AN EVAPOTRANSPIRATION RESEARCH FACILITY FOR SOIL-PLANT-ENVIRONMENT INTERACTIONS

J. A. Tolk, T. A. Howell, S. R. Evett

ABSTRACT. *The Soil-Plant-Environment Research (SPER) facility at USDA Agricultural Research Service at Bushland, Texas, opened in 1990 with 48 weighable lysimeters containing monolithic soil cores of three major soil groups and a rain shelter. Its purpose was to provide an environment for intensive plant water stress research and evaluate the impact of soil hydraulic characteristics on irrigation management strategies. The facility has now been upgraded with the addition of a fourth soil type collected using static weights, the installation of 48 deck (platform) scales for the continuous measurement of evapotranspiration (ET), and the use of a pressure-compensating drip system. The additional soil was selected to provide a wider range of nutrient and water supplying capacity compared with the other three soils. The conversion to weighing lysimeters allows the collection of diurnal ET data needed for plant physiological studies and validation of ET measurement equipment and models. The drip system reduces labor, increases precision of application amount, and reduces disturbance around the lysimeters. These improvements to the SPER facility will expand the type and quality of plant stress and irrigation management research projects that can be performed.*

Keywords. *Evapotranspiration, Rain shelter, Lysimeter, Plant water stress.*

Lysimeters have become standard tools for evapotranspiration (ET) research (Howell et al., 1991) and, in conjunction with rain shelters (Foale et al., 1986), can enhance the evaluation of plant water stress in soil-plant-water interaction studies. Such facilities have been described (Hiler, 1969; Teare et al., 1973; Meyer et al., 1985; Clark and Reddell, 1990; Schneider et al., 1993).

Lysimeters, which are containers or tanks filled with soil in which plants are grown, allow the measurement of changes in the soil water balance as water is added or evaporated from the soil, transpired from plants, and drained from the lysimeter. Rain shelters, by excluding rainfall from field plots, provide control of the timing and intensity of water deficit that the plants will experience (Foale et al., 1986).

For a lysimeter to provide representative ET data, van Bavel (1961) recommended that it be of sufficient size to have representative moisture content, moisture tension, thermal conditions, and root distribution as well as contain undisturbed soil profiles (soil monolith). Lysimeters are usually classified as monolithic or reconstructed soil profiles; as weighing, weighable, or non-weighing; and as gravity or vacuum drainage. Weighing lysimeters determine ET directly by continuously measuring the changes in mass balance. This contrasts with weighable lysimeters in which mass change is measured periodically and with non-weighing lysimeters which indirectly determine ET by volume balance (Howell et al., 1991). Since water extraction by plants and water evaporation from the soil represent about 5% to 20% of the mass of the lysimeter (depending on the lysimeter depth), many weighing lysimeters use counterbalanced scales to offset the large dead weight of the soil and lysimeter container.

Field (as opposed to laboratory or greenhouse) lysimeters often contain the research facility's indigenous soil if duplication of ET of surrounding soil and plant conditions is the objective. Other field lysimeters may contain non-indigenous soils for purposes such as examining soil-related problems with crop production occurring at a different location (Meyer, 1987), causing a more rapid depletion of plant available water during imposed water stress conditions (Clark and Reddell, 1990), or evaluating the impact of different soil characteristics on crop production under water deficits (Tolk et al., 1997, 1998).

Such studies point out the impact of soil hydraulic characteristics on crop growth and yield. In northern Australia, total water use of rain-fed spring wheat (*Triticum aestivum* L.) in a clay loam without supplemental nitrogen was within 8% of that in a sandy clay (Rickert et al., 1987). But, the wheat in the sandy clay had 25% more grain yield, 14% more dry matter, deeper root system, and greater total root length. Pal and Varade (1982) reported higher wheat transpiration rates at lower soil water potentials in clay loam compared with sandy or sandy loam soils. They attributed these responses in clay loam to higher plant available water contents and higher hydraulic conductivities in the range of soil water potentials encountered.

