CALIBRATING SATELLITE-BASED VEGETATION INDICES TO ESTIMATE EVAPOTRANSPIRATION AND CROP COEFFICIENTS

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ABSTRACT

This paper presents a procedure to estimate actual evapotranspiration (ET) using a satellite-derived vegetation index. Actual ET is computed in a traditional manner using the crop coefficient (K_c) and reference ET (ET_{ref}) procedure (i.e., ET = K_c x ET_{ref}) with K_c estimated from the satellite-based NDVI. This study calibrated relationships between K_c and NDVI using satellite-based ET determined by surface energy balance. This unique approach enables calibration of the K_c vs NDVI equations using large numbers of sampled fields (in this case, more than 3000). Thus the calibration represents a regional average K_c estimate. The study was conducted for alfalfa, beans, sugar beet, corn, potatoes, and small grain crops, which are the major crops in southern Idaho. Estimation accuracy for ET was statistically evaluated. Average error of seasonal ET was within 5 percent of the energy balance (EB) determined ET for most crop types. Error in seasonal ET from individual fields is expected to be within 10 percent. NDVI based ET was compared with lysimeter measurements of ET from grass and sugar beets. The seasonal error of the NDVI based method was only 2 percent for grass and 6 percent for the sugar beets, as compared to lysimeter measurements. Statistical accuracy assessments suggest that NDVI based ET estimation can be a robust, simple and inexpensive tool to estimate ET from irrigated agricultural crops with reasonable good accuracy.

INTRODUCTION

Evapotranspiration (ET) is the major consumptive use of irrigation water and thus, spatial and temporal quantification of ET is important in agricultural water management, especially in areas experiencing scarcity in total fresh water resources. ET has traditionally been estimated at regional and field-scales using the crop coefficient (K_c) method (ASCE - EWRI 2005):

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$$ET = K_c \times ET_{ref} \tag{1}$$

where ET_{ref} is reference ET (alfalfa (ET_r) or clipped grass (ET_o) reference).

Using recently developed techniques, accurate ET estimation, spatially and temporally, is possible via satellite-based energy balance (e.g. Anderson et al., 1997; Bastiaanssen et al., 1998; Kustas and Norman, 2000; Allen et al., 2007a). However, this approach requires surface temperature imagery along with a relatively high knowledge level of near-surface energy exchange physics and aerodynamics, which prevents many general water resources professionals from applying the technique. The K_c-based ET estimation method is often preferred for operational applications because of its simplicity (Duchemin et al., 2005). Simpler ET estimation approaches based on correlation of crop ET and NDVI from satellite images have been investigated by Allen et al., (2003), Hunsaker (2003) and Duchemin et al., (2005), where NDVI is the normalized difference vegetation index and is computed from red and near infrared bands of the satellite. While this approach is simple, accuracy of ET estimation can be limited because vegetation indices do not provide information on the soil evaporation portion of ET in irrigated agriculture. Earlier work on K_c vs. NDVI based on aerial imagery included that by Neale et al. (1989) and Bausch et al. (1989).

In this paper, we attempt to determine mean K_c by NDVI, where the NDVI- K_c relationship is calibrated using satellite based energy balance. This approach requires a one-time application of the energy balance for each area of interest to calibrate the local K_c vs NDVI function. Once the K_c is locally calibrated by NDVI, ET for the following years can be estimated with reasonable accuracy as:

$$ET = (a \cdot NDVI + b) \times ET_{ref} \tag{2}$$

where a and b are regional constants calibrated by surface energy balance, NDVI is at-satellite or at-surface NDVI from satellite image, and ET_{ref} is alfalfa or grass reference ET calculated by weather data. Other vegetation indices besides NDVI, for example SAVI, have been explored for estimating K_c. However, it appears that NDVI exhibits a desirable tendency to 'saturate' at about the same leaf area index as does K_c, thus reaching an upper limit at the same time as K_c (Allen et al., 2007c). The 'at-satellite' NDVI (computed with no atmospheric correction to bands) appears to be as consistent in estimating K_c as an at-surface NDVI (Allen et al., 2007c). Satellite based ET maps provide a robust means to analyze K_c, because the method can cover large numbers of sampled fields (Tasumi et al., 2005, Tasumi and Allen, 2006).

