A COMPARISON OF TWO METHODS FOR MEASURING PHREATOPHYTE TRANSPIRATION: POROMETRY AND WEIGHING LYSIMETER

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INTRODUCTION

Water planners in arid regions are faced with the problem of allocating scarce water resources to the multiple demands of fish and wildlife, recreation, agriculture, municipalities, and industry. An important factor they must consider is "conveyance losses," natural pathways by which water in streamflow is diverted into temporary storage or permanently lost from fluvial systems. Examples include water surface and soil evaporation, percolation to deep aquifers, streambank water table storage, and riparian vegetation transpiration.

Consumption of water by riparian plants is a two-edged sword. On the one hand, the water they transpire is removed from the riparian ecosystem and can no longer contribute to streamflow. This has led to attempts to increase streamflows by riparian vegetation removal (*e.g.*, Culler 1970). On the other hand, riparian vegetation stabilizes streambanks, reducing erosion and building river terraces where water fluxes into and out of water tables help reduce peak flows in spring and increase late-summer flows (Mizell and Skinner 1986). Riparian vegetation also benefits fish, wildlife, water quality, and recreation (Johnson and Haight 1984).

A knowledge of riparian plant transpiration is useful in a number of contexts, including predicting water delivery from mountain snowpacks to the lowlands, partitioning conveyance losses into various pathways (Hasfurther and Pahl 1986), and weighing the water "cost" of increased transpiration *vs.* the flood control, water quality, wildlife, and recreation benefits of degraded riparian zone restoration (Platts and Nelson 1985, Skinner et al. 1986).

Attempts to measure riparian zone evapotranspiration (the combination of leaf transpiration and soil evaporation) have occurred for many years. The most widespread method, used extensively in the American Southwest, has been direct measurement of water losses from non-weighing lysimeters (Gatewood *et al.* 1950, McDonald and Hughes 1968, Robinson 1970, van Hylckama 1974, Borrelli and Burman 1982, Davenport *et al.* 1982). These instruments provide long-term records of water use within specific stands of

vegetation, but they have several disadvantages. First, they are difficult to install and have long start-up times, making replication expensive. Second, their accuracy is dependent on careful measurement of the specific yield of the soil inside them, an inherently inaccurate procedure. Finally, their temporal resolution is about one month. Thus, non-weighing lysimeters cannot be used to predict how evapotranspiration changes in response to short-term changes in weather and canopy leaf area, necessary components of any predictive model for riparian evapotranspiration.

Use of direct-weighing lysimeters, with no need to measure specific yield, has provided daily and even hourly accounting of evapotranspiration from crops and trees (*e.g.*, Ritchie and Barnett 1968, Fritschen *et al.* 1973, Rodrigue *et al.* 1983, Klocke *et al.* 1985). However, these instruments are costly and difficult to maintain, so that replication is seldom feasible.

Instantaneous water loss from individual leaves may be measured with diffusion porometers. This method focuses on transpiration separate from evaporation and has a temporal resolution of minutes or seconds. Provided adequate sampling occurs and total leaf areas are measured, water use rates of entire stands of vegetation can be estimated (*e.g.*, Dolan 1988). Smith *et al.* (1987) used porometry to estimate seasonal water use by several riparian vegetation types in southeast Wyoming. The major drawback is the problems associated with extrapolation from leaves to whole canopies, *e.g.*, spatial variability in stomatal apertures (Leverenz *et al.* 1982). Nevertheless, the low cost and high portability of porometry holds great promise for its widespread use to estimate short- and long-term water use by various riparian vegetation types, stand ages, and species. However, confidence in the results of porometry requires calibration against independent methods known to be of high accuracy.

Purpose of This Research

In 1984, the Department of Agricultural Engineering at the University of Wyoming installed a sensitive weighing lysimeter for measurement of evapotranspiration by

shortgrass prairie in the Laramie Basin (Sayler *et al.* 1985). Initial tests of the instrument indicated a resolution of 0.2 mm of water, or a daytime temporal resolution of less than one hour at high rates of evapotranspiration (> 5 mm d^{-1}). Thus, this instrument promised sensitivity and resolution comparable to porometry, making it well-suited as a rigorous method, accounting for all water inputs and outputs, against which porometry could be calibrated.

This research involved a comparison of transpiration of a particular riparian species independently and simultaneously estimated by the weighing lysimeter and with a diffusion porometer.

METHODS

Study Site

Measurements were carried out on the floodplain of the Big Laramie River (41°19"N, 105°36"W; elevation 2200 m), 8 km southwest of Laramie. To avoid flooding in spring, the site was located in shortgrass prairie at the outer edge of the floodplain, approximately two meters above and 0.5 km away from the river channel. The natural water table was more than two meters below the surface.

The Weighing Lysimeter

Construction

The lysimeter consisted of a 1.05-meter diameter x 1.37-meter deep steel cylinder suspended within a slightly larger steel cylinder (Fig. 1). Both cylinders had sealed bottoms and were inserted into the ground so that their open tops were flush with the surface. The outer cylinder was anchored to concrete blocks embedded in the soil. Three circular steel rings, spaced 120° apart around the perimeter of the outer cylinder, were suspended between the two cylinders with turnbuckles (Fig. 1). Four strain gauges were glued to the sides of each ring and wired in parallel to form load cells which measured the mass of the inner cylinder. Excitation voltages were supplied to the strain gauges by

a solar-powered data logger (Campbell Scientific model CR-7). Wheatstone bridge circuitry combined, linearized, and temperature-corrected the electrical signals from the strain gauges of each load cell (Sayler *et al.* 1985).

Duct tape between the rims of the two cylinders excluded soil and rainfall from the outer cylinder and an external metal access tube permitted any water which did accumulate there to be pumped out.

Calibration

Initial calibration of the lysimeter was accomplished on July 20 by successively adding known weights to the lysimeter and recording the mean voltage output from the three load cells, as recommended by Bao (1986) (Table 1). This procedure, repeated four times, produced linear relationships between output and mass (Table 2). The slopes of these relationships were identical for each calibration trial but, as indicated by the differing intercepts, the output did not return to its original (no mass added) value between successive trials (Table 2). A repeat calibration on August 25 showed the same pattern.

Since these calibrations were not consistent among trials, an alternate calibration procedure was tried. Measured amounts of water were added several times during the summer to replenish water lost through evapotranspiration, as described below. These water additions were made nearly instantaneously via the access tubes in the lysimeter and produced increases in lysimeter mass over one to two hour periods. For each addition, the mass change indicated by the data logger was much larger than the actual mass of water added; the ratio of the two values varied from 3.80 to 5.53, with a mean of 4.54 (Table 3). This result indicated that the slope of the initial calibration was much too small. A possible explanation was the 1-2 hour time lag between mass additions and mass changes recorded by the data logger. This time lag was not accounted for in the initial calibration because weights were added to the lysimeter at intervals of less than five minutes. At the end of the summer, all lysimeter mass change values were corrected using this second type of calibration.

Plant Material

Species

Riparian zones in intermontane basins of Wyoming are dominated by phreatophytes, woody trees and shrubs possessing deep taproots which penetrate to water tables (Meinzer 1927, Robinson 1958). The major phreatophytes in Wyoming, willows (*Salix* species) and cottonwoods (*Populus* species), have transpiration rates among the largest of any plants in this region (Young *et al.* 1985, Smith *et al.* 1987). The willows, being fast growing, are the focus of attempts to restore degraded riparian zones (Skinner *et al.* 1986). We chose sandbar willow (*Salix exigua* Nutt.), the most widespread riparian species at low elevation in southeast Wyoming, for our experimental material.

Transplantation

Five whole clumps of sandbar willow were transplanted from an open willow stand adjacent to an irrigation ditch about 0.5 km from the study site but still on the Big Laramie River floodplain. The clumps had a mean height of 1.6 m and a mean crown diameter of 1.0 m. Transplantation occurred in late June, about three weeks after budbreak. The shallow lateral root system of each clump was excavated along with an encasing soil ball. As much of the deep taproots as possible was also recovered, but at least one taproot from each clump had to be severed at about 1 m depth.

The bottom of the lysimeter was filled with 10 cm of gravel and distilled, deionized water added to bring the water table to the top of the gravel. The willow clumps were placed on top of this layer, and the root balls were surrounded by soil supplied from a nearby pit. The soil was added in 20-30 cm depth increments, saturating each layer with deionized water before adding the next. A layer of gravel 10 cm deep was placed on top of the soil, flush with the lysimeter rim, to reduce surface soil heating and minimize soil evaporation (see Fig. 1).

Three vertical PVC access tubes were installed to within 3 cm of the bottom of the lysimeter (Fig. 1). Over a period of about a week, water was withdrawn from these tubes

until a water table depth of 50 cm was achieved.

Transpiration Measurements: Lysimetry

Evapotranspiration

The combination of willow transpiration and soil evaporation produced a cumulative reduction over time of the mass of the lysimeter. Water inputs occurred as precipitation and as deliberate additions to maintain the water table (Table 4). Precipitation was summarized hourly with a tipping-bucket raingauge (Sierra model RG-2501) connected to the data logger. Every 3-4 days, the water table depth was measured. The intent was that, if the water table declined by more than 5 cm, sufficient water was to be added to return the water table to 50 cm depth. In practice, the specific yield estimate (3%) turned out to be too low, probably because several days had to elapse before the water table depth equilibrated following water additions or removals. As a result, not enough water was added to maintain the 50 cm level and the water table gradually dropped to 75 cm by the end of the summer.

