THE BUSHLAND WEIGHING LYSIMETERS: A QUARTER CENTURY OF CROP ET INVESTIGATIONS TO ADVANCE SUSTAINABLE IRRIGATION


ABSTRACT. In 1987-1989, the first irrigated crops were grown on the four large, precision weighing lysimeters at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas, on the Southern High Plains (SHP). Thus began >25-years of full- and deficit-irrigated crop growth, energy and water balance, evapotranspiration (ET), yield, and water use efficiency (WUE) studies of major SHP crops, including alfalfa, corn and sorghum for both grain and forage, cotton, soybean, sunflower, and winter wheat. Alfalfa studies supported development of the ASCE Standardized Reference ET methodology. The lysimeter effort, led by Terry Howell, Sr., co-designed with Lynne Ebling and Thomas Marek and constructed by Arland Schneider, eventually grew to include a separate lysimeter to study short grass ET, again for the ASCE standard, and a 48-lysimeter facility to study soil type effects on crop water uptake, ET, and WUE using monoliths of four soils typical of SHP irrigated soils. The large lysimeters were managed to be representative of sprinkler-irrigated fields so as to develop crop coefficients used for irrigation scheduling by clients of ET networks developed by Texas A&M AgriLife in collaboration with the USDA-ARS. In addition, the lysimeters were used to test and further develop several technologies important to irrigation science, including soil water sensors, eddy covariance and Bowen ratio systems, scintillometers, thermal remote sensing based ET models, and hydrologic and crop simulation models. With the installation of subsurface drip irrigation systems on two of the lysimeter fields in 2013, the Bushland lysimeters are entering a new phase of advanced irrigation method and management studies.


Advances in irrigation technology depend on increasing understanding of the soil-plant-atmosphere continuum (SPAC) and the effects of changes in irrigation technology, methods, and management, and of crop genetics and cultural methods on the water and energy fluxes that are both beneficial and detrimental to sustainable agricultural production, for there is no sustainable irrigation without sustainable production. Sustainable production itself implies sustainability in environmental impacts and profitability. Efforts to understand the SPAC energy and water fluxes were widespread before the seminal article by Penman (1948), who considered the energy fluxes as summing to zero at an evaporating surface, those fluxes being the latent energy (LE) of evaporation (also called evapotranspiration, ET), the net radiative fluxes (\(R_n\), being the sum of incoming and outgoing shortwave and longwave radiation fluxes), the sensible heat flux (\(H\)) between the surface and atmosphere, and the soil heat flux (\(G\)). Penman combined the energy balance equation, \(0 = R_n + G + H + LE\), with flux equations to derive the Penman combination equation. Monteith improved on the combination equation, resulting in the Penman-Monteith (P-M) formulation that is still in widespread use today, mostly as a tool for estimating a reference ET value (\(ET_o\) for grass, a short crop, or ET for alfalfa, a taller crop) for use in calculating daily well-watered crop ET (\(ET_c\)) using a growth-stage dependent crop coefficient (\(K_{co}\) for a grass reference or \(K_{cr}\) for an alfalfa reference): \[ ET_c = K_{co}(ET_o) = K_{cr}(ET_o) \]
This paradigm for estimating daily crop ET is widely used in modeling and in irrigation management. It has achieved broad international acceptance as promulgated in the FAO 56 publication (Allen et al., 1998), which defined a standard formulation for P-M reference grass ET. The FAO 56 publication included tables of crop coefficients and a methodology for adjusting coefficients to account for soil wetting and plant stress. The ET estimates were based on the concept of a basal crop coefficient \( K_c \) that was not much influenced by soil evaporative loss and an adjustment factor \( (K_a) \) for evaporation from wet soil, plus an additional adjustment factor \( (K_o) \) to account for plant water stress. In 2005, the closely related ASCE P-M reference ET standard was adopted and is the most widely used in the U.S. Earlier reference or potential ET \( (E_{pot}) \) estimation methods are still used, including the energy balance approach of Penman (1948) for \( E_{pot} \), the temperature and radiation based methods of Hargreaves and Samani (1985) and Priestley and Taylor (1972) for \( E_{pot} \), and the alfalfa reference ET \( (E_{ref}) \) method of Wright and Jensen (1972). For the crop coefficient and reference ET paradigm to be useful for irrigation management, crop coefficients must be available as functions of time (days after planting), growing degree days, or crop growth stage. Since these crop coefficient functions have proved to be region, climate, and crop species specific, and probably cultivar specific as well, much research is needed to make the paradigm effective in a region, and much work is necessary to maintain that effectiveness. In addition, the reference ET equations themselves have required much SPAC research to improve them and to more fully understand and correct biases that may occur during their use. Although the paradigm is widely adopted, it also has problems, including interannual variations in crop coefficient functions in addition to those already elaborated. Moreover, it has limitations in that it provides estimates of ET, but not of plant growth and yield. Thus, many mechanistic and functional models of crop growth, water use, and yield have been developed, all of which require accurate field measurements to support model algorithm development, correction, amplification, and testing.

In 1983, Dr. Terry A. Howell, having worked with weighing lysimeter systems in California (Howell et al., 1985), was enticed by the late Jack Musick, then Research Leader of the USDA-ARS Water Management Research Unit at Bushland, to join that research team. Dr. Howell established a research program based on study of the energy and water balances of the SPAC as influenced by irrigation, tillage, and other cultural practices aimed at improving the sustainability of irrigated and dryland agriculture in the Southern High Plains (SHP). Terry initially worked with the sprinkler irrigation program and studied energy and water fluxes using soil water balance methods for ET determination, Bowen ratio equipment, and remote sensing approaches. Although initially reluctant to become involved again in weighing lysimeter research, he soon became convinced that further advances in understanding of the SPAC and development of better irrigation scheduling tools would require large weighing lysimeters as a primary measurement tool. Terry teamed with Thomas Marek and Lynn Ebling of the then Texas Agricultural Experiment Station to review the existing lysimeter facilities in the nation, often traveling for on-site inspections, and to create a weighing lysimeter design that would improve on existing lysimeters and minimize their limitations. Long-term research with the Pullman soil left no doubt that, once excavated, this soil could not be reconstructed, so monolithic lysimeters would be necessary to collect accurate data.

The four large \((3 \text{ m} \times 3 \text{ m} \times 2.3 \text{ m})\) weighing lysimeters were constructed at Bushland in the 1985-1988 period, beginning a quarter century of SPAC studies in the pursuit of sustainable water management. Dr. Arland Schneider of the USDA-ARS joined the team in 1985 and supervised construction. Later, Howell and Schneider teamed to design and build a facility housing 48 smaller \((1 \text{ m} \times 0.75 \text{ m} \times 2.3 \text{ m})\) lysimeters, termed minilysimeters, with a movable rain shelter in order to compare crop water use on different soil types. This facility, later named the Soil Plant Environment Research (SPER) facility, was completed in 1990 with the acquisition of 24 undisturbed monoliths of Ulysses silt loam from Garden City, Kansas, to complement 12 lysimeters containing Pullman clay loam soil from Bushland and 12 lysimeters containing Amarillo sandy loam soil from Big Spring, Texas. The facility was later updated by replacing 12 of the Ulysses soil lysimeters with Vingo fine sand soil from near Dalhart, Texas, as described by Dr. Judy Tolk, the lead researcher of the SPER studies, in a separate contribution (Tolk and Evett, 2015). The 53rd lysimeter \((1.5 \text{ m} \times 1.5 \text{ m} \times 2.3 \text{ m})\) deep) installed at Bushland was built to study short grass reference ET and was completed in 1994 in conjunction with the sodding of a grass-covered research weather station site immediately east of the large weighing lysimeter fields.

