Automated Lysimeter for Irrigation and Drainage Control

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Abstract

Knowledge of crop evapotranspiration (ET_c), the combined process of evaporation and plant transpiration, is important in agriculture for scheduling farm operations and designing and managing irrigation and drainage systems. Weighing lysimeters were used to measure ET_c in a real-time feedback mode to schedule irrigations for the lysimeter and several irrigation systems in surrounding experimental fields of peaches and grapes. Results of testing indicate that the method can be used to (1) determine hourly ET_c with an accuracy of ± 0.025 mm, (2) establish basic crop coefficient functions, (3) schedule irrigations in surrounding fields irrigated under similar conditions as the lysimeter, and (4) maintain the soil matric potential nearly constant within the root zone. With tree and vine crops, differences in growth and productivity between plants in the field and those in the lysimeter can occur because small growth differences are cumulative, whereas field crops are replanted annually.

Introduction

Many methods have been developed to measure evapotranspiration indirectly, but lysimeters measure evapotranspiration directly. Lysimeters are containers filled with soil, set in the field to represent the prevailing soil and climatic conditions, and permit more accurate measurement of physical processes than can be made in the open field (Tanner, 1969; Aboukhaled et al., 1982).

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Brutsaert (1982) has reviewed the history of evaporation research, Soileau and Hauck (1987) have reviewed US lysimetry research with respect to deep percolation and Howell et al. (1991) reviewed lysimetry with emphasis on evapotranspiration.

Hourly measurements of crop evapotranspiration (ET_c) in conventional lysimeters are difficult when the lysimeter is irrigated frequently because the water added from an external source increases the mass of the lysimeter simultaneously with decreases occurring from ET_c. Phene et al. (1989) proposed a method which nearly eliminated this problem. A water reservoir was attached to the lysimeter system and this reservoir was weighed with the lysimeter and refilled automatically each day at a given time (preferably when ET_c is minimal). This modification allowed measurements of ET_c to be made without interruption and the lysimeter to be used in a feedback mode for scheduling irrigation automatically; however, the surrounding field should be irrigated as frequently as the lysimeter to avoid any potential "Oasis" effects.

The purposes of this paper are to (1) describe two large automated weighing lysimeters, built in cooperation with the UC Cooperative Extension to study ET_c and water requirements of maturing peach and grapevine crops, (2) to apply the feedback concept from lysimeters developed for field crops for scheduling irrigation of perennial crops using the lysimeter as the controller and (3) to present ET_c and water requirement for young grapevines.

Procedures

The two identical lysimeter used in this study are of the weighing type using a balance beam weighing system constructed by Fred Lourence* (Precision Lysimeters, Red Bluff, Calif.). Both lysimeters were installed at the Kearney Agricultural Center, at Parlier, California. One of the lysimeters is located near the center of a 1.13-ha experimental field planted to peach (*Prunus persica* (L.) O'Henry variety) and the other is located in the middle of a 1.61-ha experimental field planted to grapevines (*Vitis vinifera* (L.) Thompson Seedless variety). Each lysimeter has a surface area of 8 m^2 (4x2 m) and an effective soil profile depth of 2 m. The soil profile, was reconstructed in each lysimeter by careful compaction of the soil in 15-cm layers corresponding to each excavated layer. The soil bulk density was 1.64 g/cm^3 after refilling. Each lysimeter was fitted with both gravity and vacuum-assisted drainage systems. During installation, 7 porous stainless tube drains 180 cm long were installed 57 cm apart, in the center of a 24-cm layer of diatomaceous earth at the bottom of the soil profile. Gravity drainage was achieved by slanting the bottom of the lysimeter towards its center where a screen-covered outlet allowed water to drain. Each lysimeter rests on a sensitive scale which measures the total mass of approximately 30 Mg to the nearest 400 g using a 40 kg load cell

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*Mention of trade names and company names does not imply endorsement of the products by the U.S. Department of Agriculture.

connected to the measuring beam section of the balance beam with 110:1 mechanical advantage ratio. The electronic signals from the load cell and other transducers in each lysimeter are measured with a data acquisition and control system (DACS) (Campbell scientific Instruments*, 21XL Micrologger, Logan, Utah). The 50 mV range of the DACS allows measurement of the load cell output voltage which ranges from 20 to 40 mV. In this range, the resolution of the micrologger is 3.33 µV which gives an overall system resolution of 400 g or 0.05 mm of ET_c. The calibrated accuracy of the lysimeter is ±0.025 mm.

Two large polyethylene water tanks 300 l volume each are suspended below the lysimeters to supply water for irrigation and are part of the mass of the lysimeter. The lysimeter (including the water in the tanks) is weighed hourly to determine the evapotranspiration of the two trees or two vines (ET_c), the mass change is compared to a threshold mass (8 kg = 1 mm ET_c). If the threshold mass is exceeded the lysimeter is irrigated until the threshold mass is met in increments of 8 kg. At midnight each day, the water tanks are refilled to a pre-set level, the water flow is measured and the new lysimeter mass is used as the base-line mass for the next day. Weekly, or at longer time intervals, the mass of dry matter accumulation can be estimated and additional irrigations may be added if necessary to make up for crop growth. Figure 1 shows the hardware installed in each lysimeter to automate the irrigation for each lysimeter in a feedback irrigation controller mode. A drainage tank is also suspended below the lysimeter to collect gravity drainage. At midnight, the daily drainage collected is determined by the scale mass change as the drainage tank is emptied with a solenoid valve controlled by the micrologger. As of this date, no gravity drainage has been collected in either the peach or the grape lysimeters.