Evapotranspiration (ET) was calculated as follows:

$$ET = M_{t-1} - M_t + P + W \qquad \text{(Eq. 1)}$$

where M = lysimeter mass at the time of the current (t) and previous (t-1) measurement, P = precipitation, and W = water added. Starting July 20, M and P were recorded hourly by the data logger and the time of water additions was noted.

Soil evaporation

Two "bucket" lysimeters (Pochop *et al.* 1978) were installed adjacent to the weighing lysimeter on July 28 to provide estimates of soil evaporation for calculating the fraction of lysimeter evapotranspiration attributable to willow transpiration. These consisted of 30-cm diameter PVC pipes, 1.37 m long, sealed at the bottom ends, and installed vertically in the ground with their open tops flush with the surface. Each was backfilled with soil and gravel and a water table was created in a fashion similar to the weighing lysimeter.

Plastic handles permitted removal for weighing on a large-capacity balance at 3- to 14-day intervals.

Climatic data

Supplementary measurements of climatic parameters and soil temperature were carried out to determine whether or not they could be used to predict diurnal or total daily evapotranspiration. Climate sensors were mounted on a steel mast 5 m downwind of the lysimeter. Air temperature and relative humidity were measured at 1 m height beneath a radiation shield with a thermistor/Vaisala probe (Phys-Chem Research model PCRC-11). Windspeed and wind direction were measured at 3 m height with a cup anemometer and a wind vane (Met-One models 014A and 024A). Solar radiation was measured with a silicon-cell pyranometer (Li-Cor model 200S). Soil temperature was measured with copper-constantan thermocouples at three depths (5, 25, and 100 cm; three replicates each depth) in the lysimeter. All sensors were scanned by the data logger at hourly intervals.

Transpiration Measurements: Porometry

Leaf transpiration rates

Transpiration rates per unit leaf area (T) of the willow foliage in the lysimeter were calculated from field measurements of stomatal (g_s) and boundary layer (g_b) conductances to water vapor, leaf and air temperature, and relative humidity as:

$$T = 1/(1/g_s + 1/g_b) \cdot LAVD \qquad \text{(Eq. 2)}$$

where g_s was summed for both leaf surfaces and LAVD = leaf-to-air water vapor deficit, the difference between saturation water vapor density at leaf temperature and water vapor density at air temperature and relative humidity. Boundary layer conductances were calculated as $283 \cdot (\text{leaf diameter/windspeed})^{0.5}$ (Campbell 1977).

Stomatal conductances were measured in the field between dawn (0600 h) and dusk (1900-2000 h) during eleven days in July, August, and September. On July 23, measurements continued through the night until 0600 h the following morning, while on August

11, measurements began at 1800 h and continued until 1800 h the next day. Thus, two 24-hour records of transpiration were obtained.

On the first sampling day, fifteen current-year shoots were selected randomly, three on each of the five clumps. A single leaf from the middle of each shoot was marked with flagging. These leaves were used for all subsequent stomatal conductance measurements. If a leaf was damaged during or between sampling, another leaf on the same clump was randomly chosen to replace it.

The hourly sampling procedure was identical for each leaf. First, leaf temperature was observed with an infrared thermometer (Barnes Engineering model 111). Then top and bottom surface stomatal conductances were measured with a steady-state, null-balance diffusion porometer (Li-Cor model LI-1600, patterned after Beardsell *et al.* 1972; Fig. 2), corrected for the effects of ambient atmospheric pressure on the diffusion coefficient of water vapor in air (Monteith 1973). Ambient relative humidity, equal to cuvette relative humidity because of the porometer's null-balance design, was measured with a Vaisala sensor inside the cuvette. Ambient air temperature and windspeed at mid-canopy height (0.85 m) were recorded with a radiation-shielded thermocouple and a sensitive cup anemometer (Thornwaite Associates model 901) mounted on an aluminum mast adjacent to the lysimeter and connected to the data logger.

The influence of leaf position along shoots on transpiration was assessed on five of the sampling days in July and August. In early to mid-afternoon, transpiration was measured on three leaves on one shoot from each clump. One leaf was located near the base of the shoot, one in the middle, and one near the end.

Senescing (yellow) leaves of *S. exigua* in autumn are known to have lower stomatal conductances than non-senescent (green) leaves (Smith *et al.* 1987). To account for this, transpiration of three still-green and three entirely yellow leaves on each clump were measured at midday on September 8.

Leaf areas

In late June, the total number of current-year shoots on each clump was counted. Every twentieth shoot on each clump was tagged for length remeasurement at two-week intervals. Following each set of remeasurements, twenty current-yr shoots, spanning the same range of shoot lengths as observed on the lysimeter willows, were removed from willows growing in the area from which the lysimeter willows were originally transplanted ("natural" willows). The lengths of these shoots, and the length and width of every other leaf from the base to the tip of each shoot, were measured. In late August, 200 leaves were randomly selected on additional shoots from the natural willows, measured for length and width, and their areas determined with a video area meter (Decagon Devices). From these data, a linear regression between leaf area and leaf length and width ($r^2 = 0.94$) was applied to the natural willow shoot lengths to estimate total leaf area per shoot. Then a regression between shoot length and shoot leaf area ($r^2 = 0.96$) was applied to the lysimeter willow shoot lengths to estimate their leaf areas. Mean shoot leaf area per clump was multiplied by the total number of current-yr shoots on each clump (range 120-477) to estimate total clump leaf area.

At the end of August, leaves started to senesce. On September 2, 8, and 22, the leaves on each tagged shoot on each clump were assigned to four categories: 90-100% green, 10-80% green, 100% yellow, and abscised. The mean proportions of leaves in each category for each clump were used to estimate the fraction of each clump's leaf area which was green, yellow, or abscised.

Cumulative water use

Hourly and daily cumulative transpiration by the willows was calculated by hourly integration of the transpiration curves for each clump on each sampling day, then multiplying these values by total leaf area of each clump on the corresponding days. After August 26, transpiration was estimated separately for green and yellow leaves.

RESULTS AND DISCUSSION

Lysimetry

Evapotranspiration

The diurnal patterns of evapotranspiration during the first two weeks (July 20-August 3) indicated problems with the mass measurement system (*e.g.*, Fig. 3A). Cumulative daily evapotranspiration increased gradually just after dawn, then more rapidly until early afternoon, the pattern to be expected as willow stomata opened, light and temperature increased, and humidity decreased. However, starting in mid-afternoon on each day, cumulative evapotranspiration became negative, regardless of whether or not rain or water addition had occurred, even though temperatures were maximal and humidities lowest at that time of day (Fig. 3).

All electrical connections and circuitry, and the data logger programming, were double-checked and no problems found. One possible source of error was that changes in environmental temperatures caused expansion or contraction of the steel rings, turn-buckles, or lysimeter walls. If so, relationships between diurnal evapotranspiration and air or soil temperatures seemed likely. Cumulative daily evapotranspiration and air temperature did cycle in a similar fashion during daytime hours, but were out of phase (*e.g.*, Fig. 3A). Also, this relationship varied from day to day and disappeared at night. Soil temperature at 25 cm depth inside the lysimeter showed little diurnal variation (*e.g.*, Fig. 3A).

On August 4 the lysimeter was partially dismantled and a thermocouple could was taped to the inside of each load cell. Subsequently, load cell temperatures were measured concurrently with lysimeter mass changes. Load cell temperatures, like soil temperatures, showed only slight diurnal changes (*e.g.*, Fig 3B).

Linear regression of lysimeter mass change *vs.* load cell temperature was performed for midnight-to-midnight data collected for 12 days from September 30 to October 11 (Table 5). This period was selected because transpiration had ceased (all the leaves on the willows had abscised or been removed by hand), soil evaporation was expected to be

low, and, unlike summer, load cell temperatures changed noticeably during successive midnights. The regression was highly significant ($r^2 = 0.945$, $P < 0.001$), suggesting that load cell temperature did indeed influence the cells' response to lysimeter mass. Unfortunately, it was not possible to apply this regression to the seasonal lysimeter data because 1) load cell temperatures were not measured prior to August 4 and 2) the highest temperature used to derive the regression, 14.0°C, was much less than the maximum midnight load cell temperature earlier in the summer, 20.7°C.

Because of the diurnal cycles of lysimeter mass changes, hourly water use measurements were not reliable and the shortest time period for which lysimeter mass changes were possibly accurate was 24 hours, from midnight to midnight. This was the case because during the summer load cell temperatures generally returned to similar values on successive midnights. The time lag in the lysimeter response to mass changes did not appear to be a significant factor for midnight data because water use rates after sunset were very low.

All midnight-to-midnight lysimeter evapotranspiration data for the 65-day period, July 20 to September 22, were visually screened and days with obvious errors were either eliminated or, if possible, adjusted. There were two sources of error. First, following the partial dismantlement of the lysimeter on August 4, lysimeter mass data were very erratic. Much effort was expended in readjusting the lysimeter, with several additional days of erratic or missing data occurring before the lysimeter was successfully readjusted on August 30. Evapotranspiration data from many of these days was excluded from further analysis. Second, the data logger load cell programming was altered immediately following each lysimeter calibration (Table 1), producing abrupt shifts in recorded lysimeter mass. Data from these two days were adjusted to account for these shifts.

