MAPPING EVAPOTRANSPIRATION IN THE TEXAS PANHANDLE

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Abstract. *Agriculture in the Texas High Plains accounts for approximately 92% of groundwater withdrawals. Because, groundwater levels are declining in the region, efficient agricultural water use is imperative for sustainability and regional economic viability. Accurate regional evapotranspiration (ET) maps would provide valuable information on crop water demand and usage. In this study, a regional ET map was produced for an 11-county area in the Texas High Plains, using METRIC™ [a/] (Mapping Evapotranspiration at High Resolution using Internalized Calibration), a remote sensing based ET algorithm, and meteorological data measured at four ET weather stations maintained by the Texas High Plains Evapotranspiration Network (TXHPET). For mapping ET, a Landsat 5 Thematic Mapper image acquired on 27 June 2005 was used. Performance of the ET model was evaluated by comparing predicted daily ET with values derived from a soil water budget at four different commercial irrigated fields. Good agreement was found between the remote sensing based ET and soil water budget ET for low to moderate ET rates. Less agreement resulted for higher ET rates. Use of METRIC™ for advective conditions of the Texas High Plains is promising; however, further evaluation is needed using lysimeter or scintillometer derived ET measurements for different agroclimatological conditions and/or a larger number of image scenes.*

Keywords. *Ogallala Aquifer Region; Texas Panhandle; Regional ET; semi-arid environment*

[a/] Mention of trade or manufacturer names in this article is made for information only and does not imply an endorsement, recommendation, or exclusion by the United States Department of Agriculture.

Introduction

The Ogallala Aquifer has been the main source of water supply for the High Plains population and is being depleted at an unsustainable rate (Axtell, 2006). Irrigation alone uses approximately 89% of the water pumped from the Ogallala aquifer, where the High Plains area represents 27% of the total irrigated land in the United States (Dennehy, 2000). For this reason and considering the trends in population growth, there is a tremendous emphasis for greater efficiency in irrigation water management in the Texas High Plains.

Improved irrigation water management is achieved when beneficial crop water use is accurately quantified in time and space to facilitate real-time decisions regarding application rates and scheduling. In this regard, remote sensing (RS) based evapotranspiration (ET) methods have a fundamental role in improved irrigation efficiency and management. Numerous RS algorithms have been developed to spatially estimate crop water consumption or ET and are being tested around the world. Most of these algorithms mainly solve the energy balance of the land surface for latent heat flux (LE) at the time of satellite or airborne RS system overpass, and use different techniques to extrapolate the instantaneous values to daily values (Chávez, 2005).

The Texas High Plains is a semi-arid region with a heterogeneous landscape in which irrigated fields are surrounded by dryland crops, fallow land, and/or rangeland. Therefore, advection of sensible heat flux from dry surfaces is a significant source of energy that has a major impact on ET from crop growing areas. For example, Tolk et al. (2006) reported an average ET rate of 11.3 mm d^{-1} for an irrigated alfalfa in Bushland, TX with ET for some days exceeding 15 mm d^{-1} due to regional advection. Trezza (2002) observed that the RS methodology based on the alfalfa reference ET fraction (ET_rF), for estimating daily ET for a variety of crops (potatoes, snap beans, wheat, sugar beets, etc.) at Kimberly, Idaho, worked better under advective conditions than the evaporative fraction (EF) suggested by Bastiaanssen et al. (1998) in the Surface Energy Balance Algorithm for Land (SEBAL). The energy balance method that uses ET_rF was further refined and incorporated in METRIC™ (Mapping ET at High Resolution using Internalized Calibration), a RS ET algorithm based on SEBAL, to estimate daily and seasonal ET. A full description of the METRIC™ can be found in Allen et al. (2005a)

The main objective of this study was to use the METRIC™ algorithm for mapping regional ET on the Texas High Plains. METRIC™ was selected as an ET mapping tool to be applied in the Texas High Plains since it could be an algorithm that performs better under advective conditions and requires minimal ground data.

