Simple weighing lysimeters for measuring evapotranspiration and developing crop coefficients

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Abstract: Knowledge of cotton crop evapotranspiration (ET) is important in scheduling irrigations, optimizing crop production, and modeling ET and crop growth. The ability to measure, estimate, and predict ET and cotton crop water requirements can result in better satisfying the crop's water needs and improving water use efficiency. Weighing lysimeters have been used for many years to measure and study water use, and to develop crop-coefficient functions necessary in estimating ET. Electronic weighing lysimeters, consisting of a steel outer tank and inner tank, electronic loadcell assemblies, and a PVC drain system, were designed, constructed, and installed. Each lysimeter cost approximately US$1700 (in 2001) in materials, required two people and 40 hours of labor to construct, and were installed by two people using minimal excavation and hand tools. Daily ET data for cotton were collected from 2003 to 2006 to quantify cotton water-use and to develop crop coefficient functions. Seasonal water use ranged generally from 2 to 8 mm/d. Seasonal water-use patterns varied considerably among growing seasons due to variable environmental and crop-growth conditions, making determination of an "average" crop-coefficient function difficult.

Keywords: weighing lysimeter, evapotranspiration, crop coefficient, water use efficiency, cotton
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1 Introduction

Knowledge of crop evapotranspiration (ET) is important in modeling ET and crop growth, scheduling irrigations, and optimizing crop production. The ET is the combined process of evaporation from soil and plant surfaces, and plant transpiration, and is a measure of the amount of water used by a soil-plant-atmosphere system. The ability to measure, estimate, and predict ET and crop water requirements can result in better satisfying the water needs of crops and improving water-use efficiency.

A number of methods have been developed for estimating ET mainly based on climatic and agronomic information. Guidelines established in the United Nations Food and Agriculture Organization's FAO-24 publication[1] were in use for many years. These guidelines were updated, and a standardized method of estimating ET was outlined in the FAO-56 publication[2]. This standardized method involves firstly calculating the ET from a "reference" surface, usually grass, based on weather variables to estimate the evaporative demand of the atmosphere. The reference, ET and ET_o are then adjusted by applying a crop-specific crop coefficient function, K_c, which accounts for physical and agronomic differences between the crop and the reference surface. The actual crop ET and ET_c are estimated as $ET_c = K_c \times ET_o$.

Crop water use and crop-coefficient functions have been developed for a number of crops in several parts of the world, and are included in the FAO-24 and FAO-56 guidelines[1,2]. Allen et al.[2], however, suggested that, since varietal, environmental, and cultural conditions

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could vary significantly among locations, functions developed in one environment would likely not be readily transferable to another. To develop crop coefficient functions, measurements of actual crop-water use are collected throughout the growing season. Daily K_c values are calculated as the ratio of crop *ET* to reference *ET*, and a relationship is developed to estimate K_c throughout the season.

Weighing lysimeters have been used for many years to measure and study water use, to calibrate reference *ET* methods for a local area, and to develop crop-coefficient functions for specific crops. A weighing lysimeter provides a direct measure of the amount of water used in evaporation and transpiration by isolating and continuously monitoring a vegetated area in a field. A number of researchers around the world have reported on recent studies using lysimeters to develop crop-coefficient functions for a variety of crops, such as pulse crops in India[3], corn in Spain[4], rice and sunflower in India[5], wheat and maize in China[6], and cotton and wheat in the USA[7].

Lysimeters of many different designs, sizes, shapes, and measurement systems have been built over the years[8]. Early weighing lysimeters often contain mechanical mechanisms and electrical circuitry to obtain relatively high-resolution measurements, and required regular maintenance. This could result in high costs in terms of purchase, operation, and labor. Advances in electronics, datalogging equipment, and strain-gage loadcells have allowed for the design of simpler lysimeters which are less expensive, accurate and reliable, and require less maintenance.

The objectives of this project were to 1) design, construct, and install simple electronic weighing lysimeters for measuring reference (grass) *ET* and crop *ET*; 2) measure *ET* continuously throughout the growing season; and 3) evaluate the use of crop *ET* measurements for developing crop-coefficient functions under local environmental conditions.

2 Materials and methods

2.1 Design and construction

Weighing lysimeters were designed with ease of fabrication, simple installation, minimal maintenance requirements, and low cost being important considerations. Each lysimeter consisted of four main components; an inner tank, outer tank, loadcell assemblies, and drain system. Installed in the field, the inner tank contained a volume of soil and vegetation isolated from the field. The outer tank isolated the inner tank from the field and provided a foundation for mounting the loadcell assemblies. The loadcell assemblies supported and monitored the weight of the inner tank. The drain system allowed for any excess water accumulated in the inner tank to be removed.

