Lysimetric Evaluation of Simplified Surface Energy Balance Approach in the Texas High Plains

P. H. Gowda, G. B. Senay, T. A. Howell, T. H. Marek

Abstract. *Numerous energy balance (EB) algorithms have been developed to make use of remote sensing data to estimate evapotranspiration (ET) regionally. However, most EB models are complex to use and efforts are being made to simplify procedures mainly through the scaling of reference ET. The Simplified Surface Energy Balance (SSEB) is one such method. This approach has never been evaluated using measured ET data. In this study, the SSEB approach was applied to 14 Landsat TM images covering a major portion of the Southern High Plains that were acquired during 2006 and 2007 cropping seasons. Performance of the SSEB was evaluated by comparing estimated ET with measured daily ET from four large monolithic lysimeters at the USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas. Statistical evaluation of results indicated that the SSEB accounted for 84% of the variability in the measured ET values with a slope and intercept of 0.75 and 1.1 mm d^{-1}, respectively. Considering the minimal amount of ancillary data required and excellent performance in predicting daily ET, the SSEB approach is a promising tool for mapping ET in the semiarid Texas High Plains and in other parts of the world with similar hydro-climatic conditions.*

Keywords. *Texas panhandle, Semiarid, Operational ET mapping, Remote sensing.*

Efficient water use for irrigation is of great importance to producers and water resource managers in the Texas High Plains where water scarcity often affects crop productivity. Therefore, reliable regional ET estimates are essential to improve irrigation management. Further, ET has long been recognized as an important process in determining exchanges of energy and mass between the hydrosphere, atmosphere, and biosphere (Sellers et al., 1996).

Land surface energy balance (EB) models utilizing ground-, airborne-, or various satellite platform-based remote sensing data at different spatial resolutions have been demonstrated to accurately map daily and seasonal ET at a regional scale. A detailed review of different ET algorithms was presented in Gowda et al. (2008). They reported that ET estimation accuracy varied from 67% to 97% for daily ET and above 94% for seasonal ET, indicating that remote sensing technology with appropriate algorithms has the potential to estimate regional ET adequately. Some of the commonly used EB-based ET algorithms include Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen et al., 1998a; 1998b), Two-Source Model (TSM; Norman et al., 1995), Surface Energy Balance Index (SEBI; Menenti and Choudhury, 1993), Surface Energy Balance System (SEBS; Su, 2002), the excess resistance (kB^{-1}; Kustas and Daughtry, 1990), Beta (β) approach (Chehbouni et al., 1996), and most recently the Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC; Allen et al., 2007a,b) method. However, most of these ET mapping algorithms are complex to use and may not be suitable for operational ET remote sensing application. Efforts are being made to simplify procedures to estimate regional ET mainly through the scaling of reference ET. The Simplified Surface Energy Balance (SSEB), a two-step approach by Senay et al. (2007) is one such method. This study focuses on the validation of the SSEB using lysimeter data.

Rationale for Simplified Surface Energy Balance (SSEB)

Land surface EB approaches are based on the rationale that ET is a function of change of the state of water using available energy in the environment for vaporization (Su et al., 2005). Remote sensing-based EB models convert satellite sensed radiances into land surface characteristics such as albedo, leaf area index, vegetation indices, surface emissivity, and surface temperature to estimate ET as a "residual" of the land surface energy balance equation assuming no horizontal advection:

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

where R_n is the net radiation resulting from the balance incoming and emitted/reflected radiation in both short and long wavelengths, LE is the latent heat flux from evapotranspiration to the atmosphere, G is the soil heat flux into/from the soil, and H is the sensible heat flux to the atmosphere (all components in W m^{-2}). LE is converted to ET (mm h^{-1} or mm

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d^{-1}) by dividing it by the latent heat of vaporization (λ_v; ~2.45 MJ kg^{-1}), density of water (ρ_w; ~1.0 Kg m^{-3}), and an appropriate time constant (e.g., 3600 s h^{-1} for hourly ET or 86400 s d^{-1} for daily ET).

