EVALUATING MODIS DATA TO ESTIMATE IRRIGATED CROP PRODUCTION IN AFGHANISTAN USING A THERMAL-BASED ET FRACTION APPROACH

Senay, G.B, M. Budde, and J. Rowland
SAIC, Under Contract to US Geological Survey EROS

J.P. Verdin
US Geological Survey EROS
47914 252nd Street
Sioux Falls, SD 57198, USA
senay@usgs.gov

ABSTRACT

Accurate crop performance monitoring and production estimation is critical for timely assessment of the food balance of several countries in the world. Recently, the Famine Early Warning System Network (FEWS NET) has been monitoring crop performance and to some extent relative production using satellite derived data and simulation models in Africa, Central America and Afghanistan where ground based monitoring is limited due to the scarcity of weather stations. The commonly used crop monitoring models use a crop water balance algorithm with inputs from satellite-derived rainfall. While these models provide useful monitoring for rain-fed agriculture, they are ineffective for irrigated areas. Over 80% of the agricultural production in Afghanistan is from irrigated agriculture. In this study, we implemented a thermal-based ET fraction approach to monitor and assess the performance of irrigated agriculture in Afghanistan using the combination of 250-m NDVI and 1-km Land Surface Temperature (LST) data from MODIS. Six images per year were used to estimate seasonal evapotranspiration (ET) from irrigated lands in a given growing season between 2000 and 2004. Seasonal ET estimates from the different years were used as relative indicators of year-to-year production magnitude differences. The results were comparable to field reports and crop water balance based estimates for irrigated watersheds in that 2003 was a good year for crop production in Afghanistan. The advantage of this method over crop water balance method is that it helps identify irrigated areas directly and thus helps estimate total irrigated area and its spatial distribution in a given region.

INTRODUCTION

Food security assessment in many developing countries such as Afghanistan is vital because the early identification of populations at risk can enable the timely and appropriate actions needed to avert widespread hunger, destitution, or even famine. The assessment is complex, requiring the simultaneous consideration of multiple socioeconomic and environmental variables. Since large and widely dispersed populations depend on rainfed and irrigated agriculture and pastoralism, large-area weather monitoring and forecasting are important inputs to food security assessments. The Famine Early Warning Systems Network (FEWS NET), an activity funded by the United States Agency for International Development (USAID), employs a crop water balance model (based on the water demand and supply at a given location) to monitor the performance of rainfed agriculture and forecast relative production before the end of the crop growing season. While a crop water balance approach appears to be effective in rainfed agriculture (Verdin and Klaver, 2002; Senay and Verdin, 2003), irrigated agriculture is best monitored by other methods since the supply (water used for irrigation) is usually generated from upstream areas, farther away from the demand location.

The surface energy balance method has been successfully applied by several researchers (Bastiaanssen et al., 1998; Bastiaanssen, 2000; Bastiaanssen et al., 2005, Allen et al., 2005) to estimate crop water use in irrigated areas. Their approach requires solving the energy balance equation at the surface (Equation 1) where the actual evapotranspiration (ET) is calculated as the residual of the difference between the net radiation to the surface and losses due to the sensible heat flux (energy used to heat the air) and ground heat flux (energy stored in the soil and vegetation).
LE = Rn - G - H

LE = Latent heat flux (energy consumed by evapotranspiration) (W/m²)
Rn = Net radiation at the surface (W/m²)
G = Ground heat flux (W/m²)
H = Sensible heat flux (W/m²)

The estimation of each of these terms from remotely sensed imagery requires quality data sets. Allen et al (2005) described well the various steps required to estimate actual ET using the surface energy balance method that employs the hot and cold pixel approach of Bastiaanssen et al. (1998). In summary, for the net radiation, data on incoming and outgoing radiation and the associated surface albedo and emissivity fractions for shortwave and long wave bands are required. The ground heat flux is estimated using surface temperature, albedo, and normalized difference vegetation index (NDVI). The sensible heat flux is estimated as a function of the temperature gradient above the surface, surface roughness, and wind speed.