The design was based on the reports of Allen[9], which was modified to change the location of the loadcells. Originally mounted above ground, on top of the lysimeter's inner tank, the loadcells were exposed directly to the environment, resulting in rapid temperature changes which adversely affected loadcell performance and lysimeter measurements[10]. This design was modified to minimize thermal effects on the loadcells by positioning the loadcells under the tank, below the surface where temperature changes were much smaller. The modified lysimeter was designed for monitoring crop *ET*, and had an inner tank with surface-area dimensions of 1 m wide x 1.5 m long and inside-depth of 1.5 m. An assembly drawing showing cutaway top and side views is represented in Figure 1. The inner and outer tanks were constructed of steel plate and U-shaped channel stock. The four side walls and bottom plate were made of standard 4.8-mm (3/16-in) steel plate. Steel 76-mm (3-in) U-channels was welded to the side and bottom plates to provide additional strength and to prevent the plates from bending. Continuous welds along each corner joined the side and bottom plates to form each tank and to provide a water-tight seal. Each completed tank was then painted with white enamel paint to protect against rust.

The four loadcell assemblies consisted of stainless steel shear-beam loadcells and leveling mounts. Each loadcell, Sensortronics Model 65023 (Vishay Sensortronics, Covina, CA USA) had a 2272-kg (5000-lb) capacity. Stainless steel leveling mounts, LEVEL-IT Model 19T2LTM (J.W. Winco, Inc., New Berlin, WI USA) were threaded into the loadcells to support the inner tanks. The height of the mounts could be adjusted to ensure that the inner tank was level and that there was an even distribution of weight on each loadcell. Views of the loadcell mounting assemblies are shown in Figure 2.

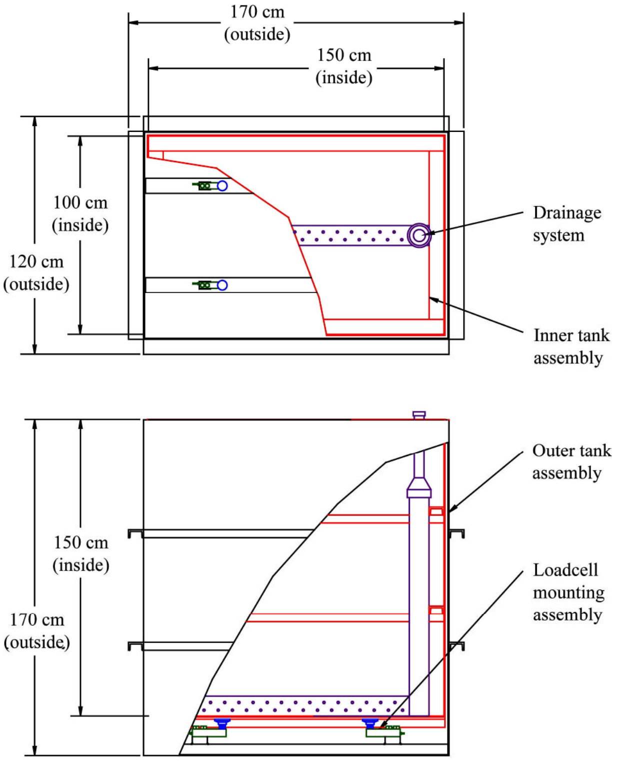


Figure 1 Top and side cutaway views of lysimeter assembly

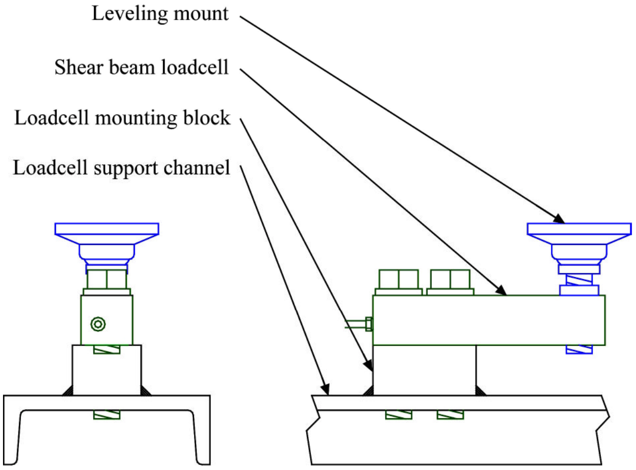


Figure 2 Views of the loadcell mounting assemblies

The drain assembly was constructed from 15-cm (6-in) and 7.6-cm (3-in) diameter PVC pipe and fittings (Figure 1). A section of 15-cm diameter perforated pipe was laid horizontally, and an end cap was glued to one end. A 1-m length non-perforated, 15-cm diameter pipe was set vertically and glued into a hole to cut in the perforated pipe. A reducer fitting and length of 7.6 cm pipe was glued to top of the vertical pipe so that the overall length of the standpipe reached 155 cm and an end cap was placed on top.