Materials and Methods

Study Area

This study was focused on the portion of the Texas High Plains Region (Panhandle counties) covered by Landsat 5 Thematic Mapper (TM) scene with a path/row of 30/35. The TM scene comprised 11 counties, underlain by the Ogallala aquifer (Fig. 1). Soils are mainly Pullman clay loam and Sherm silty clay loam (NCSS Web Soil Survey, 2006). Land use/cover in the study area consists of crops (described later), mesquite shrubs (grassland), mesquite brush, sandsage (Harvard Shin oak brush), buffalo grass (grassland), cottonwood-hackberry-salt cedar brush/wood, and mesquite-juniper brushes (Frye et al., 2000). More detailed analysis was concentrated in Ochiltree County located at the center of the scene, where ground truth data were acquired as part of another study.

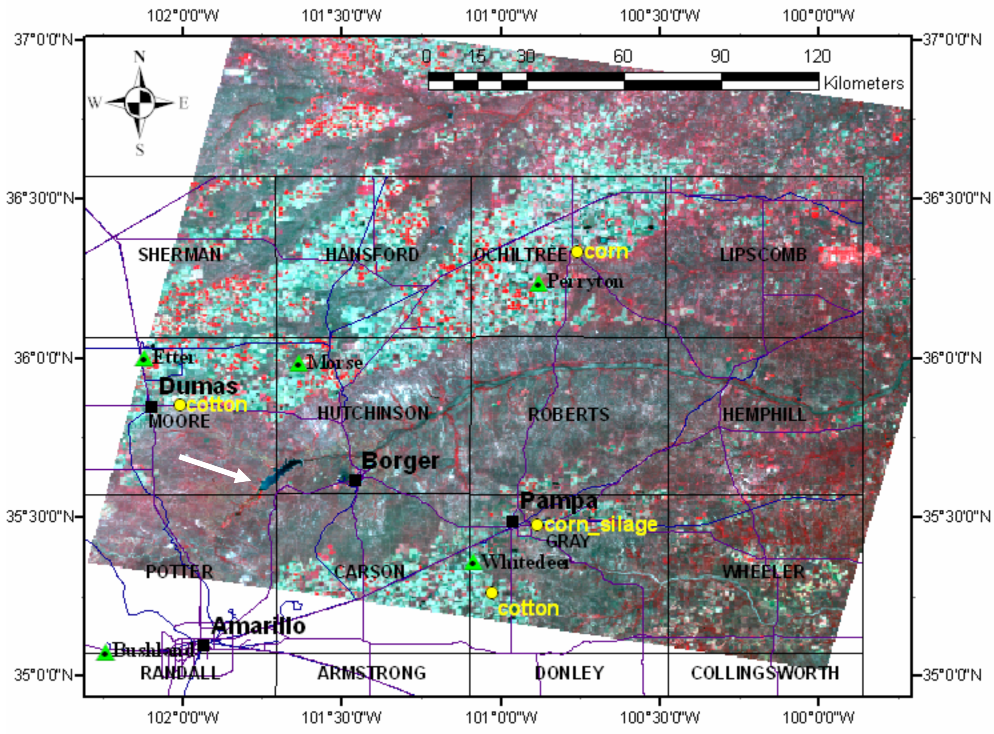

Figure 1. False color Landsat 5 TM image acquired on June 27 2005 covering several Counties of the Texas Panhandle.

The Ochiltree County area is about 234,911 ha (580477.7 ac) with 44% of the land in row crop production. Annual average precipitation is approximately 562 mm (22.1 in), and about 11% of the cropland is irrigated. Sorghum, winter wheat and corn are the major crops in the county. Sherm silty clay soils with nearly level to gently sloping fields occupy most of the cropland. Wind direction is predominantly from the southwest.

METRIC^{TM}

In METRIC^{TM}, ET is computed as a residual from the surface energy balance equation as an instantaneous ET or latent heat flux (LE) for the time of the satellite overpass, as in Eqn. (1).

