SEBAL FOR ESTIMATING HOURLY ET FLUXES OVER IRRIGATED AND DRYLAND COTTON DURING BEAREX08

P.H. Gowda[1], T.A. Howell[2], G. Paul[3], P.D. Colaizzi[4] and T.H. Marek[5]

[1]Prasanna H. Gowda, Research Agricultural Engineer, USDA-ARS Conservation and Production Research Laboratory, PO Drawer 10, Bushland, TX 79012; Ph (806)356-5730; Fax (806)356-5750; email: Prasanna.Gowda@ars.usda.gov
[2]Terry A. Howell, Research Leader & Acting Laboratory Director, USDA-ARS Conservation and Production Research Laboratory, PO Drawer 10, Bushland, TX 79012; Ph (806)356-5746; Fax (806)356-5750; email: Terry.Howell@ars.usda.gov
[3]George Paul, Graduate Research Assistant, Department of Agronomy, Kansas State University, Manhattan, KS 66506; Ph (785)532-7802; Fax (785)341-7355; email: gpaul@k-state.edu
[4]Paul D. Colaizzi, USDA-ARS Conservation and Production Research Laboratory, PO Drawer 10, Bushland, TX 79012; Ph (806)356-5735; Fax (806)356-5750; email: Paul.Colaizzi@ars.usda.gov
[5]Thomas H. Marek, Senior Research Engineer, Texas AgriLife Research, Texas A&M System, 6500 Amarillo Blvd., Amarillo, TX 79106; Ph (806)677-5665; Fax(806)677-5644; t-marek@tamu.edu

ABSTRACT
Numerous energy balance (EB) algorithms have been developed to make use of remote sensing data for mapping evapotranspiration (ET) on a regional basis. Adopting any or combination of these models for an operational ET remote sensing program requires thorough evaluation. The main objective of this paper was to evaluate the Surface Energy Balance for Land (SEBAL), an EB based ET estimation algorithm, using lysimeter data and three Landsat TM images covering a major portion of the Texas High Plains acquired during the Bushland Evapotranspiration and Agricultural Remote Sensing Experiment 2008 (BEAREX08). Performance of the SEBAL was evaluated by comparing estimated surface temperature, net radiation, soil heat flux, and hourly ET with measured data on four large lysimeters at the USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas [35^0 11' N, 102^0 06' W; 1,170 m elevation MSL]. Crops on the lysimeter fields include irrigated and dryland cotton. Performance statistics indicated that SEBAL performed well estimating hourly ET rates for both irrigated and dryland cotton surfaces. Currently, more evaluation is being done to evaluate the SEBAL for other major summer crops grown in the Texas High Plains.

INTRODUCTION
Remote sensing has long been recognized as the most feasible means to provide spatially distributed regional ET information on land surfaces (Park et al., 1968; Jackson, 1984). This is based on the rationale that ET is a change of the state of water using available energy in the environment for vaporization (Su et al., 2005). Remote sensing based energy balance (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:

$$LE = R_n - G - H \qquad (1)$$

where R_n is the net radiation resulting from the energy budget of short and long wave radiation, LE is the latent heat flux from evapotranspiration, G is the soil heat flux, and H is the sensible heat flux (all in W m^{-2} units). LE is converted to ET (mm h^{-1} or mm 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 Mg m^{-3}), and an appropriate time constant (e.g. 3600 s hr^{-1} for hourly ET).

Numerous remote sensing algorithms were available for estimating magnitude and trends in regional evapotranspiration. These models included Two-Source Model (TSM; Norman et al., 1995; Kustas and Norman, 1996), where the energy balance of soil and vegetation are modeled separately and then combined to estimate total LE, Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen et al., 1998a,b) and Mapping Evapotranspiration with Internalized Calibration (METRIC^{TM}; Allen et al., 2007a,b) that both use 'hot' and 'cold' pixels to develop an empirical temperature difference equation, and Surface Energy Balance system (SEBS; Su, 2002) based on the contrast between wet and dry areas. Other models include Simplified Surface Energy Balance Index (S-SEBI; Roerink et al., 2000); the excess resistance (kB^{-1}; Kustas and Daughtry, 1990); the aerodynamic temperature parameterization models proposed by Crago et al. (2004); Beta (β) approach (Chehbouni et al, 1996); and most recently ET Mapping Algorithm (ETMA; Loheide and Gorelick, 2005).

