This is not a peer-reviewed article.
5th National Decennial Irrigation CD-ROM Proceedings
Phoenix Convention Center, 5 - 8 December 2010, Phoenix, AZ USA
M. Dukes ed. St Joseph Mich: ASABE
ASABE Publication Number 711P0810cd

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An ASABE Conference Presentation
Paper Number: IRR10-9701

Two Source Energy Balance Model – Refinements and Lysimeter Tests in the Southern High Plains

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Written for presentation at the
5th National Decennial Irrigation Conference
Sponsored jointly by ASABE and the Irrigation Association
Phoenix Convention Center
Phoenix, Arizona
December 5 - 8, 2010

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Abstract. *A thermal two-source energy balance model (TSM) was evaluated for predicting daily evapotranspiration (ET) of corn, cotton, grain sorghum, and wheat in a semiarid, advective environment. Crop ET was measured with large, monolithic weighing lysimeters. The TSM solved the energy budget of soil and vegetation using a series resistance network, and one-time-of-day latent heat flux estimates were scaled to daily ET using the ASCE Standardized Reference ET equation for a short crop. The TSM included several refinements, including a geometric method to account for the nonrandom spatial distribution of vegetation for row crops with partial canopy cover, where crop rows were modeled as elliptical hedgerows. This geometric approach was compared to the more commonly used, semi-empirical clumping index approach. Both approaches resulted in similar ET estimates, but the elliptical hedgerow approach performed slightly better. Using the clumping index, root mean squared error, mean absolute error, and mean bias error were 1.0 (22%), 0.79 (17%), and 0.093 (2.0%) mm d^{-1}, respectively, between measured and modeled daily ET for all crops, where percentages were of the observed mean ET (4.62 mm d^{-1}). Using the elliptical hedgerow, root mean squared error, mean absolute error, and mean bias error were 0.86 (19%), 0.69 (15%), and 0.17 (3.6%) mm d^{-1}, respectively, between measured and modeled daily ET for all crops. The TSM refinements will improve the accuracy of remote sensing-based ET maps, which is imperative for water resource management.*

Keywords. Evapotranspiration, remote sensing, row crops, Texas, latent heat flux, clumping index, fractional cover, radiometric temperature

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Introduction

Judicious irrigation management is expected to play a key role in mitigating the dilemma of increased demands for agricultural production by an expanding world population and rapidly declining available water resources. Irrigation management entails numerous strategies, such as time- and site-specific water application, deficit or limited irrigation, and various combinations of these. Implementing these strategies has been impeded by the lack of automated, real-time information on crop and soil water conditions, such as maps of crop evapotranspiration (ET) and crop water stress. Consequently, adoption of advanced irrigation management techniques has lagged compared with other industrial systems, where feedback, automation, and decision support systems are more routinely used (Evans and King, 2010). As irrigated farms continue to consolidate (USDA, 2008), it is expected that larger areas will be managed by fewer personnel. Therefore, feedback and information systems tailored to reduce management time will be essential to maintain farm profitability with decreasing available water.

Remote sensing, where the reflectance and temperature of the surface is measured by non-contact radiometers, was recognized as a potential feedback tool for agricultural management at least since the 1960s (e.g., Park et al., 1968). Remote sensing provided by satellite, aircraft, or ground-based platforms can be used to derive maps of ET and crop water stress, which are essential information for irrigation management. Real-time irrigation and crop management at the field scale generally require a spatial resolution of a few meters, a repeat frequency of a few days, and a turn around time (i.e., time interval from field measurement to final information product) on the order of minutes (Jackson, 1984). Despite nearly a half-century history, airborne and satellite remote sensing platforms have not met all three of these requirements. Some barriers were related to extensive image processing requirements and the lack of information delivery systems (i.e., web-based systems), which had been serious limitations until recently (Moran, 1994).

The recent availability and standardization of wireless technology have made ground-based sensors feasible for agricultural applications (O'Shaughnessy and Evett, 2010). This has resulted in renewed interest in remote sensing as an irrigation management tool. At least one stationary, wireless, ground-based remote sensing system has been commercialized recently (Mahan et al., 2010). Self-propelled irrigation systems (i.e., center pivot and lateral move) can provide a mobile sensor platform, reducing the number of sensors required, because these systems pass over fields at regular intervals (e.g., Peters and Evett, 2008). Self-propelled irrigation systems are used on nearly 50 percent of the 23 million ha of irrigated land in the United States, and nearly 80 percent of the irrigated land in the Southern High Plains, with continued adoption expected (USDA, 2008). Therefore, these systems may be amenable for more widespread adoption of ground-based remote sensing, which could provide the real-time feedback information required to implement advanced irrigation management and automation strategies.

Several remote sensing algorithms are available to estimate ET and quantify crop water stress. The thermal-based algorithms typically combine reflectance and thermal measurements of a vegetated surface with point-based agricultural meteorological data to drive a surface energy balance model, where the remotely sensed and meteorological data provide the spatial and temporal domains, respectively. Since remotely sensed surface temperature is often a composite of vegetation and soil temperatures, especially for row crops, two-source energy balance models (TSM) have become popular, which solve the energy balance of the soil and canopy sources separately and combine these to derive total latent heat flux of the surface. Norman et al. (1995) developed an operational TSM that only required input data and

parameters that were either readily available or could be reasonably estimated based on knowledge of local vegetation and soil characteristics. Kustas and Norman (1999; 2000) described several refinements to the model, including use of the Campbell and Norman (1998) radiation scattering model, estimation of soil resistance to heat transport, and the effects of the nonrandom spatial distribution of vegetation. Nonrandom spatial distribution of vegetation commonly occurs for row crops or sparse heterogeneous natural vegetation, and results in different partitioning of energy fluxes to the soil and canopy compared with a uniform, homogenous canopy. Nonrandom spatial distribution of vegetation has been commonly accounted for using the clumping index approach (e.g., Chen and Cihlar, 1995), which is a semi-empirical factor that is multiplied by the leaf area index and has been adopted for row crops (e.g., Kustas and Norman, 1999; Anderson et al., 2005). The clumping index has different values for solar beam radiation, diffuse radiation, and the view factor of a directional radiometer. In the row crop formulation, the clumping index depends on the zenith and azimuth view angles relative to the rows, row spacing, and canopy height and width.