Daily lysimeter evapotranspiration data are shown in Table 6 and daily climatic data in Table 7. Seasonal patterns of several meteorologic variables are plotted together with daily evapotranspiration in Figure 4. Precipitation is a major determinant of the soil water supply for plant use. Solar radiation, air temperature, and atmospheric vapor

pressure deficit (VPD, the difference between saturation and ambient vapor pressure at ambient air temperature and relative humidity) influence LAVD, the driving force for transpiration (Eq. 2). There were, however, no significant correlations ($P > 0.05$) between daily evapotranspiration and any of these variables, singly or in combination; this lack of correlation is evident in Figure 4. Considering the apparent errors in daily lysimeter mass changes, this was a not unexpected result.

Soil evaporation

Water loss from the bucket lysimeters was very slow, so water additions were never necessary to maintain the water table at 50 cm depth. Cumulative evaporation (Table 8) was negative whenever rainfall exceeded soil evaporation. Total evaporation for the July 28-September 22 measurement period, corrected for rainfall and converted to the same surface area as the weighing lysimeter, was 46.3 kg. During this same period, cumulative weighing lysimeter evapotranspiration was estimated by summing daily evapotranspiration values (Table 6), with linear interpolation for periods lacking valid data. The estimated value was 191 kg. Thus, soil evaporation was, over the long term, 24% of evapotranspiration.

At least two factors could have caused differences in evaporation rates between the bucket and weighing lysimeters. First, the water tables in the bucket lysimeters remained near 50 cm, while that in the weighing lysimeter gradually dropped to 75 cm. Second, the lack of willows in the bucket lysimeters eliminated shading of the soil surface (although this was not substantial in the weighing lysimeter) and may have resulted in more depletion of soil moisture above the water table in the bucket compared to the weighing lysimeters.

Porometry

Leaf areas

Willow clump leaf areas did not differ significantly between mid-July and late August,

as indicated by analysis of variance (ANOVA, $P > 0.05$). Therefore, clump leaf areas were assumed constant during this time period at values equal to the means of all the biweekly shoot leaf area measurements (Table 9). Leaf yellowing commenced during the last few days of August, while leaf abscission started in mid-September. By September 22, the last day of measurements, 40% of the total leaf area in the lysimeter was still green, 27% was yellow, and 33% was abscised (Table 10).

Influence of clump, shoot position, and senescence

Transpiration rates differed significantly between clumps 27% of the time (ANOVA, $P < 0.05$), but the differences were not large except during the middle of the day on August 11 and September 22 (Fig. 5). Therefore, cumulative daily transpiration was calculated separately for each clump. However, the error incurred by using mean transpiration for all clumps combined would have been quite small (except on Sept 22) because most differences occurred at night or in the early morning, when transpiration was very low. Between-clump differences in transpiration of natural willows are probably larger because they often grow in dense thickets where light and wind levels experienced by individual leaves vary widely. This was not the case for the lysimeter willows, where most leaves were sunlit and fully exposed to the wind.

During no day did transpiration differ significantly with leaf position along shoots (ANOVA, $P > 0.05$; Table 11). Therefore, transpiration measurements from leaves in the middle of shoots, the sampling position for hourly transpiration measurements, were assumed representative of all leaves along a shoot. However, yellow senescing leaves on September 8 had mean transpiration 22% less than that of green leaves (1.32 vs. 5.92 mmol m^{-2} s^{-1}), a significant difference (ANOVA, $P < 0.05$). Therefore, daily transpiration was calculated separately for green and yellow leaves on and after August 30.

Hourly and daily transpiration

Transpiration rates increased rapidly on most days from zero (if dew was present) or

near zero (if foliage was dry) at dawn to maximum values by late morning (Fig. 5). On September 22, maximum daily transpiration was not attained until mid-afternoon, possibly because hard frost (-8°C) occurred the previous night (Table 7). The period of maximum transpiration on rainless days (all days except August 7 and 26) lasted 4 to 8 hours. Transpiration then generally declined to zero or near zero values by darkness, except for August 19, when it was still 50% of the midday maximum at dusk, and August 7 and 26, when evening rain occurred (Fig. 5). The clear-day patterns were qualitatively similar to those previously observed for willows in southeast Wyoming (Young *et al.* 1985, Smith *et al.* 1987).

During the night of July 23-24, stomata did not fully close and transpiration continued at low levels after dusk; there was even a transient "spike" in transpiration in the early morning for which we have no explanation (Fig. 5). The pattern was somewhat different the night of August 11-12, with transpiration declining to zero at dusk and a much smaller early morning spike (Fig. 5).

Cumulative daily transpiration by the willows varied from 0.82 to 4.55 kg (seven daytime-only values and two 24-hour values; nine of these values are shown in Fig. 6). For days without rain, transpiration was greatest in late July and diminished into September. Declining daylength and a dropping water table may have contributed to this decline. Daily transpiration was least on days with afternoon rain (Fig. 6). It increased throughout the night of July 23-24 because the stomata remained partially open, but did not increase the night of August 11-12 because the stomata remained closed or nearly closed (Figs. 5,6).

Water Use Comparisons

Seasonal comparisons

Most applications of water use measurements for riparian plants require seasonal estimates of transpiration or evapotranspiration. Short-term measurements must be extrapolated over time to obtain seasonal estimates. Ideally, this extrapolation is

accomplished through use of predictive models based on climatic, plant, and soil parameters. However, model development and validation are time-consuming and expensive. In addition, once predictive models are developed, field data required for future applications of the models may not be available. Several alternative, though more approximate, approaches are available. One of the most direct and easiest to apply is to interpolate water use measurements over time using averages of periodically-measured values. This is the approach used herein for the porometer data and for the days with missing lysimeter data.

Cumulative seasonal evapotranspiration was calculated for the period July 20 to September 22 in six ways: 1) Cumulative daily lysimeter mass changes (midnight-to-midnight), with linear interpolation when data were missing (Table 6). 2) Eleven daily values for porometry transpiration (Fig. 6), with linear interpolation for non-measured days. These values were divided by 0.76 to include soil evaporation, based on the bucket lysimeter data. No correction for nighttime transpiration was applied, although on some nights measurable transpiration probably occurred (Fig. 5). 3) The sum of water additions and precipitation (Table 4). 4) Class A pan evaporation at a weather station operated by the Wyoming Water Research Center at the Laramie lagoons (Table 6). 5) The modified Jensen-Haise formula (Jensen 1966; Table 6). 6) The ASCE Penman formula (Jensen 1973; Table 6). The latter two methods used daily weather data from the lysimeter weather station (Table 7). Due to malfunction of the cup anemometer, windspeed data collected at the Laramie lagoons were used.

Cumulative daily evapotranspiration is shown in Figure 7. Estimated seasonal values were 224 kg (lysimeter), 240 kg (porometry + evaporation), 156 kg (water additions + precipitation), 368 kg (pan evaporation), 281 kg (Jensen-Haise), and 365 kg (ASCE Penman). The sum of water additions + precipitation did not account for changes in the water table or in soil moisture storage above the water table, which probably was reduced by willow transpiration and soil evaporation and increased by precipitation. Assuming a seasonal drop in water table depth of 25 cm and a soil specific yield of 15%

(Borelli and Burman 1982), a maximum of 33 kg of water loss due to the water table drop was not accounted for by this method.

The other methods overestimated seasonal evapotranspiration compared to the water addition + precipitation method, but the differences were largest for pan evaporation and the two evapotranspiration formulae. Pan data are for a free water surface, where only available energy and boundary layer conductance limit evaporation. In contrast, water loss from the lysimeter was also limited by the gravel mulch and, more importantly, by stomatal conductances of the willow foliage. Thus, pan evaporation should have usually exceeded lysimeter evapotranspiration.

The Jensen-Haise and ASCE Penman methods are for well-watered reference crops with higher leaf areas per unit ground area than the willow clumps in the lysimeter. The willows probably also had lesser stomatal conductances than crops, implying less transpiration per unit leaf area. Deciduous woody plants have lower average maximum stomatal conductances (~3 mm s-1) than do crops (5-6 mm s-1) (Korner *et al.* 1979).

Lysimeter data, as previously discussed, were subject to time lag and calibration errors. Therefore, a small error in the water addition calibration method would have translated into a large error for seasonal evapotranspiration. Based on only eleven days of measurement, interpolation between porometry days probably missed much day-to-day variation in weather, and, hence, in transpiration rates. Therefore, the relatively close agreement between the porometry and lysimetry estimates, although encouraging, may be coincidental.

Diurnal and daily comparisons

Unfortunately, lysimeter data were either missing or erratic during six of the eleven days when transpiration was estimated by porometry. Because of this, and because of the low precision of the daily lysimeter data, no attempt was made to compare daily lysimetry and porometry transpiration estimates, the primary objective of this project.

