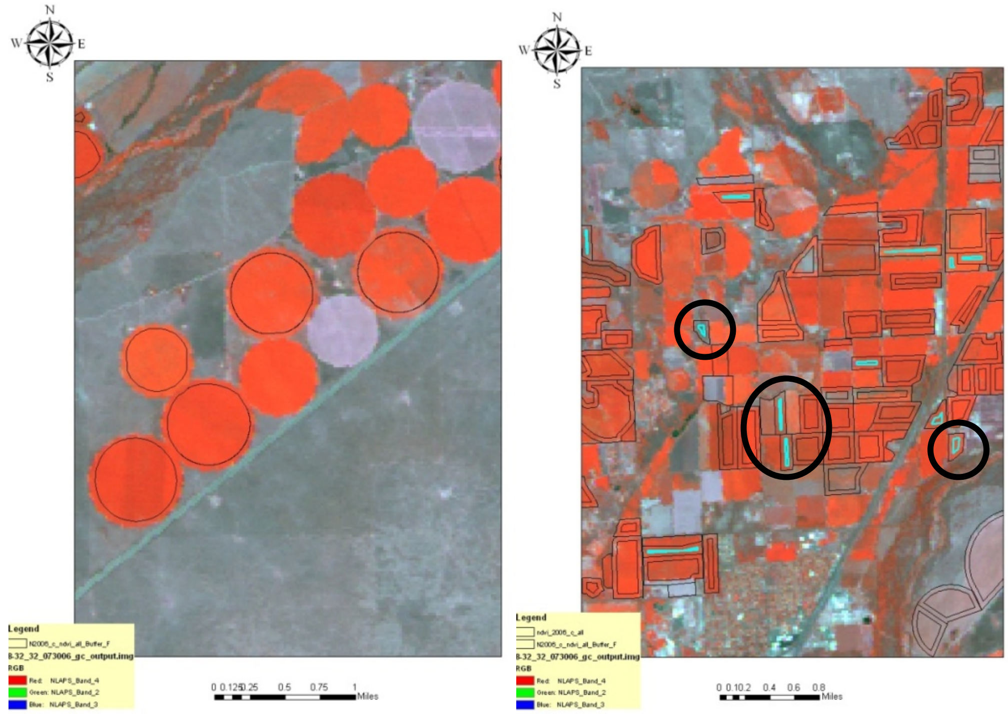

Figure 7. a) Buffered corn fields b) Smaller fields selected and excluded

Within each polygon (field) using the zonal statistics function in ArcGIS a set of values are calculated:

- ReSET estimated hourly ET (mean values).
- NDVI (mean, standard deviation).
- Reference hourly ET from weather stations grid (mean values).
- Corn Kc for each image date is calculated by dividing the mean value of the hourly ET from the ReSET model by the weather station reference hourly ET corresponding value.

Mean corn Kc values for each date are obtained from the attribute table of the final shapefile Fig (8).

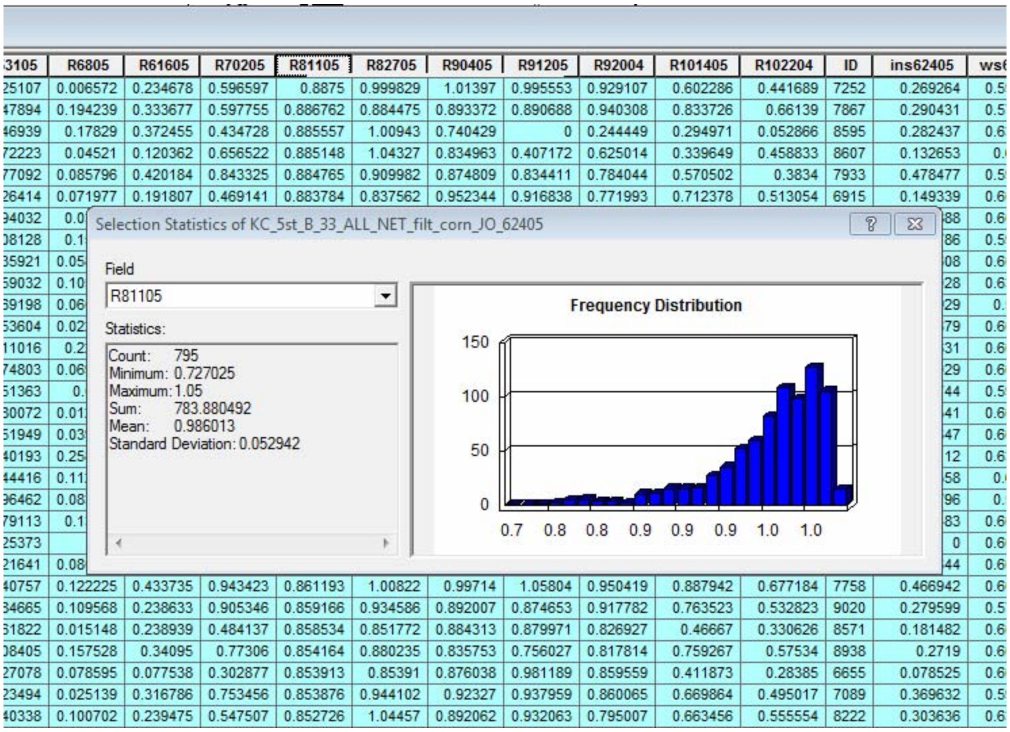

Figure 8. Corn Kc values for each date.