Schneider et al. (1993) first described the Soil-Plant-Environment Research (SPER) facility (fig. 1) located at the USDA-Agricultural Research Service Conservation and Production Research Laboratory at Bushland, Texas. It had 48 weighable lysimeters with a 0.75- × 1.00-m surface area

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Figure 1. The Soil-Plant-Environment Research facility with rain shelter and lysimeter irrigation equipment.

and 2.30-m depth which contained monolithic soil cores of one of three Great Plains benchmark soils, and a 13- × 18- × 2.7-m rain shelter. The facility has been in operation since 1990. This article describes recent improvements to the facility, including the addition of a fourth soil type, conversion of the 48 lysimeters from weighable to weighing through the installation of deck scales, and use of a pressure-compensating drip irrigation system that allows simple, accurate irrigation application to each lysimeter.

THE SOIL-PLANT-ENVIRONMENT RESEARCH FACILITY

Construction and equipment details are fully described in Schneider et al. (1993). The SPER facility is located in a 0.25-ha uniformly cropped area. The rain shelter is a metal building with all drive components and control sensors mounted on the building, which automatically traverses rails to shelter the lysimeters when about 2 mm is caught by the rain sensor. It contains a top-running, double-bridge gantry crane used to move the lysimeters that was previously used to weigh the lysimeters using a load cell and data acquisition system for the weekly measurement of ET. The lysimeters are arranged in two concrete pits, each pit containing two side-by-side rows of 12 lysimeters each. The soil monoliths were collected with the hydraulic pulldown procedure described by Schneider et al. (1988). The soil series were the Amarillo fine sandy loam (fine-loamy, mixed, thermic Aridic Paleustalfs) collected at Big Spring, Texas; Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustolls) from Bushland, Texas; and Ulysses clay loam (fine-silty, mixed, superactive, mesic Aridic Haplustolls) from Garden City, Kansas (Soil Survey Staff, NRCS, USDA, 2004).

FOURTH SOIL MONOLITH COLLECTION

The Amarillo, Pullman, and Ulysses soil series are major agricultural soils of the Great Plains. The permeability of the Amarillo and Ulysses soils is moderate, and the Pullman slow. The Amarillo and Pullman have calcium carbonate horizons consisting of at least 50% calcium carbonate below depths of 1 to 1.5 m. The water holding capacity of the Pullman and Ulysses is high and the Amarillo moderate. A fourth soil type was selected to provide a contrast to the three soil series in both permeability, water holding capacity, and the presence of a calcic horizon. The Vingo fine sand (coarse-loamy, mixed, mesic Aridic Paleustalfs) is a moderately rapidly draining soil formed in sandy materials of eolian origin. At the monolith collection site, the profile contained an average of 86% sand, with a buried B horizon beginning at 1.7 m, which contains about 15% clay. A calcic horizon was not present in the 2.3-m profile that was collected. The textural analyses by depth of the soils including depth of calcium carbonate is shown in figure 2.

Prior to monolith collection, a temporary dike was placed around the area from which the monoliths were to be obtained. The area was then flooded several times to wet the soil throughout the profile to reduce the soil resistance to the downward movement of the lysimeter box. [Note: The lysimeter boxes had a specially designed beveled cutting edge as described by Schneider et al. (1993)].

The monoliths were collected using static weights similar to procedures outlined by Tackett et al. (1965). The weights were stackable crane counterweights provided by the crane service which assisted in the collection and transport of the

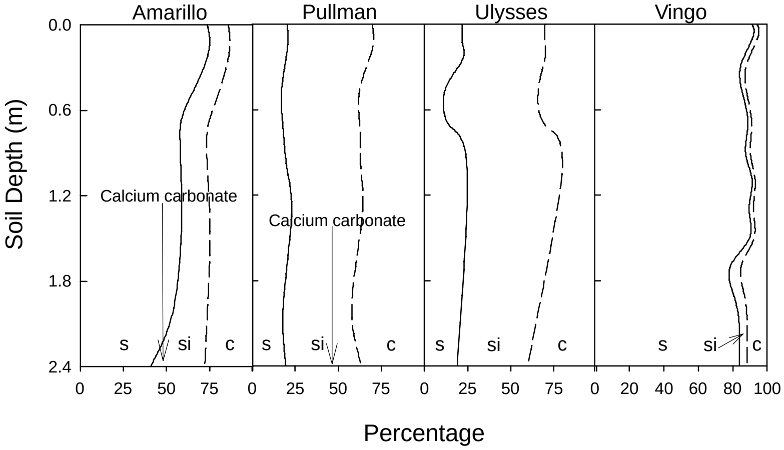

Figure 2. Percentages of sand (s), silt (si), and clay (c) by depth in the Amarillo, Pullman, Ulysses, and Vingo soil profiles, with depths of calcium carbonate (caliche) indicated for the Amarillo and Pullman soils.