CONCLUSIONS

Daily and hourly water consumption by the willow species, *Salix exigua*, near Laramie, Wyoming, was measured with two independent methods, weighing lysimeter and diffusion porometry. Five willow clumps were planted in a 1.37-m deep lysimeter with an artificial water table. Load cells connected to a data logger measured hourly mass changes of the lysimeter, and these values, corrected for rainfall and water additions to maintain the water table, represented total evapotranspirational water loss from the lysimeter. Separate non-weighing lysimeters without willows provided an estimate of soil evaporation. A steady-state porometer was used to measure stomatal conductances of individual leaves and transpiration rates per unit leaf area were calculated from conductances, leaf and air temperatures, and relative humidities. Multiplication of transpiration rates by total leaf area yielded estimates of total transpirational water use by the willows in the lysimeter.

Lysimeter evapotranspiration values displayed at least two types of error, one believed to be caused by changes in temperature somewhere in the system and one attributed to delayed responses in recording mass changes. Use of daily (midnight-to-midnight) lysimeter evapotranspiration minimized these sources of error. However, a lack of confidence in the precision of daily lysimeter evapotranspiration data, as well as an insufficient number of days with simultaneous porometry and lysimetry data, prevented a comparison of daily measurements between the two methods. How quantitatively valid the hourly and daily porometry data were remains unknown because they could not be compared with independently-calculated lysimetry data.

Comparisons of cumulative seasonal evapotranspiration estimates for the 65-day measurement period gave close agreement between porometer and lysimeter data, although the extensive use of interpolation, and the various errors associated with the lysimetry, could mean that this agreement is fortuitous. Both methods yielded larger values than the sum of water additions, precipitation, and estimated water table decline. The latter value, however, did not account for possible soil moisture changes which were not directly measured.

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Table 1. Load cell millivolt output vs. mass added for the first two lysimeter meter calibrations. Weights were added successively for all trials except trials 2 and 4 on the first date, when they were subtracted successively.

Date	Mass Added (kg)	Millivolts Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
07-20-87	0	3.6603	3.6644	3.6637	3.6620	------	------
	2	3.6661	3.6692	3.6688	3.6697	------	------
	5	3.6730	3.6758	3.6775	3.6753	------	------
	7	3.6801	3.6812	3.6816	3.6792	------	------
	10	3.6879	3.6883	3.6895	3.6871	------	------
	12	3.6924	3.6935	3.6945	3.6911	------	------
	15	3.7019	3.7010	3.7019	3.6996	------	------
	17	3.7070	3.7071	3.7054	3.7054	------	------
	20	3.7151	3.7156	3.7112	3.7143	------	------
	22	3.7200	3.7200	3.7191	3.7208	------	------
08-25-87	0	4.8120	4.8169	4.8218	4.8223	4.8207	4.8258
	2	4.8187	4.8246	4.8232	4.8276	4.8257	4.8262
	5	4.8308	4.8337	4.8272	4.8314	4.8355	4.8340
	7	4.8285	4.8335	4.8313	4.8386	4.8384	4.8394
	10	4.8369	4.8462	4.8394	4.8444	4.8455	4.8470
	12	4.8489	4.8475	4.8456	4.8527	4.8491	4.8518
	15	4.8514	4.8571	4.8544	4.8553	4.8583	4.8584
	17	4.8563	4.8626	4.8576	4.8585	4.8624	4.8644
	20	4.8591	4.8664	4.8638	4.8690	4.8662	4.8718
	22	4.8687	4.8668	4.8714	4.8684	4.8763	4.8752

Table 2. Results of linear regressions for lysimeter calibrations. Equation is mass added = intercept + (slope x millivolt output).

Date	Trial	Intercept	Slope	r^2
07-20-87	1	3.6603	0.002732	0.999
	2	3.6635	0.002552	0.999
	3	3.6645	0.002440	0.999
	4	3.6621	0.002572	0.998
08-25-87	1	4.8143	0.002439	0.987
	2	4.8198	0.002342	0.989
	3	4.8179	0.002337	0.993
	4	4.8227	0.002191	0.993
	5	4.8217	0.002399	0.996
	6	4.8229	0.002454	0.993

Table 3. Water additions and lysimeter mass changes indicated by the load cells 1-2 hours later.

Date	Water Added (kg)	Lysimeter Mass Change (kg)	Ratio Mass Change to Water Added
July 21	2	11.1	5.53
July 26	6	23.0	3.83
July 31	6	30.9	5.15
August 3	6	28.5	4.75
August 19	10	48.3	4.83
August 25	8	39.6	4.95
Sept 2	6	26.7	4.45
Sept 7	5	21.6	4.32
Sept 11	10	38.2	3.82
Sept 21	10	38.1	3.80

Table 4. Precipitation and water additions to the lysimeter.

Date	Precipitation (kg)	Water Addition (kg)
July 20	-----	5
July 21	-----	2
July 26	-----	6
July 27	1.47	--
July 28	2.86	--
July 30	4.85	--
July 31	-----	6
August 3	-----	6
August 6	4.59	--
August 7	12.38	--
August 8	0.52	--
August 11	0.61	6
August 13	2.86	--
August 14	0.26	--
August 15	2.86	--
August 19	-----	10
August 21	11.52	--
August 22	1.99	--
August 24	4.33	--
August 25	1.99	8
August 26	5.11	--
August 27	9.18	--
August 29	0.61	6
Sept 2	-----	6
Sept 3	0.52	--
Sept 4	0.26	--
Sept 7	-----	5
Sept 11	-----	10
Sept 15	0.52	--
Sept 16	0.26	--
Sept 21	-----	10
Total	69.55	86

Table 5. Lysimeter mass change and load cell temperature measured on successive midnights.

Date	Mass Change (kg)	Load Cell Temperature (°C)
Sept 30	-6.42	14.0
Oct 1	-5.69	14.0
Oct 2	-5.83	14.0
Oct 3	-5.83	14.0
Oct 4	-6.82	13.8
Oct 5	-11.23	13.0
Oct 6	-14.21	12.6
Oct 7	-14.63	13.0
Oct 8	-12.22	12.5
Oct 9	-20.45	9.9
Oct 10	-28.26	10.4
Oct 11	-23.72	10.6

Mass = -72.97 + 4.746·temperature $r^2 = 0.945$

Table 6. Measured (lysimeter) and estimated daily reference evapotranspiration.

Date	Lysimeter* (kg)	Jensen-Haise (kg)	ASCE Penman (kg)	Pan Evap-oration* (kg)
July 20	5.88	5.41	6.43	4.62
July 21	2.94	6.35	7.11	4.62
July 22	3.33	6.62	7.48	3.96
July 23	2.30	7.45	8.23	5.61
July 24	3.08	8.27	8.76	5.28
July 25	5.07	5.90	6.84	3.30
July 26	4.02	5.55	5.83	3.96
July 27	6.09	4.05	4.94	7.24
July 28	7.04	3.51	4.39	2.11
July 29	4.30	6.20	6.34	2.97
July 30	9.60	5.90	5.29	↓
July 31	7.97	5.94	6.45	9.02
August 1	5.88	7.04	7.10	7.26
August 2	9.10	6.43	6.63	8.58
August 3	7.10	6.23	6.85	10.56
August 4	----	6.16	7.36	9.24
August 5	----	5.25	6.52	8.58
August 6	----	3.41	5.06	4.18
August 7	----	3.39	4.80	3.30
August 8	----	5.22	5.76	3.96
August 9	----	6.04	6.65	7.26
August 10	----	6.18	7.26	10.56
August 11	----	3.32	4.94	6.60
August 12	3.79	5.38	5.96	7.92
August 13	3.12	3.85	5.41	5.94
August 14	1.17	5.12	6.67	7.26
August 15	6.34	4.17	5.98	10.12
August 16	0.33	5.29	8.03	7.92
August 17	2.26	5.17	7.51	9.90
August 18	1.87	5.31	7.15	10.56
August 19	4.06	5.41	7.48	7.92
August 20	3.95	3.21	6.04	9.24
August 21	----	3.45	5.23	↓
August 22	----	3.81	4.26	9.68
August 23	----	2.32	3.40	3.96
August 24	----	2.40	3.68	3.89
August 25	----	2.63	4.00	3.74
August 26	----	2.30	3.10	2.31
August 27	----	4.40	4.99	↓
August 28	↓	3.72	5.17	7.70
August 29		4.96	6.32	8.58
August 30	7.98	3.84	5.44	9.68
August 31	2.94	4.85	5.93	1.91
Sept 1	1.32	4.54	5.63	↓
Sept 2	0.88	3.86	5.56	
Sept 3	3.93	2.75	4.86	
Sept 4	3.01	2.84	4.18	↓
Sept 5	1.81	3.78	4.74	12.10
Sept 6	1.34	4.00	5.68	1.32

Table 6. Measured and estimated daily evapotranspiration (continued).

Sept 7	3.72	3.01	4.09	3.30
Sept 8	2.25	3.79	5.82	4.62
Sept 9	1.91	3.64	5.39	7.26
Sept 10	2.88	2.62	3.91	5.28
Sept 11	2.47	3.31	4.37	5.28
Sept 12	0.69	4.10	5.87	↓
Sept 13	2.03	3.00	5.23	
Sept 14	3.38	3.00	4.66	9.03
Sept 15	3.05	2.27	4.08	4.62
Sept 16	1.47	2.44	4.52	3.96
Sept 17	1.66	1.33	2.32	3.96
Sept 18	----	2.87	5.04	↓
Sept 19	0.63	2.84	4.58	10.56
Sept 20	0.18	3.08	5.24	5.28
Sept 21	↓	2.87	4.81	6.60
Sept 22	1.50	3.18	5.24	3.96

*"---" means missing value. Values following days with arrows are cumulative over that time span.