METHODOLOGY

ET images and related field data produced by surface energy balance by Tasumi et al. (2005) and Tasumi and Allen (2006) were used to evaluate relationships between alfalfa-reference K_c (K_{cr}) and at-satellite NDVI ($NDVI_{as}$). The study area is the Magic Valley in Idaho, a large irrigated agricultural area in south-central Idaho having a semi-arid climate (Figure 1). The major crops of the area are alfalfa, dry, edible beans, field and sweet corn, small grains, peas, potatoes and sugar beets. Typical field sizes in the region are 400 m by 400 m to 800 m by 800 m, thus, ET from individual fields is amenable to sampling from Landsat images having 30 m by 30 m spatial resolution.

During previous studies, twelve Landsat images from March through October, 2000, were processed for the study area using the METRIC model to estimate ET and K_{cr}. The METRIC program and applications are described in Allen et al, (2007a, b). METRIC K_{cr} was developed for each Landsat image on a 16 to 32 day frequency. K_{cr} values were interpolated between satellite-image dates using a spline function (Excel Cubic Spline 1.01 by SRS1 Software) applied pixel by pixel. A crop-type classification was conducted for the same year using the Landsat images and independent ground truth information. In total 3420 fields were sampled that included eight crop types (Table 1).

Figure 2 shows the $NDVI_{as}$ vs. K_{cr} relationships from March to October. $NDVI_{as}$ vs. K_{cr} relationships tended to be linear and converged after NDVI > 0.7 (i.e. maximum cover season). The general relationships (solid lines) in Figure 2 were drawn past the point of $NDVI_{as}$ vs K_{cr} convergence, and the intercept was determined so that the average estimation error is zero when ET is estimated using equation 2. Using the general calibration developed in Figure 2, equation 2 can be reexpressed as:

$$ET = \left(1.18 \cdot NDVI_{as} + 0.04\right) \times ET_r \quad (3)$$

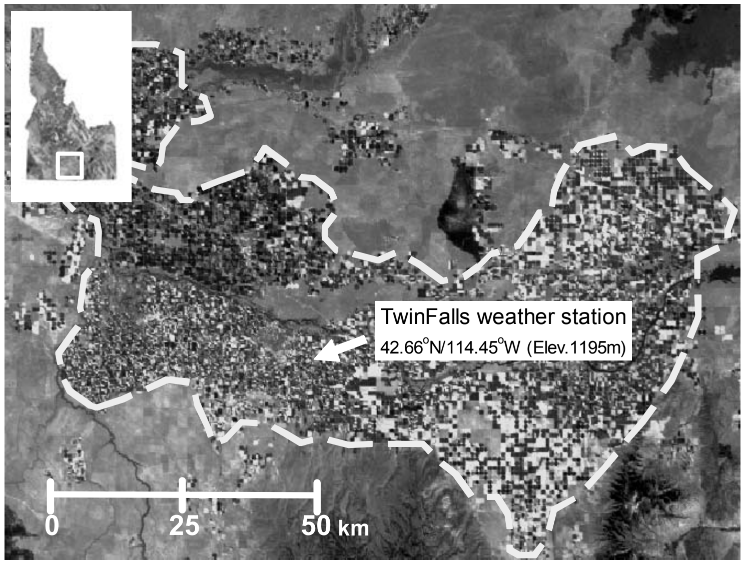

Figure 1. Agricultural Study Area in Magic Valley, Idaho (Circled by Dotted Line) and Location of Weather Station Used to Calculate Reference ET Used as a Basis of the Surface Energy Balance and Derivation of Crop Coefficients

Table 1. Investigated Crops and Numbers of Sampled Fields.

Crop type	Alfalfa	Bean	Corn	Potato(S) *	Potato(L) *	Sugar Beet	Spring Grain	Winter Grain	Total
Sample field number	325	432	451	396	221	495	536	564	3420

* Potato(S) and Potato(L) are potato crops having short (S) and long (L) full cover periods respectively.