Fabrication of each lysimeter required two people and approximately 40 hours of labor to assemble and weld the components. The total cost of materials for each lysimeter (in Mississippi USA 2001) was approximately US$ 1 700: US$750 for steel plates and channels, US$ 820 for four loadcells, US$ 100 for leveling mounts, and US$ 30 for PVC pipe and fittings.

2.2 Installation

The lysimeters were installed at the USDA Agricultural Research Service's Jamie Whitten Delta States Research Center, Stoneville, Mississippi USA (33.4° N, 90.9° W, elevation 38 m). Two lysimeters were installed in a 2.4 ha (6-ac) field dedicated to row-crop research in summer, 2002. The center-pivot irrigated field had plant rows running north-south, and the lysimeters were installed in the north-east quadrant of the field. Both lysimeters were installed in the same row, 1 m apart positioned, so that the long (1.5 m) dimensions had one plant row running down the centers of the inner tanks. The soil type is a Dundee silty clay loam.

Installation was accomplished by two people using a backhoe, forklift, hand shovels, and hand tools. The locations for each lysimeter inner tank were marked, and the soil in the rectangular area was removed with a hand shovel to a depth of approximately 30 cm. The soil was removed in large blocks to preserve as much of the existing soil structure as possible, and the intact soil blocks were set aside.

The hole was then enlarged to accommodate the dimensions of the outer tank. Soil was excavated using a backhoe by removing soil in layers of 30 cm to 40 cm thick, with each layer deposited in a separate pile. Excavation continued to a depth of 168 cm, and the bottom of the hole was leveled. The outer tank was installed in the hole using a forklift, the tank was checked to ensure that it sat level on the bottom of the hole, and soil was backfilled around the outer tank with hand shovels to a depth of about 1 m to stabilize the tank.

The loadcell assemblies were bolted to steel mounting blocks welded to the bottom support channels of the outer tank, and the heights of the leveling mounts were adjusted to achieve a level support platform for the inner tank. Loadcell wires were routed to a common corner of the tank, brought up the side and out of the tank to the surface, and connected to a datalogger. The inner tank was lowered slowly into the outer tank until it rested on the leveling mounts. The weight supported by each loadcell was checked with the datalogger to ensure that the load was evenly distributed. If the weights on each loadcell were not similar, the inner tank was lifted out, the heights of one or more leveling mounts were adjusted, the inner tank was reinstalled, and the loadcell weights were checked again.

The PVC drain system was positioned along the bottom of the inner tank. The tank and perforated pipe were covered with a layer of coarse gravel 20 cm deep, followed by a layer of coarse sand 15 cm deep, to help prevent clogging of the drain system when the inner tank was filled with soil.

The inner tank was backfilled by returning soil in layers from which it had been excavated to replicate the original soil profile. The soil was packed periodically to return it to its original bulk density, and backfilling continued until the soil reached 15 cm below the top of the tank. The soil blocks taken from the surface layer were replaced, and the remaining excavated area around the outer tank was backfilled and packed.

2.3 Measurement resolution

Lysimeter measurements were collected using a Campbell Scientific, Inc. (Logan, Utah USA) Model CR21 x electronic datalogger. The four loadcells from each lysimeter were connected to a separate input channel and monitored independently. Long-term, non-volatile data backup was provided by a Campbell Scientific, Inc. Model SM-192 storage module.