Although solving the full EB-based approach has been shown to give good results, the data and skill requirements to solve various terms in the equation are prohibitive for operational applications. The SSEB approach estimates actual ET while maintaining and extending the major assumption in SEBAL (Bastiaanssen et al., 1998a) and METRIC (Allen et al., 2007a), whereby the aerodynamic temperature gradient between the land surface and air (near-surface temperature gradient) varies linearly with land surface temperature. This relationship is based on two anchor pixels known as the hot and cold pixels, representing bare dry agricultural fields and well-vegetated wet fields, respectively. In SEBAL, at the cold (satellite) pixel, H is assumed negligible (i.e. H_{cold} = 0) and at the hot pixel, LE is set to zero which results in $H_{hot} = (R_n\text{-}G)_{hot}$. In METRIC, at the cold pixel, LE is based on a reference ET (Allen et al., 2007a) using ground weather data using the Penman-Monteith equation for tall (~0.5 m) alfalfa and at the hot pixel, and LE is set to zero which results in $H_{hot} = (R_n\text{-}G)_{hot}$ similar to SEBAL. In SSEB, this assumption is extended where LE also varies linearly between the hot and cold pixels in proportion to the land surface temperature based on the logic that the temperature difference between soil surface and air are linearly related to soil water (Sadler et al., 2000). Furthermore, crop water balance models estimate actual ET using a linear reduction from the potential ET depending on the soil water (Allen et al., 1998; Senay and Verdin, 2003). This SSEB approach can be compared with the Crop Water Stress Index (CWSI) (Jackson, 1982) derived from the temperature difference between the crop canopy and the air. Dividing the canopy-air temperature difference by the known upper and lower canopy-air temperature difference creates a ratio index varying between 0 and 1. The upper limit is reached when plant transpiration is zero, this occurs when water is not available in the root zone (Qiu et al., 1999) and the lower limit is reached when the crop transpires at full rate. In SSEB, surface temperature values of cold and hot pixels are equivalent to the lower and upper limiting canopy temperatures of the CWSI method.

Limited evaluation has been done to determine the ability of the SSEB to estimate daily ET values using Landsat Thematic Mapper (TM) data. For example, SSEB-estimated daily ET values from Landsat TM data were compared with METRIC- and SEBAL-estimated values for corn and soybean fields in Brookings and Moody Counties in South Dakota (Senay et al., 2007). The r^2 values in their study varied from 0.94 to 0.99 for METRIC and from 0.55 to 0.79 for SEBAL. However, SSEB has never been tested with measured ET data. The main objective of the current study was to evaluate the SSEB approach for estimating daily ET using Landsat 5 TM images where groundtruth measurements were provided by large monolithic weighing lysimeters.

Study Area

This study was conducted in the area covered by Landsat 5's path/row of 31/36 in the Southern High Plains (parts of the Texas High Plains and northeastern New Mexico), south-central United States (fig. 1). The climate is semiarid with highly variable rainfall. The annual average rainfall is 475 mm, with 348 mm occurring during the summer growing season. The dominant soil in the study area is classified as a Pullman clay loam (fine, mixed, super active, thermic torrertic Paleustolls) with low permeability. The major crops are corn, sorghum, winter wheat, and cotton. The typical cropping season in the study area starts in May and ends in October. The SSEB approach was evaluated using soil water mass change-based daily ET values from four large monolithic precision weighing lysimeters located at the USDA-ARS Conservation and Production Research Laboratory (CPRL) in Bushland, Texas (fig. 1) (Howell et al., 1995). The CPRL is located in the northeastern corner of the Landsat scene and its geographic coordinates are 35° 11' N, 102° 06' W, and elevation is 1170 m above mean sea level.

Each lysimeter (3 m length × 3 m width × 2.4 m depth) is located in the middle of a 4.7-ha field and all four lysimeters are arranged in a block pattern (fig. 1). Changes in lysimeter mass were measured for determining ET using a data logger (Campbell Scientific, Inc., model CR7-X, Logan, Utah) to measure and record the lysimeter load cell (Interface, model SM-50, Scottsdale, Ariz.) with the signal sampled at 0.17-Hz frequency. The lysimeters were calibrated using techniques similar to those found in Howell et al. (1995). The lysimeter mass measurement accuracy in water depth equivalent was 0.01 mm, as indicated by the root mean squared error of calibration. The load cell signal was averaged for 5 min and composited to 60-min means. The lysimeter mass data were reported on the midpoint of the 60 min, that is, data were averaged from 0 to 60 min and reported at the midpoint of the averaging period. Daily ET was calculated as the difference between lysimeter mass recorded at 2330-h CST of one day and 2330-h CST of the next day to determine mass losses (from evaporation and transpiration) to which lysimeter mass gains (from irrigation or precipitation) were added.