While solving the full energy-balance approach has been shown to give good results in many parts of the world, the data and skill requirements to solve for the various terms in the equation are prohibitive for operational applications in large regions where anomalies are more useful than absolute values. In this study we propose a simplified version of the surface energy balance approach to estimate actual ET while maintaining and extending the major assumptions in the Surface Energy Balance Algorithm for Land (SEBAL) and the Mapping Evapotranspiration at High Resolution using Internalized Calibration (METRIC). Both methods assume that the temperature difference between the land surface and the air (near-surface temperature difference) varies linearly with land surface temperature. They derive this relationship based on two anchor pixels known as the hot and cold pixels, representing dry and bare agricultural fields and wet and well-vegetated fields, respectively. SEBAL and METRIC methods use the linear relationship between the near-surface temperature difference and the land surface temperature to estimate the sensible heat flux which varies as a function of the near-surface temperature difference, by assuming that the hot pixel experiences no latent heat, i.e., ET = 0.0, whereas the cold pixel achieves maximum ET.

In this study, we extended this assumption with a simplification by stating that the latent heat flux (actual evapotranspiration) also varies linearly between the hot and cold pixels. This assumption is based on the logic that temperature difference between soil surface and air is linearly related to soil moisture (Sadler et al., 2000). On the other hand, crop soil water balance methods estimate actual ET using a linear reduction from the potential ET depending on soil moisture (Allen et al., 1998, Senay and Verdin, 2003). Therefore, by transitivity we argue that actual ET can be estimated by the near-surface temperature difference, which in turn is estimated from the land surface temperatures of the hot and cold pixels in the study area. In other words, while the hot pixel of a bare agricultural area experiences little ET and the cold pixel of a well-watered irrigated field experiences maximum ET, the remaining pixels in the study area will experience ET in proportion to their land surface temperature in relation to the hot and cold pixels. This approach can be compared to the crop water stress index (CWSI) first developed by Jackson (1982). The CWSI is derived from the temperature difference between the crop canopy and the air. Dividing the current temperature difference with known upper and lower canopy air temperature values creates a ratio index varying between 0 and 1. The lower limiting canopy temperature is reached when the crop transpires without water shortage, while the upper limiting canopy temperature is reached when the plant transpiration is zero due to water shortage (Qiu, 1999). In this study, the cold and hot anchor land surface temperature pixel values are the equivalent of the lower and upper limiting canopy temperatures of the CWSI method.

The main objective of this study was to produce actual evapotranspiration estimates using a combination of ET fractions generated from MODIS thermal imagery and global reference ET data over known irrigated fields in Afghanistan.
METHODS

Study site

The study site is located in Baghlan province of north central Afghanistan as shown in Figure 1. A polygon was defined around an irrigated area (Figure 1) using a combination of Landsat and Moderate Resolution Imaging Spectroradiometer (MODIS) data sets. The total area of the polygon is approximately 62,400 hectares and consists of both well-vegetated and sparsely vegetated areas, with some arid/semi-arid areas at the periphery of the polygon.

Figure 1: Study site showing the irrigated fields in Baghlan Province with a network of streams and drainage basins. The streamflow within the basin that includes our study area is northward, originating from the central highlands.

Data Set Characteristics

The primary data sets for this study were derived from the MODIS sensor flown onboard the Terra satellite. MODIS Land Surface Temperature (LST) data were used to calculate the crucial evapotranspiration (ET) fractions explained in the procedures portion of this manuscript. Additionally, MODIS NDVI data were used for irrigated area delineation and identifying highly-vegetated versus sparsely vegetated areas within the agricultural zone. The global reference ET data were obtained from the archives of USGS/FEWS NET operational model outputs. Each data set is further described.

MODIS Land Surface Temperature. Thermal surface measurements were collected from the MODIS 8-day Land Surface Temperature/Emissivity (LST/E) product (MOD11A2). The MODIS instrument provides 36 spectral bands, including 16 in the thermal portion of the spectrum. The LST/E products provide per-pixel temperature and emissivity values at 1-km spatial resolution for 8-day composite products and 5-km resolution for daily products. Temperatures are extracted in degrees Kelvin with a view-angle dependent algorithm applied to direct observations. This study utilized average daytime land surface temperature measurements for 8-day composite periods throughout the growing season. Table 1 shows Julian dates representing the first day of the 8-day MODIS LST composite period and corresponding calendar dates.
Table 2: Julian days and corresponding calendar dates for each growing season.