Numerous studies have tested the TSM at a variety of locations, climates, and vegetation types. A few examples include grass and desert shrubs near Tombstone, Arizona (Norman et al., 1995); prairie grass near Manhattan, Kansas (Norman et al., 1995); irrigated cotton near Maricopa, Arizona (Kustas, 1990; Kustas and Norman, 1999; 2000); rangeland, pasture, and bare soil near El Reno, Oklahoma (Norman et al., 2000); riparian zone along the Rio Grande in the Bosque Del Apache National Wildlife Refuge in Central New Mexico (Norman et al., 2000); corn, soybean, and bare soil near Ames, Iowa (Li et al., 2005; Anderson et al., 2005); and irrigated spring wheat near Maricopa, Arizona (French et al., 2007). Nearly all of these studies used Bowen ratio, eddy covariance, or Meteorological-Flux tower (METFLUX) techniques for ground truth measurements of energy fluxes, although French et al. (2007) derived ET from a soil water balance using neutron probe measurements. These systems are relatively portable, low cost, and robust. However, the Bowen ratio method assumes that fluxes are vertical and is therefore subject to errors during advective conditions and can also be sensitive to fetch and instrument bias (Todd et al., 2000). Eddy covariance techniques measure turbulent fluxes across a field directly, but the energy balance is often not closed (Twine et al., 2000) unless additional procedures or corrections are used (e.g., Chavez et al., 2009). Few, if any, studies have used weighing lysimeters to test the TSM, which can be the most accurate means of measuring ET (Howell et al., 1995a, 1997). The USDA Agricultural Research Service Conservation and Production Research Laboratory at Bushland, TX have measured ET using large, monolithic weighing lysimeters for several major crops in the U.S. Southern High Plains. This region is semiarid and is characterized by very high atmospheric demand due to strong regional advection, abundant solar radiation, and high vapor pressure deficits. It therefore represents a unique location for studies in energy balance and ET models.

Preliminary tests of the Kustas and Norman (1999) version of the TSM were conducted at Bushland for several row crops, where ET was measured by weighing lysimeters and surface temperature was measured by stationary infrared thermometers (IRTs) viewing the lysimeter surface. Large errors were observed for partial canopy cover, and large errors were also obtained for partial canopy cover when comparing measurements of transmitted and reflected radiation with those computed by the Campbell and Norman (1998) radiative transfer model. In both models, the widely-used clumping index approach was used to account for the nonrandom spatial distribution of row crop vegetation. The clumping index formulations do not directly account for the circular or elliptical footprint of a ground-based radiometer, which would result in a different fraction of vegetation appearing in the footprint compared with a square pixel (i.e., obtained from satellite or airborne scanners). Also, the clumping index does not directly account for the different portions of sunlit and shaded soil, which depend on solar zenith and azimuth angle relative to row orientation, and have a large impact on radiation partitioning to the soil and

canopy and hence ET. Since many row crops under center pivot irrigation are planted in a circle, row orientation would be expected to contribute to the spatial variability of ET, especially for partial canopy cover.

To address these limitations, Colaizzi et al. (2010a) developed a method to estimate the fraction of soil and vegetation of a row crop appearing in a radiometer footprint, and Colaizzi et al. (2010b; 2010c) describe and test a modification to the Campbell and Norman (1998) radiative transfer model in accounting for the spatial distribution of row crop vegetation. These studies explicitly accounted for row crop geometry by modeling crop rows as elliptical hedgerows. The elliptical hedgerow approach consistently improved estimates of soil and vegetation appearing within the radiometer footprint, as well as estimates of transmitted and reflected radiation, compared with the clumping index approach. The objectives of this study were to test the TSM where the nonrandom spatial distribution of row crop vegetation was accounted for using the elliptical hedgerow approach, and compare these results with the clumping index approach.

Materials and Methods

Two Source Model Overview

Most energy balance algorithms, including the two-source model (TSM) of Norman et al. (1995), consider the four major energy flux components of the soil-canopy-atmosphere continuum, which are net radiation (R_N), soil heat flux (G), sensible heat flux (H), and latent heat flux (LE), and assume other energy components such as canopy heat storage and photosynthesis are negligible. The available energy is equal to the turbulent fluxes, expressed as $R_N - G = H + LE$, where turbulent fluxes are positive away from the canopy. In the TSM, R_N, H, and LE are further partitioned to their canopy and soil components, and the energy balance is expressed as

$$LE_C = R_{N,C} - H_C \tag{1a}$$

$$LE_S = R_{N,S} - G - H_S \tag{1b}$$

where the subscripts *C* and *S* refer to the canopy and soil, respectively. $R_{N,C}$ and $R_{N,S}$ were determined by the canopy radiative transfer model of Campbell and Norman (1998), which computes the photosynthetic, near-infrared, and long wave components separately. Non-homogeneous canopies, such as forests and row crops, will scatter radiation differently than homogeneous canopies. Campbell and Norman (1998) suggested this could be accounted for by multiplying leaf area index by a simple clumping index, which has been demonstrated operationally (e.g., Kustas and Norman, 1999; Anderson et al., 2005). However, Colaizzi et al. (2010b; 2010c) accounted for the nonrandom spatial distribution of row crop vegetation by modeling crop rows as elliptical hedgerows, which was also used to compute $R_{N,S}$ and $R_{N,C}$.

Previous TSM studies have usually estimated G as a constant fraction of $R_{N,S}$; however, G may exhibit a strong phase difference with $R_{N,S}$, which was observed at our location. Therefore, G was estimated using a phase difference equation described by Santanello and Friedl (2003):

$$G = R_{N,S}\left\{a \cdot \cos\left[\frac{2\pi}{b}(t + c)\right]\right\} \tag{2}$$

where t is the solar time angle (seconds) and a, b, and c are empirical constants. Santanello and Friedl (2003) showed that these parameters depend on near-surface soil water content as well as other soil characteristics. In the present study, a = 0.30, b = 80,000, and c = 3,600 s were derived by minimizing the error between G estimated using in-situ measurements (soil

heat flux plates and thermocouples) and G estimated with (2). A more exhaustive study on soil heat flux models is presently underway using field measurements at our location.

Sensible heat flux is modeled by temperature gradient-transport resistance networks between the soil, canopy, and air above. The networks were formulated as either parallel or series by Norman et al. (1995). In the parallel network, turbulent fluxes occur as separate (parallel) streams between the soil or canopy and atmosphere, and there is no direct interaction between the soil and canopy. In the series network, flux exchange between the soil and canopy may occur directly (Figure 1). Li et al. (2005) reported that the parallel model was more sensitive to errors in vegetation cover estimates, and that these uncertainties may be moderated by the additional parameter of within-canopy air temperature that is used in the series formulation (T_{AC} in Figure 1). Kustas and Norman (1999), Kustas et al. (2004), and Li et al. (2005) concluded that the series was preferable over the parallel model for heterogeneous landscapes containing a large range of vegetation cover. Since the present study included four different crops (Table 1) having a wide range of vegetation cover, we used the series formulation.