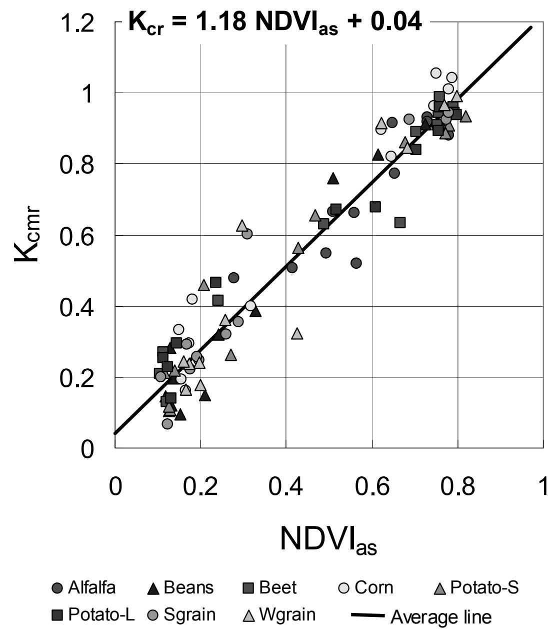

Figure 2. Mean K_{cr} vs. $NDVI_{as}$ by Crop Type from March to October (5 day average).

RESULTS AND DISCUSSION

ET was estimated using equation 3 for the twelve Landsat images of southern Idaho, 2000. Figure 3 shows the result image for 7/5/2000. Figure 4 shows daily ET averaged over multiple fields of sugar beets where ET was estimated using $NDVI_{as}$ and K_{cr}. The ET estimated from $NDVI_{as}$ corresponds well with METRIC results for all evaluated crops.

Seasonal ET was calculated for average field conditions (i.e. using NDVI averaged over all sampled fields having the same crop type) by employing a spline curve to interpolate daily between average NDVI from each Landsat date. Daily ET was calculated by multiplying K_{cr} computed for each day of the season via the spline by alfalfa-reference ET (ET_r) for that day. Seasonal ET was then calculated by summing daily values across the growing season, which in this case was defined as March 15 – October 17 for all crops (these were the first and last dates for Landsat coverage for 2000).

Mean differences between seasonal ET estimated by NDVI and seasonal ET determined directly from METRIC for the same groups of fields are compared in Table 2. Results indicate that, in general, equation 3 estimates ET with reasonable accuracy for the primary crops grown in southcentral Idaho, with average error within 5 percent in most crop types. Also, error of seasonal ET estimation is within 10 percent for most individual fields as compared to ET derived directly from the METRIC energy balance.

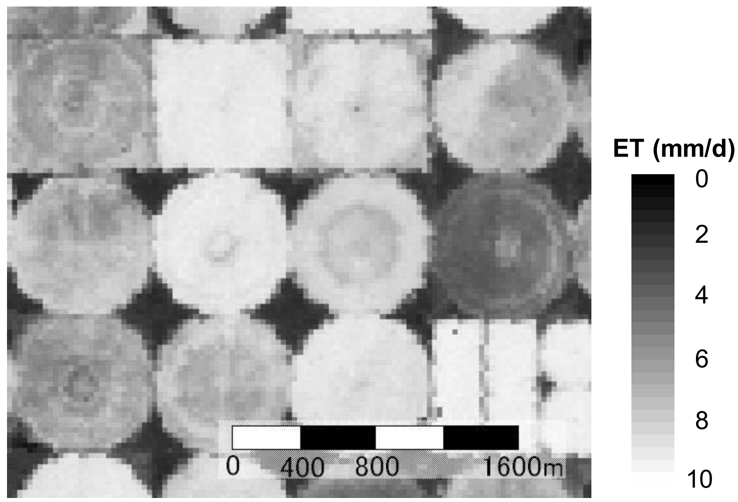

Figure 3. ET Estimated by $NDVI_{as}$ on 7/5/2000, (Landsat 5, path 40, row 30).

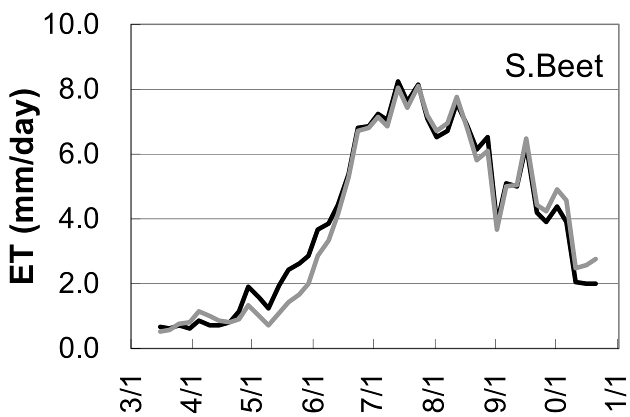

Figure 4. Comparisons Between Daily ET (5-day Mov. Avg.) Determined by METRIC and ET Determined from the General K_{cr} vs. $NDVI_{as}$ Relationship, Averaged Over All Sugar Beet Sampled Fields