As the lysimeters were filled with soil, soil matric potential sensors (Agwatronic, model AGWA II, Merced, CA) were installed at depths of 1.50, 1.00, 0.50, and 0.25 m. Six sensors were installed at a depth of 1.50 m, 12 were installed at the 1.00 m depth and 8 sensors were installed later in each lysimeter at depths of 0.50 and 0.25 m. Measurements taken hourly by the microloggers are used to determine soil matric potentials and calculate hydraulic gradients. Two neutron access tubes were also installed 1 m apart in the center of each lysimeter to a depth of 180 cm.

The mass $M_{(t)}$ of the lysimeter at any time t, (including drainage) can be defined as:

$$M_{(t)} = (M_o + M_w + P_y) - ET_c + P \qquad [1]$$

M_o = The mass of the lysimeter system at midnight
P_y = The fresh crop biomass
ET_c = The crop water use from the lysimeter
M_w = The mass of the water in the supply tanks
P = precipitation received by the lysimeter.

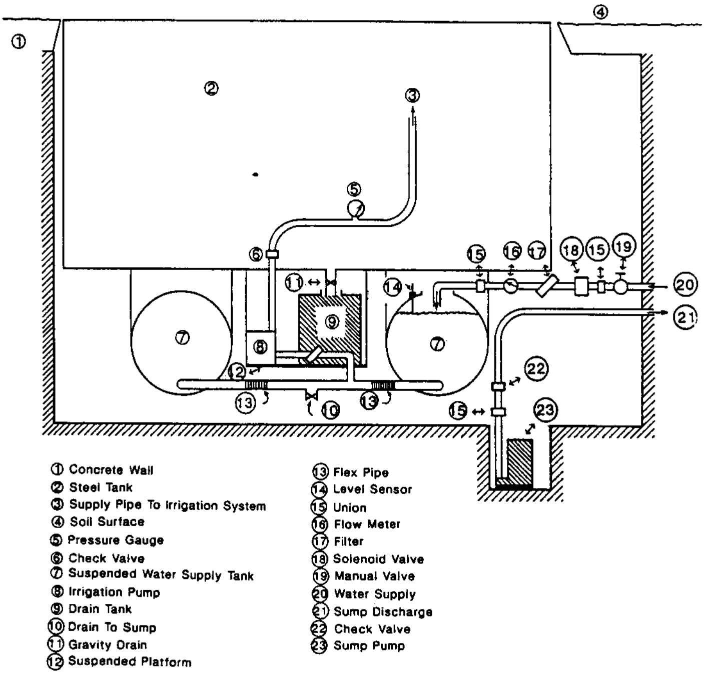

Figure 1. Schematic of automated irrigation and drainage control and measuring equipment used in each lysimeter.

During the growing season, The lysimeter mass is controlled to prevent any change in soil water, although redistribution of water can occur within the soil profile. When averaged over the entire season, the rate of biomass accumulation is about 25 g/h as compared to a mean ET_c of about 740 g/h. Irrigation (I) is simply the mass transfer of water from M_w to M_t. At midnight, D and I for the day are measured. D is the mass change in a short time permitted to empty the drainage tank based on the lysimeter scale (±400 g). I is the volume of water required to refill M_w. Hence, the hourly mass loss to be replaced by irrigation is:

$$I = ET_c - P \qquad [2]$$

Biomass accumulation was accounted for weekly by accumulating the small daily gain in M_o. The lysimeter data are collected automatically every day with an IBM compatible personal computer. This host computer is located at the USDA-ARS-Water Management Research Laboratory in Fresno, California and communicates with the microloggers via a telephone modem. Hardware and software available from the micrologger manufacturer are used to automate the data collection. The micrologger program and real time data are remotely from any modular telephone line using a laptop computer.

A software package has been developed to (1) use the 21X micrologger for controlling field irrigations at several ET_c levels within each of the experiments, (2) communicate automatically with the WMRL computer to transmit all data recorded during the previous day, and (3) to reduce raw data into easily readable reports including graphs (Microsoft WINDOWS and EXCEL).