The resolution of lysimeter measurements was determined from the electrical characteristics of the datalogger and the loadcells. The CR21x utilized a 14-bit analog-to-digital converter (13 data bits + 1 sign bit) provides the capability of converting an analog signal into 2^{13}, or 8 192 digital values. An input channel range of 0 to 15 mV resulted in an input-signal resolution of 15 mV/8 192 bits = 0.00183 mV/bit. The resolution of the loadcells was based on their full-scale weight and signal output ratings. A full-scale rating of 2 272 kg, an output rating of 3 mV/V$_{\text{excitation}}$, and an excitation voltage of 2.00 V resulted in a loadcell resolution of 2272 kg / (3 mV/V$_{\text{excitation}}$ × 2.00 V$_{\text{excitation}}$) = 378.7 kg/mV. Combining the datalogger and loadcell resolutions resulted in a weight measurement resolution of 0.00183 mV/bit × 378.7 kg/mV = 0.69 kg/bit. Assuming the specific weight of water to be 1 g/cm^3, and knowing the surface-area dimensions of the inner tank (1 m × 1.5 m), the weight resolution could be converted to express the measurement resolution as a depth of water: 0.69 kg/bit / 1 g/cm^3 / 1.5 m^2 = 0.46 mm/bit.

2.4 Calibration

Following installation of the lysimeters in the field, a calibration routine was followed to ensure the proper functioning and accuracy of the loadcells. For each lysimeter, a series of eight known weights was placed one at a time on the lysimeter, and the total lysimeter weight was recorded. The weights were then removed one at a time, and the total lysimeter weight was recorded. The changes in weight recorded by the loadcells were then calculated and compared to the known changes in weight. Results from one lysimeter are shown in Figure 3, with results from the other lysimeters equivalent to that shown. The loadcells accurately accounted for the weight changes, both increasing and decreasing.

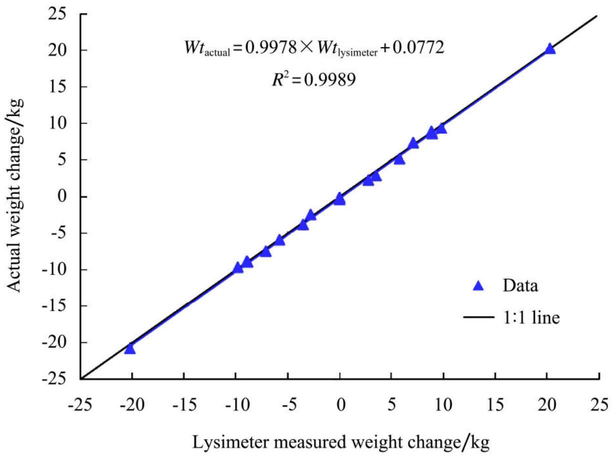


Figure 3 Calibration results for one lysimeter

2.5 Operation

The datalogger was programmed to collect and record loadcell measurements at one-hour intervals. For each lysimeter, an excitation voltage was sent to the four loadcells, each loadcell was read 10 times, and the average of the 10 readings was calculated. The four average weights were summed to determine the total weight of the lysimeter, and the four average weights and total weight were stored in the datalogger memory and the backup storage module. Data were periodically downloaded from the storage module and input to a spreadsheet for graphing and analysis.

Routine maintenance involved periodic visits to the lysimeter sites to check the condition of the vegetation on and around the lysimeters. The lysimeters was occasionally tilled, fertilized, and sprayed by hand if the mechanized field equipment was not able to access the lysimeters. Occasionally, excess water accumulated inside the inner tank due to restricted drainage caused by the inner tank's bottom plate, and the water was removed using a battery-powered electric pump. On a few occasions, heavy or prolonged rainfall caused local flooding in the fields, and water entered between the inner and outer tanks. The loadcells were not damaged, but the data were not available during these periods and had to be pumped out.

Hourly and daily ET amounts were determined from changes in lysimeter weight from one period to the next. Water evaporating from plant and soil surfaces and transpiring through plant tissues caused the weight of the inner tank to decrease. Weight changes, in kilogram, were converted to an equivalent depth of water, in millimeter, by dividing the weight change by the density of water (g/cm^3) and the surface area of the inner tank (m^2).

A sample of hourly data collected during a four-day period in the 2005 growing season is shown in Figure 4. Total lysimeter weight decreased continuously during the first three days due to ET. On the fourth day, a brief rain event was observed, which caused the weight to increase. Each day, the total change in water content was determined by accumulating the hourly weight changes and converting to equivalent water content. Daily changes were determined by summing the 24 hourly values from 07:00 on one day to 06:00 on the following day, to correspond with daily weather data reported by the weather station located at the experiment station.