Surface Energy Balance Algorithm for Land (SEBAL) has been applied with Landsat Thematic Mapper (TM) data through out the world. However, the SEBAL algorithm has never been compared with lysimeter data from fields larger than the Landsat Thematic Mapper's thermal pixel size (120 by 120 m). This is important because smaller lysimeter fields cause contamination of thermal pixels from surface temperatures from surrounding fields and limits our ability to evaluate ET algorithms accurately (Kramber et al., 2002). The main objective of this paper was to evaluate SEBAL, an EB based ET estimation algorithm using lysimeter data and three Landsat TM images covering a major portion of the Texas High Plains acquired during the Bushland Evapotranspiration and Agricultural Remote Sensing Experiment 2008 (BEAREX08) conducted during 2008 summer growing season.

During the 2008 summer growing season, the BEAREX08 was conducted in and around the USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas. The main objectives of this research effort are to: evaluate the ability of land surface energy balance and crop coefficient-based ET models to estimate ET at point, plot, field, landscape and regional scales; evaluate effects of remote sensing pixel resolution (thermal band) on modeled energy balance components in irrigated and dryland cropping systems and rangeland systems; evaluate existing and new algorithms to improve spatial resolution of surface

temperature data derived from Aircraft/Landsat/ASTER/MODIS thermal images using high resolution visible, NIR and SWIR images; evaluate the ability of Large Aperture Scintillometer (LAS) systems to estimate path weighted sensible heat fluxes over heterogeneous landscapes; and evaluate Bowen Ratio and Eddy Covariance systems to estimate sensible and latent heat fluxes in the semi-arid, highly advective Southern High Plains. As part of BEAREX08, six field campaigns were conducted to coincide with Landsat 5 and ASTER overpasses. Data collection included reflectance and thermal data from two aircrafts, SPOT, Landsat TM, and MODIS sensors, soil water content, crop parameters, surface reflectance, surface temperature and near-surface red and infrared images using hand-held instruments in addition to net radiation and soil heat flux measurements. Surface energy fluxes measured using lysimeters, three Bowen ratio systems, seven eddy covariance systems, and three Large Aperture Scintillometers.

METHODS AND MATERIALS

Study Area

This study was conducted at the CPRL. The geographic coordinates of the CPRL are 35° 11' N, 102° 06' W, and its elevation is 1170 m above mean sea level. Soils around Bushland are classified as slowly permeable Pullman clay loam soils. The major crops in the study area are corn, sorghum, winter wheat, and cotton.

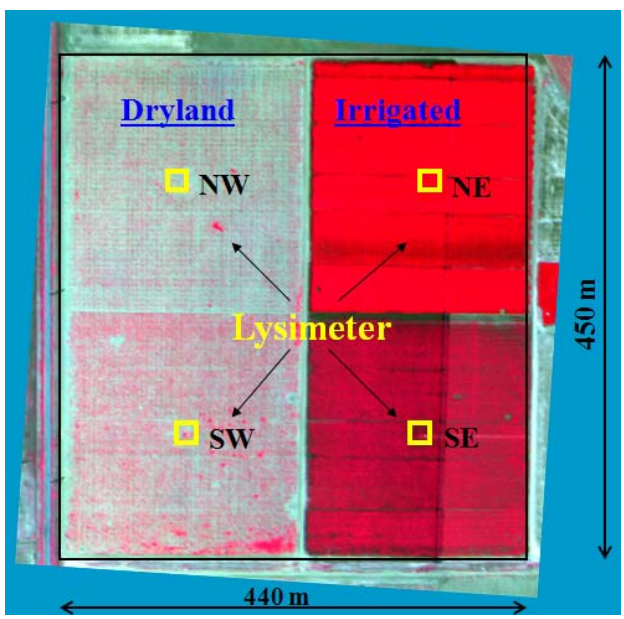

Figure 1. Lysimeter fields in the USDA-ARS Conservation and Production Research Laboratory.

SEBAL estimated ET values were verified by comparison to soil water mass change-based hourly ET fluxes from 4 large monolithic precision weighing lysimeters located at the CPRL. Each lysimeter (3 m length × 3 m width × 2.4 m depth) is located in the middle of 4.7-ha fields and all four lysimeters are arranged in a block pattern (Fig. 1). 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. In 2008, all four lysimeter fields were planted to cotton. A grass reference ET weather station field (0.31 ha), which is a part of the Texas High Plains ET Network (TXHPET, 2006) is located on the eastern side of the irrigated lysimeter fields. Each lysimeter field was equipped with one net radiometer [Q*7.1, Radiation and Energy Balance Systems (REBS)[1/], Seattle, Washington] and two infrared thermometers (IRT) (2G-T-80F/27C, Exergen, Watertown, Mass.) for measuring net radiation and surface temperature, respectively. More information of lysimeter setup can be found in Howell et al. (1995).