The importance of the Bushland site for ET and water and energy balance research is heightened by its location in the SHP, where irrigation is necessary for sustained annual crop production. Irrigation water comes completely from the Ogallala (High Plains) aquifer (fig. 1, left), which is recharged at perhaps only 2.5 cm (1 in.) per year in the face of irrigation withdrawals several times that large, leading to a steadily declining aquifer. Just as important is that the location is in a region that experiences as large an environmental evaporative demand as any cultivated region in the U.S. (fig. 1, right) and perhaps the world, which makes it an excellent and robust test bed for models and methods of sensing ET. Pan evaporation at Bushland averages \(>2400 \text{ mm per year (Kohler et al., 1959),}\) and it is larger than in many desert areas, such as the eastern Egyptian desert (Evett et al., 2000b), the Sonoran desert in Arizona, and the Jordan Valley in the Middle East (Evett et al., 2009a). The large evaporative demand is due to a combination of factors that include large solar irradiance due to its altitude \((1170 \text{ m})\) and many cloud-free days \((300+ \text{ annually})\), fast wind speeds \((\text{wind energy density varies seasonally from class 4 to class 5, the largest; Elliott et al., 1986; NREL, 2011,})\), and the dryness and temperature of the air. Winds at Bushland are predominantly from the southwest, particularly in the spring and summer months. After crossing the Sonoran and Chihuahuan deserts of the southwest...
U.S. and Mexico, the winds ascend over the southern Rocky Mountains, where much of the residual moisture is lost as precipitation, and then descend to sweep unobstructed across the SHP. The already dry air becomes hotter and drier as it undergoes adiabatic heating while descending across the eastern slopes of the Rockies, explaining the region of very large evaporative demand in the Texas Panhandle and southwestern Kansas illustrated in figure 1 (right).

In this severe climate, it is natural that agricultural engineers and scientists would focus on studies of energy and water balances and ET as affected by environment, crop selection, irrigation method and management, tillage and residue management, and other factors common to Great Plains agriculture. This article describes the research effort begun by Dr. Terry Howell, Sr., and carried out by him and his research team for more than 25 years at Bushland. It describes the research facility, the uses to which it has been put, and the products of these efforts with the intention of demonstrating the breadth and depth of scientific contributions engendered by the facility and research program.

LYSIMETER FACILITIES AND INSTRUMENTATION

The four large weighing lysimeters contain undisturbed monoliths of Pullman silty clay loam soil (fine, mixed, superactive, thermic Torrertic Paleustoll). They are located at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas (35° 11’ N, 102° 6’ W, 1170 m elevation above MSL). In the top 0.30 m of soil, the mean clay content is 0.33 g g⁻¹, the mean bulk density is 1.39 g cm⁻³, and the mean organic matter content is 0.018 g g⁻¹. Although it is slowly permeable, the Pullman soil is well drained, and high water tables never affected the lysimeter design, construction, or operation. The design of the all-steel large weighing lysimeters (fig. 2) was described by Marek et al. (1988), the procedure and equipment for collecting the undisturbed monoliths were described by Schneider et al. (1988), and the calibration procedures were reported by Howell et al. (1995a). Each of the lysimeters is located in the center of a 4.4 ha, 210 m (E-W) × 210 m (N-S) field. The four contiguous fields are arranged in a rectangular pattern, oriented to the cardinal points, and designated NE (northeast), SE (southeast), NW (northwest), and SW (southwest) (fig. 2b). The predominant wind direction is SW to SSW, and the unobstructed fetch (fallow fields or dryland cropped areas) in this direction exceeds 1 km. The field slope is less than 0.3%. Lysimeter mass is determined using a data logger (model CR7, Campbell Scientific, Inc., Logan, Utah) to measure and record the lysimeter load cell signal at 6 s intervals. The load cell signal is averaged for 5 min and typically composited to 30 min means (reported on the midpoint of the 30 min, i.e., data are averaged from 0 to 30 min and reported at 15 min). Lysimeter mass resolution is 0.01 mm, and calibrated accuracy is 0.04 (Evett et al., 2012b) to 0.05 mm (Howell et al., 1995a). Half-hourly and daily ET values are determined as the difference between lysimeter mass losses (from evaporation and transpiration) and lysimeter mass gains (precipitation, irrigation, and dew) divided by lysimeter area (9 m²). A pump regulated to 10 kPa vacuum provides drainage, and the drainage effluent is held in two tanks suspended from each lysimeter (their mass is part of the total lysimeter mass) and independently weighed.
by additional load cells. ET for each 24 h period is multiplied by 0.98 to adjust the lysimeter area to the midpoint between the soil container wall and the outer enclosure wall (10 mm air gap; 9.5 mm wall thickness; 9.18 m² area instead of 9.00 m² inside soil area). Lysimeters are operated as either irrigated or dryland depending on the experiment. A full suite of micrometeorological variables is measured at each lysimeter, as are soil water content, heat flux, and temperature.

Until 2013, all lysimeters were irrigated, if not in fallow or dryland crop production, with an end-hose fed, ten-span, linear-move sprinkler system (Lindsay Manufacturing, Omaha, Neb.). The sprinkler system was aligned N-S and moved E-W or W-E during irrigation. The system was equipped with gooseneck fittings and drops, and spray heads (model D3000, Nelson Irrigation Corp., Walla Walla, Wash.) with medium grooved, concave spray plates were located 1.5 m above the ground and 1.52 m apart. Each spray head was equipped with a 100 kPa pressure regulator and a 1 kg polyethylene drop weight. Beginning in 2013, the two east weighing lysimeters were irrigated using sub-surface drip irrigation (SDI) so that crop coefficients relevant to SDI could be developed and so that direct comparison of energy and water balances could be made between SDI and sprinkler irrigation application methods. The SDI tape is buried 0.30 to 0.35 m deep in the crop interrow, emitters with a discharge rate of 0.68 L h⁻¹ at 69 kPa are spaced at 0.30 m on each line, and lines are spaced 1.52 m apart.

Daily after midnight, data for the preceding day are downloaded automatically to a computer at the research laboratory. This was done initially using modems and voice telephone lines, later by wireless Ethernet and presently via fiber optic cable. Quality control and assurance is maintained through daily graphing and visual inspection of all data for obvious errors, missing data, and exceedance of physically possible values. Data are loaded into spreadsheets, and a suite of macros is run to make primary calculations, for instance, of mass gain and loss corresponding to dewfall, frost, precipitation, ET, and wind loading. Data processing to determine ET, precipitation, and irrigation amounts is based on 5 min mean mass data and is described by Marek et al. (2014). Many of the experiences and knowledge gained by the Bushland team are reflected in other publications on ET information reporting (Allen et al., 2011a, 2011b; Ritchie et al., 1996).

Lysimeter and field soil profile water contents and water storage were determined to 2.4 m depth by neutron probe (NP) at one to two week intervals during the crop growing season and through harvest, but usually not during the off-season. Measurements were made in increments of 0.2 m beginning at the 0.1 m depth, with a depth control stand used to ensure accuracy at the 0.1 m depth (Evett et al., 2003). Two neutron probe access tubes were installed permanently in each lysimeter, and four access tubes were installed in the field outside each lysimeter in order to check the lysimeter profile water content and change in storage against the field profile and change in storage. Beginning in 2011, the network of NP access tubes around each lysimeter was increased to eight to provide a more reliable determination of field ET by soil water balance.