For the year 2001, twenty two Landsat images were used to develop corn Kc for that year, ten of them are Landsat 7 and 12 are Landsat 5. Of these images thirteen fall on path 33/32 and nine images fall on path 32/32. A maximum number of 1,295 corn fields were used from path 32/32 and a maximum number of 1,701 were used from path 33/32. Figure 9 shows the 2001 Kc for corn developed using ReSET plotted against growing degree days and Figure 10 shows the 2001 Kc for corn plotted against dates. The regression curves shown in each image have an R^2 value of 0.97 and 0.96 respectively. For 2004 twenty one Landsat images were used to develop corn Kc values which resulted in an R^2 value of 0.90 and 0.95 for growing degree days and dates respectively. For 2005 only thirteen Landsat images were used to develop Kc due to high cloud cover which resulted in an R^2 value of 0.93 and 0.94 for growing degree days and dates respectively. For 2006 twenty three Landsat images were used to develop corn Kc which resulted in an R^2 value of 0.96 and 0.94 respectively. Figure 11 and 12 show a combined graph for all years (2001 to 2006) of the corn Kc plotted against growing degree days (Figure 11) and against day of the year (Figure 12). Each year is treated as a separate data series, years 2004 and 2005 show lower corn Kc values at the beginning of the season compared to years 2001 and 2006. The R^2 value of a polynomial fitted through the data for all the years is 0.89 and 0.91 respectively for growing degree days and day of the year. The intent of using growing degree days as a scale for Kc values is to reduce the variability due to temperature differences between years.

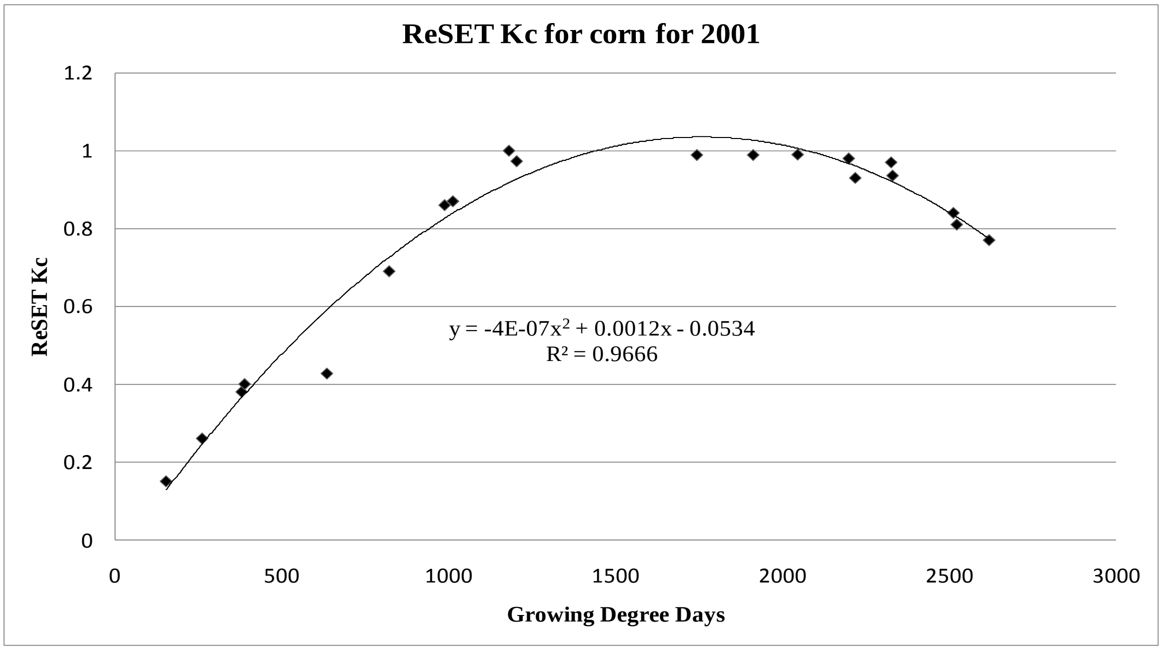

Figure 9. ReSET growing degree day corn Kc curve developed using 2001 data.