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

where R_n is net radiation (W m^{-2}), G is the soil heat flux (W m^{-2}), and H is the sensible heat flux (W m^{-2}). R_n is the result of the surface energy budget between short and long wave radiation.

G was modeled as a function of R_n, vegetation index, surface temperature, and surface albedo for near midday values according to the Bastiaanssen (2000) model. In METRIC^{TM}, H is estimated using a temperature difference (dT) function of surface temperature (T_s). For dT estimation, cold/wet and hot/dry pixels are selected in the image. These are extreme pixels in agricultural fields. For the cold pixel ET, METRIC uses a reference evapotransporation or ET_r which is the hourly tall reference crop (e.g. alfalfa) ET calculated using the standardized ASCE Penman-Monteith equation. A 1.05 coefficient was used to estimate LE_{cold} as the cold pixels typically have an ET rate 5% larger than that for the reference ET (ET_r) due to wet soil surface beneath a full vegetation canopy that will tend to increase the total ET rate, Allen et al. (2005b). A hot pixel was chosen after careful screening of fallow/bare agricultural fields displaying high temperatures, high albedo and low biomass (leaf area index, LAI). Similarly, the cold pixel was determined on the basis of low temperature, high biomass, and albedo of 0.18-0.24.

An instantaneous LE image was obtained using Eqn. 1, and it was converted to ET_i in mm h^{-1} by dividing it by the latent heat of vaporization (λ_{LE}; ~2.45 MJ kg^{-1}) and the density of water (ρ_w; ~1.0 Mg m^3) as shown in Eqn. 2:

$$ET_i = 3600\ LE / \{[2.501 - 0.00236\ (T_s - 273.15)]\ (10^6)\ (1.0)\} \quad (2)$$

The reference ET fraction (ET_rF) is the ratio of ET_i to the reference ET_r that is computed from weather station (WS) data at overpass time. The WS information is explained in a subsequent section. Finally, the computation of daily ET (ET_{24}), for each pixel, is performed as shown in Equation (3):

$$ET_{24} = ET_rF \times ET_r24 \quad (3)$$

where: ET_r24 is the cumulative 24-h ET_r for the day (mm d^{-1}).

Data

A Landsat 5 TM satellite image was obtained for DOY 178 (June 27) of 2005; the overpass time was 17:07 GMT (11:07 CST). The satellite path/row was 30/35 where the image scene center coordinates were Latitude 36.048º N and Longitude 100.910º W. Image pixel size was 30 m for TM bands 1, 2, 3, 4, 5 and 7 and 120 m for TM band 6 (thermal band). Figure 1 shows the satellite image in false color. Ground truth data for Ochiltree County consisted of GPS readings taken in 29 fields to identify cover crops during the 2005 cropping season. This information was utilized in the un-supervised classification to produce a land use map.

For the calculation of alfalfa based ET_r and ET_r24, data from four reference WS (Perryton, Etter, White Deer, and Morse; Fig. 1) identified within the geographic coverage of the satellite scene were used. These WS are part of the Texas High Plains ET Network (TXHPET, 2006) and the Texas North Plains ET Network (TNPET, 2006). The TXHPET and TNPET reports hourly and daily weather data as well as grass (ET_o) and alfalfa (ET_r) reference ET calculated using the standardized ASCE Penman-Monteith method. The WS grass cover types were: native pasture (Perryton), Buffalo grass (Etter), native pasture (White Deer), and native grass (Morse). These grasses were rainfed with the exception of the Etter grass that was irrigated (limited).