Dryland cropping systems are managed on two lysimeter fields in the west and irrigated cropping systems are managed on two lysimeter fields in the east with a 10-span lateral-move sprinkler system. A grass reference ET weather station field (uniformly cut, 120-mm tall fescue blend grass on 0.31-ha area), which is a part of the Texas High Plains ET Network (Porter et al., 2005), is located adjacent to the eastern side of the irrigated lysimeter fields. Grass is the generally preferred reference crop in arid and semi-arid areas such as the Texas High Plains principally due to the fact it is more representative of "native reference" conditions (Marek et al., 2009).

Materials and Methods

In this study, the SSEB approach was applied on 14 Landsat 5 Thematic Mapper (TM) images acquired during the 2006 and 2007 cropping seasons, as part of the Bushland Evapotranspiration and Agricultural Remote Sensing Experiment 2007 (BEAREX07) (Gowda et al., 2007). The temporal range of the images used in the study covers the entire cropping seasons during 2006 and 2007 and allowed evaluation of SSEB at various crop stages. Table 1 presents the Landsat 5 TM data acquisition dates, measured wind speed (u) and relative humidity (RH) at the TXHPET grass reference weather station in Bushland, Texas (see fig. 1), and

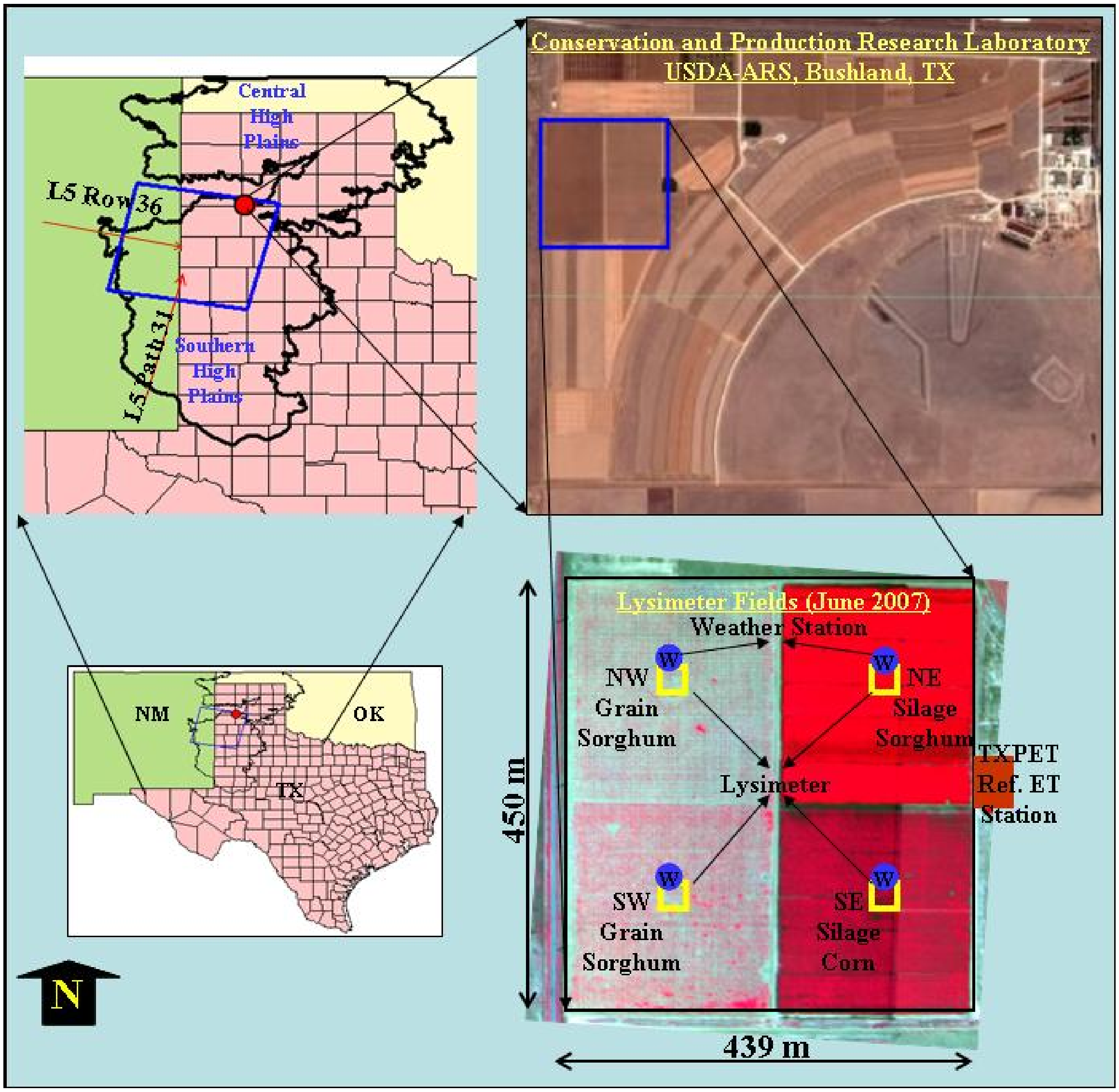

Figure 1. Location of Texas High Plains and four large weighing lysimeters at the USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas.

estimated grass reference evapotranspiration (ET_o) using American Society of Civil Engineers (ASCE) Standardized Reference ET equation (Allen et al., 2005).

In 2006, the SW and NW lysimeter fields were planted to dryland grain sorghum in rows and clumps, respectively, as part of another study. The irrigated SE and NE lysimeter fields were planted to forage sorghum and corn in rows, respectively, for silage. In 2007, the dryland grain sorghum was planted in clumps in SW field and rows in NW field. In irrigated lysimeter fields, the crops were switched to have corn in SE field and forage sorghum in NE field; both were in rows and for silage.

The evaluation of SSEB approach in this study consists of four steps: (1) identification of hot and cold pixels in every Landsat TM image, (2) estimation of ET fraction (ET_f), (3) estimation of daily ET values for each pixel in the image, and (4) model performance evaluation. In the first step, sets of 10 hot and 10 cold pixels on TM Band 6 images were identified and averaged to