<table>
<thead>
<tr>
<th>Julian Day</th>
<th>161</th>
<th>177</th>
<th>193</th>
<th>209</th>
<th>225</th>
<th>241</th>
</tr>
</thead>
</table>

**MODIS Vegetation Index.** MODIS Vegetation Index (VI) products use reflectance measures in the red (620 – 670 nm), near infrared (841 – 876 nm), and blue (459 – 479 nm) bands to provide spectral measures of vegetation greenness. The MODIS VI products include the standard normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI). Both indices are available at 250-m, 500-m, and 1-km spatial resolution. The primary difference between the two indices is that EVI uses blue reflectance to provide better sensitivity in high biomass regions. Since this study was concentrated on irrigated agriculture in an otherwise dry land environment, we used the NDVI product at 250-m resolution for this analysis.

These data are distributed by the Land Processes Distributed Active Archive Center, located at the U.S. Geological Survey's EROS [http://LPDAAC.usgs.gov](http://LPDAAC.usgs.gov).

**Reference ET.** The global 1-degree reference ET (ETo), based on the 6-hourly Global Data Assimilation Systems (GDAS) model output, is calculated daily at the Earth Resources Observation and Science (EROS) Center on an operational basis (Verdin and Klaver, 2002; Senay and Verdin, 2003). The GDAS ETo uses the standard Penman-Monteith equation as outlined in the FAO publication for short-grass reference ETo by Allen et al. (1998). The feasibility of using the GDAS ETo for such applications was recommended by Senay and Verdin (2005) after a comparison with station-based daily ETo showed encouraging results with $r^2$ values exceeding 0.9. Daily global reference ET values were available for all days between 2001 and 2004. For 2000, the daily reference ET values were not complete. This study used 6 thermal image dates during the peak-growing season. Three of the 6 images dates in 2000 did not have a corresponding reference ET. For the missing time periods, the average reference ET from 2001 to 2004 was used.

**Procedures/Analysis**

A set of three hot and three cold pixels were selected for each 8-day composite period for each year of growing season data. An average of the 3 pixels was used to represent the hot and cold values throughout the study area. The pixels were selected using a combination of MODIS 250-m NDVI, MODIS land surface temperature, and Landsat ETM+ imagery when available. For a given time period, cold pixels, representing well vegetated and well watered crops, were selected based on either visual interpretation of the Landsat imagery or high values in the MODIS NDVI. Similarly, hot pixels, representing low-density vegetation and relatively dry land, were identified either visually or by selecting pixels with very low NDVI values. Land surface temperature data were used to verify that the selected pixels adequately represented the temperature contrast within the study area for each 8-day composite period.

Land surface temperature values for each of the six pixels (3 hot, 3 cold) were extracted using ArcGIS software (ESRI, 2004). The resulting database files were imported into an Excel spreadsheet where average hot and cold pixel values were calculated.

Since we know that hot pixels experience very little ET and cold pixels represent maximum ET throughout the study area, the average temperature of hot and cold pixels could be used to calculate proportional fractions of ET on a per pixel basis. The ET fraction (ETfrac) was calculated for each pixel by applying the following equation (Equation 2) to each of the 8-day MODIS land surface temperature scenes.

$$\text{ETfrac} = \frac{\text{TH} - \text{Tx}}{\text{TH} - \text{TC}}$$
where TH is the average of the three hot pixels selected for a given scene; TC is the average of the three cold pixels selected for that scene; and Tx is the land surface temperature value for any given pixel in the composite scene.

The ETFrac formula was applied to the six 8-day growing season composites for each year, resulting in a series of six images per season. The images contained ET fractions for each pixel that were used to estimate actual ET throughout the growing season.

The ETfrac is used in conjunction with a reference ET to calculate the per pixel actual ET values in a given scene. The reference ET is calculated on both daily and dekadal (10-day) time steps for the globe at 1-degree spatial resolution. The dekadal period that corresponded closest to the 8-day MODIS composite period was used to extract average daily ET values by dividing the dekadal sum into 10 daily values. Since our analysis uses every other 8-day period between June and September, each composite period essentially represents the 16 days between observations. Thus, the average daily ET values were multiplied by 16 to provide a summation of reference ET (ETref) for each period. The calculation of actual ET (ETact) was achieved using the following formula (Equation 3).