Soil water content measurements from four commercial fields: 1) fully irrigated corn 2) irrigated silage corn, 3) irrigated cotton, and 4) on a cotton field under limited irrigation were used to derive ET for comparison with RS estimates by means of the soil water balance (SWB). The soil water measurements were taken as a part of the Agripartners Program (New, 2005). Soil water was monitored by means of a KS-D1 Gypsum block meter (Delmhorst Instruments Company, Towaco, NY) connected to GB-1 Gypsum blocks sensors. In the SWB, irrigation water application efficiencies (E_a) of 90% were assumed. Is E_a value was determined by New and Fipps (2000) for LESA center pivot irrigation systems as common for the Texas High Plains area. The SWB calculations were performed over a period of 3 or 4 days depending on the number of readings per week.

Results stemming from the comparison of ET using the METRIC™ and the ET from SWB, for each field, were reported as absolute differences and in percent errors relative to ET_r. A more comprehensive evaluation of ET estimation errors (comparison of estimated/measured ET_c) was carried out comparing Mean Bias Error (MBE) and Root Mean Square Error (RMSE).

Results and Discussion

Cropping Conditions, Net radiation and heat fluxes

A land use map was derived from the Landsat 5 TM image. A subset of the land use map, comprising most of Ochiltree County, was analyzed. In this map, total area was 57,487 ha (142,054 ac), of which most of the area was not irrigated; 58.4% of the area was either fallow fields/bare soils and/or natural vegetation (pasture, grass, shrubs, bushes) while the cropped land accounted for 39.5% of the area: 11.2% for irrigated corn, 15% for irrigated soybean, 8% for irrigated sorghum, and 5.2% for both irrigated/non-irrigated cotton. These results were matched well with corn and cotton crop acreage reported in the 2005 National Agricultural Statistics Report (USDA-NASS, 2006).

Surface temperatures derived from Landsat 5 TM scene ranged from 18.6 to 34.9°C (65.5 to 94.82ºF). This variation highlights the uniqueness of cropping conditions in the Texas High Plains where irrigated/non-irrigated crop fields intermix with fallow/bare soil lands and where local and regional advection may increase ET rates by augmenting sensible heat flux. Tolk et al. (2006) found that an average of 61% of total ET could be attributed to advective sensible heat in Bushland, TX (Fig. 1), for average wind speeds of 4.4 m s^{-1} (9.8 mph). In our study, wind speed (u) at the time of satellite overpass was 7.0 m s^{-1} or 15.7 mph (Perryton WS), i.e. higher than the values reported in Tolk et al (2006) and ranged between 7.5 and 8.5 m s^{-1} (16.8 and 19.1 mph) from noon to about 7:00 PM CST. In addition, more than half of the area was not irrigated and some irrigated cotton, soybean and sorghum fields were at very early growth stage (LAI<1.5) with partial canopy cover, a situation that may have contributed to local advection.

In the determination of H, the colder (wet) pixel was located in a recently irrigated corn field that had surface temperature of 18.6ºC (65.5ºF). The hotter (dry) pixel was found in a nearby fallow dry field. For the hot pixel, ET_rF was assumed to be zero (0), i.e. no ET, since the last "significant" rainfall event occurred on June 12 (15 days prior to the satellite overpass) and the amount of daily rainfall varied from 7-44 mm (0.275-1.73 in) in the study area.

Setting ET_rF to 1.05 for the cold pixel resulted in a negative H value, meaning that the air temperate was higher than the corn canopy temperature, thus extra heat was brought in by local and regional advection. This extra heat produced an H (cold pixel) that enhanced LE beyond available energy (633.9 W m^{-2}) by 24.4%. These results are in agreement with results reported by Tolk et al. (2006).

Daily ET Estimation

Average daily ET (ET_{24}) was 5.7 mm d^{-1} (0.224 in d^{-1}) with a mode and maximum values of 6.9 and 14.5 mm d^{-1} (0.272 and 0.571 in d^{-1}), respectively, for the entire satellite scene. Using all four WS, the average ET_r was 13.5 mm d^{-1} (0.531 in d^{-1}) for the day, and ET_r was 1.1 mm h^{-1} (0.043 in h^{-1}) at the time of satellite overpass.