**RESEARCH WEATHER STATION**

Weather data are necessary, both for interpreting other measured field data and for the added value obtained through modeling of SPAC processes. Weather data needed in conjunction with specific field experiments must be measured as proximally as possible. As a general guideline, a basic agricultural weather station (Hubbard and Hollinger, 2005) is best located within 2 km of each field research site. The permanent research weather station (table 1) is immediately adjacent and east of the lysimeter fields, close enough to provide weather data for experiments, except perhaps for precipitation. Important amounts of precipitation may derive from the rain shafts of convective thunderstorms, which have distinct edges and which create large spatial variability in precipitation amounts over short (<1 km) distances (Evett et al., 2011). Thus, separate
Table 1. Instruments at the research weather station at Bushland, Texas.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Instrument</th>
<th>Manufacturer (Model)</th>
<th>Elevation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_u$</td>
<td>Pyranometer</td>
<td>Eppley (PSP)</td>
<td>2 m</td>
<td>Solar irradiance (two replicate sensors)</td>
</tr>
<tr>
<td>$R_d$</td>
<td>Silicon photodiode</td>
<td>LI-COR (LI-200)</td>
<td>2 m</td>
<td>Solar irradiance</td>
</tr>
<tr>
<td>$L_1$</td>
<td>Pyrogeometer</td>
<td>Kipp &amp; Zonen (CG4)</td>
<td>2 m</td>
<td>Downwelling longwave radiation</td>
</tr>
<tr>
<td>$\alpha R_{iso}$</td>
<td>Pyranometer</td>
<td>Eppley (8-48)</td>
<td>2 m</td>
<td>Reflected solar irradiance (instrument inverted and facing the ground)</td>
</tr>
<tr>
<td>$R_{IR}$</td>
<td>Quantum sensor</td>
<td>LI-COR (LI-190)</td>
<td>2 m</td>
<td>Photosynthetically active radiation, 400-700 nm</td>
</tr>
<tr>
<td>$L_1\uparrow$</td>
<td>Pyrogeometer</td>
<td>Eppley (PIR)</td>
<td>1 m</td>
<td>Incoming long wave radiation</td>
</tr>
<tr>
<td>$L_1\downarrow$</td>
<td>Pyrogeometer</td>
<td>Eppley (PIR)</td>
<td>1 m</td>
<td>Outgoing long wave radiation (instrument inverted and facing the ground)</td>
</tr>
<tr>
<td>$R_2$</td>
<td>Net radiometer</td>
<td>REBS (O**2.1)</td>
<td>1 m</td>
<td>Net radiation</td>
</tr>
<tr>
<td>$T_a$ and RH</td>
<td>PRT, capacitive polymer chip</td>
<td>Vaisala (HMP45)</td>
<td>2 m and 10 m</td>
<td>Air temperature and relative humidity</td>
</tr>
<tr>
<td>$T_a$ and RH</td>
<td>PRT, capacitive polymer chip</td>
<td>Vaisala (HMT330)</td>
<td>1.8 m</td>
<td>Air temperature and RH in cotton belt shelter</td>
</tr>
<tr>
<td>$P_1$</td>
<td>Pressure sensor, 0-2.5 VDC</td>
<td>Campbell Scientific (CS105)</td>
<td>1.8 m</td>
<td>Barometric pressure in cotton belt shelter</td>
</tr>
<tr>
<td>$U_2$</td>
<td>DC generator cups</td>
<td>R.M. Young (03101 and 05103)</td>
<td>2 m and 10 m</td>
<td>Wind speed</td>
</tr>
<tr>
<td>$T_2$</td>
<td>Potentiometer vane</td>
<td>R.M. Young (05103)</td>
<td>10 m</td>
<td>Wind direction</td>
</tr>
<tr>
<td>$T_2$</td>
<td>Thermistor</td>
<td>Campbell Scientific (107)</td>
<td>2 m and 10 m</td>
<td>Air temperature</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Cu-Co thermocouple</td>
<td>Omega (304SS)</td>
<td>-10 mm and -40 mm</td>
<td>Soil temperature (four replicate sensors)</td>
</tr>
<tr>
<td>$T_o$</td>
<td>PRT</td>
<td>REBS PRT</td>
<td>-10 mm to -40 mm</td>
<td>Average soil temperature (four replicate sensors)</td>
</tr>
<tr>
<td>$G_{so}$</td>
<td>Plates thermopile</td>
<td>REBS (HFT-1.1)</td>
<td>-50 mm</td>
<td>Soil heat flux (four replicate sensors)</td>
</tr>
<tr>
<td>$P$</td>
<td>Heated tipping-bucket rain gauge</td>
<td>Met One (385)</td>
<td>1 m</td>
<td>Precipitation</td>
</tr>
</tbody>
</table>

[a] Manufacturers are Campbell Scientific, Inc. (Logan, Utah), The Eppley Laboratory, Inc. (Newport, R.I.), Interface, Inc. (Scottsdale, Ariz.), Kipp & Zonen (Delft, The Netherlands), LI-COR Environmental (Lincoln, Neb.), Omega Engineering, Inc. (Stamford, Conn.), Radiation and Energy Balance Systems (REBS, Seattle, Wash.), Vaisala Oyj (Helsinki, Finland), and R.M. Young Co. (Traverse City, Mich.).

[b] Eppley pyrogeometers are deployed discontinuously for studies of radiation balance and net radiometer calibration.

Rain gauges are deployed at each lysimeter. In addition, the lysimeters themselves are very accurate rain gauges. Only rarely do precipitation events cause the lysimeters to overflow onto adjacent land or receive runoff from upslope areas. However, snow and drifting snow are problematic, since snow can drift onto and off the lysimeter surface, and the lysimeter mass change can be affected by snow bridges that form across the lysimeter edges.

The basic weather measurements made since 1987 include wind speed, air temperature and humidity at 2 m and 10 m heights, wind direction at 10 m height, and solar irradiance (Dusek et al., 1987). Other measurements have included shortwave and longwave incoming and outgoing radiation, net radiation (over the grass lysimeter), soil temperature, soil heat flux, Cotton Belt shelter measurements of air temperature and dew point, etc. From its inception, data from the research weather station have been automatically downloaded to a computer in the laboratory each day at 0100 h for QA/QC later in the day (or on Monday after a weekend), initially by visual inspection of graphed data. Quality assurance and control are also achieved through calibration of lysimeters (Howell et al., 1995a; Evett et al., 2012b), relative humidity sensors (using salt solutions and a calibration chamber) (Dusek et al., 1993; Dusek and Howell, 1996), soil water sensors (e.g., Evett et al., 2008), heat flux plates (Howell and Tolk, 1990), radiation sensors (sent to manufacturers), anemometers (in a test stand), and tipping-bucket rain gauges (comparison to lysimeter mass change and to USWB standard rain gauges). Solar irradiance is compared to theoretical clear-sky radiation (Evett, 2002). Multiple redundant measurements are made of important properties (air temperature and RH, wind speed and solar irradiance) for intercomparison and replacement of faulty or missing data.

A weighing lysimeter (1.5 m × 1.5 m × 2.3 m deep) was installed within the research weather station in 1994 (Schneider et al., 1998) to measure reference grass ET$_o$. A subsurface drip irrigation system was installed on the 0.3 ha site, and mixed fescue was sown, reaching full cover in 1995 (Howell et al., 2000). The grass is mowed regularly to 0.10 to 0.11 m height before it exceeds 0.15 m height. Irrigation and fertilization are managed to achieve a well-watered and fertilized grass surface. Irrigation applications are metered separately for the station and lysimeter surfaces, and meter readings are checked against lysimeter mass changes. Use of SDI rather than sprinkler irrigation greatly improved the accuracy and certainty of lysimeter ET data since there are redundant (lysimeter mass change and water meter reading) measures of irrigation applied to the lysimeter and there is no difficult-to-quantify evaporative loss from spray wetting of grass leaves.

The research weather station has served as a reference site for evaluation of numerous instruments and measurement methods over the years, including electronic relative humidity and air temperature sensors (Dusek et al., 1993), effects of instrument shelters on weather measurements (Dusek et al., 1996), and vapor pressure deficit calculation method comparisons (Howell and Dusek, 1995). Net radiation sensors were compared with four component radiation measurements using pyrogeometers and albedometers and shown to closely follow the four component measurements (Howell et al., 1993). Recently, testing of two-dimensional (2-D) sonic anemometers versus cup-type anemometers has led to replacement of the existing cup anemometers with 2-D sonic anemometers.

There is also a suite of SPAC measurements at each of
the four large weighing lysimeters. Typical measurements and instrumentation are listed in tables 1 and 2. Measurements are typically taken every 6 s, with mean values (and in some cases standard deviations) reported at 5 min intervals.