lysimeters. A frame was constructed which was used to move the empty lysimeter boxes into position (fig. 3), and center and hold the weights on the lysimeter box as it was pushed into the soil. A forklift maintained lysimeter vertical alignment and controlled the speed of downward movement of the lysimeter box into the soil (fig. 4). The crane moved successive weights into position.

Fourteen Vingo soil monoliths were to be collected. The average monolith depth reached with 89 kN was 0.9 m and with 222 kN was 1.7 m. The target depth of 2.3 m was achieved for eight monoliths using 311 kN, which was similar to the force needed to collect monoliths from the Amarillo fine sandy loam (Schneider et al., 1993). The collection of two more monoliths required 444 kN and, for the final two, 577 kN. Two monoliths were not collected, since depths of less than 2 m were achieved with the total available force.

The lysimeter monoliths that could not be collected were nearest to the dike, with the greatest resistance to downward movement beginning at the depth with the highest clay content (fig. 2). This suggests that the wetting at the lower depths was insufficient to reduce soil resistance. The lysimeters were removed and transported following techniques described in Schneider et al. (1993).

DECK SCALES

DESCRIPTION

The SPER facility was designed for the lysimeters to be manually weighed using the overhead crane and load cell system. The simplest design option to convert the facility to weighing lysimeters was the use of deck (platform) scales in which the entire mass of the lysimeter box and soil would be measured, similar to the system first described by Kirkham et al. (1984). The first installation of four deck scales (model DS30x40-10K, Weigh-Tronix, Fairmont, Minn.) was in 1995. Successive installations converted one-half of the lysimeters to weighing lysimeters by 2000. The installation of all 48 deck scales was completed in 2004.

Figure 3. Lysimeter box being moved into position for collection of a Vingo soil monolith.

Figure 4. First weight on top of lysimeter box while forklift maintains alignment and controls rate of downward movement.

The deck scale is of steel construction and consists of a base structure, four load beams with individual suspension assemblies, a suspended platform, horizontal checks, overload stops, and junction box. Each load beam consists of four strain gages bonded to a steel bar and connected to form a balanced wheatstone bridge with a resistance of 350 ohms (87.5 ohms for the four load cells connected in parallel) and an output of 2 mV/V at full capacity of 4.54 Mg. The scale dimensions are 1 × 0.75 × 0.2 m. To maintain level and provide stability, the scales were mounted on 3- × 1.5-m tubular steel frames positioned on the bottom of the concrete pits.

The deck scales are excited and measured by a Campbell Scientific, Inc. (Logan, Utah). CR-7X data acquisition system with a 15-bit resolution, using a 6-wire full bridge program instruction which compensates for lead wire resistance. Excitation voltage from the data acquisition system is 2 V, keeping the excitation current below the 50-mA maximum source current of the data logger. Data are acquired on a 0.1-Hz sampling interval and composited into 30-min means for output.

CALIBRATION PROCEDURES

Since the lysimeter surface area is 0.75 m^2, 0.75 kg of mass represents 1 mm of water depth equivalence based on a water density of 1.0 Mg m^{-3}. Calibration results are reported in terms of water depth equivalence. Calibration took place in early spring; the lysimeters had not been cropped or irrigated in two years thus reducing the potential for evaporation during calibration.

During calibration, each lysimeter box was completely covered with 0.02-m plywood upon which the calibration mass standards were loaded. The calibration mass standards used meet National Institute of Standards and Technology Class F requirements. Ten mass standards, each with a water depth equivalence of 30.27 mm, were loaded one at a time for a total loading of 302.7 mm. The mass standards were then removed one at a time to check for hysteresis. During calibration, lysimeter mass was sampled at a 0.1-Hz interval and averages output for each minute.