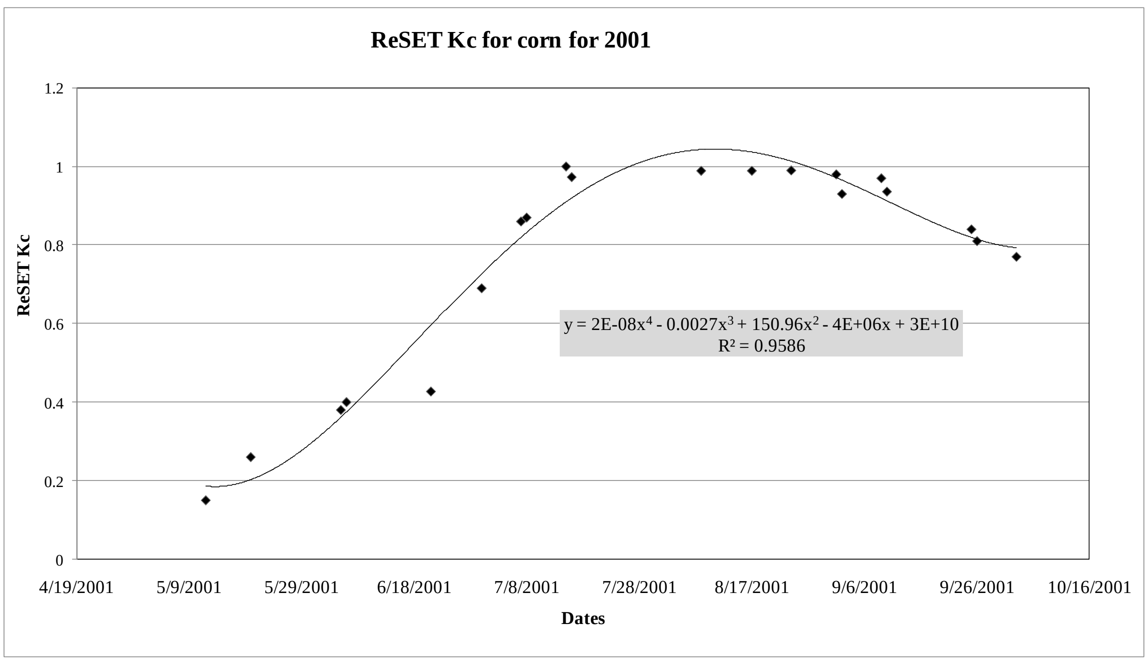

Figure 10. ReSET corn Kc curve developed using 2001 data.

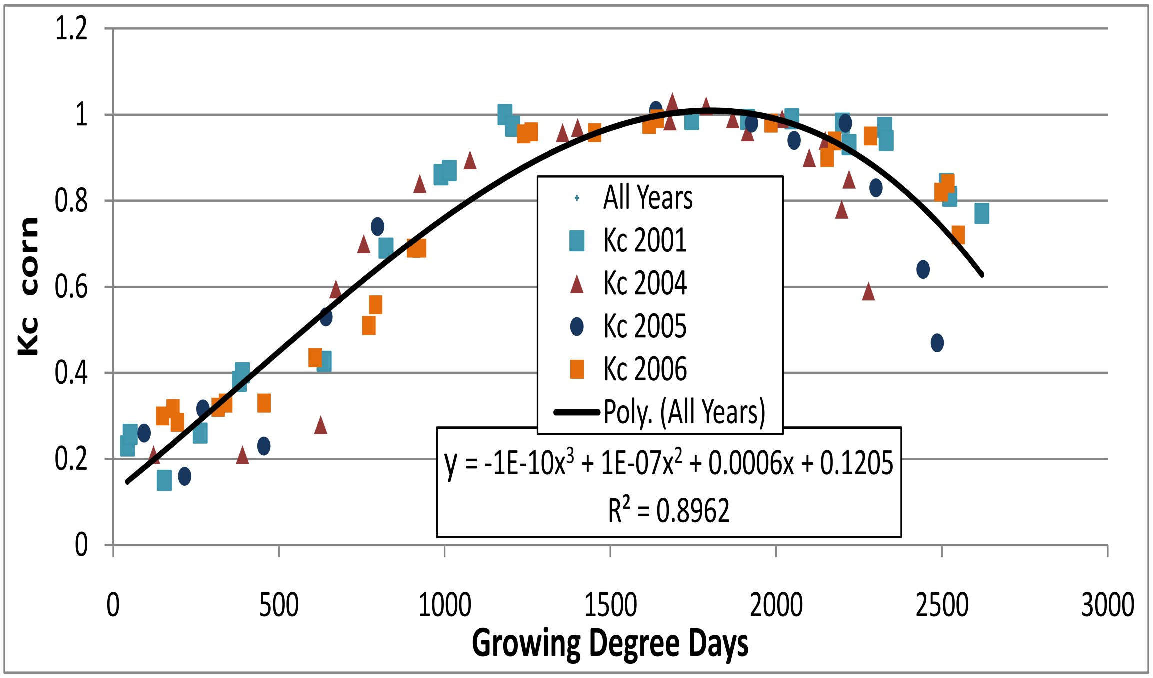

Figure 11. ReSET corn Kc values developed using 2001, 2004, 2005 and 2006 data.