**CROPS STUDIED**

Lysimeter experiments have included dryland and full- and deficit-irrigated crop growth, energy and water balance, ET, yield, and water use efficiency (WUE) studies of important SHP crops, including alfalfa (*Medicago sativa* L.), corn (*Zea mays* L.) and sorghum (*Sorghum bicolor* (L.) Moench) for both grain and forage, cotton (*Gossypium hirsutum* L.), soybean (*Glycine max* L.), sunflower (*Helianthus annuus* L.), and winter wheat (*Triticum aestivum* L.) (table 3). Alfalfa was studied to support development of the ASCE Standardized Reference ET methodology. Grass ET was studied for 15 years, also in support of the ASCE team extended their cooperation to assessment of the Texas High Plains Evapotranspiration (TXHPET) Network comprised 21 stations stretching from Pecos at the southeast edge of the Plains, to Munday and Chillicothe in the Rolling Plains in the east, and to Dalhart and Perryton in the north and received grant support from the Texas Water Development Board (Marek et al., 2005). Marek and Dana Porter to establish and support networks of weather stations covering the Texas Panhandle and to provide the weather data necessary to establish daily crop water use estimates for all producers and all major crops in the region (Marek et al., 1996, 1998, 2005, 2010a, 2011). At one time, the Texas High Plains Evapotranspiration (TXHPET) Network comprised 21 stations stretching from Pecos at the southeast edge of the Plains, to Munday and Chillicothe in the Rolling Plains in the east, and to Dalhart and Perryton in the north and received grant support from the Texas Water Development Board (Marek et al., 2005). Daily crop water use estimates were provided by facsimile transmission, and later by email and Internet, for the major crops currently growing in the region, with separate values of ET, for three to four planting dates (for annual crops) and with growth stage estimates. The TXHPET Network data were used for both full and deficit irrigation strategies (e.g., Schneider et al., 2001). Economic benefits due to reductions in pumping costs alone ranged from $12 to $22 million yearly. The Texas A&M AgriLife Research and USDA-ARS team extended their cooperation to assessment of ET networks across the state of Texas, identifying sources of error due to lack of consistent quality control

<table>
<thead>
<tr>
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<th>Manufacturer (Model)[a]</th>
<th>Elevation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S )</td>
<td>Lysimeter scale</td>
<td>Cardinal (FS-7 agronomy scale)</td>
<td>-3 m</td>
<td>Soil water storage</td>
</tr>
<tr>
<td>( M_i )</td>
<td>Lysimeter scale load cell, mV/V</td>
<td>Interface (SM-50)</td>
<td>-3 m</td>
<td>Lysimeter mass</td>
</tr>
<tr>
<td>( R_c )</td>
<td>Net radiometer</td>
<td>REBS (Q*7.1)</td>
<td>1 m</td>
<td>Net radiation</td>
</tr>
<tr>
<td>( R_o )</td>
<td>Albedometer</td>
<td>Kipp &amp; Zonen (CM14)</td>
<td>1 m</td>
<td>Solar irradiance and reflected shortwave radiation</td>
</tr>
<tr>
<td>( L_i )</td>
<td>Pyrgeometer</td>
<td>Kipp &amp; Zonen (CGR3)</td>
<td>1 m</td>
<td>Downwelling longwave radiation</td>
</tr>
<tr>
<td>( U_\theta )</td>
<td>Anemometer</td>
<td>R.M. Young (03101)</td>
<td>2 m</td>
<td>Wind speed</td>
</tr>
<tr>
<td>RH and ( T_a )</td>
<td>RH and temperature sensor</td>
<td>Vaisala (HMP45)</td>
<td>2 m</td>
<td>Relative humidity (calibrated to RH over salt solutions obtained from Vaisala in a calibration platform from Vaisala)</td>
</tr>
<tr>
<td>( R_{\text{PAR,} T} )</td>
<td>Quantum sensor</td>
<td>LI-COR (LI-190SB)</td>
<td>1 m</td>
<td>Reflected PAR</td>
</tr>
<tr>
<td>( T_s )</td>
<td>Infrared thermometer (thermocouple output)</td>
<td>Exergen (IRT/c.2)</td>
<td>1 m</td>
<td>Surface (canopy) temperature (approximate zenith angles of 45° and approximate azimuth angles of S45W and S60W)</td>
</tr>
<tr>
<td>( G )</td>
<td>Soil temperature</td>
<td>Omega (TMTSS-020G -6)</td>
<td>-20 mm and -60 mm</td>
<td>Soil temperature (four pairs of replicate sensors)</td>
</tr>
<tr>
<td>( \theta_i )</td>
<td>Heat flux plates (thermoplastes)</td>
<td>REBS (HFT-1.1)</td>
<td>-80 mm</td>
<td>Soil heat flux (four replicate sensors)</td>
</tr>
<tr>
<td>( \theta_s )</td>
<td>Time domain transmission sensor</td>
<td>Acclima, Inc. (ACC-SEN-SDI)</td>
<td>-20 mm and -60 mm</td>
<td>Volumetric water content (two replicate sensors)</td>
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<td>( \theta_r )</td>
<td>Line quantum sensors</td>
<td>LI-COR (LI-191SB)</td>
<td>0 m</td>
<td>Transmitted photosynthetically active radiation (two replicate sensors)</td>
</tr>
<tr>
<td>( P )</td>
<td>Rain gauge</td>
<td>Qualometrics (6011B)</td>
<td>0.5 m</td>
<td>Precipitation</td>
</tr>
</tbody>
</table>

**TRANSLATIONS OF THE ASABE**
and assurance methods across networks. Errors could easily approach 25 mm over a growing season, which for Region A could cause an increase in irrigation demand of 53 million m³ (42,700 acre-ft) per year (Marek et al., 2010b). Due to budget cuts, the TXHPET Network is no longer operating.

Howell’s team also worked with others in Texas to determine crop coefficients. The simplified weighing lysimeter cropping record for years 1987-2014 is shown in Table 3. The four large weighing lysimeters and fields are designated according to their positions relative to the cardinal points (NE = northeast, SE = southeast, NW = northwest, and SW = southwest).

Table 3. Large weighing lysimeter cropping record for years 1987-2014. The four large weighing lysimeters and fields are designated according to their positions relative to the cardinal points (NE = northeast, SE = southeast, NW = northwest, and SW = southwest).