Table 7. Daily climatic data measured by the weather station.

Julian Day	Solar Radiation (ly)[1]	Air Temperature (°C) mean	max	min	Relative Humidity (%) mean	max	min	Wind-speed[2] (m/s)	Rain-fall (mm)
201	586	16.6	27.2	3.1	33.4	70.9	11.6	2.1	0.0
202	624	19.3	31.0	6.8	39.4	71.3	11.1	2.2	0.0
203	628	20.3	29.5	8.9	40.6	75.0	14.2	3.3	0.0
204	705	20.4	30.7	6.1	33.2	71.4	7.1	3.0	0.0
205	716	23.2	33.7	8.5	30.4	74.8	5.1	2.9	0.0
206	510	23.2	33.7	16.1	32.7	61.0	8.7	1.9	0.0
207	517	20.9	30.1	12.9	46.7	71.3	23.8	1.7	0.0
208	412	18.3	29.2	8.5	55.7	75.6	28.1	2.1	1.7
209	366	17.7	28.3	10.8	60.1	99.9	27.9	1.8	3.3
210	607	19.4	29.7	7.2	51.7	99.9	25.4	2.1	0.0
211	459	19.3	28.2	10.4	51.3	70.5	31.5	2.3	0.0
212	587	19.1	26.7	12.4	52.1	68.8	37.8	3.0	0.0
213	676	20.0	29.9	8.3	41.5	75.5	15.7	2.0	0.0
214	595	21.1	31.1	8.9	35.8	73.3	10.4	1.7	0.0
215	624	18.7	28.0	8.4	47.4	73.0	16.9	2.9	0.0
216	647	17.6	28.3	6.9	44.0	87.3	11.8	3.1	0.0
217	525	18.8	29.3	5.8	31.1	67.4	8.9	2.4	0.0
218	380	15.9	26.2	9.3	49.2	69.6	23.5	2.6	5.3
219	393	14.9	23.7	8.2	57.6	79.1	----	3.3	14.3
220	620	14.3	22.3	7.3	56.0	76.1	35.2	2.4	0.6
221	634	17.4	27.3	7.4	49.1	71.9	14.5	2.5	0.0
222	619	18.8	28.0	8.8	35.4	70.3	----	2.9	0.0
223	350	17.4	26.9	10.3	45.7	70.4	23.6	2.6	0.7
224	607	15.6	22.9	7.4	53.7	79.8	29.2	3.0	0.0
225	431	15.8	27.0	6.9	47.7	87.0	12.6	2.5	3.3
226	557	16.5	24.9	7.6	43.8	77.9	18.5	3.9	0.3
227	501	14.1	22.2	7.3	50.2	74.2	33.4	4.2	3.3
228	651	13.5	22.4	5.6	42.5	71.0	20.0	5.7	0.0
229	615	14.3	24.5	2.4	35.5	70.7	13.4	4.3	0.0
230	649	13.7	24.7	0.9	39.7	79.9	8.9	3.5	0.0
231	585	16.7	28.5	2.2	28.0	58.7	8.9	3.2	0.0
232	340	17.2	28.7	5.5	34.0	54.7	12.4	3.7	0.0
233	374	16.6	27.3	10.0	51.3	75.3	20.8	2.9	13.3
234	486	12.7	15.8	8.5	66.5	85.6	51.3	3.8	2.3
235	324	10.8	14.9	7.7	69.5	89.1	45.6	4.6	0.0
236	309	12.5	22.8	5.3	59.6	76.4	26.9	2.1	5.0
237	366	10.9	19.7	4.8	55.1	99.9	33.5	2.5	2.5
238	341	9.6	14.7	5.1	60.1	76.0	29.6	2.1	5.9
239	579	12.0	18.8	6.0	53.6	73.7	31.1	1.9	10.6
240	491	11.9	21.3	3.1	43.6	64.9	15.7	2.5	0.0
241	595	14.1	24.5	3.0	42.4	73.8	14.6	2.8	0.7
242	463	14.0	24.4	4.6	52.0	78.7	17.5	3.2	0.0
243	575	14.4	24.7	3.2	43.7	72.5	20.5	2.3	0.0
244	522	15.1	27.0	1.9	46.7	79.4	16.3	2.1	0.0
245	418	16.6	28.0	6.0	37.6	76.5	10.8	2.4	0.0
246	306	15.9	25.0	8.0	39.5	57.4	18.1	3.1	0.0
247	371	12.1	20.0	5.0	52.8	73.3	33.6	2.7	0.3
248	534	10.5	20.0	0.0	51.9	83.2	15.6	2.0	0.0
249	524	12.1	23.0	0.0	35.2	81.5	----	2.5	0.0

Table 7. Daily climatic data (continued).

250	441	9.8	18.0	0.0	54.1	70.5	36.8	2.5	0.0
251	473	13.2	23.0	3.0	38.1	72.2	12.9	3.4	0.0
252	450	13.4	22.2	3.4	37.9	77.3	13.3	3.1	0.0
253	395	9.3	19.5	-0.7	52.6	71.7	27.9	2.1	0.0
254	482	10.0	18.1	0.5	50.7	72.8	23.4	2.3	0.0
255	532	12.3	24.7	1.4	37.4	97.1	9.5	2.2	0.0
256	369	13.5	25.0	1.7	31.5	55.2	9.0	2.7	0.0
257	383	12.7	19.6	7.8	42.8	55.4	26.4	3.0	0.0
258	314	11.0	20.9	4.6	56.5	90.1	25.3	3.1	0.6
259	363	9.5	21.7	-0.9	52.9	84.7	18.8	3.1	0.3
260	230	6.8	12.2	2.6	61.0	93.5	39.5	2.3	0.0
261	477	7.5	19.7	-9.0	36.0	69.8	9.5	2.9	0.0
262	431	9.2	19.7	-3.7	37.1	80.2	11.6	2.5	0.0
263	476	8.9	19.4	-0.8	33.2	64.5	11.1	2.8	0.0
264	499	6.8	20.1	-7.8	36.3	75.6	10.1	2.8	0.0
265	495	8.7	23.8	-7.4	31.0	67.0	8.3	1.7	0.0

[1]One langley = one cal cm^{-2} s^{-1}
[2]Recorded at Laramie lagoons

Table 8. Soil evaporation from the bucket lysimeters.

Date	Precipitation (kg)	Lysimeter Mass (kg) #1	#2	Cumulative Evaporation (kg)
July 28	----	80.74	84.26	----
July 29	0.23	81.06	83.89	0.57
August 2	0.39	80.97	84.51	0.38
August 4	0.00	81.08	84.37	0.40
August 5	0.00	81.01	84.78	0.22
August 6	0.37	81.19	85.05	0.37
August 12	1.10	81.53	84.60	1.52
August 19	0.48	82.10	85.73	1.15
August 25	1.60	82.46	86.64	2.12
August 30	1.21	83.24	86.41	3.06
Sept 8	0.06	82.78	86.18	3.46
Sept 22	0.06	82.56	85.96	3.74

Total precipitation = 5.50 kg
Bucket lysimeter surface area = 700 cm^2 each
Lysimeter surface area = 8660 cm^2
Equivalent evaporation for weighing lysimeter = 46.3 kg
[equation is (5.50-((82.56-80.74)+(85.96-84.26))/2)·(8660/700)]

Table 9. Willow clump leaf areas (m^2).

Date	Clump 1	2	3	4	5	Total
July 23	0.30	0.35	0.36	0.30	0.56	1.87
July 29	0.32	0.38	0.33	0.30	0.56	1.81
August 7	0.35	0.32	0.34	0.28	0.59	1.88
August 12	0.32	0.38	0.33	0.25	0.57	1.85
August 19	0.34	0.32	0.34	0.27	0.63	1.90
August 26	0.34	0.31	0.34	0.27	0.57	1.83
August 30	0.38	0.43	0.33	0.30	0.62	2.06
mean	0.34	0.36	0.34	0.28	0.59	1.89

Table 10. Willow leaf senescence and abscission.

Date	Clump	percent leaves: green	yellow	abscised
Sept 2	1	91	9	0
	2	93	7	0
	3	94	6	0
	4	82	18	0
	5	91	9	0
Sept 8	1	78	22	0
	2	71	29	0
	3	80	20	0
	4	59	41	0
	5	76	24	0
Sept 22	1	53	33	14
	2	48	32	20
	3	47	13	40
	4	10	23	67
	5	45	33	22

Table 11. Influence of leaf position on shoot on leaf transpiration rates at midday (between 1200 and 1400 h). Values are means ± standard errors.

Date	Transpiration (mg m^{-2} s^{-1}) base	middle	top
July 23	32.1(5.0)	33.5(2.5)	46.8(7.0)
July 29	50.4(7.6)	43.2(5.6)	38.4(11.2)
August 7	80.7(13.0)	82.9(10.6)	83.6(14.6)
August 12	53.7(13.2)	60.9(13.2)	53.0(14.4)
August 19	42.7(2.2)	30.6(10.6)	34.8(6.8)
August 30	41.8(4.3)	32.1(3.8)	49.0(8.8)

Figure 1. Side and top views of the weighing lysimeter. An inner steel cylinder (1.03 x 1.37 m) was nested within an outer steel cylinder. Three layers of fill are shown: two 10-cm thick layers of gravel at the bottom and the top, with soil between. Water was added or removed via the access tubes. The water table (wt) is shown at its starting depth (50 cm). The load cells were located inside buried steel chambers spaced 120° around the periphery of the outer cylinder.