estimate radiometric surface temperature at hot and cold pixels. A cold pixel on the selected Landsat image represents a well irrigated area with large values of NDVI (normalized difference vegetation index) with low thermal brightness values. Similarly, a hot pixel on the image represents no/low density vegetation areas with relatively dry conditions characterized by land with large radiometric surface temperature and very small NDVI values.

With the assumption that hot and cold pixels experience very little and maximum ET throughout the study area, respectively, the temperature of hot and cold pixels can be used to calculate proportional (fractional) ET_f for each pixel. In the second step, the ET_f is calculated for each pixel in the image using the equation:

$$ET_f = (T_H - T_X) / (T_H - T_C) \quad (2)$$

where T_H and T_C are the average radiometric surface temperature at hot and cold pixels, respectively; and T_X is the radiometric surface temperature for any pixel in that image. In the third step, the actual ET (ET_a) for each pixel in the image is calculated as:

$$ET_a = ET_f \times 1.1\ ET_o \quad (3)$$

Table 1. Landsat 5 Thematic Mapper (TM) data acquisition dates, mean measured 2-m wind speed (u) and mean relative humidity (RH) at the TXHPET grass reference weather station in Bushland, Tex., and estimated grass reference evapotranspiration (ET_o) using American Society of Civil Engineers (ASCE) Standardized Reference ET equation.

Sl. No.	Acquisition Date (DOY[a])	Daily ET_o (mm)	u (m/s)	RH (%)
1	18 April 2006 (108)	8.3	5.81	17.6
2	20 May 2006 (140)	9.1	3.55	22.9
3	5 June 2006 (156)	12.6	5.71	21.0
4	23 July 2006 (204)	6.3	2.76	68.1
5	8 August 2006 (220)	7.6	3.83	50.9
6	24 August 2006 (236)	6.9	3.66	59.8
7	25 September 2006 (268)	3.9	1.81	57.9
8	11 October 2006 (284)	3.1	1.87	78.3
9	4 March 2007 (63)	4.0	3.9	51.8
10	23 May 2007 (143)	6.6	4.51	63.5
11	8 June 2007 (159)	6.6	4.95	54.2
12	10 July 2007 (191)	8.0	3.5	50.1
13	26 July 2007 (207)	8.0	4.52	57.4
14	11 August 2007 (223)	7.9	3.88	55.3

[a] DOY - Day of year.

where ET_o is daily reference ET calculated using the ASCE Standardized Reference ET equation (Allen et al., 2005). The 1.1 factor is applied to account for some fields in the Texas High Plains with wet soil surface beneath the leafy vegetation canopy (e.g. irrigated forage corn and sorghum) in a large image that may be likely to increase the total ET rate about 10% above that of ET_o. The ET_o values were obtained from the TXHPET database (Porter et al., 2005).