<table>
<thead>
<tr>
<th>Year</th>
<th>Lysimeter</th>
<th>Crop or Activity[a]</th>
<th>Year</th>
<th>Lysimeter</th>
<th>Crop or Activity[a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>NE</td>
<td>Irrigated corn fallow, tilled(WERM)</td>
<td>1987</td>
<td>NW</td>
<td>Irrigated grain sorghum</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated corn fallow, tilled</td>
<td></td>
<td>SW</td>
<td>Irrigated grain sorghum</td>
</tr>
<tr>
<td>1988</td>
<td>NE</td>
<td>Construction</td>
<td>1988</td>
<td>NW</td>
<td>Irrigated grain sorghum</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Construction</td>
<td></td>
<td>SW</td>
<td>Irrigated grain sorghum</td>
</tr>
<tr>
<td>1989</td>
<td>NE</td>
<td>Irrigated corn</td>
<td>1989</td>
<td>NW</td>
<td>Dryland sunflower</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated corn</td>
<td></td>
<td>SW</td>
<td>Dryland sunflower</td>
</tr>
<tr>
<td>1990</td>
<td>NE</td>
<td>Irrigated corn</td>
<td>1989-1990</td>
<td>NW</td>
<td>Fully irrigated winter wheat</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated corn</td>
<td></td>
<td>SW</td>
<td>Irrigated (limited) winter wheat</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1990-1991</td>
<td>NW</td>
<td>Wheat fallow, no-fill (fall residue)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SW</td>
<td>Wheat fallow, no-till (short residue)</td>
</tr>
<tr>
<td>1991</td>
<td>NE</td>
<td>Irrigated corn fallow, tilled</td>
<td></td>
<td>NW</td>
<td>Sorghum fallow, tilled</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated corn fallow, tilled</td>
<td></td>
<td>SW</td>
<td>Sorghum fallow, tilled</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated (50%) winter wheat</td>
<td></td>
<td>SW</td>
<td>Sorghum fallow, tilled</td>
</tr>
<tr>
<td>1992</td>
<td>NE</td>
<td>Wheat fallow, tilled</td>
<td></td>
<td>NW</td>
<td>Sorghum fallow, tilled/REBAL '92</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Wheat fallow, no-till</td>
<td></td>
<td>SW</td>
<td>Sorghum fallow, tilled/REBAL '92</td>
</tr>
<tr>
<td>1993</td>
<td>NE</td>
<td>Fully irrigated grain sorghum</td>
<td>1993-1994</td>
<td>NW</td>
<td>Irrigated (50%) winter wheat</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated (50%) grain sorghum</td>
<td></td>
<td>SW</td>
<td>Fully irrigated winter wheat</td>
</tr>
<tr>
<td>1993-1994</td>
<td>NE</td>
<td>Sorghum fallow, tilled</td>
<td></td>
<td>NW</td>
<td>Wheat fallow, tilled</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Sorghum fallow, tilled</td>
<td></td>
<td>SW</td>
<td>Wheat fallow, no-till</td>
</tr>
<tr>
<td>1994</td>
<td>NE</td>
<td>Fully irrigated corn</td>
<td>1994</td>
<td>NW</td>
<td>Dryland corn</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Fully irrigated corn</td>
<td></td>
<td>SW</td>
<td>Dryland corn</td>
</tr>
<tr>
<td>1995</td>
<td>NE</td>
<td>Tilled corn fallow</td>
<td>1995</td>
<td>NW</td>
<td>Fully irrigated soybean</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Tilled corn fallow</td>
<td></td>
<td>SW</td>
<td>Fully irrigated soybean</td>
</tr>
<tr>
<td>1995-1996</td>
<td>NE</td>
<td>Fall planting of fully irrigated alfalfa</td>
<td>1995-1997</td>
<td>NW</td>
<td>Soybean fallow</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Fall planting of fully irrigated alfalfa</td>
<td></td>
<td>SW</td>
<td>Soybean fallow</td>
</tr>
<tr>
<td>1996</td>
<td>NE</td>
<td>Fully irrigated alfalfa</td>
<td></td>
<td>NW</td>
<td>Dryland sorghum, row planted</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Fully irrigated alfalfa</td>
<td></td>
<td>SW</td>
<td>Dryland sorghum, drilled</td>
</tr>
<tr>
<td>1997</td>
<td>NE</td>
<td>Fully irrigated alfalfa</td>
<td></td>
<td>NW</td>
<td>Dryland sorghum</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Fully irrigated alfalfa</td>
<td></td>
<td>SW</td>
<td>Dryland sorghum</td>
</tr>
<tr>
<td>1998</td>
<td>NE</td>
<td>Fully irrigated alfalfa</td>
<td></td>
<td>NW</td>
<td>Dryland sorghum</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Fully irrigated alfalfa</td>
<td></td>
<td>SW</td>
<td>Dryland sorghum</td>
</tr>
<tr>
<td>1999</td>
<td>NE</td>
<td>Fully irrigated alfalfa</td>
<td></td>
<td>NW</td>
<td>Dryland sorghum</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Fully irrigated alfalfa</td>
<td></td>
<td>SW</td>
<td>Dryland sorghum</td>
</tr>
<tr>
<td>2000</td>
<td>NE</td>
<td>Limited irrigated cotton</td>
<td></td>
<td>NW</td>
<td>Dryland cotton</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated cotton</td>
<td></td>
<td>SW</td>
<td>Dryland cotton</td>
</tr>
<tr>
<td>2001</td>
<td>NE</td>
<td>Limited irrigated cotton</td>
<td></td>
<td>NW</td>
<td>Dryland cotton</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated cotton</td>
<td></td>
<td>SW</td>
<td>Dryland cotton</td>
</tr>
<tr>
<td>2002</td>
<td>NE</td>
<td>Irrigated cotton</td>
<td></td>
<td>NW</td>
<td>Cotton fallow</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Limited irrigated cotton</td>
<td></td>
<td>SW</td>
<td>Cotton fallow</td>
</tr>
<tr>
<td>2003</td>
<td>NE</td>
<td>Irrigated soybean</td>
<td></td>
<td>NW</td>
<td>Dryland sorghum</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated soybean</td>
<td></td>
<td>SW</td>
<td>Dryland sorghum</td>
</tr>
<tr>
<td>2004</td>
<td>NE</td>
<td>Irrigated soybean</td>
<td></td>
<td>NW</td>
<td>Dryland cotton</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated soybean</td>
<td></td>
<td>SW</td>
<td>Dryland sorghum</td>
</tr>
<tr>
<td>2005</td>
<td>NE</td>
<td>Irrigated sorghum</td>
<td></td>
<td>NW</td>
<td>Fallow</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated sorghum</td>
<td></td>
<td>SW</td>
<td>Fallow</td>
</tr>
<tr>
<td>2006</td>
<td>NE</td>
<td>Forage corn</td>
<td></td>
<td>NW</td>
<td>Dryland sorghum (clump)</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Forage sorghum</td>
<td></td>
<td>SW</td>
<td>Dryland sorghum (rows)</td>
</tr>
<tr>
<td>2007</td>
<td>NE</td>
<td>Forage sorghum</td>
<td></td>
<td>NW</td>
<td>Dryland sorghum (rows)</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Forage corn</td>
<td></td>
<td>SW</td>
<td>Dryland sorghum (clump)</td>
</tr>
<tr>
<td>2008</td>
<td>NE</td>
<td>Irrigated cotton N-S rows</td>
<td></td>
<td>NW</td>
<td>Dryland cotton NS rows</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated cotton E-W rows</td>
<td></td>
<td>SW</td>
<td>Dryland cotton E-W rows</td>
</tr>
<tr>
<td>2009</td>
<td>NE</td>
<td>Irrigated sunflower</td>
<td></td>
<td>NW</td>
<td>Fallow</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated sunflower</td>
<td></td>
<td>SW</td>
<td>Fallow</td>
</tr>
<tr>
<td>2010</td>
<td>NE</td>
<td>Irrigated cotton</td>
<td></td>
<td>NW</td>
<td>Dryland soybean</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated cotton</td>
<td></td>
<td>SW</td>
<td>Dryland soybean</td>
</tr>
<tr>
<td>2011</td>
<td>NE</td>
<td>Irrigated sunflower</td>
<td></td>
<td>NW</td>
<td>Fallow after bad planting of sunflower</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Irrigated sunflower</td>
<td></td>
<td>SW</td>
<td>Fallow after bad planting of sunflower</td>
</tr>
<tr>
<td>2012</td>
<td>NE</td>
<td>Fallow for SDI installation</td>
<td></td>
<td>NW</td>
<td>Irrigated cotton</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>Fallow for SDI installation</td>
<td></td>
<td>SW</td>
<td>Irrigated cotton</td>
</tr>
<tr>
<td>2013</td>
<td>NE</td>
<td>SDI corn</td>
<td></td>
<td>NW</td>
<td>Irrigated corn, 75%</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>SDI corn</td>
<td></td>
<td>SW</td>
<td>Irrigated corn, 100%</td>
</tr>
<tr>
<td>2014</td>
<td>NE</td>
<td>SDI short-season sorghum</td>
<td></td>
<td>NW</td>
<td>Irrigated short season sorghum</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>SDI short-season sorghum</td>
<td></td>
<td>SW</td>
<td>Irrigated short season sorghum</td>
</tr>
</tbody>
</table>

[a] Irrigated = spray sprinkler irrigation, and SDI = subsurface drip irrigation.
ter design of Schneider et al. (1998) served as the basis for
design and construction of seven weighing lysimeters at
Uvalde in the Texas Winter Garden area (Marek et al.,
2006). These were used to determine crop coefficients for
vegetable crops (Piccinni et al., 2007), cotton and wheat
(Ko et al., 2009), and maize and sorghum (Piccinni et al.,
2009). Currently, they are being used to determine cabbage
and artichoke $K_c$ values.