Figure 2. Diagrams of the Li-Cor steady-state diffusion porometer.

Figure 3. (A) - Cumulative evapotranspiration (ET) from the weighing lysimeter (●), air temperature (▲) at mid-canopy height (0.85 m) adjacent to the lysimeter, and soil temperature (Δ) at 25 cm depth inside the lysimeter. (B) Cumulative daily lysimeter ET (●), air temperature (▲), and mean load cell temperature (Δ).

Figure 4. Seasonal changes in total daily solar radiation, daily rainfall, mean daytime (dawn-to-dusk) air temperature and atmospheric vapor pressure deficit (VPD), and total daily lysimeter evapotranspiration (ET).

Figure 5. Instantaneous leaf transpiration rates of the willows in the lysimeter on two different days. Each symbol/line combination represents a different clump. The largest standard error observed, and the clump it was associated with, is shown next to each set of curves. Zero values during the afternoons of August 7 and 26 indicate foliage wetted by rain.

Figure 6. Cumulative transpiration by the willows in the lysimeter on various days between late July and late September. The number in the upper left-hand corner of each panel is cumulative daily transpiration (kg). To facilitate comparison, measurements for August 11-12 are shown as if they occurred from 0600 h to 0600 h, whereas in reality they occurred from 1800 h to 1800 h. Two days are now shown: July 21 and September 1, with 2.55 and 3.03 kg cumulative transpiration, respectively.

Figure 7. Cumulative seasonal evapotranspiration (ET) estimated by six methods for the period July 20 to September 22.

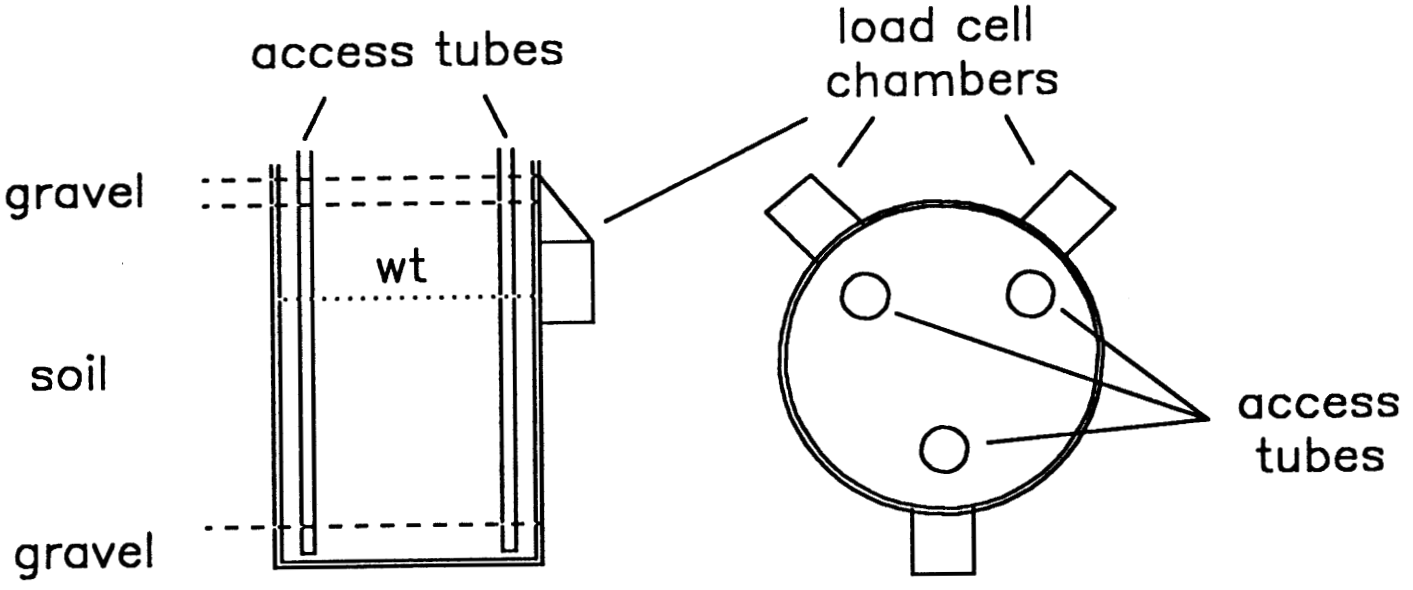
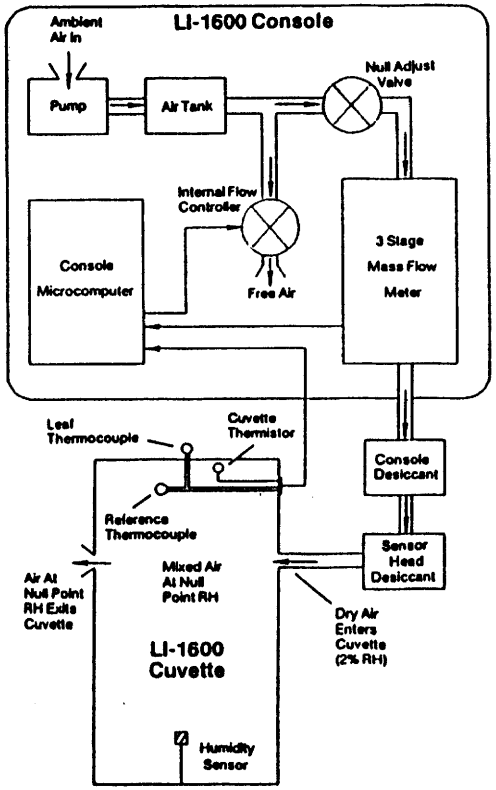

access tubes
load cell
chambers
gravel
wt
soil
gravel
access
tubes

Fig. 1

LI-1600 SYSTEM DIAGRAM



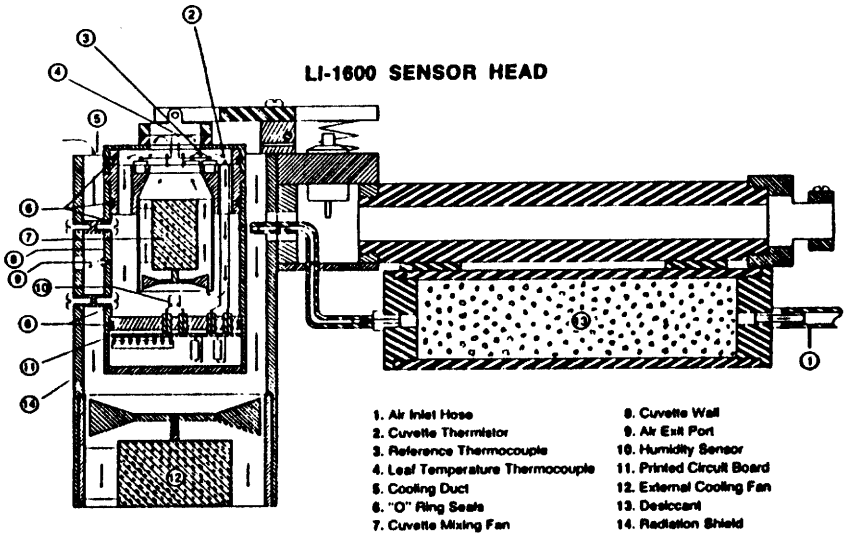
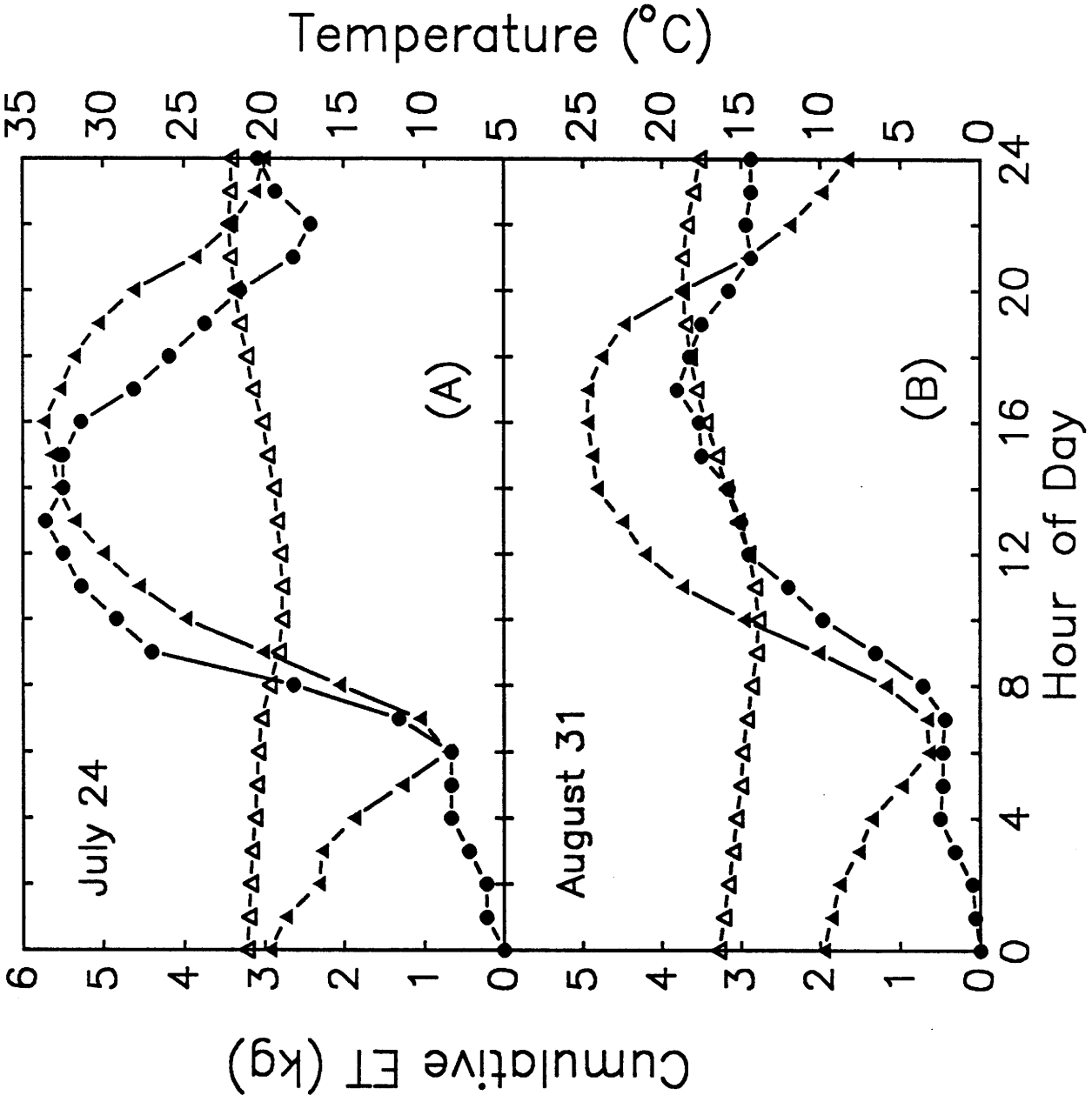