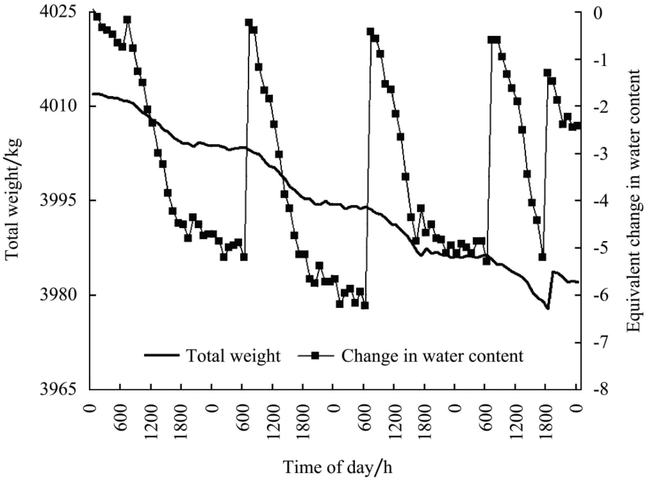


Figure 4 Hourly cotton lysimeter data showing total weight and cumulative change in water content for a four-day period

3 Results and discussion

3.1 Lysimeter measurements

Cotton was planted in the lysimeters and surrounding field in spring, 2002. The 2002 season was used to resettle the soil inside the inner tanks, with soil added as slight settling occurred, and to ensure that electronic components functioned properly. In the four-year period from 2003 to 2006, cotton was grown and data were collected to evaluate water use and develop crop coefficient functions for water-balance modeling and irrigation scheduling. Planting and harvest dates for the ST4892 variety in the four years are listed in Table 1.

Table 1 Planting and harvest dates, and summary of seasonal weather data in 2003-2006

Properties	2003	2004	2005	2006
Planting date	22 Apr.	22 Apr.	12 Apr.	15 May
Harvest date	8 Sept.	20 Sept.	21 Sept.	11 Sept.
Mean air temperature (°C)	25.7	25.3	25.9	27.3
Mean relative humidity (%)	71.0	66.3	64.3	64.6
Mean solar short-wave radiation (MJ·m^{-2})	19.8	21.4	22.1	23.3
Windrun mean (km·d^{-1})	78.8	83.4	75.4	63.9
Total growing-degree days (DD15)	1427	1499	1602	1417
Total rain (mm)	430	645	340	153
Length of season (d)	140	152	153	120
Lysimeter ET_c (mm)	567	546	496	530
FAO-56 ET_o (mm)	630	708	737	616

Lysimeter measurements of daily cotton crop-water use are shown for the 2003 through 2006 growing seasons in Figure 5. Also shown in the figures are daily rainfall amounts. Daily ET_c values varied considerably throughout each season and among seasons, and generally ranged from less than 1 mm/d to about 8 mm/d. In 2004 and 2006, a few days with ET_c values reaching 9 mm/d to 10 mm/d were observed. Maximum water use occurred approximately 90 days after planting in 2003 and 2006, and 120 days after planting in 2004 and 2005.

Environmental conditions, especially rainfall, varied greatly during the four-year study. In 2003, rainfall was distributed throughout the growing season, with total rainfall of 430 mm, close to the long-term average of 480 mm (see Table 1). Early in the season, daily ET_c of around 2 mm/d continued for around 30 days, after which crop-water use increased as the cotton plants grew. Peak ET_c approaching 8 mm/d lasted for about days, after which daily ET_c decreased steadily to a rate of less than 2 mm/d at harvest.

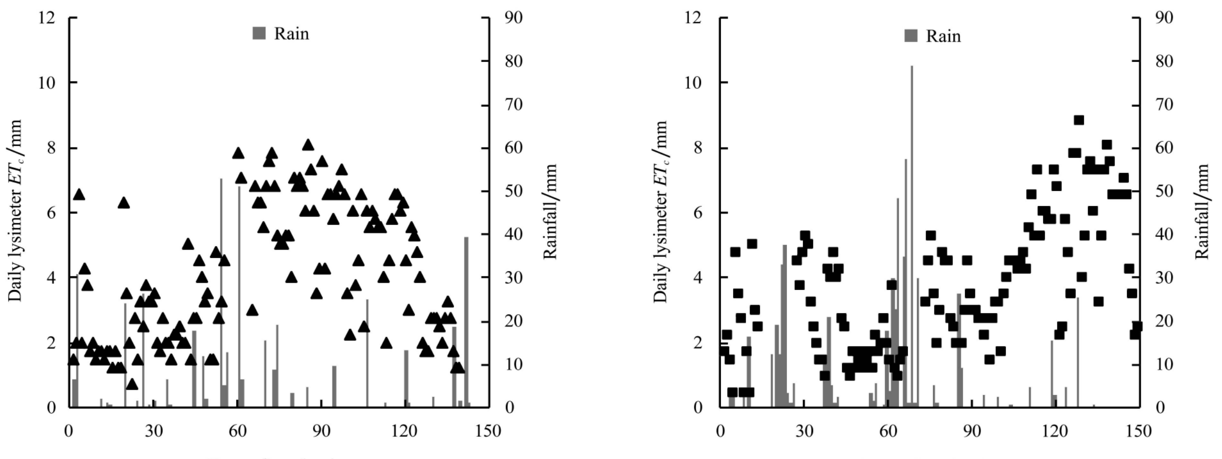
In 2004, high rainfall was experienced in the region which affected growing conditions and crop-water use. Rainfall early in the season resulted in wet soil conditions and high ET_c values due to wet-soil evaporation. Starting around 60 days after planting, the region experienced a nearly three-week-long period of rain totaling to 340 mm. Soils with very low intake rates and high rainfall resulted in flooded fields, with standing water visible for several weeks. This caused a delay in crop development region-wide, as well as in the lysimeters. As conditions improved and crop-growth resumed, daily ET_c increased to a peak lasting about 20 days before beginning to decrease.