Surface Energy Balance Algorithm for Land (SEBAL)

SEBAL is a single-source model that solves the EB for LE as a residual. R_n absorbed by the surface is the sum of the net shortwave and longwave radiations. It is estimated as:

$$R_n = (R_S\downarrow - R_S\uparrow) + (R_L\downarrow - R_L\uparrow) \qquad (2)$$

where $R_S\downarrow$ and $R_S\uparrow$ are the incoming and shortwave radiation, respectively. $R_L\downarrow$ and $R_L\uparrow$ are the longwave incoming and outgoing radiation, respectively. The $R_S\downarrow$ and $R_S\uparrow$ are estimated as:

$$R_S\downarrow = G_{sc} \cos\theta \, d_r \, \tau_{sw} \qquad (3)$$

$$R_S\uparrow = \alpha \, R_S\downarrow \qquad (4)$$

where G_{sc} is the solar constant (1367 W m^{-2}), cos θ is the cosine of the solar incidence angle, d_r is the inverse squared relative earth-sun distance, τ_{sw} is the broadband one-way atmospheric transmissivity for shortwave radiation, and α is the broadband albedo of land surfaces. The τ_{sw} is computed as a function of elevation (Allen et al., 1998):

$$\tau_{sw} = 0.75 + 0.0002z \qquad (5)$$

where z is the elevation above the mean sea level in m. The albedo (α) of land surfaces is estimated using albedo of the top of the atmosphere (α_{TOA}), the path radiance albedo ($\alpha_{path\ radiance}$), and τ_{sw} as:

$$\alpha = (\alpha_{TOA} - \alpha_{path\ radiance}) / \tau^2_{sw} \qquad (6)$$

The $\alpha_{path\ radiance}$ ranges between 0.025 and 0.04, and Bastiaanssen (2000) recommends a value of 0.03.

The $R_L\downarrow$ is the downward thermal radiation flux originating from the atmosphere (W m^{-2}) and is estimated as:

[1/] Mention of trade or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

$$R_L\downarrow = \varepsilon_a \sigma T_a^4 \qquad (7)$$

where ε_a (dimensionless) is the atmospheric emissivity, is the Stefan-Boltzmann constant (5.67 x 10^{-8} W m^{-2} K^{-4}), and T_a (K) is the near-surface air temperature. The empirical equation for ε_a is given (Bastiaanssen et al., 1998a) as:

$$\varepsilon_a = 0.85 (-\ln \tau^2_{sw})^{0.09} \qquad (8)$$

The $R_L\uparrow$ is the thermal radiation flux emitted from the earth surface to the atmosphere and is determined by the Stefan-Boltzmann law:

$$R_L\uparrow = \varepsilon_s \sigma T_s^4 \qquad (9)$$

where ε_s is the surface emissivity (the ratio of the energy radiated by a surface to that by the blackbody at the same temperature) and T_s is the surface temperature (K), respectively. In SEBAL, ε_s is estimated using the normalized difference vegetation index (NDVI) when NDVI > 0 as:

$$\varepsilon_s = 1.009 + 0.047 \ln (NDVI) \qquad (10)$$

It is assumed ε_s to be one for NDVI < 0. Surface temperature (T_s) is calculated from the thermal band radiance values for Landsat 5 sensors using the simplified Planck function (Markham and Barker, 1986) and corrected using ε_s as:

$$T_s = k_2 / \ln [(\varepsilon_s k_1/R) + 1] \qquad (11)$$

where R is the Landsat TM/ETM+ band 6 radiance, and k_1 and k_2 are the calibration constants. For Landsat TM, k_1 and k are 607.76 mW cm^{-2} sr-1 μm^{-1} and 1260.56 K, respectively.

Soil heat flux (G) is the rate of heat storage into the soil and vegetation due to conduction. SEBAL computes the ratio of G/R_n using an empirical equation developed by Bastiaanssen (1995) representing near-midday values as:

$$G/R_n = T_s (0.0038 + 0.0074 \alpha) (1 – 0.98 NDVI^4) \qquad (12)$$

Sensible heat flux (H) was estimated using the bulk aerodynamic resistance model and a procedure that assumed a linear relationship between the aerodynamic surface temperature-air temperature difference (dT) and radiometric surface temperature (T_s) calculated from extreme pixels. Basically, extreme pixels showing cold/wet and hot/dry spots were selected to develop a linear relationship between dT and T_s. At the cold pixel in the satellite imagery, H was assumed non-existent i.e. H_{cold}=0 and at the hot pixel, LE was set to zero which in turn allows one to set H_{hot} = $(R_n–G)_{hot}$. Then, dT_{cold}=0 and dT_{hot} can be obtained by solving the bulk aerodynamic resistance equation for the hot pixel as:

$$H = \rho_a C_p dT / r_{ah} \quad (13)$$

where ρ_a is air density (kg/m^3), C_p is specific heat of air (1004 J kg^{-1} K^{-1}) and r_{ah} is the aerodynamic resistance to heat transport (s m^{-1}). After calculating dT at both cold and hot pixels, a linear relationship between dT and T_s is developed to estimate H iteratively correcting r_{ah} for atmospheric stability. This was done by applying the Monin-Obhukov Similarity (MOS) theory (Foken, 2006). This step required T_a and horizontal wind speed (u, m s^{-1}) that were measured at a nearby weather station, and a mechanism that extrapolates wind speed to a blending height of 100-200 m. In this study, a height of 200 m was used in the calculation of distributed friction velocity, a term utilized in the estimation of H. The dT artifice is expected to compensate for errors due to lack of proper atmospheric effects correction in the calibration of "at-sensor" brightness surface temperature in the process of obtaining radiometric surface temperature estimates. Furthermore, the SEBAL algorithm does not assume that radiometric and aerodynamic temperatures are equivalent. A detailed step-by-step procedure is presented in Morse et al. (2001). Finally, SEBAL was evaluated by comparing predicted R_n, G, H and instantaneous (hourly rates at satellite overpass time) ET (ET_{Inst}) with observed data. Root Mean Square Error (RMSE) and regression coefficient were used in the comparison of predicted against measured data.

RESULTS AND DISCUSSION

SEBAL algorithm was applied to three Landsat 5 TM image acquired on 26 June (DOY 178), 28 July (210), and 29 August (241) to derive α, T_s, R_n, G, H and hourly ET maps.

Figure 2(a-d) illustrates the comparison of predicted T_s, R_n, G, and ET_{Inst} with measured data on four lysimeters. Predicted T_s values were slightly lower than the observed data under both on dryland and irrigated cotton. The observed mean T_s (34.1 ^{o}C) was under predicted by 9% (31.1 ^{o}C). The RMSE was about about 9.7% of the observed mean T_s. Among the predictions, relatively higher prediction errors were associated with lysimeter fields with dryland cotton. However, the comparison of SEBAL predictions against observed T_s gave an r^2 of 0.95 with a slope and intercept of 0.99 and 2.60 ^{o}C, respectively.

The anchor cold and hot pixels were selected in an agricultural setting where the cold pixel was planted to corn/cotton under center pivot irrigation systems. The hot pixels were always found on bare soil surfaces. After determining the hot and cold pixels, initial estimation of dT and H was made for them under neutral atmospheric conditions and were subsequently adjusted for the unstable atmospheric conditions encountered using the MOS length scale iterative method. After five iterations, changes in r_{ah}, for the hot/cold pixels satisfied the convergence criteria of 5% difference in r_{ah} for each iteration cycle.