Fig. 2

Fig. 3


Temperature (°C)
Cumulative ET (kg)
Hour of Day
July 24
August 31
(A)
(B)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
0
4
8
12
16
20
24

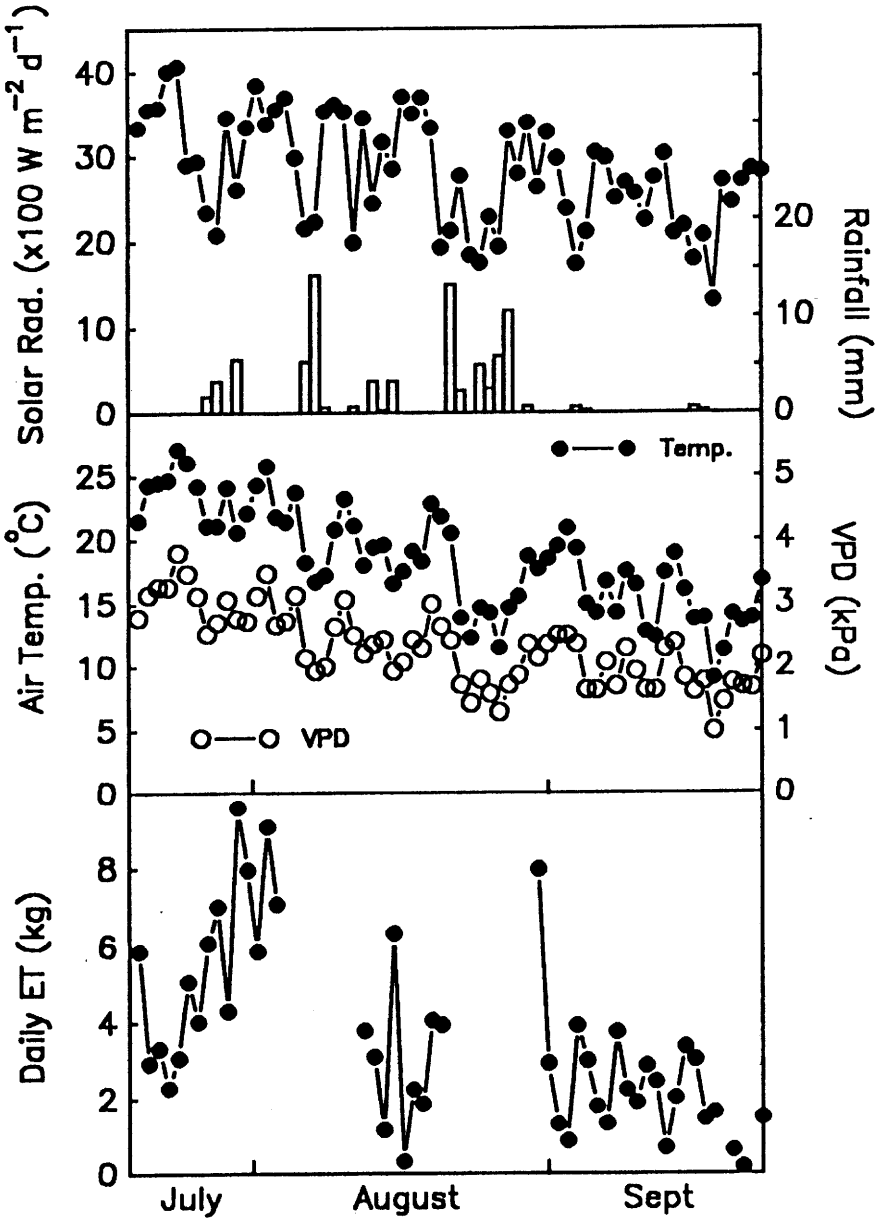

Solar Rad. (x100 W m^{-2} d^{-1})
Rainfall (mm)
Air Temp. (°C)
VPD (kPa)
Daily ET (kg)
Temp.
VPD
July
August
Sept

Fig. 4

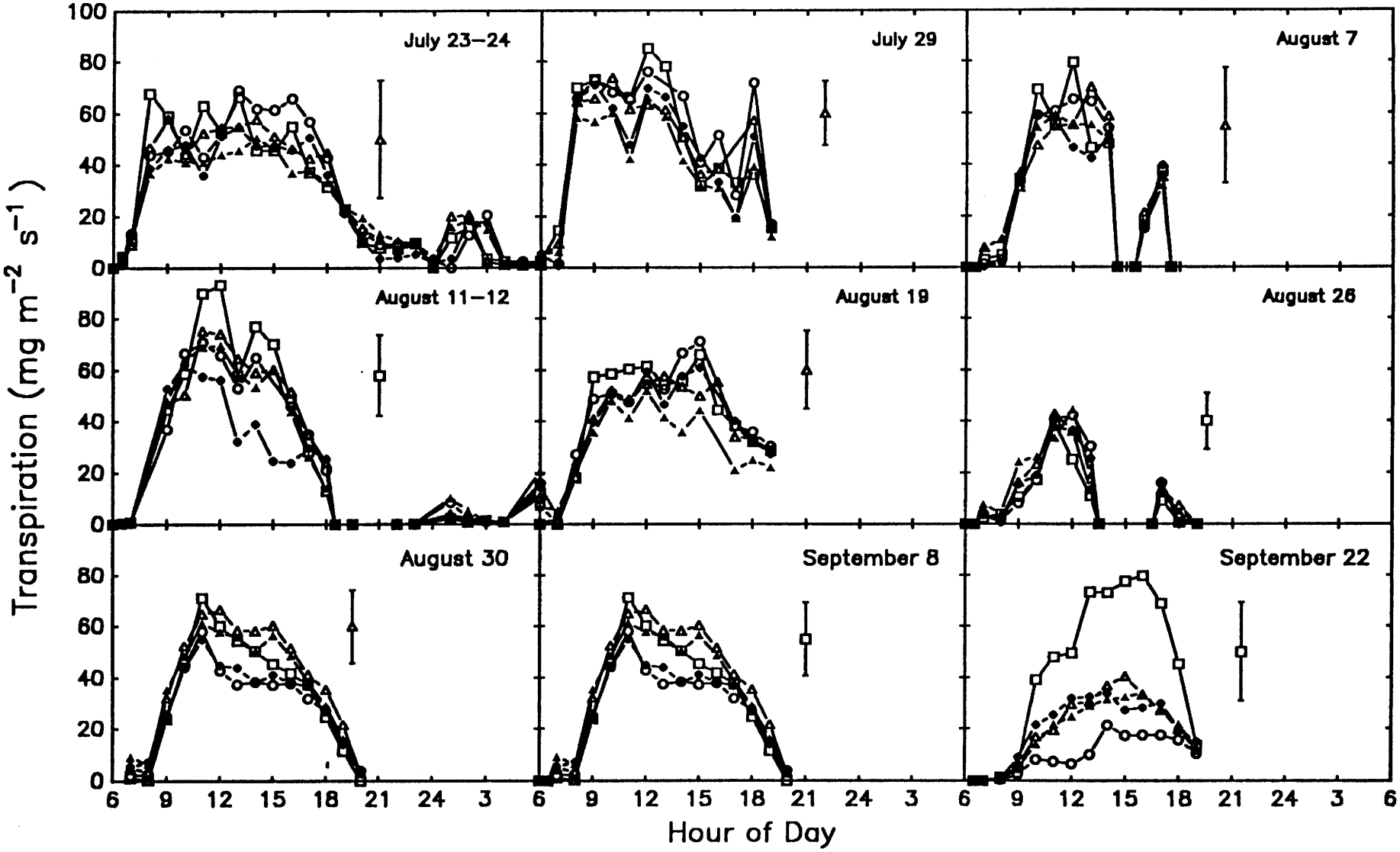

July 23–24
July 29
August 7
August 11–12
August 19
August 26
August 30
September 8
September 22
Transpiration (mg m^{-2} s^{-1})
Hour of Day
0
20
40
60
80
100
6
9
12
15
18
21
24
3