In the last step, the performance of the SSEB approach was evaluated by comparing predicted average daily ET in 3 × 3 pixels covering the lysimeter against measured data. Root Mean Square Error (RMSE), Mean Bias Error (MBE), and coefficient of determination (r^2) were used in the performance evaluation.

Results and Discussion

Daily actual ET maps were developed by applying the SSEB approach on 14 Landsat 5 TM images acquired during 2006 and 2007 cropping seasons. The ET_o values used in the mapping of actual ET varied from 3.1 to 12.6 mm, with the smaller and higher values observed on 11 October and 5 June 2007, respectively. Larger values of ET_o were the result of high wind speed and low relative humidity conditions that are common in the Southern High Plains during the growing season. The NDVI for hot pixels varied from 0.02 to 0.08 whereas it varied from 0.67 to 0.78 for cold pixels.

The daily ET values for the four large lysimeter locations were extracted from the ET maps and compared with the lysimeter data. Figure 2 illustrates the 1:1 comparison of predicted daily ET values against the lysimeter data. Daily ET estimates accounted for 84% of the variation in the observed data with the MBE±RMSE of -0.6±1.2 mm. The RMSE was about 22% of the observed mean and this relatively larger error was due to (1) over prediction of observed ET values that were less than 2.5 mm d^{-1} which occurred during the pre-planting season, (2) consistent under prediction of measured ET in dryland lysimeter fields when

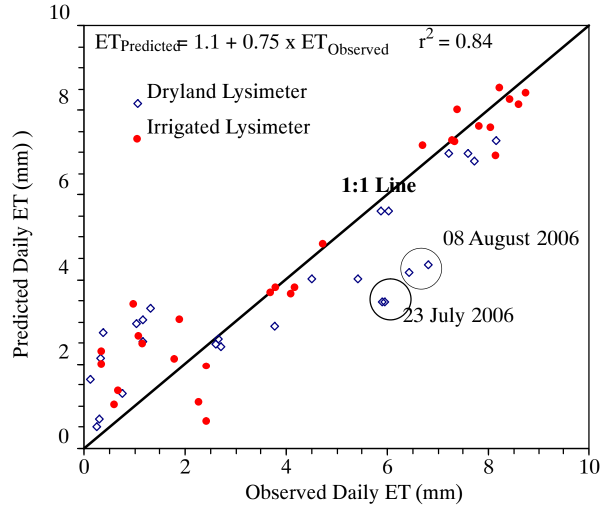

Figure 2. Predicted vs. observed daily ET of four large lysimeters in Bushland, Texas.

measured ET was more than 4.5 mm d^{-1}, and (3) gross under prediction of measured ET in dryland lysimeter fields on 23 July and 8 August 2006 (see fig. 2).

The over prediction errors observed with smaller ET values may possibly be due to (1) a combination of the presence of vigorous weeds in the fields surrounding the lysimeters causing lower ET on the lysimeters compared with that in the cropland around them and (2) errors in the SSEB model assumption that the cold pixel in the image is transpiring at the potential rate early in the season. This problem may be solved by adjusting the ET_o of the cold pixel during the early stage of the planting season to reduce actual crop ET (Allen et al., 1998). The gross under prediction errors in dryland lysimeter fields on 23 July and 8 August 2006 were greater than 35% of the observed ET. On 26 July, occurrence of 2.7-mm rainfall and high wind speed, varying from 1 to 7 m/s with an average speed of 2.76 m/s, may have contributed to a large prediction error. Similar high wind conditions existed on August 8, 2006 with wind speed varying from 1 to 8 m/s with an average speed of 3.83 m/s.

Conclusions

The Simplified Surface Energy Balance (SSEB) model is one of the most simplified approaches available in literature for mapping ET at a regional scale. This approach requires only reference ET in addition to satellite imagery for estimating ET. The SSEB was applied on 14 Landsat 5 TM images acquired during the 2006 and 2007 cropping season. Statistical evaluation of results indicates that the SSEB can be used to predict daily ET quickly. Overall, the performance of the SSEB approach was comparable with other data-intensive techniques such as METRIC, SEBAL, and TSM (Gowda et al., 2008). Considering the minimal amount of ancillary data required for applying SSEB and excellent performance in predicting daily ET on irrigated fields and relatively good performance in predicting ET on dryland fields, the SSEB is a promising tool for mapping ET in the semiarid Texas High Plains and other parts of the world with similar hydro-climatic conditions.

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