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ETact = ETfrac \times ETref
\]

This simplified energy balance approach allowed us to use known reference ET at a coarse spatial resolution of 1-degree to derive spatially distributed ET measurements based on land surface temperature variability at 1-kilometer resolution. Improvements in the spatial representation of ET distribution during the growing season can provide important insight into the extent of irrigated crop areas and the quality of the growing season.

Actual crop ET for the five year period, 2000 – 2004, was used to assess the quality of each growing season in the north central Afghanistan study area. Using a mask of the irrigated crop area, described earlier in Figure 1, we used the actual 1-km gridded ET values to calculate spatially averaged ET for each season. The results and implications of these comparisons are outlined in detail in the following section.

RESULTS AND DISCUSSION

The results of the analysis are presented in Figures 2 through 7. Figure 2 shows the hot and cold pixel values for the 6 time periods used for 2003. Similar temporal patterns were also observed in the other years. For 2003, the hot and cold pixels were separated by an average of approximately 15 C throughout the season between June and August. Furthermore, they appeared to increase or decrease in the same direction by about the same magnitude during the peak portion of the crop growing season. However, this separation approaches close to 0.0 (data not shown) during the off-seasons, particularly close to the start of the season. The existence of such temporal patterns between the hot and cold pixels is believed to be potentially useful in detecting time of start of season for crop monitoring activities. Figure 2 shows the boundary (extreme) conditions for surface temperature distribution in the study site for each of the growing seasons. By properly selecting the extreme temperature areas representing the hot (dry/bare) and the cold (wet/vegetated) land areas, the remaining pixels in the study area will fall in between these temperature values. The two extreme temperatures also represent extremes in ET values. The range of these values varies from zero ET for the hot and dry areas to a high ET, comparable to a reference ET, for the cold and wet areas (Allen et al, 2005). In this study, we extended this assumption to include the remaining pixels by suggesting that pixels having land surface temperature values in between these extremes will experience an ET value in direct proportion to the ET fraction as shown in equation 2.
Figure 2: Temporal variation of the hot and cold pixel values during the 2003 crop growing season in degrees C.

Figure 3 shows the temporal trend of spatially-averaged ET fractions during the peak growing season for each of the 5 years used in this study. The ET fractions showed both intra-seasonal and inter-seasonal variability of up to 20% from their respective mean values. The major separation between the different years was shown in the middle of the peak season for composite periods beginning on days 193 and 209 (Figure 3) when the spatially-averaged ET fraction appears to be the lowest. The relatively high ET fraction in the beginning of the season may be explained by the fact that there is more uniformity in ground cover condition across the study site due to young crops that are not yet at closed-canopy level. As is shown in Figure 2, the separation between the hot and cold pixels on day 161 is the smallest. This suggests that early in the season there are more pixels closer to the cold pixel than the hot pixel when compared to the remainder of the season. This may be due to the accumulated moisture from the preceding spring even in non-irrigated areas that would run out of moisture in the remaining part of the summer unlike the irrigated areas.

Figure 3: Temporal patterns of spatially-averaged ET fractions for peak-season (Jun 10 - Aug 29) 2000-04.

Figure 4 shows daily reference ET values that correspond to ET fractions from Figure 3. For the majority of the points, the daily reference ET varied between 6 and 8 mm per day. Unlike the ET fraction in Figure 3, the reference
ET values did not show a marked difference from year to year in any particular time period, with the exception of the 2003 reference ET, which showed distinctly higher ET values for periods 193 and 209. The 2003 data suggest that the region benefited from two important factors during the 2003 crop growing season: 1) good water supply as evidenced by the high ET fractions, and 2) good energy supply and vapor transport mechanism (clear sky, favorable wind) as evidenced by the high reference ET which is mainly a measure of the available energy and vapor transport mechanism under optimum water supply conditions.

![Temporal patterns of daily reference ET for peak-season (Jun 10 - Aug 29) 2000-04.](image)