According to the ET_rF results, the WS grasses had an ET rate that was only 43 to 51% of ET_r24 and 60 to 76% of the "potential" grass ET_o, i.e., to that rate of a non-water limited clipped grass; assuming that the calculated reference ET, with the weather parameters that incorporate advection, represent ET that otherwise would have been attained had the grass been fully irrigated (Howell, 2000).

Considering E_a of 90% for ET derivation through the SWB procedure, METRIC™ ET_{24} estimation for a fully irrigated corn compared reasonably with the crop ET (ET_c) derived from the SWB for the same corn field. There was an overestimation error of 2.0 mm d^{-1} (0.078 in d^{-1}) or a bias of 14.7% (relative to the four WS average ET_r). For the irrigated silage corn field, the error was 8.1%, 1.5% for irrigated cotton and –7.4% for the limited irrigated cotton field; with an average (overall) error of 1.1±0.9 mm d^{-1} (0.043±0.035 in d^{-1}) or 8.0±6.5%, MBE±RMSE, respectively.

In general, the relative higher ET estimation error was found in the fully irrigated corn field, which had an ET rate closer to the reference crop ET rate. The higher discrepancy in ET may be due to the fact that the cold pixel(s) should be selected in a field with a crop with bio-physical characteristics similar to the alfalfa reference crop, i.e., similar biomass, height and fully-irrigated crop ET. However, errors could be introduced when the satellite image does not contain such crop conditions. Moreover, ET_{cold} is assumed by METRIC as 1.05 ET_r and it may happen that the selected cold pixel belongs to a crop with a crop coefficient (K_c) that is greater than 1.0 at the time of the image acquisition, which will increase its ET value beyond the 5% proposed for a crop with characteristics similar to the alfalfa reference crop hence resulting in an overestimation of ET for colder highly evapotranspirating pixels (crops). In our case, the cold pixel was located on a well irrigated corn field. The underestimation error for ET_c of -7.4% for the cotton field that had limited irrigation may be due to late planting in the season, had low biomass with partial canopy cover, and surface temperatures were high (dT ~ 4 K).

METRIC™ captured the difference in water management between fully irrigated corn and somewhat water stressed silage corn, where the fully irrigated grain corn ET was almost double of that for silage corn. This result was supported by New (2005) where he showed that the amount of water applied to the grain corn as irrigation and rainfall was in excess of the corn potential ET (PET) as calculated by TXHPET.

Regional ET_{24} for the entire satellite scene are shown in Fig. 2, where darker dots are high ET rates mainly for center pivot irrigated corn and soybean fields. Irrigated corn had the greatest ET rate, from 7.3 to 14.1 mm d^{-1} (0.287 to 0.555 in d^{-1}). This result is in excellent agreement with a 3-yr study by Howell et al. (1996) and Howell et al. (1998) in Bushland-TX, where the authors reported that the average ET for well irrigated corn on lysimeters, exceeded 10 mm d^{-1} or 0.394 in d^{-1} (with a maximum ET slightly exceeding 14 mm d^{-1} or 0.551 in d^{-1}) in mid and late June, when monthly average wind speeds were 4.0-5.5 m s^{-1} (9.0 to 12.3 mph).

Overall, the daily ET results indicate that METRIC™ performs well for the advective conditions of the Texas High Plains with prediction errors of 4-20%. Some errors in the evaluation may have been introduced by the soil water content balance procedure and by the weather data. According to Wright and Jensen (1978), a common standard error for ET prediction equations based on weather data using Penman or Penman-Monteith type equations is as much as 10% of daily estimates.