The USDA-ARS team also made important contribu-
tions to the ASCE P-M standardized reference ET equa-
tions for short (grass) and tall (alfalfa) crops (Allen et al.,
2005) as well as the FAO 56 P-M reference ET method
(Allen et al., 2006). Both grass (Howell et al., 2000) and
alfalfa (Evett et al., 1998, 2000) were grown as reference
crops, the former for several years on the grass weather
station lysimeter and the latter on the NE and SE lysi-
meters in 1996 through 1999. The importance of advection
and nighttime ET on alfalfa water use in the SHP were reported
by Tolk et al. (2006a, 2006b). Alfalfa canopy surface re-
sistance was studied by Lascano and Evett (2010). Using
data from Bushland and elsewhere, Irmak et al. (2005)
found that hourly computation better accounted for impacts
of abrupt weather changes on reference ET than did com-
putation using daily mean, maximum, and minimum
weather values, and that hourly computation could result in
reference ET values 4% to 5% larger than daily computa-
tion. Discrepancies between hourly and daily computation
results were largest for locations where advection contrib-
uted energy in excess of that available from $R_n$ and $G$.
In addition, Bushland data were used to improve methods of
predicting daily $R_n$ from weather data for use in reference
ET estimation (Irmak et al., 2003).

Despite the successes in determining and using crop co-
efficients for irrigation scheduling, the Bushland experi-
ce also showed the shortcomings of the crop coefficient
approach. Interannual variability of functions of crop coeffi-
cient vs. days after planting, crop growth stage, or grow-
ing degree days was large for different varieties of the same
crop species, primarily due to differences in cover, leaf area
index, and plant height (Howell et al., 1995b, 2012). Crop
coefficient functions were sometimes different across years
for the same variety and for different varieties of the same
species (Howell et al., 2006). Differences occurred in both
timing and maximum value. The Bushland alfalfa reference
ET data set was used in several studies aimed at developing
alternatives to the ASCE P-M reference ET equation with
the aim of improving accuracy by considering the complete
energy and water balance equations, and with a view to-
ward replacing the crop coefficient paradigm with more
direct estimation of crop ET based on understanding of
crop and growth stage specific canopy resistances. This is
still a work in progress. Lascano et al. (2010) found that a
recursive (iterative) calculation method that solved the full
single-surface energy and water balance could estimate
alfalfa ET with good accuracy. They contended that, to the
extent that crop surface resistance values are crop and vari-
ety specific rather than climate specific, the recursive
method could be more accurate than a crop coefficient ap-
proach if surface resistances were known. Lascano and
Evett (2012) showed that solutions to the recursive method
could be used to determine crop canopy resistance if either
crop canopy temperature or crop ET were measured on an
hourly basis. They showed that diurnal changes in surface
resistance for alfalfa could be large, although average val-
ues were $45 \text{ s m}^{-1} \pm 12 \text{ s m}^{-1}$. Evett et al. (2012c)
compared the full single-surface energy balance to a two-
surface (soil and plant canopy) energy balance formulation,
built solved iteratively, and to the ASCE P-M reference ET
method as well as to lysimeter-measured alfalfa ET. They
found both iterative methods to be accurate, although the
assumption of constant daytime and nighttime surface re-
sistances in the ASCE method could lead to errors. In
summary, this work points to a need to consider the full
energy balance and to consider methods of estimating or
measuring automatically the diurnal variation of canopy
surface resistance.

**FIELD-SCALE SIMULATION STUDIES: MODEL TESTING AND DEVELOPMENT**

The first simulation studies conducted using Bushland
lysimeter data involved the testing and further develop-
ment of the ENErgy and WATer BALance (ENWATBAL) mod-
el originally developed by Lascano and van Bavel and used
to simulate evaporation from soil (E) and transpira-
tion (T) from plants (Lascano et al., 1987). Originally written
for mainframe and other centralized computing systems, EN-
WATBAL was ported to run on personal computers in the
BASIC language by Evett and Lascano (1993), who tested
it using sorghum weighing lysimeter data. They also made
several improvements to the model, including modularizing
the code, correcting the root water uptake algorithm, in-
cluding calculation of dewfall, allowing multiple precipita-
tion events on a single day, allowing sub-daily times steps
such as half-hourly weather data input, dynamically chang-
ing time steps to avoid divergence and code failure, allow-
ing up to nine soil horizons with different hydraulic proper-
ties, and allowing soil albedo to vary as a function of sur-
face water content. ENWATBAL was made available on
the CPRL web site and subsequently used by several hun-
dred researchers nationally and internationally for studies
of E and T separation and dynamics in response to differ-
cent crop leaf area index values and weather and soil condi-
tions. Studies at Bushland included energy and water balance
modeling of winter wheat and bare soil (Evett et al., 1994a,
1994b; Tunick et al., 1994).

ENWATBAL was later modified to allow subsurface
drip irrigation and used to study the reduction (approx. 36% or
80 mm for corn) in evaporative loss from the soil surface
when switching from surface irrigation to SDI (Evett et al.,
1995a). Studies comparing mechanistic modeling to the
predominate irrigation scheduling paradigm involving crop
coefficients and reference ET estimates showed the value
of modeling in scenarios with frequent irrigations (Evett et
al., 1995b). Finally, ENWATBAL was modified to simu-
late a reference ET condition and shown to provide refer-
ence ET values comparable to those from the ASCE (2005)
Standardized Reference ET method (Evett et al., 2010,
2012).

Bushland lysimeter data have been instrumental in sev-
eral other model development and testing efforts. These
include improvement and testing of the hydrology submodel of WEPS (Durán et al., 1995) and testing the Cupid-DPE model to simulate partitioning of sprinkler-applied water to evaporation and infiltration (Thompson et al., 1994, 1996, 1997). In the early 2000s, two years of alfalfa data and two years of corn data were used to test the EPIC (Environmental Policy Integrated Climate) and HELP (Hydrologic Evaluation of Landfill Performance) hydrologic models for use in design of ET landfill covers (Hauser et al., 2005; Hauser and Gimons, 2004). More recently, the Bushland team was involved in the development and testing of the AquaCrop model developed by FAO (Evett and Tolk, 2009; Heng et al., 2009; Steduto et al., 2009), in the evaluation of the CROPWAT, MODWht, and CERES-Wheat models for estimating winter wheat ET (Kang et al., 2009) and in the calibration and testing of a new model, PALMScot, developed by Booker et al. (2014) for landscape-scale simulation of cotton production. The PALMScot model is a combination of the PALMS (Precision Agricultural Landscape Modeling System) and the Cotton2K model of cotton growth and yield. The Bushland lysimeter data are currently being used to evaluate hydrologic and other crop models for their ability to estimate the ET component of the water balance by comparing simulated ET values to measured ET values as affected by agronomy and irrigation as previously mentioned, including SWAT (Soil and Water Assessment Tool), RZWQM (Root Zone Water Quality Model II), and the EPIC model.

REMOTE SENSING BASED SIMULATION STUDIES

Interest in remote sensing at Bushland grew out of early work on winter wheat canopy temperature sensing (Howell et al., 1986) and radiation and energy balances of sorghum as influenced by row geometry (Steiner, 1986, 1987; Graham and Steiner, 1988). Multi-spectral measurements of sorghum in the 1980s were used to compute values of four vegetation indices, including the normalized difference vegetation index (NDVI), perpendicular vegetation index (PVI), near-infrared to red ratio index (RVI), and transformed soil-adjusted index (TSAVI). These were related to green leaf area index to develop general relationships useful across three widespread Texas locations (Richardson et al., 1992). With the construction of the weighing lysimeters at Bushland, their usefulness for remote sensing studies became quickly apparent. The first study occurred in 1992 and was called the Radiation and Energy Balance (REBAL ’92) study (Tunick et al., 1992, 1994). The study involved near-field and far-field thermal infrared imagery, a full suite of shortwave and longwave incoming and outgoing radiation measurements, five-level micrometeorological profiles, scintillometry for sensible heat flux, and soil water content and soil heat flux measurements combined with weighing lysimeter ET data (Tunick et al., 1994). Detailed measurements allowed parameterization of a Brunt-type emissivity model for Bushland conditions and the successful testing of the ENWATBAL model for bare soil evaporation (Howell et al., 1993).