Loading of each mass standard and time for deck scale stabilization took less than 1 min, and this data point was eliminated. Two calibration data points were obtained for each addition or removal of mass standards for a total of 42 data points. Figure 5 shows a typical calibration in 2004 of a deck scale in use since 1995. The root mean square error of the calibration was 0.09 mm. The calibration slope has varied less than 1% since calibration in 1996. Of the 48 deck scales calibrated in 2004, the lowest coefficient of determination was 0.999996 with a RMSE of 0.2 mm.

PERFORMANCE

Deck scale output converted to ET of cotton grown in the Pullman soil is shown in figure 6. The ET rate appears "noisy" in the unsmoothed data, while the 30- and 60-min equally weighted averages (three and five 30-min averages, respectively) are considerably more stable. Normally this noise is not a factor, since ET is calculated from the difference in scale output from midnight to midnight. Typical measured standard deviations of the signal voltages were 30 to 40 microvolts, corresponding to 0.09 to 0.12 mm. Some of the "noise" in the system can also be attributed to wind. Howell et al. (1995), when evaluating the effects of wind on the signal output of large weighing lysimeters, reported increased standard deviations with wind speeds above 5 m s^{-1}. Wind speed was measured at a 2-m height for 10 d in a dryland cotton crop about 175 m south of the SPER facility and compared with the standard deviation of the deck scale output signal. The deck scale was measuring the mass balance of a cotton crop about 1 m tall. While there was considerable scatter in the data, figure 7 also indicates increased standard deviations as wind speed increased as wind speed increased from 3 to 7 m s^{-1}.

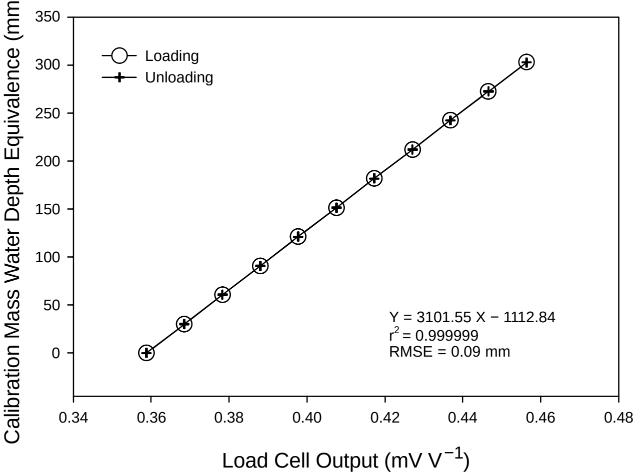

Figure 5. Results from a typical deck scale calibration.

DRIP IRRIGATION SYSTEM

Initially, each set of 12 lysimeters was irrigated using a single drip line with in-line emitters whose flow was regulated using a pressure regulator. The accuracy in

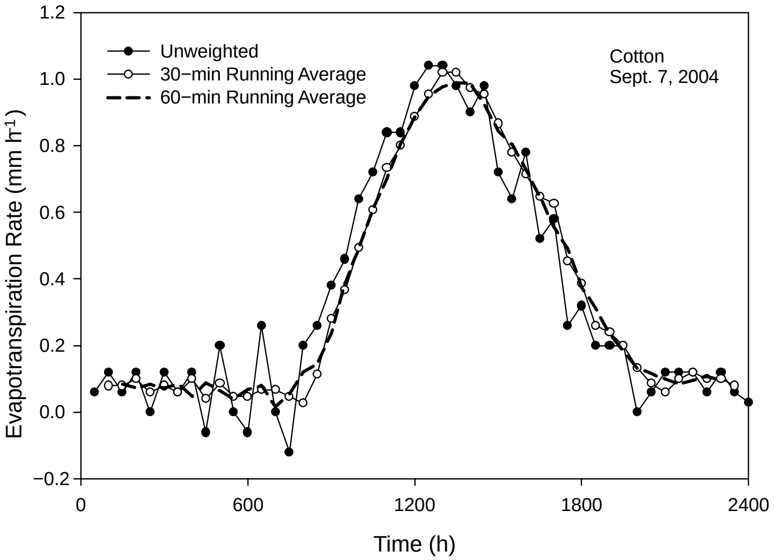

Figure 6. Unweighted 30- and 30-min and 60-min equally weighted running averages of ET of cotton.