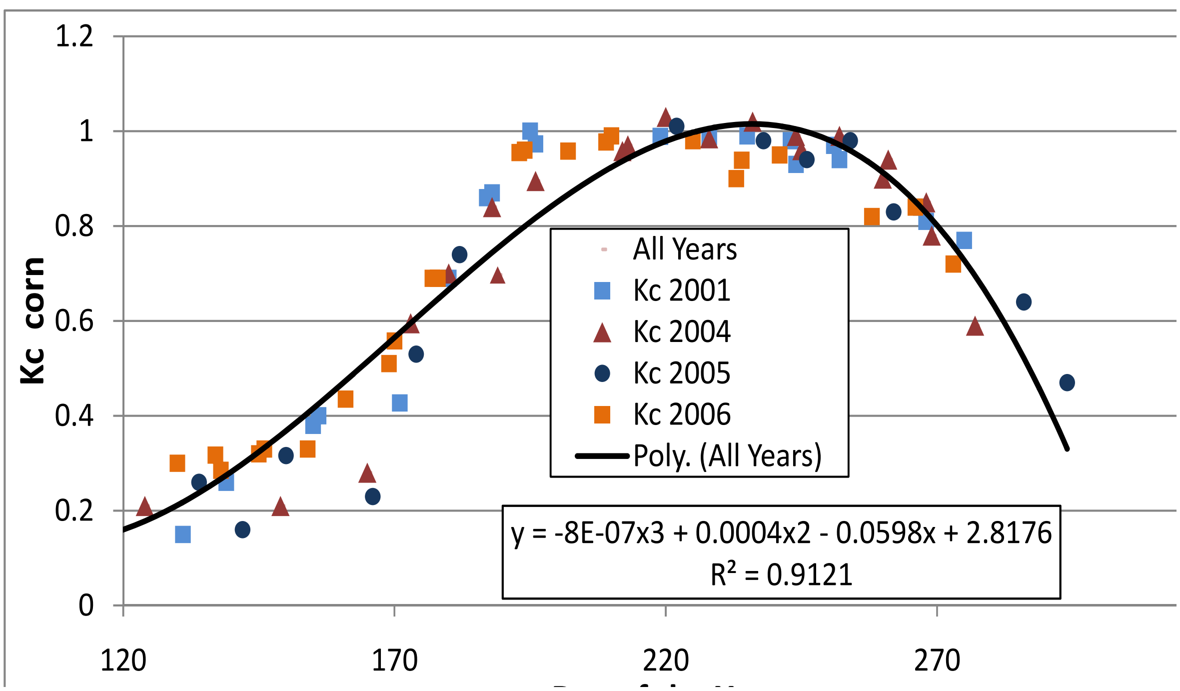

Figure 12. ReSET corn Kc values developed using 2001, 2004, 2005 and 2006 data.

As seen in all the years of the study the variability in the model calculated corn Kc is large at the start and the end of the corn growing season while it is smaller during the middle of the season. This is probably due to the temporal variability in planting and irrigation dates as the model is sensitive to surface temperature of irrigated fields which are likely to have more transpiration from bare soil early in the season which would result in higher values for Kc. The variation in Kc at the end of the season is most likely caused by senescence of the crop; crop harvesting or because of variable drying of the field at the end of the season. Since all these events are field dependent they all contribute to the larger variation in Kc at the end of the season. Corn Kc during the middle of the season (mid July to end of August) has much less variation because of the similarity in crop conditions in most of the fields and because of the high crop coverage which minimizes the impacting of wet soil.

SUMMARY AND CONCLUSIONS

The results of this study show that surface energy balance models such as the ReSET model can be used to develop regional Kc values for agricultural crops. The Kc developed for grain corn fields in the South Platte of Colorado used data for a period of four years, with a total of 79 Landsat images using over 1,000 corn fields during the growing season which extends from May to October. The Kc for each of the years (Figures 11 and 12) matched well which supports the approach for using models such as ReSET in developing Kc for agricultural crops. This approach provides a convenient and practical way of estimating a regional crop Kc. These Kc values can be compared to others developed for other regions to determine if there are local conditions that are reflected in the regional Kc values.

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