The canopy, soil, and composite sensible heat flux components in Figure 1 are expressed as

$$H_C = \rho C_P \frac{T_C - T_{AC}}{r_X} \tag{3a}$$

$$H_S = \rho C_P \frac{T_S - T_{AC}}{r_S} \tag{3b}$$

$$H = \rho C_P \frac{T_{AC} - T_A}{r_A} \tag{3c}$$

where ρ is the air density (kg m^{-3}), C_P is the specific heat of air (assumed constant at 1013 kJ kg^{-1} K^{-1}), T_C, T_A, T_S, and T_{AC} are the temperatures of the canopy, air, soil, and air temperature within the canopy boundary layer, respectively (K), r_X is the resistance in the boundary layer near the canopy (s m^{-1}), r_S is the resistance to heat flux in the boundary layer immediately above the soil surface (s m^{-1}), and r_A is the aerodynamic resistance (s m^{-1}). In equation 3c, advected energy is indicated when $T_{AC} < T_A$, resulting in negative H. The directional radiometric surface temperature (T_R, derived from remotely sensed directional brightness temperature) was assumed related to T_C and T_S as

$$T_R^4 = f_{VR} T_C^4 + (1 - f_{VR}) T_S^4 \tag{4}$$

where f_{VR} is the fraction of vegetation appearing in the radiometer field-of-view where directional brightness temperature is measured. In order to solve the temperature and resistance network, T_C is initially estimated using the Priestley-Taylor approximation for latent heat flux (Priestley and Taylor, 1972), where the Priestley-Taylor parameter (α_{PT}) of 1.3 was used for the present study location (Agam et al., 2010). In equation (4), f_{VR} never physically reaches 1.0 because of canopy extinction, but this constraint would be required in any case in order to solve for T_S. If f_{VR} is close to 1.0, T_S can be sensitive to small errors in f_{VR} resulting in unrealistic values. Therefore, T_S was constrained from falling below the air wet bulb temperature, where the wet bulb temperature is the lower limit for an evaporating surface (Wanjura and Upchurch, 1996). In the case of water-stressed vegetation, non-transpiring canopy elements (e.g., senesced leaves or non-leaf elements), or low vapor pressure deficit, T_C may be underestimated, resulting in overestimates of T_S and H_S, and possibly resulting in $LE_S < 0$ (from equation 1b). This would imply condensation at the soil surface, which is unlikely for conditions expected when obtaining remote sensing measurements (i.e., near midday and clear skies), especially in less humid

climates. Therefore, if the model solution resulted in $LE_S < 0$, then α_{PT} was reduced below 1.3 in increments of 0.1 until $LE_S \geq 0$. For a dry soil surface, it is possible that the resulting LE_S could still be negative even though $\alpha_{PT} = 0$, which in this case LE_S is set to zero, and from equation (1b), $H_S = R_{N,S} - G$, and the remaining energy flux components are recalculated according to these constraints. The rationale for the Priestley-Taylor approximation and procedures for computing the temperatures and resistances in equations (3 and 4) are in Norman et al. (1995) and Kustas and Norman (1999).

Irrigation management typically entails using a soil water balance to estimate soil water depletion at daily time steps, and this requires estimates of daily evapotranspiration (ET). Therefore, daily ET was derived from instantaneous total latent heat flux (i.e., $LE = LE_C + LE_S$) by first converting LE to ET at 30-min time steps, and then using a one-time-of-day estimate of 30-min ET to estimate daily ET. LE was converted to 30-min ET averages by multiplying by 1800 s and dividing by the latent heat of vaporization (λ), where $\lambda = 2.501 - 0.002361T_A$, and λ is in MJ kg^{-1} and T_A is air temperature in °C, and assuming the density of water is constant at 1000 kg m^{-3}. Daytime λ was typically 2.44 MJ kg^{-1} at the study location. The 30-min ET average during solar noon (12:30 to 13:00 at the study location) was scaled to daily ET as

$$ET_{24} = ET_{0.5}\left(\frac{ET_{OS-24}}{ET_{OS-0.5}}\right) \tag{5}$$

where ET_{24} is the daily (24 h) modeled ET, $ET_{0.5}$ is the 30-min modeled ET (computed from LE), $ET_{OS-0.5}$ is the ASCE-Standardized Penman Monteith equation for a short reference crop (ASCE, 2005) computed at 30-min time steps, and ET_{OS-24} is the daily (24 h) sum of each $ET_{OS-0.5}$ time step. The Penman-Monteith method provided better agreement between modeled daily ET (scaled from one-time-of-day 30-min ET) and lysimeter-measured daily ET compared with the more commonly used evaporative fraction method (Colaizzi et al., 2006).

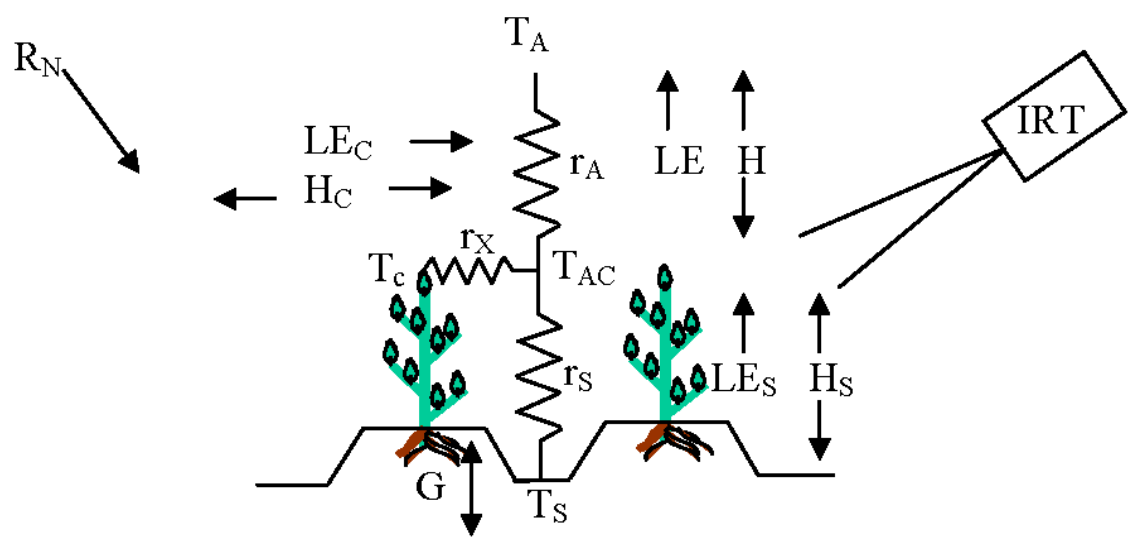


Figure 1. Series resistances and flux components for the two source energy balance model, adopted from Norman et al. (1995), Fig. 11. See text for symbol definitions.