In 2005, two tropical storms late in the growing season brought high winds and heavy rain. Early season growth was slower than in previous years, perhaps due to insufficient fertilizer application. As the period of peak ET_c approached, crops were damaged by heavy wind and rain that stripped the cotton plants of leaves and bolls. ET_c dropped immediately to less than 4 mm/d and rapidly decreased to about 1 mm/d.

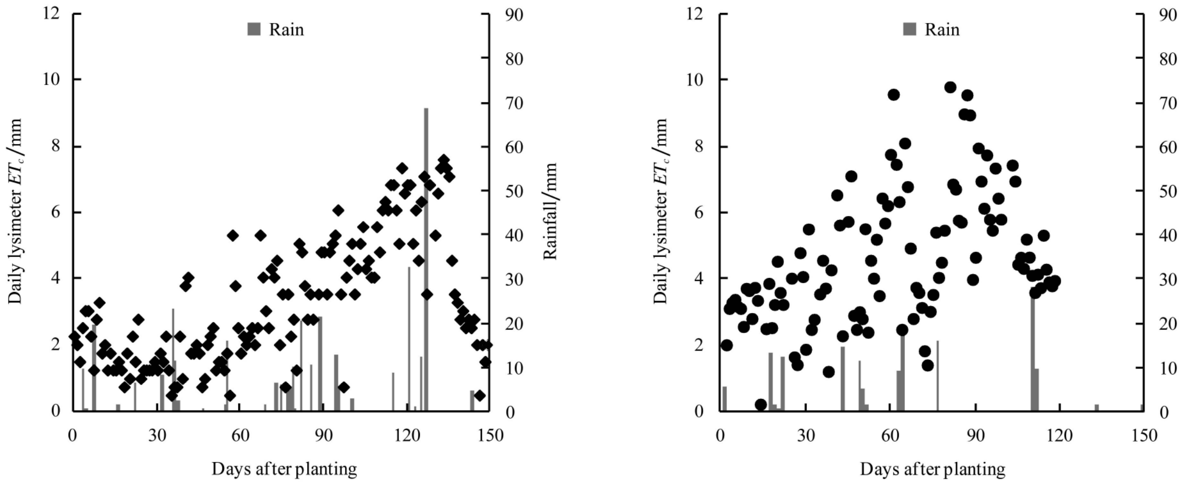
In 2006, planting was delayed for several weeks due to excessive rainfall early in the spring. The late planting resulted in a higher average air temperature and higher total solar radiation since the shorter growing season was comprised of longer and hotter days in late spring and summer. Lower-than-average rainfall in 2005 and 2006 required the cotton to be irrigated with the center-pivot overhead-irrigation system.