In the 2000s, remote sensing work included the mapping of tillage practices in the Texas Panhandle (Gowda et al., 2006, 2008a) and the development of RS-based LAI models (Gowda et al., 2007). Remote sensing based ET models are useful for mapping of ET across large regions and should be tested against mass balance ET data. Research at Bushland included calibration and use of remote sensing models to scale one-time-of-day RS-based ET estimates to daily estimates (Colaizzi et al., 2005a, 2006), comparison of single-source and two-source energy balance models of ET (Colaizzi et al., 2005b); separation of ET into E and T (Colaizzi et al., 2014) and evaluation of METRIC, a simplified surface energy balance (SSEB) model (Gowda et al., 2009); problems with hot and cold pixel selection in SEBAL that can lead to substantial ET errors (24% to 28%) with that model (Gowda et al., 2008b; Paul et al., 2013); and modifications to the surface roughness length algorithm in the model to accommodate differences in irrigated and dryland (sparser cover) surfaces (Paul et al., 2014), the surface energy balance system (SEBS) model (Gowda et al., 2013), the two-source energy balance (TSEB) model, and the ATEB model for ET mapping (Chávez et al., 2007, 2009b; Gowda et al., 2009).

In 2007 and 2008, the Bushland Evapotranspiration and Remote Sensing Experiments (BEAREX07 and BEAREX08) were conducted with a broad partnership involving USDA-ARS laboratories at Maricopa, Arizona; Beltsville, Maryland; and Ames, Iowa; and the University of Alabama, University of Oklahoma, and Utah State University (Chavez et al., 2009b; Evett et al., 2012a). The large weighing lysimeters and associated soil water sensing networks around each were the basis for mass balance ET ground truthing in these experiments. Much work on testing and improvement of the RS-based two-source energy balance model resulted from this effort (Anderson et al., 2012; Colaizzi et al., 2012a, 2012b, 2014; Kustas et al., 2012), including methods of calibrating radiometric surface temperature data (Chávez et al., 2009a), replacement of the Priestly-Taylor potential ET formulation with the more physically based P-M formulation for more accurate partitioning of E and T (Colaizzi et al., 2012b), and a geometric method that deals with the non-random spatial orientation of row crops (Colaizzi et al., 2012a). Data assimilation techniques were used to estimate soil profile water contents using an RS-based TSEB ET modeling approach (Neale et al., 2012). Some reasons for the persistent underestimation of ET by eddy covariance systems were illustrated in a study of patch-scale turbulence by Prueger et al. (2012) in which large-scale eddies were shown to penetrate the surface boundary layer. Overall, the BEAREX study results promoted caution in interpreting ET values from simulation models, atmospheric flux sensing equipment (e.g., eddy covariance), and even weighing lysimeters. On the positive side, the source of errors in ET values was identified in most cases, which provides direction for future research, and methods to reduce error magnitudes were improved or created, which improves future research outcomes.

ET SENSING METHODS

While weighing lysimeters afford arguably the most accurate and direct measurements of ET, they also have some disadvantages compared with other methods. Lysimeters intended for crop water use determination are typically
managed to be representative of the much larger fields in which they are situated in order to prevent crop surface differences that could lead to over- or underestimation of ET. But the footprint of a lysimeter is small, and a lysimeter may not be representative of the larger field for several reasons, including differences in plant stand, tillage, antecedent moisture, fertilization, herbicide application, and simple random variability. For this reason, the lysimeters at Bushland have always been accompanied by a network of neutron probe (NP) access tubes in the surrounding field for monitoring soil water content from the surface to 2.3 m depth in 0.20 m increments, plus two NP access tubes in each lysimeter. The NP network not only allows comparison of the soil profile water content in the lysimeter with that in the surrounding field, it also allows the field ET to be estimated with good accuracy over weekly or biweekly periods by application of the soil water balance equation. The fields are typically furrow diked to limit runoff, the lysimeters are excellent rain gauges for measuring relatively rapid irrigation and precipitation events, and deep percolation losses below 2.5 m depth are rare in this semi-arid climate. For these reasons, the NP network is the primary alternative ET sensing method at use on the station and was shown to be useful in determining if lysimeter ET was representative of field ET (Evett et al., 2012b).

Determination of field crop ET and crop coefficients using NP networks as an alternative to weighing lysimeters has been very successful, but the regulatory burden on the use of the NP has decreased its use for ET determination nationally and internationally. Possible alternatives to the NP include capacitance sensors used in access tubes and time domain reflectometry (TDR) systems. Several alternative capacitance and TDR systems were compared with direct soil core sampling and the weighing lysimeters to evaluate their performance for ET determinations vis-à-vis the NP (Evett et al., 2008). The TDR methods were shown to be accurate in most soils but not useful for the deep profile water content sensing necessary for ET determination (Evett et al., 1995a). A combination of field and laboratory studies showed conclusively that the capacitance methods were incapable of accurately determining soil profile water content and changes in profile water storage necessary for determining ET by the soil water balance (Evett et al., 2006, 2008, 2009b; Mazahrihi et al., 2008). The reasons for this involve the fundamental physical equation ruling capacitance measurements in soils, which includes a geometric factor that is strongly influenced by the small-scale variations of soil bulk density, bulk electrical conductivity, and soil structure near access tubes. Because these soil properties vary randomly, so too does the measured capacitance, independently of the soil water content (Evett et al., 2012d). This result led to new work to develop a TDR-based down-hole profiling water content sensor system (Casanova et al., 2012a, 2012b, 2012c, 2013a, 2013b) that was recently patented (Evett et al., 2014).

Other ET sensing methods are also commonly used in E and ET studies and have been the subject of studies at Bushland to determine their accuracy and the sources of problems with their use for ET studies. These include Bowen ratio energy balance (BREB), eddy covariance (EC), aerodynamic, scintillometer, and related systems. A spatial averaging Bowen ratio system was constructed by Bausch and Bernard (1990) and tested against the Bushland weighing lysimeters with ET agreement within 1% after initial 8% disagreement on the day after irrigation. Todd et al. (1998, 2000) studied switching arm BREB systems and found that 91% of daytime measurements and 71% of nighttime measurements were valid, with invalid measurements being generated close to sunset due to net radiation approaching zero and making the Bowen ratio indeterminate. The BREB systems tended to overestimate ET compared with the lysimeters. The largest differences occurred on hot, windy, dry days, when the Bowen ratio was less than zero and when the quantity \( (R_e - G) \) was less than ET. The fact that Bowen ratio data are often missing near sunset, coupled with the fact that irrigated crop ET continues through and after sunset at relatively large rates (up to 20% of daily ET occurs after sunset; Tolk et al., 2006a, 2006b), renders the Bowen ratio method not useful for daily ET estimates, although it can be quite accurate for hourly estimates during daylight hours.

Through comparisons with the Bushland weighing lysimeters, eddy covariance (EC) systems have been studied to determine if they reliably sense ET and to investigate reasons for energy balance closure errors that are common with these systems. Most of these studies occurred during BEAREX07 and BEAREX08, which used the four large weighing lysimeters and, in some cases, the associated NP access tube networks for ground truthing. Chávez et al. (2009e) compared two EC systems placed near the NE and SE lysimeters and found energy balance closures of 73% to 78% and underestimation of ET of about 30% on a daily basis after normal EC system corrections had been applied. Errors in ET were larger on a percentage basis during nighttime but were relatively small in magnitude. Errors in ET diminished, after energy balance closure was forced, to 22% to 24% underestimation and further diminished with further adjustments to between 1 and 7% disagreement. The EC system had difficulty measuring \( H \) and LE fluxes at nighttime, which is problematic since 7% to 10% of daily ET at Bushland can occur at night in the dry, windy, and advective environment at Bushland (Tolk et al., 2006a, 2006b).