Field Measurements

All field measurements used in this study were obtained at the USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas, USA (35º 11' N lat., 102º 06' W long., 1,170 m elevation M.S.L.). The climate is semi-arid with a high evaporative demand of about 2,600 mm per year (Class A pan evaporation) and low precipitation averaging 470 mm per year. The precipitation pattern is bimodal, where most rainfall occurs in mid spring (i.e., around planting for summer crops) and again in late summer (i.e., around the water-sensitive reproductive stage for summer crops, or prior to planting for winter crops). This pattern has made dryland production feasible for drought-tolerant crops such as cotton, grain sorghum, and winter wheat. Strong advection of heat energy from the south and southwest is typical. The soil is a Pullman clay loam (fine, mixed, super active, thermic torrertic Paleustolls) with slow permeability, having a dense B2 layer from about 0.15- to 0.40-m depth and a calcic horizon that begins at the 1.1-m depth (USDA, 2010).

Evapotranspiration (ET) of four of the region's major crops was measured with large monolithic weighing lysimeters. There were four lysimeters; each lysimeter was located in the center of a 4.7 ha square field (217 m on each side). The fields were arranged in a square pattern, and herein are designated NW, SW, NE, and SE. The unobstructed fetch in the predominate wind direction (southwest to south-southwest) is greater than 1 km. The fetch within each lysimeter field was sufficient so that ET measurements were not likely to be influenced by local advection (Tolk et al., 2006). The crops included grain corn (*Zea mays* L.; 1989 season), winter wheat (*Triticum aestivum* L.; 1991-92 season), grain sorghum (*Sorghum bicolor* L.; 1998 season), and upland cotton (*Gossypium hirsutum* L.; 2008 season) (Table 1). Cultural practices were similar to those used for high-yield production in the Southern High Plains. Irrigation was applied with a hose-fed lateral move sprinkler system. Most crops were planted in raised beds except for winter wheat, which was flat plated. Furrow dikes were installed across raised beds following crop establishment to control runoff and run on of irrigation and rainfall (Schneider and Howell, 2000). Row orientation was east-west except for the winter wheat (both lysimeters) and cotton crops (NE lysimeter), which were north-south. Row spacing was 0.76 m for corn, cotton, and grain sorghum, and 0.25 m for winter wheat. Agronomic details and additional references for each crop are given in Table 1.

Table 1. Crops where evapotranspiration was measured using monolithic weighing lysimeters.

Crop	Season (lysimeters)	Irrigation rate (% ET replacement)	Additional references
Corn	1989 (NE, SE)	100%	Howell et al. (1995a), Howell et al. (1997), Tolk et al. (1995)
Cotton	2008 (NE, SE)	100%	
Grain sorghum	1998 (NW, SW)	Dryland	
Winter wheat	1991-92 (NE, SE)	100% (NE) 50% (SE)	Evett et al. (1994), Howell et al. (1995a), Howell et al. (1995b), Howell et al. (1997)

Each monolithic weighing lysimeters had a surface area of 9.0 m^2 (3.0 m x 3.0 m) and was 2.4 m deep (Marek et al., 1988), with an accuracy of 0.02 to 0.05 mm d^{-1} (Howell et al., 1995a). ET was determined by the net change in lysimeter mass divided by the lysimeter area, which included losses (evaporation and transpiration) and gains (irrigation, precipitation, dew).

Lysimeter mass was measured using a load cell (Alphatron[1] S50, 0.5 Hz frequency; Alphatron Industries, Inc. Davie, Florida, USA; Interface, Scottsdale, Arizona, USA) and cantilever system, reported as 30-min averages. Drainage from the lysimeter was maintained with a 10 kPa vacuum pump system, and the drainage effluent was stored in two tanks suspended by separate load cells from the lysimeter. For full cover crops, a small correction factor (1.02) was applied to the lysimeter area to account for the canopy extending to the midpoint between the lysimeter inner and outer walls (9.5 mm wall thickness and 10 mm air gap). The 30-min ET averages were summed to daily (24 h) totals.

Table 2. Instruments used to measure meteorological variables for the two source model.

Meteorological variable	Manufacturer and model	Crops
Incident Solar Radiation	Eppley PSP (1)	All
Net Radiation	REBS Q*4 (2)	Corn
Net Radiation	REBS Q*5.5 (2)	Winter wheat, grain sorghum
Net Radiation	REBS Q*7.1 (2)	Cotton
Soil heat flux	REBS HF-1 Heat Flux Plates (2)	All
Soil temperature	Omega Thermocouples (3)	All
Directional brightness temperature	Everest IRT (4)	Corn, winter wheat
Directional brightness temperature	Exergen IRT/c (5)	Grain sorghum, cotton
Wet/dry bulb air temperature	Aspirated psychrometers designed after (6)	Corn, winter wheat
2-m air temperature & RH	Rotronics MP-100 (7)	Grain sorghum
2-m air temperature & RH	Vaisala HMP45 (8)	Cotton
Wind profile (1.0 m, 1.3 m, 1.8 m, 2.8)	Met One Model 014a (9)	Corn, winter wheat
2-m wind speed	RM Young Model 03101 Wind Sentry (10)	Grain sorghum, cotton

1. Eppley Laboratory, Inc., Newport, Rhode Island, USA; these measurements were obtained from a nearby grass reference site.
2. Radiation and Energy Balance Systems, Inc., Seattle, Washington, USA.
3. Omega Engineering, Inc. Stamford, Connecticut, USA.
4 Everest Interscience, Inc., Tucson, Arizona, USA.
5. Exergen Corp., Watertown, Massachusetts, USA.
6. Lourence and Pruit (1969).
7. Rotronics Instrument Corp., Huntington, New York, USA.
8. Vaisala, Inc., Boston, Massachusetts, USA.
9. Met One Instruments, Inc., Grants Pass, Oregon, USA.
10. R. M. Young Co., Traverse City, Michigan, USA.