3.2 Crop coefficient functions

To develop crop coefficient functions, weather data were required for input to the FAO-56 reference ET model. Weather data were downloaded from the Mississippi State University weather-station network (http//:www.msucares.com) for the Stoneville location. Weather data included daily values of maximum and minimum air temperature, maximum and minimum relative humidity, total solar radiation, total windrun, and total rainfall. Maximum and minimum air temperatures were also used to calculate daily growing-degree days using a base temperature of 15.6℃. Summaries of seasonal weather data for each year are shown in Table 1.



a. 2003 b. 2004

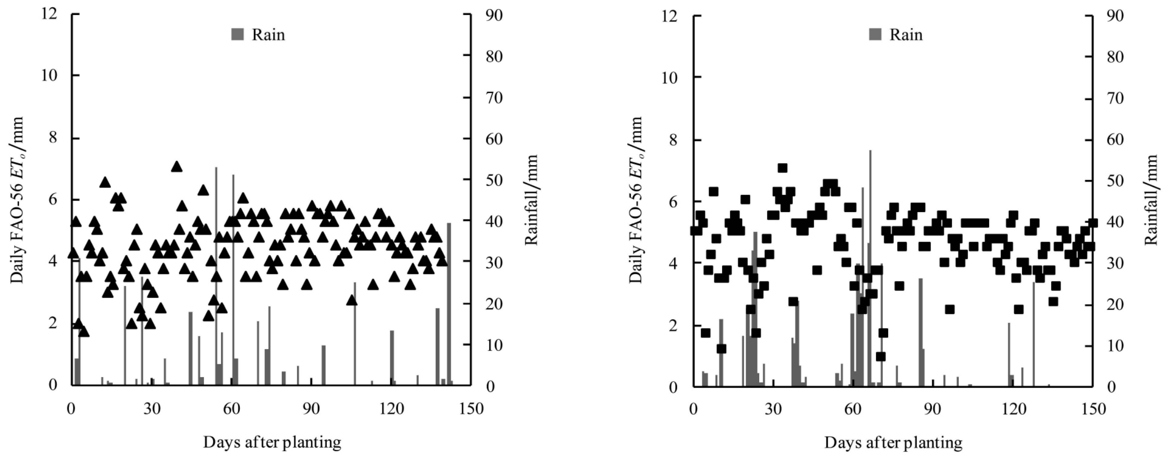


c. 2005

d. 2006

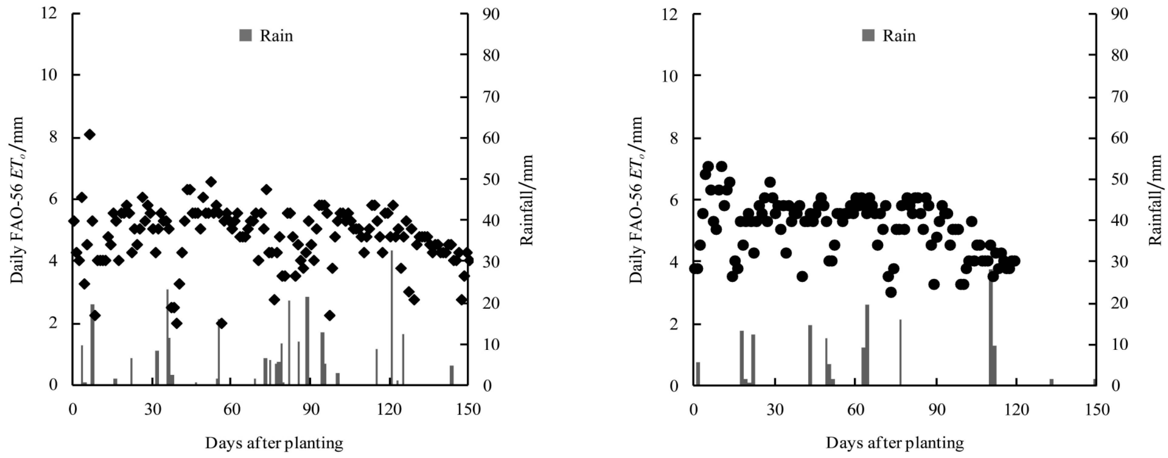
Figure 5 Daily lysimeter-measured ETc values for cotton grown in the growing seasons of 2003-2006

Daily reference *ET* values were estimated for each year by the FAO-56 model using the RefET: Reference ET Calculator computer software[11]. Daily weather data for each growing season were input to the software, which output daily ET_o estimates. Daily ET_o values for each season, shown in Figure 6a-6d, ranged mainly from 3 mm/d to 6 mm/d. Excessive rainfall in 2004, accompanied by extended periods of cool temperatures, resulted in ET_o values as low as 1 mm/d in many days.



a. 2003

b. 2004



c. 2005

d. 2006

Figure 6 ET_o estimates from weather data input to the FAO-56 model for each growing season

Daily crop coefficient, K_c, values for each season were calculated by dividing lysimeter measured ET_c values by reference ET_o estimates ($K_c = ET_c / ET_o$). A best-fit line, a third-order polynomial, was then fit to the data for each year. Daily Kc values and best-fit lines for each growing season, plotted against the number of days after planting, are shown in Figure 7. For each year, Kc values early in the season ranged from about 0.2 to 0.6, and from 1.1 to almost 1.3 during the peak period. The K_c curves varied greatly among years, indicating the large differences in crop growth patterns among years. During 2004 and 2005, the K_c curves were delayed by several weeks compared to those from 2003 and 2006. Such large differences in timing make it difficult to develop an "average" K_c curve, which could be used each season to estimate ET_c and crop-water use.