Conclusion

METRIC™ algorithm was applied on the Texas High Plains using a Landsat 5 TM image acquired on DOY 178. Estimated ET for well-irrigated crops and high biomass vegetation was estimated with errors below 15%. Errors were less than 9% for lower biomass-higher temperature surfaces. It is believed that the 5% increment over ET_r suggested in METRIC for the instantaneous ET estimation on the cold pixel, might have caused the overestimation of ET on well watered crops with high ET with bio-physical characteristics that were different from the reference crop, i.e., with a crop coefficient greater than unity at the time of the remote sensing system imagery acquisition. However, ET estimates were compared with ET derived from soil water measurements using gypsum blocks that may have errors around 20% (Gardner, 1986)

Nevertheless, it appears that METRIC™ is a promising tool in estimating ET for well irrigated, medium to high biomass crops, natural vegetation and open water bodies as well as for low/drier biomass vegetation covers. Further, METRIC™ does not need ground information in terms of accurate surface and air temperature, planting date, land use and land cover. The only ground measured input needed is horizontal wind speed and dew point temperature.

Additional evaluation of METRIC™ is needed under a variety of crop/weather conditions to fully assess its capability to accurately estimate spatially distributed ET values, including evaluations with lysimetric or scintillometer data and/or a large number of satellite imagery scenes.

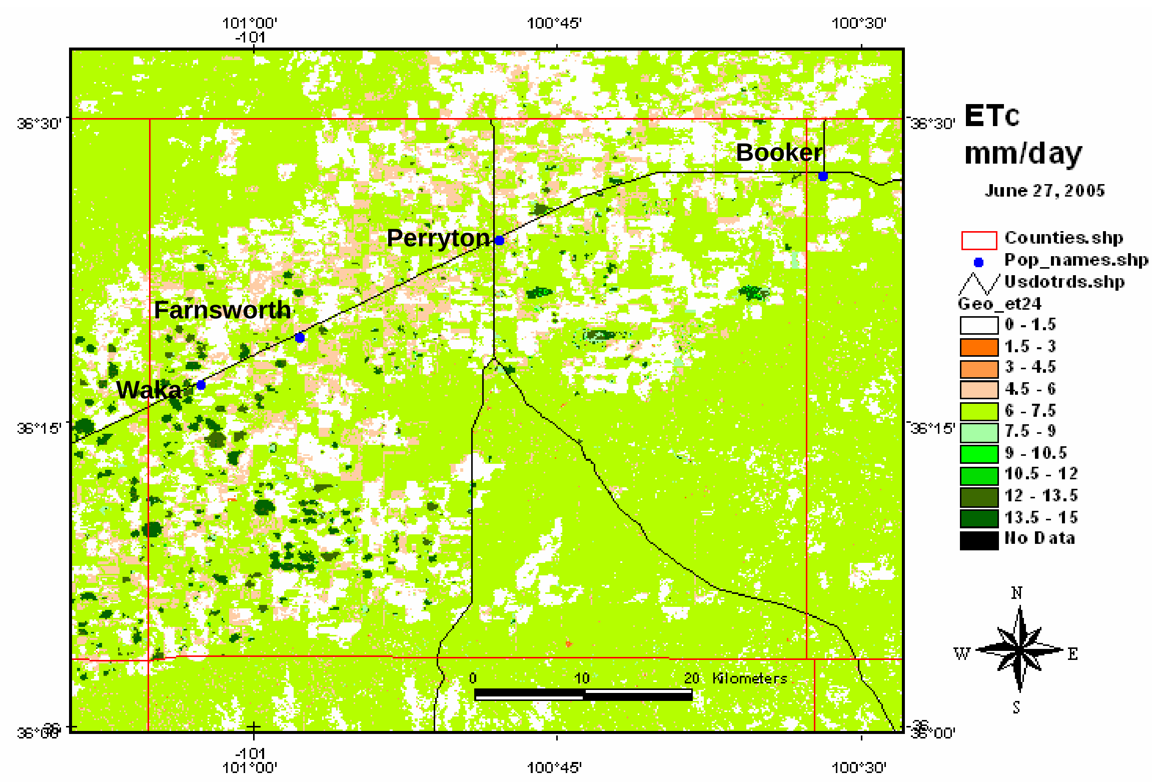

Figure 2. Spatially distributed daily ET for Ochiltree County on DOY 187

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