Each lysimeter site included a mast located at the midpoint of the north edge that contained micrometeorological instruments. Measurements used in this study included net radiation (R_N),

[1] The mention of trade names of 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.

soil heat flux (G), soil temperature (T_S), air temperature (T_A), wet bulb temperature (T_W) (or relative humidity, RH), wind speed (U), and the directional brightness temperature (T_B) (Norman and Becker, 1995) of the lysimeter surface (Table 2). Measurements were made at 6-s intervals and reported as 30-min averages, simultaneously with lysimeter mass measurements. All measurements, including lysimeter mass, were recorded and averaged by a Campbell Scientific CR-7X data logger (Campbell Scientific, Inc., Logan, Utah, USA). Global shortwave incoming solar radiation (R_S) was measured at a site immediately east of the SE lysimeter field that was planted in tall fescue since 1995 (Howell et al., 2000). R_N, T_A, T_W or RH, U, and T_B were typically measured at a 2.0-m height above the soil surface. Surface G was computed from measurements of G by soil heat flux plates buried at 50 mm below the surface, and soil heat storage was computed from measurements of the average soil temperature by thermocouples buried at 10 and 40 mm near the soil heat flux plates. There were four soil heat flux plate-thermocouple sets, with two positioned beneath adjacent crop rows and two beneath adjacent interrows.

T_B was measured with stationary infrared thermometers (IRTs) viewing the lysimeter surface at a 60° zenith angle and an azimuth toward the southwest (45° from due south; Huband and Montieth, 1986), with a 2:1 field-of-view. Everest IRT model series 4000 (Everest Interscience, Inc., Tucson, Arizona, USA) were used for corn and winter wheat; Exergen IRT model IRT/c (Exergen Corp., Watertown, Massachusetts, USA) were used for grain sorghum and cotton. The Everest IRTs were factory calibrated annually, and the Exergen IRTs were calibrated using an Everest Model 1000 black body or an Omega Black Point BB701 black body (Omega Engineering, Inc., Stamford, Connecticut, USA). The Exergen IRTs did not feature a chopper or detector temperature measurement; therefore, they were insulated from the outside air to reduce the influence of longwave radiation variability from the internal body cavity on the detector. It is not known to what extent the lack of detector temperature for the Exergen IRTs may have degraded the accuracy of calibration (Kalma et al., 1988; Bugbee et al., 1998); however, no differences in TSM model performance were apparent between the IRT manufacturers. The use of ground based IRTs were nonetheless deemed advantageous over aircraft or satellite data because atmospheric correction was not required and 30-min measurements were available. Directional radiometric surface temperature (T_R) was estimated by subtracting the reflected atmospheric longwave radiation from the contribution to T_B (Norman and Becker, 1995), where longwave reflectance was assumed equal to the bulk (soil and canopy) surface emittance, which was assumed 0.98. Soil emittance equal to 0.98 was verified by measurements over bare soil using a Cimel CE 312 multiband thermal radiometer (Cimel Electronique, Paris, France), and canopy emittance equal to 0.98 was assumed based on Idso et al. (1969) and Campbell and Norman (1998). Atmospheric emittance was estimated using the Brutsaert (1982) equation.

Plant measurements and samples were taken periodically at key growth stages at 1.0 to 1.5 m^2 sites about 10 to 20 m from the lysimeters. Leaf area was measured with a LI-COR leaf area meter (model LI-3100, Lincoln, Nebraska), and the meter accuracy was verified periodically with a 0.005 m^2 standard disk. Plant height (h_C) and leaf area index (LAI) were related to growing degree days by linear interpolation so that these parameters could be estimated between sample dates. The TSM was evaluated for a fairly wide range of h_C and LAI, from early development to maturity and senescence.

Data were restricted to clear-sky days, when measured R_S closely matched ($r^2 \geq 0.98$) theoretical clear sky radiation (ASCE, 2005) to assure relatively steady-state energy fluxes. Data were excluded when T_A was below freezing, which included several days during the winter wheat season. Data were not used during days when irrigation, precipitation, plant measurements, or instrument maintenance and repair occurred.

Model Evaluation

The two source model was evaluated by comparing modeled daily ET with observed daily ET measured by weighing lysimeters. Agreement between modeled vs. observed daily ET was assessed by root mean square error (RMSE), mean absolute error (MAE), mean bias error (MBE), and the modified coefficient of model efficiency (E_C), where $-\infty < E_C \leq 1.0$, with greater E_C values indicating better model agreement (Legates and McCabe, 1999). If $E_C \leq 0$, then the mean of all observations is actually a better predictor than the model. The E_C is a non-squared version of the original Nash and Sutcliffe (1970) model efficiency parameter, which Legates and McCabe (1999) argued was less sensitive to outliers. The extent that RMSE is greater than MAE is related to outliers in modeled vs. observed scatter. Additional parameters reported were the modeled vs. observed slope, intercept, and coefficient of determination (r^2).

In addition to daily ET, agreement between modeled vs. observed instantaneous net radiation (R_N), soil heat flux (G), and latent heat flux (LE) were assessed. Observed LE was derived by converting 30-min ET averages (12:30 to 13:00 CST) measured by the lysimeters. R_N, G, LE, and ET were initially estimated using the TSM where the nonrandom spatial distribution of row crop vegetation was accounted for using the clumping index approach (Norman and Kustas, 1999; Anderson et al., 2005). For comparison, R_N, G, LE, and ET were estimated using a modified form of the TSM where the nonrandom spatial distribution of row crop vegetation was accounted for by modeling the rows as elliptical hedgerows (Colaizzi et al., 2010a, 2010b, 2010c). Agreement between observed and modeled energy fluxes (R_N, G, and LE) were assessed using the average of 12:30 to 13:00 (i.e., 30-min average during solar noon). Data were pooled for all four crops (corn, cotton, grain sorghum, and winter wheat).

The two-source model (TSM) was evaluated under a wide range of climatic conditions, which may occur within just a few days in continental climates such as Bushland, Texas. Most days evaluated occurred during the summer crop growing season (late spring to mid autumn), although winter wheat included some days during winter or early spring when air temperature was slightly above freezing. Wind speed measured at 2 m above the soil surface averaged 3.4 to 5.4 m s^{-1}; the greatest wind runs typically occurred during spring (March, April, and May), and the least occurred during late summer (around August).