Table 2. METRIC Seasonal ET (March 15-October 17) and Error in Seasonal ET Estimated Using NDVI (Averaged Over Multiple Fields of the Same Crop), and Estimation Error for Individual Fields for year 2000

Crops	Alfalfa	Beans	Beet	Corn	Potato(S)	Potato(L)	S.Grain	W.Grain
METRIC ET (mm/season)	1001	479	904	846	733	846	720	837
Average error* (%)	5	7	-2	-7	1	-2	-2	-2
Error range* (%, 1σ)	+1 to +8	0 to +14	-7 to +1	-12 to -2	-3 to +6	-6 to +3	-7 to +3	-8 to +3

* Positive values indicate over estimation by the NDVI-based method. Error range represents differences between seasonal METRIC ET and ET by Eq. 3 for individual fields.

Performance of NDVI based ET estimation was tested at two fields equipped with precision weighing lysimeters near Kimberly, Idaho. The lysimeter ET data were collected by Dr. J.L.Wright at the USDA Agricultural Research Service facility during the 1970's and 1980's (Wright, 1982; Wright, 1991). Daily and seasonal NDVI based ET was estimated for the Lysimeter field from eight clear-sky Landsat 5 images in 1989 (4/18, 5/4, 5/20, 6/5, 6/21, 7/7, 7/23 and 9/25) using equation 3. $NDVI_{as}$ values used in this analysis were averages taken from three pixels near the center of the grassed lysimeter field (i.e. for the center 120m by 30m area), and from four pixels near the center of the sugar beet lysimeter field (i.e. for the center 60m by 60m area). $NDVI_{as}$ computed for each satellite image date was then interpolated for days between dates using a cubic spline function.

The NDVI-based ET estimations corresponded relatively well with the actual lysimeter measurements for both the grass and sugar beet fields. The standard error of daily ET estimates as compared to lysimeter measurements was 0.6 mm d^{-1} and 1.3 mm d^{-1} for grass and sugar beets, respectively. On a seasonal basis, the $NDVI_{as}$-based ET estimates using the general equation developed for southern Idaho using year 2000 date (i.e. equation 3) estimated seasonal ET relatively accurately for the two lysimeter fields during 1989. The estimation error for seasonal ET was 2 percent for grass and 6 percent for sugar beets, both of which were underestimated. The expected error range for grass is unknown, but the observed error for sugar beet was within the expected error range determined in Table 2 (i.e. from 7 percent underestimation to 1 percent overestimation). This comparison study demonstrates a good potential for using NDVI based ET estimates, even for applications to individual fields.

SUMMARY AND CONCLUSIONS

This study developed a simple vegetation index-based equation to estimate total ET via satellite. The empirical NDVI based K_c relationship was calibrated using ET information developed by satellite-based energy balance, so that the calibration represents mean K_c vs. NDVI relationships and conditions over large number of fields (3420 individual agricultural fields). Accuracy of ET estimated using the calibrations is expected to have similar accuracy, when averaged over enough fields to average out differences in ET caused by individual irrigation events, to the original ET maps developed from METRIC.

Alfalfa, beans, sugar beets, corn, two variety groups of potatoes, and spring and winter grains in south-central Idaho were evaluated. Results indicated that one single equation was sufficient to estimate ET for all of the investigated crop types. This means that crop classification is not required to estimate ET via the NDVI-based method, which is a strong advantage and permits low expense and rapid application.

Average error of seasonal ET was within +/-5 percent for most crop types. Error in seasonal ET estimated for any individual field lies within 10 percent in most cases. In the comparison with Lysimeter-measured ET, the seasonal error for the NDVI based method was only 2 percent for grass, and 6 percent for sugar beets.

The statistical assessment of accuracy, including comparisons with actual lysimeter measurements, suggests that NDVI based ET estimation may represent a dependable tool to estimate ET over large areas. Achieving the accuracy levels reported herein using the traditional ET estimation methods without the aid of satellites is difficult. The high accuracy reported herein was achieved partly because the NDVI based ET equation was calibrated to the particular region using ET derived using a reliable energy balance (METRIC). The NDVI based ET approach is empirically based, thus, specific calibration may be necessary for other regions.

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