Alfieri et al. (2010) found substantial underestimation of ET by EC systems. In a later study, they applied several steps of more progressive corrections and adjustments to the EC data but were still unable to obtain closure to better than approximately 14% (Alfieri et al., 2012; Evett et al., 2012a, 2012b). In a companion study, Joy et al. (2011) found that ET was underestimated by 19% to 21% by EC systems, largely due to underestimation of \( H \) and LE, and they also found that much of the error occurred during nighttime. In another companion study, French et al. (2012) investigated the surface renewal method for ET sensing but encountered difficulties due to the advective environment that characterizes much of the SHP. Studies of EC and other flux sensing methods continue at Bushland, including work with arrays of taller (12 m) aerodynamic towers to detect large turbulent eddies adding advective energy into the SPAC system. To date, however, the work with EC
systems indicates that even with careful and thorough corrections, the EC method is unable to account for all the sensible and latent heat flux present in the environment above agricultural fields in the SHP. Furthermore, it appears that many of the adjustments made to EC data, in the several publications using Bushland data, were ad hoc in nature and were made with knowledge of what the “correct” ET values should be, in that the authors knew what the lysimeter ET data were. It thus becomes clear that only completely blind tests of EC system adjustments can determine if routine adjustments can result in ET estimates that closely match mass balance ET determinations.

**EXTRAMURAL AND INTERNATIONAL COOPERATION**

The Bushland weighing lysimeter research program, which grew to 53 lysimeters, has garnered widespread national and international recognition. Engineers and scientists on the Bushland staff have been asked to design, help in site selection of, and advise on operation of numerous weighing lysimeters, including those described earlier at Uvalde, Texas. Two large (4 m x 2 m x 2.75 m deep) lysimeters installed at the USDA-ARS laboratory in Parlier, California, were designed to allow simulation of a shallow water table for studies of vegetable crop ET and crop coefficients under California Central Valley conditions (Schneider et al., 1996). Design of the pulldown equipment for collection of the large soil monoliths benefited from the experience gained at Bushland (Schneider et al., 1994). Research collaboration with scientists of the Soil, Water, and Environment Research Institute in Giza, Egypt, led to the design of a simplified weighing lysimeter, two of which were installed in the desert at Ismailia, Egypt, near the Suez Canal (Schneider et al., 1998) and used for determination of ET of alfalfa, fava bean, maize, and other crops under microirrigation and sprinkler irrigation (Evett et al., 2000b). Later, a large (2.4 x 3 m x 2.5 m deep) weighing lysimeter was designed in cooperation with the Jordanian Center for Agricultural Research and Extension to accommodate the wide variety of crops and row spacings used in the diverse agriculture there. The lysimeter did not follow the simplified lysimeter design but instead employed a counterweighted balance beam scale mechanism and included some improvements on the design of lysimeters at Bushland. These included a larger separation of the entrance hatch from the lysimeter and a deeper roof so that soil immediately adjacent to the lysimeter could be at least 1.5 m deep, thus avoiding soil water storage limitations that might affect plant growth. The lysimeter, installed in 2008 in the Jordan Valley at 224 m below sea level and irrigated with surface drip lines, has been used to determine crop water use of onion, potato, sweet corn, tomato, and other vegetable crops in that hot, arid climate where 95% of irrigated area is irrigated by surface drip systems (Evett et al., 2009a).

The Bushland team has lent expertise to several other lysimeter design and operation efforts over the years:

- **Design of three large (7.43 ft diameter x 9.8 ft deep) weighing lysimeters at the Desert Research Institute facility in Boulder City, Nevada, that are used to study the hydrology and ecosystem of plant communities in the Mojave Desert (Chief et al., 2009).**
- **Design of two lysimeters, one for crop water use and one for reference grass ET, at the West Side Field Station in the San Joaquin Valley of California.**
- **Design of three large weighing lysimeters at the University of Arizona (Young et al., 1996).**
- **Design and operation of the lysimeters at Rocky Ford, Colorado, run by Colorado State University in order to determine alfalfa reference ET and crop ET in southeastern Colorado (Andales et al., 2010).**
- **Design of 24 small and one large weighing lysimeter for the National Engineering Research Center for Information Technology in Agriculture (NERCITA) in Beijing, China.**
- **A lysimeter design for the Soil and Water Research Center of the Oman Ministry of Agriculture and Fisheries.**

The team is also participating in the International Long-Term Lysimeter Project led by the Forschungszentrum Jülich, Germany, and aimed at assessing the impact of climate change on ET on a global scale (Puetz et al., 2014). Projects currently underway involve researchers from Austria, Germany, Israel, Tunisia, and Uzbekistan. Recent and current visiting scientists carrying out projects with the Bushland team include those from Bangladesh, Mexico, Israel, Spain, Tunisia, Turkey, and Uzbekistan.

**SUMMARY**

The Bushland large weighing lysimeters have served a plethora of purposes, including development of crop coefficients for the major SHP crops, investigation and improvement of reference ET formulations, field-scale crop simulation model development and testing, remote sensing based ET model development and testing, and testing and improvement of ET and soil water sensing equipment and methods. The more than 140 publications cited herein enumerate the impact of the Bushland large weighing lysimeter project, initiated and led by Terry Howell, on irrigation engineering and science practice and understanding. They also serve to illustrate the breadth of scientific and technical interests of Terry and his team and the national and international partnerships and impacts engendered by this effort. Still, they represent just one part of Terry’s contribution to irrigation science, which includes seminal contributions to understanding irrigation application method effects on irrigation efficiency, yield, and WUE [microirrigation (Howell and Hiler, 1974; Howell and Barinas, 1980), low-energy precision-application (LEPA) and spray sprinkler (Howell et al., 1995c; Schneider and Howell, 1998, 1999)], and to understanding crop WUE as affected by crop and variety, tillage, irrigation method and management, and soil and climatic environments (Howell, 2000, 2001, 2002, 2006; Tolk and Howell, 2012; Tolk and Evett, 2015).
THE FUTURE

The importance of weighing lysimeter ET and complementary micrometeorological data for simulation model development, calibration, and testing has been emphasized by recent efforts in the modeling community to unify, cross check, and test mechanistic models of plant growth, water and nutrient use and yield, watershed hydrology, and RS-based regional ET. One such effort is AgMIP, the Agricultural Model Comparison and Improvement project, which is evaluating a wide suite of crop models for their ability to estimate crop yields under current and future climate scenarios (www.agmip.org). Because the crop growth, yield, water use, micrometeorological, and soil water content data from the Bushland large weighing lysimeter experiments are among the best in the world, preparing these datasets with complete metadata and quality assurance is a high priority for future sharing of the data with the modeling community.

The effects of irrigation application method on crop yield and WUE have been well documented, but understanding of the mechanisms for these effects is lacking due to the paucity of detailed energy and water balance information in past studies. The use of weighing lysimeters and microlysimeters to determine soil evaporative losses of water and separate ET into E and T, in conjunction with detailed radiation balance, sensible and latent heat flux sensing, and aerodynamic profile sensing offers the opportunity to more fully understand the mechanisms and incorporate them into crop simulation models, including models of ET for irrigation management. The contrast of two lysimeters with SDI and two with sprinkler irrigation, recently made possible, allows better differentiation of the fluxes and energy and water balances than before.

The Bushland team understands full well how expensive and difficult it is to build, maintain, and operate a quality weighing lysimeter program. The maintenance and operations required to report quality data, including quality assurance and control, constitute the greatest items of program commitment. At least two full-time salaries are committed to these functions for the four large weighing lysimeters and research weather station. The agronomic and scientific efforts are in addition to this. Also understood is that weighing lysimeters are not a feasible method for most ET determination needs of researchers, where expense, topography, geology, remoteness, soil depth, and other factors prevent their use. Thus, research into alternative ET determination methods, including those based on soil water sensing for soil water balance determinations of ET and sensible and latent heat flux sensing, will continue in order to address the present problems with those methods. Research currently underway involves intensive aerodynamic profile and multi-level sensible and latent heat flux sensing, coupled with soil heat flux and water content sensing to address these research questions.

Cooperation with extramural partners has been a highlight of the lysimeter-based research at Bushland from its inception, and strong partnerships are foreseen to continue with universities involved in the Ogallala Aquifer Program, other USDA-ARS locations, and university and government researchers in other states and nations. As agricultural research becomes ever more cooperative and enabled by advanced communications technology, the potential for partnerships is increasing rapidly.

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