Results and Discussion

The wide range of canopy height (h_C) and leaf area index (LAI) evaluated resulted in a wide range of the fraction of vegetation appearing in the infrared thermometer field of view (f_{VR}) for each crop (Figure 2). The value of f_{VR} using the clumping index and elliptical hedgerow approaches was similar for corn for the entire range of f_{VR} (i.e., near zero to one), but f_{VR} was different for cotton, grain sorghum, and winter wheat. The elliptical hedgerow approach resulted in consistently greater f_{VR} compared with the clumping index approach for winter wheat, but consistently smaller f_{VR} for grain sorghum. For cotton, f_{VR} was smaller for the elliptical hedgerow compared with the clumping index when $f_{VR} < 0.2$, but inconsistent for f_{VR} between 0.6 and 0.9. These differences were likely related to the different sensitivities to input variables for each approach. For example, Colaizzi et al. (2010a) showed that the elliptical hedgerow was more sensitive to the radiometer zenith and azimuth view angles but less sensitive to the canopy height and width compared with the clumping index. The wide range of f_{VR} as well as differences in f_{VR} values for both approaches was desirable in order to evaluate the two versions of the TSM. As expected, the clumping index and elliptical hedgerow approaches also resulted in different partitioning of net radiation (R_N) to the canopy ($R_{N,C}$) and soil ($R_{N,S}$) components around solar noon (Figure 3). This was mainly related to differences in direct beam shortwave radiation intercepted by the canopy, in that assumptions about canopy structure would be expected to

have a greater impact on direct beam compared with diffuse components (Campbell and Norman, 1998). $R_{N,C}$ tended to be greater for corn, cotton, and winter wheat using the elliptical hedgerow approach, but inconsistent for grain sorghum. However, $R_{N,S}$ was usually less for all crops for the elliptical hedgerow compared with the clumping index. When canopy cover was very sparse (resulting in low $R_{N,C}$ and large $R_{N,S}$), there were little differences in either approach.

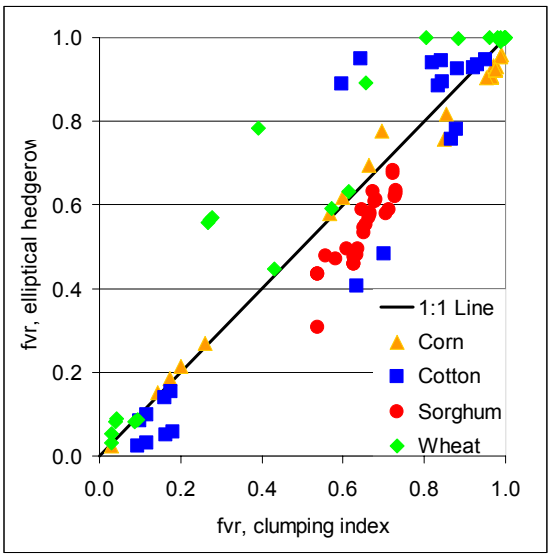
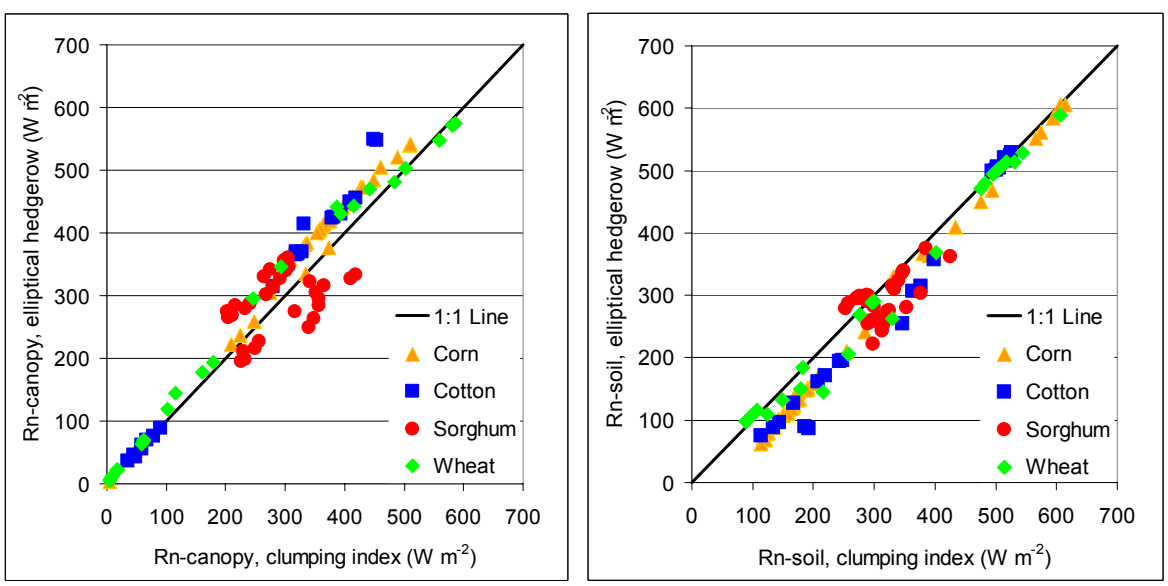


Figure 2. Comparison of the fraction of vegetation appearing in the radiometer field of view (f_{VR}) using the clumping index and elliptical hedgerow approaches.



a. b.

Figure 3. Comparison of (a) net radiation to the canopy ($R_{N,C}$) and (b) net radiation to the soil ($R_{N,S}$) using the clumping index and elliptical hedgerow approaches.

Agreement between modeled and observed total net radiation (R_N) near solar noon was very similar using both the clumping index (Table 3) and elliptical hedgerow (Table 4) approaches,

with the latter approach giving slightly better agreement. Overall errors between modeled and observed R_N was somewhat greater compared with other studies that investigated the TSM; for example, Kustas and Norman (1999; 2000) and Li et al. (2005) reported RMSE and MAE ranging from 17 to 21 W m^{-2}. However, errors as a percent of the observed mean in the present study were similar to other TSM studies. The larger RMSE and MAE reported in the present study may have been related to a larger range of R_N measurements (resulting from the larger range of canopy cover) compared with other studies, as well as inconsistencies in measurements reported by net radiometers, which have been shown to vary by make and model (Kustas et al., 1998; Blonquist et al., 2009).