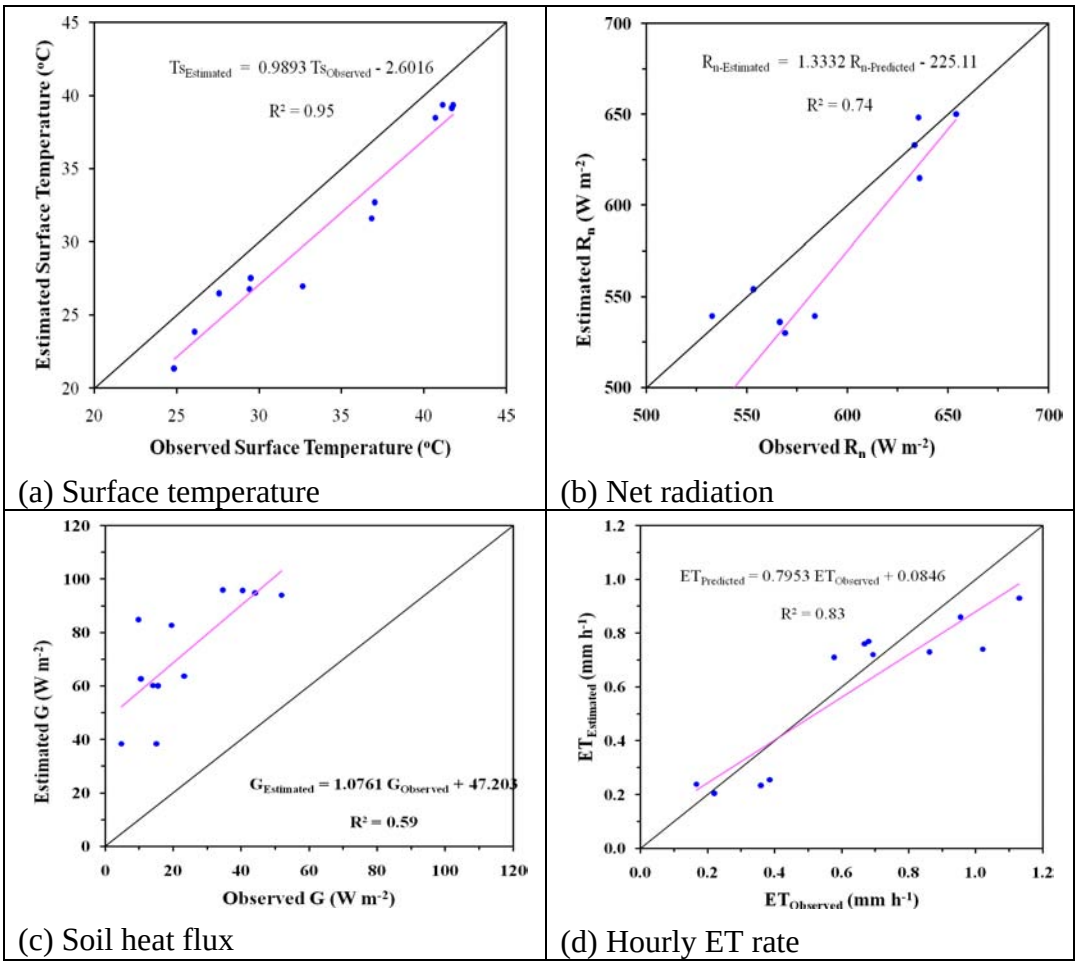

Figure 2. Predicted versus observed surface temperature (T_s), net radiation (R_n), soil heat flux (G) energy fluxes on four large lysimeters in Bushland, Texas.

Net radiation (R_n) estimates were compared well with the observed data. The RMSE was only about 7.6% of the observed mean R_n (44.6 W m^{-2}) on all four lysimeters. Relatively higher prediction errors (more than 14%) were associated with Landsat TM image acquired on 23 June (DOY 178). However, the SEBAL estimated R_n accounted for 74% of the variability in the observed data. Comparison of G estimates with observed data indicated that the G sub-model used in the SEBAL grossly over predicted for all four lysimeters approximately by 2 times. The predicted mean G for all four lysimeters were 72.62 W m^{-2} compared mean observed G of 23.62 W m^{-2}. The RMSE for predicted G was 50.78 W m^{-2}. Consequently, the SEBAL-based G estimates accounted for only 59% of the variability in the observed data. This may be partly due to the fact the observed G data were not corrected for heat storage above the soil heat flux plates. Application of this correction is expected to improve the performance statistics significantly.

The SEBAL estimated hourly ET rates were compared well with lysimeter data for all four lysimeters with a RMSE of 0.13 mm h^{-1}. This is about 21% of the

observed mean hourly ET for all four lysimeters. Predicted ET values accounted for 83% of the variability found in the lysimeter data with a slope and intercept of 0.79 and 0.09 mm h^{-1}, respectively. Errors in the estimation of hourly ET may be partly due to errors associated with atmospheric interference corrections in the calibration of "at-sensor" brightness surface temperature. Atmospheric effects corrections using a radiative transfer model corrects hotter pixels in greater proportion than cooler pixels. Thus, errors in the true value of T_s coupled with errors in the selection of the Hot pixel may have contributed to the determination of a bias dT vs. T_s relationship. The benefits of properly calibrating the satellite thermal band, considering surface emissivity and atmospheric effects can be found in Chávez et al. (2007).

SUMMARY

SEBAL is a single-source model requiring minimal amount of ancillary data. It was applied on three Landsat 5 TM images acquired during the 2008 summer cropping season as part of the BEAREX08. Predicted T_s values compared well with observed values on all four lysimeter fields, however with a RMSE of 3.3 ^{o}C. Predicted R_n compared well with the measured data for irrigated cotton and slightly underestimated for dryland cotton. Predicted hourly ET for both irrigated and dryland lysimeter fields compared well with measured data. Considering the minimal amount of ancillary data required for applying SEBAL and excellent performance in predicting hourly ET on both dryland and irrigated fields, the SEBAL is a promising tool for mapping ET in the Texas High Plains where intensively irrigated fields surrounded by crops managed under dryland conditions.

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