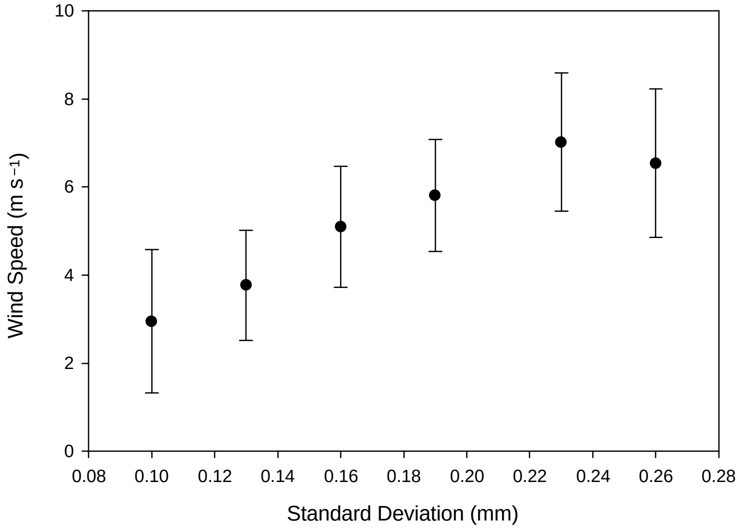

Figure 7. The relationship between standard deviation of the deck scale signal output and wind speed. Error bars represent ±1 S.D. of the mean wind speed.

irrigation application amounts was variable. To increase accuracy, later irrigations were measured and applied by hand which proved very time consuming. The improved system used six pressure compensating point source drippers (model WPC20, Netafim USA, Fresno, Calif.) on each lysimeter, with a cutoff valve to the 17-mm OD water distribution line so that each box could be irrigated independently (fig. 1). The drippers have internal check valves to prevent drainage. The lines remain filled after the first irrigation, and the volume of water remaining in the line on the lysimeter is equivalent to about 0.25 mm. The consistency in flow under a range of pressures (data not shown) allows irrigation application amounts to be determined as a function of time.

COST OF UPGRADES

The crane service for the collection and transport of the lysimeters containing the fourth soil was $11,500. The cost of 48 deck scales was $144,000, at an average cost of $3000 each, and the steel for the deck scale mounting frames $1400. The additional data acquisition system was $9000. The parts for the drip system cost $400.

OPERATING EXPERIENCE

The current configuration of the SPER facility addresses some of the problems described in Schneider et al. (1993). The use of deck scales eliminates the shading of the crop which occurred when the lysimeters were being weighed using the crane/data acquisition system in the rain shelter. Soil compaction due to foot traffic around the pits has been reduced. However, the permeable Vingo soil has resulted in the need for frequent drainage. Currently, the lysimeters must be manually drained using a suction system which disrupts the measurement of ET. An automated system to run at night during periods of low ET is currently under development. The size of the pits was designed to allow sufficient clearance for manually weighing the lysimeters, but also allows sufficient space for small animals to fall to the bottom of the pit and chew on the wires. While the wiring from the deck scales to the data acquisition system is shielded in conduit, the exposed wiring within the deck scales was not shielded in earlier purchases. Deck scales obtained later have armored cable.

Other problems have occurred during the operation of the facility. The standard I-beam rails upon which the rain shelter travels warped and had to be cut and pushed back into alignment. Strong winds moved the rain shelter down the rails to cover the lysimeters when there was no rainfall, and a holding brake was installed on the motor reducer output shaft to fix the shelter in the correct position until it was needed. The sintered drain tubes clogged with calcium carbonate deposits which prevented drainage. A procedure was developed in which the tubes were filled with a solution of hydrochloric and sulfamic acids and allowed to sit overnight. The solution was vacuumed out, and the tubes were flushed clean by filling and vacuuming out water repeatedly.

These improvements to the SPER facility have expanded the type and quality of plant stress and irrigation management research projects that can be performed. The addition of the Vingo soil increased the range of soil nutrient and water holding capacities needed for more detailed plant stress studies. The installation of deck scales allows the continuous, short-term measurement of ET. Irrigations are performed rapidly, easily, and accurately. Research projects currently underway include drip irrigation frequency and amount studies on cotton yield, validation of ET measurement by a gas exchange chamber, and validation of models which simulate soil water evaporation and transpiration separately.

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