Surface soil heat flux (G) estimated as a function of soil net radiation ($R_{N,S}$) (equation 2) near solar noon agreed poorly with surface G derived from soil heat flux plates and thermocouples, using both the clumping index (Table 3) and elliptical hedgerow (Table 4) approaches, in terms of E_C, RMSE, and MAE. However, MBE using the clumping index was small (<1 W m^{-2}). The elliptical hedgerow, on the other hand, tended to underestimate G, which was consistent with $R_{N,S}$ tending to be smaller using this approach compared with the clumping index (Figure 3b). The generally large errors may have been related to inadequate sampling of G, since only two soil heat flux plate and thermocouple locations were available, and G has been shown to vary considerably beneath row crops due to variation of sunlit and shaded soil (e.g., Ham and Kluitenberg, 1993). Despite the overall poor agreement, accounting for the phase difference between $R_{N,S}$ and G improved agreement with G derived from soil heat flux plates and thermocouples compared with assuming G as a constant fraction of $R_{N,S}$ (data not shown). A more detailed study of measured and modeled G is presently underway at our study location, where ten soil heat flux plates and thermocouples were deployed within adjacent crop rows.

Modeled latent heat flux (LE) agreed fairly well with LE derived from lysimeters measurements using both the clumping index (Table 3) and elliptical hedgerow (Table 4), with the latter approach resulting in slightly less RMSE and MAE but greater MBE. The greater MBE for the elliptical hedgerow may have resulted from underestimates of G, leading to overestimates of available energy and hence turbulent fluxes. This was related to differences in $R_{N,C}$ and $R_{N,S}$ partitioning as noted previously. For both approaches, the magnitude of RMSE and MAE were substantially greater compared with those reported in previous TSM studies where infrared thermometers were used, which were 31 to 55 W m^{-2} (Norman et al., 1995; Kustas and Norman, 1999; Kustas and Norman, 2000; and Li et al., 2005). However, in the present study, RMSE as a percentage of the observed mean was similar to those reported in previous TSM studies, which were around 20 to 30 percent. Hence the greater magnitude of RMSE and MAE in the present study was in part due to the much greater LE resulting from strong regional advection, high solar radiation, and high vapor pressure deficit at the study location.

Agreement between modeled and measured daily ET followed very similar trends as LE, which was expected since modeled daily ET was derived from modeled LE (Tables 3 and 4). Both the clumping index and elliptical hedgerow approaches resulted in RMSE and MAE within 1.0 mm d^{-1}, and MBE less than 0.20 mm d^{-1}. The elliptical hedgerow approach resulted in slightly less scatter compared with the clumping index approach for most of the range of ET measurements (Figure 4). Although the differences between the two approaches were marginal and could have been related to compensating errors in the energy balance, this result was consistent with previous studies, where the elliptical hedgerow resulted in better agreement with f_{VR} estimated with digital photography (Colaizzi et al., 2010a), as well as better agreement with measurements of transmitted and reflected shortwave radiation (Colaizzi et al., 2010c) compared with the clumping index.

Table 3. Statistical parameters of agreement between observed and modeled net radiation (R_N), soil heat flux (G), and latent heat flux (LE), average of 12:30 to 13:00 CST, and daily evapotranspiration (ET) using the clumping index approach (n = 121).

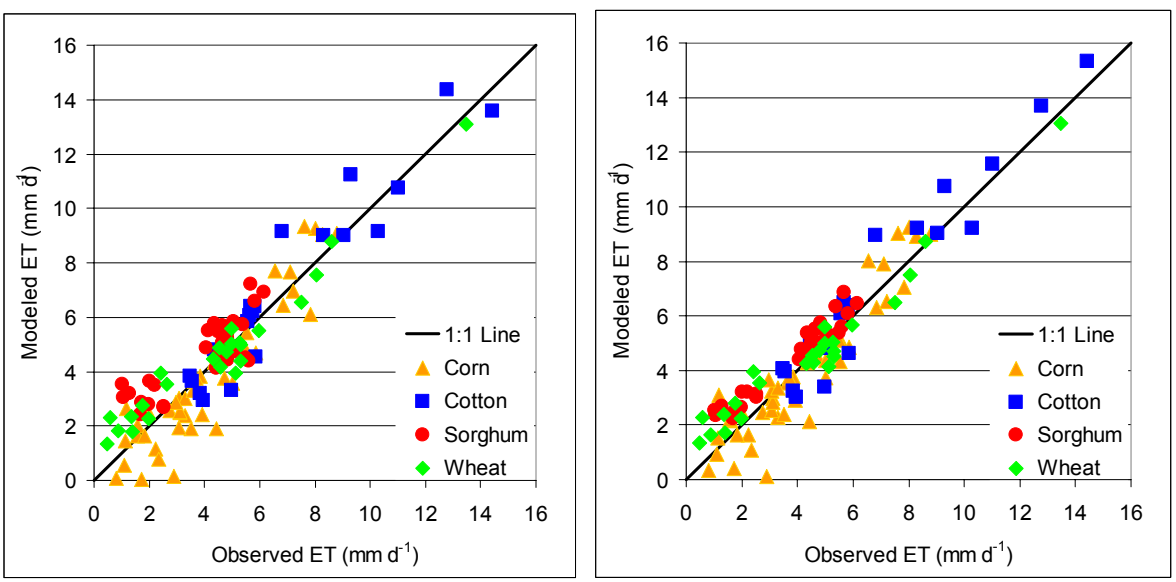
	R_N W m^{-2}	G W m^{-2}	LE W m^{-2}	ET mm d^{-1}
Observed mean	596	73.2	350	4.62
Observed standard deviation	81.8	40.3	191	2.63
Modeled mean	595	73.44	352	4.72
Modeled standard deviation	80.8	41.8	186	2.71
Slope	0.88	0.60	0.89	0.96
Intercept	68.9	29.3	39.9	0.28
r^2	0.80	0.34	0.84	0.87
Modified model efficiency (E_C)	0.56	0.18	0.60	0.59
RMSE	37.2	37.4	76.8	1.00
% RMSE of observed mean	6.3%	51%	22%	22%
MAE	29.4	26.8	59.8	0.79
% MAE of observed mean	4.9%	37%	17%	17%
MBE	-0.59	0.23	2.4	0.093
% MBE of observed mean	-0.10%	0.32%	0.67%	2.0%

Table 4. Statistical parameters of agreement between observed and modeled net radiation (R_N), soil heat flux (G), and latent heat flux (LE), average of 12:30 to 13:00 CST, and daily evapotranspiration (ET) using the elliptical hedgerow approach (n = 121).