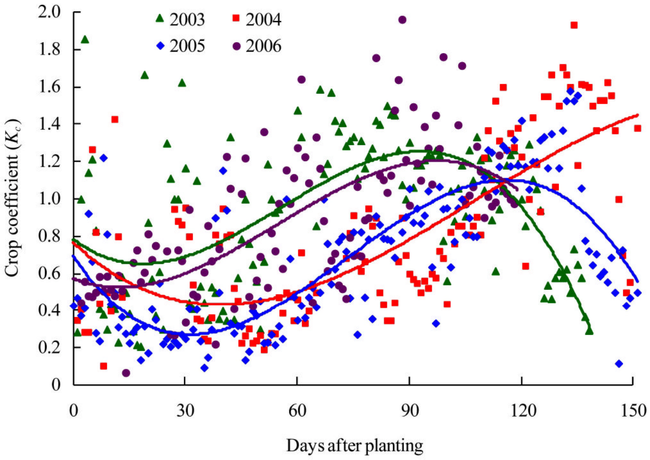


Figure 7 Daily K_c values and best-fit, third-order polynomials, plotted against days after planting

In an effort to account for variability in crop-growth development during the season, K_c curves were developed based, not on days after planting, but on growing-degree days (DD15). Daily K_c values were plotted against daily cumulative DD15s, as shown in Figure 8. The use of DD15s, however, did not reduce the variability in the seasonal Kc curves nor allow for the determination of a single "average" K_c curve usable from one season to the next. To account for seasonal differences in crop growth and water use, additional agronomic information (plant height, plant density, leaf-are index, physiological growth stage, etc.) may need to be collected to better identify comparable periods and relate them among different growing seasons.

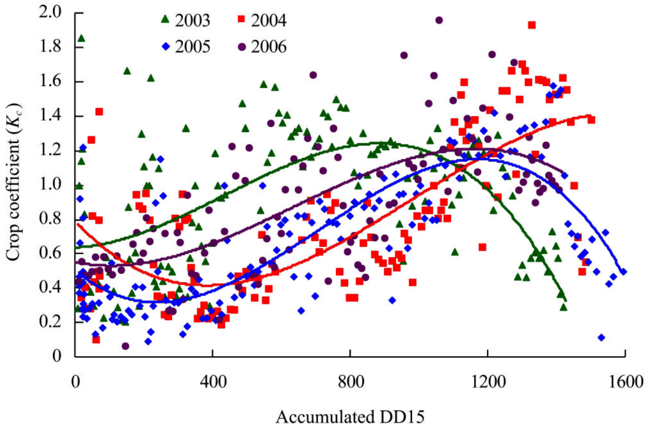


Figure 8 Daily K_c values and best-fit, third-order polynomials, plotted against accumulated growing degree days

4 Conclusions

Electronic weighing lysimeters were designed and constructed for monitoring reference (grass) and crop ET in the humid, southeast region of the United States. The lysimeters were designed to be simple and inexpensive, and consisted of a steel outer tank and inner tank, electronic loadcell assemblies, and a PVC drain system. Each lysimeter cost approximately US$ 1 700 (in 2001) in materials, and required two people and 40 hours of labor to construct. Installation of a pair of lysimeters was accomplished in two days by two people using minimal excavation and hand tools.

The ET data for cotton were collected each growing season from 2003 through 2006. Lysimeter data were used to quantify crop-water use under local environmental conditions, and cotton water use was found to range from 2 mm/d to 8 mm/d. Environmental conditions, including rainfall, varied greatly in this region from one growing season to the next, affecting crop-growth and crop-water use patterns. Crop coefficient functions also varied greatly among seasons, making development of a single "average" crop-coefficient curve difficult. In a region with considerable seasonal variability, a crop-coefficient function based on days after planting or growing-degree days may not properly account for changing growth patterns, and additional agronomic information may be needed to develop functions usable from one season to the next.

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Disclaimer

Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the U.S. Department of Agriculture and does not imply approval of the product to the exclusion of others that may be available.

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