Fig. 5

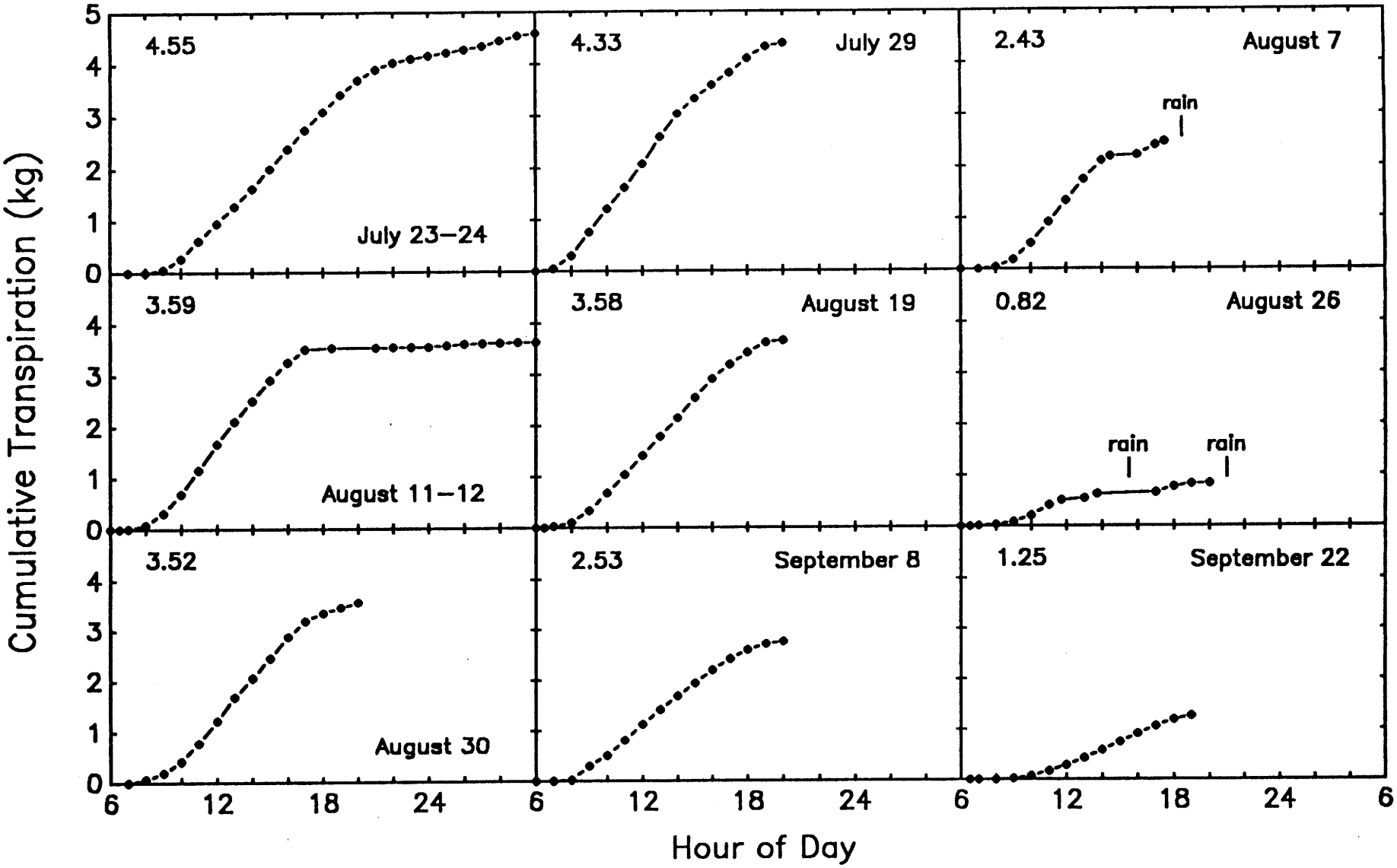

Cumulative Transpiration (kg)
Hour of Day
4.55
July 23–24
4.33
July 29
2.43
August 7
rain
3.59
August 11–12
3.58
August 19
0.82
August 26
rain
rain
3.52
August 30
2.53
September 8
1.25
September 22
0
1
2
3
4
5
6
12
18
24

Fig. 6

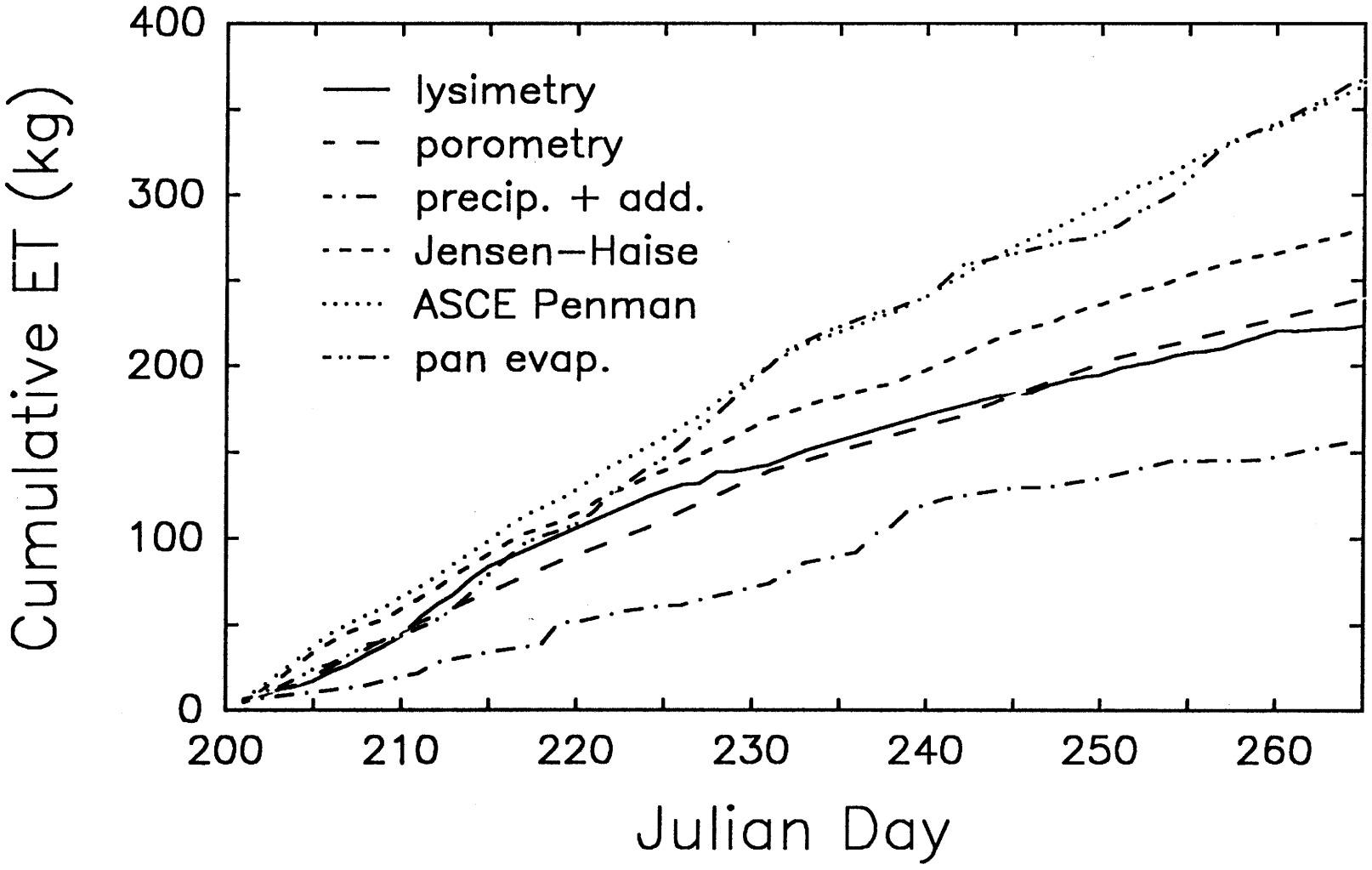

Cumulative ET (kg)
400
300
200
100
0
200
210
220
230
240
250
260
Julian Day
lysimetry
porometry
precip. + add.
Jensen–Haise
ASCE Penman
pan evap.

Fig. 7