	R_N W m^{-2}	G W m^{-2}	LE W m^{-2}	ET mm d^{-1}
Observed mean	596	73.2	350	4.62
Observed standard deviation	81.8	40.3	191	2.63
Modeled mean	596	66.3	358	4.79
Modeled standard deviation	81.1	43.1	184	2.70
Slope	0.91	0.64	0.90	0.98
Intercept	51.4	19.6	42.9	0.28
r^2	0.85	0.36	0.87	0.90
Modified model efficiency (E_C)	0.63	0.17	0.65	0.64
RMSE	32.0	38.0	68.5	0.86
% RMSE of observed mean	5.4%	52%	20%	19%
MAE	24.7	27.2	53.0	0.69
% MAE of observed mean	4.1%	37%	15%	15%
MBE	0.43	-6.9	8.3	0.17
% MBE of observed mean	0.073%	-9.4%	2.4%	3.6%

For the lower range of ET values (i.e., < 3 mm d^{-1}), both the clumping index and elliptical hedgerow approaches resulted in overestimates of ET for grain sorghum and winter wheat, but tended to underestimate ET for corn (Figure 4). This occurred mainly later in the season when f_{VR} began to include non-transpiring plant components, leaves began to senesce, and bulk canopy resistance would be expected to increase. The TSM contains two provisions to account for this indirectly, which are to decrease the fraction of green LAI, and to reduce the Priestley-Taylor parameter (α_{PT}) below the typical value of 1.3. Both provisions result in increasing the

canopy temperature (T_C) and sensible heat flux (H) away from the surface, and reducing LE and ET. In order to simplify model diagnostics, the fraction of green LAI was not reduced in the present study (although a rational procedure could have been developed such as basing this on red and near infrared reflectance measurements). However, the TSM did reduce α_{PT} to between 0.8 and 1.2 for winter wheat and grain sorghum, but this still resulted in overestimates in LE and ET. In a previous study where ET was estimated with the TSM for spring wheat, French et al. (2007) also reported overestimates that became greater toward the end of the season as leaves senesced, although they used a constant α_{PT} = 1.26. In the present study, reducing α_{PT} resulted in ET underestimates for corn later in the season, in contrast to grain sorghum and winter wheat. This mainly occurred when vapor pressure deficit was relatively low (i.e., 0.5 to 1.5 kPa; more typical values being 2 to 5 kPa). However, if α_{PT} was not reduced, late season LE and ET underestimates for corn were largely mitigated, but late season LE and ET overestimates for wheat and grain sorghum were exacerbated (data not shown). These results clearly point to a need to improve estimates of T_C, especially late in the season when the assumptions in the Priestley-Taylor approximation begin to deteriorate. Although French et al. (2007) pointed out that for the purposes of irrigation scheduling, ET model accuracy later in the season after irrigation is terminated is not as important, it would be nonetheless desirable to achieve consistent model accuracy throughout the season and during fallow periods in order to predict the soil water balance.



a. b.

Figure 4. Two source modeled vs. observed daily evapotranspiration (ET) using different approaches for accounting for the nonrandom spatial distribution of vegetation; (a) clumping index; (b) elliptical hedgerow. See Tables 3 and 4 for statistical parameters of agreement.

Several days included ET observations between 8 and 16 mm d^{-1}, which occurred for corn, cotton, and winter wheat (Figure 4). For each crop, the largest ET values occurred during mid season when canopy cover was complete and days of strong regional advection. Wind speeds at the 2-m height were from 5 to 8 m s^{-1}, vapor pressure deficits were greater than 2 kPa, and advected energy contributed up to 30 percent toward LE, which was similar to that reported by Tolk et al. (2006) for irrigated alfalfa at this location. Daily ET was predicted fairly well using both

the clumping index and elliptical hedgerow approaches, with errors less than 1.0 mm d^{-1} for the latter approach. This suggests that measurements of directional brightness temperature and air temperature directly over the crop can be used to estimate advected energy contributing to ET with acceptable accuracy in the TSM. However, it should be noted that in most practical applications, measurements of air temperature are usually only available at agricultural weather stations, which may not be representative of all crop conditions. To what extent this could degrade TSM performance was beyond the scope of this study, but it will be addressed in future studies; a procedure described by Norman et al. (2000) has been shown to reduce errors using surface and air temperature measurements at two times of day.

Conclusion

Daily evapotranspiration (ET) was estimated using a thermal-based two source energy balance model (TSM) for four crops, and compared to ET measured by large, monolithic, weighing lysimeters in Bushland, Texas, USA. Crops included corn, cotton, grain sorghum, and winter wheat. The TSM was evaluated using two methods of accounting for the nonrandom spatial distribution of row crops, including the widely-used clumping index approach, and an approach were crop rows were modeled as elliptical hedgerows. Each approach resulted in different partitioning of energy flux components to the soil and canopy, and the elliptical hedgerow approach resulted in slightly better ET prediction. Root mean square error (RMSE), mean absolute error (MAE), and mean bias error (MBE) were 1.0 (22%), 0.79 (17%), and 0.093 (2.0%) mm d^{-1} (percentage of observed mean of 4.62 mm d^{-1}), respectively, using the clumping index approach. RMSE, MAE, and MBE were 0.86 (19%), 0.69 (15%), and 0.17 (3.6%) mm d^{-1}, respectively, using the elliptical hedgerow approach. These error rates were similar to those reported in previous studies, although the present study was conducted for a wider range of vegetation cover and climatic conditions. Given the possible sources of error inherent in thermal energy balance models, especially uncertainties in estimating soil heat flux, the fraction of canopy cover, leaf area index, and surface-to-air temperature gradients, the performance of the TSM in estimating ET was deemed acceptable. Additional refinements to the TSM are presently underway in estimating initial canopy temperature, resistance components, and soil heat flux. Future studies will apply the TSM with the elliptical hedgerow approach using wireless radiometers aboard center pivot machines to estimate ET, with the aim of providing producers remote sensing tools that will reduce management time and enhance water and energy conservation.

Acknowledgements

This research was supported by the USDA-ARS National Program 211, Water Availability and Watershed Management and by the USDA-ARS Ogallala Aquifer Program, a consortium between USDA-Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University. We are grateful to Dr. Andrew French, USDA-ARS, Maricopa, Arizona for allowing us to use the Cimel multiband thermal radiometer and for his critical reviews of this and previous manuscripts. We thank the numerous biological technicians and student workers for their meticulous and dedicated efforts in executing experiments and obtaining and processing data.

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