**Figure 4:** Temporal patterns of spatially-averaged daily reference ET for peak-season (Jun 10 - Aug 29) 2000-04.

The actual crop evapotranspiration is estimated from the product of ET fraction and the reference ET as shown by equation 3. Figure 5 shows the temporal patterns of the actual crop ET for the 5 periods. Each data point represents a 16-day actual ET estimate that is spatially averaged over the study area. Due to the small size of the study area compared to the spatial resolution of the reference ET, all pixels in the study area have an identical reference ET value for each of the 6 image dates. Thus, the spatial variation in the actual ET is a result of the spatial variation of the ET fractions. The spatially-averaged seasonal actual ET magnitudes are presented in Figure 6 to illustrate the year-to-year variability in actual ET. Figure 6 highlights the fact that 2003 was the best agricultural season during the 5-year period, which is corroborated by various field reports that the cycle of three consecutive drought years, between 2000 and 2002, was alleviated by good precipitation in the 2003 season. These results are comparable to watershed-based analysis of an operational FEWS NET irrigation supply and demand model output showing that 2002 and 2004 were below an average supply while the 2003 irrigation water supply met the average demand, defined using a 30-year rainfall average from 1961 to 1990 (www.cgiar.org/iwmi/WAtlas/atlas.htm).
While Figures 3 to 6 show spatially-averaged temporal variation of the ET fractions, reference ET, and actual ET, Figures 7a and 7b present the spatial variation of the seasonal actual ET for 2002 and 2003, respectively. As is shown in Figure 6, the higher values of the 2003 seasonal ET is illustrated by the expanded extent of higher actual ET classes (dark green colors) compared to the 2002 actual ET map. A similar pattern of expansion/reduction in greenness for the corresponding years was observed from MODIS seasonal maximum NDVI data. The reduction in actual ET values in 2002 has mainly occurred in the downstream irrigated fields (northern fields) where a short tributary joins the main river. The geographic area where lower actual ET values were observed seems to suggest downstream irrigators/fields would have access to water only if there was a surplus in excess of the demands of the upstream users. This is more in line with a common practice in regions where water rights are not well established or regulated. Furthermore, Figures 7a and 7b suggest the possibility of using this method of analysis to estimate harvested irrigated areas for a given year based on a threshold of actual ET required for successful crop growth. For
example, in the study area where certain fields consumed up to 700 mm in about 3 months, areas that only used half (350 mm) of the water demand by a well-watered crop could be considered as unsuccessful and removed from harvested irrigated areas (Doorenbos and Pruitt, 1977; Verdin and Klaver, 2002; Senay and Verdin, 2003). Although the accuracy of the magnitudes of the estimated actual ET values require field validation using other methods or field studies, the method’s relative performance in terms of capturing the year-to-year variability suggests that the method has a potential to characterize irrigated field crop performance in relative terms on reasonably homogeneous flat irrigated fields.

Figure 7a: Seasonal (Jun 2 – Sep 6) actual ET distribution in irrigated fields of the study area in 2002.
CONCLUSIONS

The main objective of this study was achieved with the demonstration of the successful use of MODIS thermal data sets in producing actual ET estimates in an irrigated agricultural area of Afghanistan. The ET fractions generated using the hot and cold boundary pixels are comparable in principle to the Crop Water Stress Index of Jackson (1982). With ET fractions, values close to 1.0 represent well-watered vegetated areas while values close to 0.0 represent water stressed areas. In contrast, CWSI is calculated to represent the reverse case of the ET fraction. The ET fractions resemble the commonly known crop coefficient (Kc) and thus are directly multiplied with reference ET values to obtain actual ET estimates.

The actual ET values of the irrigated fields in the study area showed year-to-year variability that was consistent with field reports and other independent data sets such as the seasonal maximum NDVI and output from an irrigation supply/demand water balance model. Particularly, the 2003 seasonal actual ET of the study area was much higher than the rest of the studied years, and about 15% more than the average of the 5 years. This was in agreement with published reports (FEWS NET, 2003) and news sources that stated 2003 precipitation appeared to have broken the sequence of preceding consecutive dry years in Afghanistan.

A close examination of the spatial distribution of the actual ET estimates during 2003 and 2002 revealed that the reduction in area of high actual ET values during 2002 was in the downstream part of the basin. Since this corresponds to a common practice where water is generally used first by those upstream, the result reinforces the reliability of this approach and points to the potential application of this method for spatially estimating cropped area in irrigated fields. The existence of a variable temporal pattern between the hot and cold pixels during the crop season is also believed to be potentially useful in detecting time of start of season for crop monitoring activities.

While the results obtained from the thermal-based ET fraction approach are encouraging for applications in remote locations where field-based information is not readily available, the method needs to be further investigated and validated using more robust surface energy balance methods and higher spatial resolution data sets before using it in an operational crop monitoring activity.
REFERENCES