Vines planted in and around the lysimeter were 2.15 m apart along the row and rows were spaced 3.5 m from center to center. Lysimeter vines were planted in the middle of a treatment receiving full ET_c to avoid the "Oasis" effect. In 1989, the three-year old vines were pruned to two, 12-node canes and three trellis systems were used in the vineyard: (1) a single wire, (2) a 45-cm cross arm with two wires and (3) a 90-cm cross arm with 4 wires. All trellis systems were 1.8 m above the soil surface. Vines in the lysimeter used a 45-cm cross arm with two wires. Field vines were irrigated at various fractions of the amount of water used by the vine in the lysimeter. There were eight irrigation treatments each replicated eight times. Each plot within a replication consisted of 16 vines. The experimental design was a complete randomized block. The irrigation treatments were designed to have been 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, and 1.4 times the amount of water used by the lysimeter. However, the irrigation system was not automated until mid-July. Thus, vines did not receive enough water to meet the above mentioned treatment amounts. The actual amounts of water applied to the vines in the irrigation treatments were 0, 0.17, 0.29, 0.41, 0.61, 0.71, 0.89, and 1.0 times the amount of water used by the vines in the lysimeter. The irrigation treatments were numbered consecutively from 1 to 8, corresponding to applied water from 0 to 1.0 times the lysimeter water use, respectively.

Results

An example of the daily output generated by the lysimeter system in grapes is shown in Figure 2. Hourly data include time, load cell reading, rain, lysimeter ET_c, calculated reference ET (ET_o) from the nearby weather station, calculated lysimeter K_c, number of irrigations, and the power supply voltage for the load cell, flowmeter measurement of the tank refill, as well as calculated volume from mass balance; daily lysimeter ET_c, rain, ET_o, lysimeter K_c, and total irrigation are also provided. The Figure also shows the diurnal patterns of ET_c and ET_o. The irrigation events are provided for quick evaluation. Reference ET (ET_o) is calculated using the Modified Penman equation integrated hourly (Pruitt and Doorenbos, 1977) and standard weather station instruments over an 8-15 cm tall, cool season grass, frequently cut. This method is used statewide to estimate hourly ET_o at 90 locations operated by the California Irrigation Management Information System (CIMIS).

GRAPE Lysimeter KAC			Day 168			Date: 6/17/89	
Time (hour)	Load cell Reading (kg)	Rain (mm)	Lysimeter ETc (mm)	Cimis ETo (mm)	Lysimeter Kc ($\lvert ETc/ETo \rvert$)	Irrigation (numbers)	Power Supply (V)
30	3279.2						
101	3279.4	0.0	-0.02	0.01	2.30	0	15.18
201	3279.5	0.0	-0.01	-0.02	0.35	0	15.19
301	3279.3	0.0	0.02	-0.03	0.57	0	15.06
401	3279.1	0.0	0.03	-0.03	0.83	0	15.10
501	3278.9	0.0	0.03	-0.02	1.35	0	15.06
601	3278.4	0.0	0.06	0.04	1.55	0	15.12
701	3277.1	0.0	0.16	0.18	0.91	0	15.06
801	3274.9	0.0	0.28	0.32	0.87	0	15.11
901	3271.5	0.0	0.43	0.44	0.97	0	15.23
1001	3266.7	0.0	0.60	0.58	1.03	0	15.12
1101	3261.1	0.0	0.70	0.69	1.02	1	15.10
1201	3254.4	0.0	0.84	0.76	1.10	0	15.18
1301	3247.4	0.0	0.88	0.78	1.13	1	15.21
1401	3240.5	0.0	0.85	0.80	1.07	0	15.24
1501	3233.6	0.0	0.87	0.74	1.18	0	15.08
1601	3227.1	0.0	0.81	0.64	1.26	1	15.07
1701	3222.1	0.0	0.62	0.51	1.22	0	15.24
1801	3218.2	0.0	0.50	0.37	1.35	0	15.09
1901	3216.6	0.0	0.20	0.13	1.55	1	15.21
2001	3216.7	0.0	-0.02	0.09	0.24	0	15.18
2101	3216.4	0.0	0.04	0.05	0.88	0	15.03
2201	3216.1	0.0	0.04	0.01	3.70	0	15.09
2301	3216.1	0.0	-0.01	-0.01	0.50	0	15.09
2400	3215.7	0.0	0.06	0.01	5.60	0	15.08

FLOW(mm) Meters:	Mass Change: (kg)	Totals (mm)	Totals (mm)	Totals (mm)	Totals ($\lvert ETc/ETo \rvert$)	Totals (numbers)	Mean (V)
7.96	63.9	0.0	8.01	7.15	1.12	4	15.13
Mass	Daily ETc:(mm)						STD
8.16	8.0						0.06
							CV
							0.004

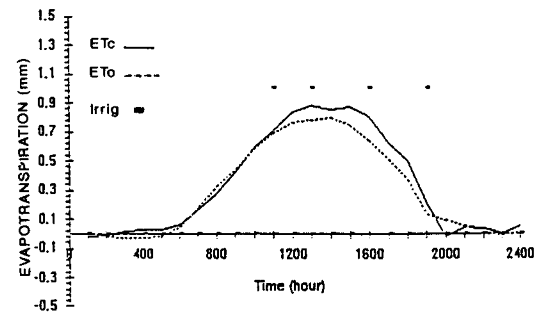

Figure 2. Daily report generated automatically by the lysimeter data management and control system (grapes).

The K_c's reported in Tables 1 and 2 are based on the soil surface area of the lysimeter (4 m^2); however, the soil surface area potentially occupied by one vine is 7.52 m^2 and therefore the field K_c should be adjusted as:

$$K_c = \frac{ET_c\ (Lysimeter)}{ET_o} \times \frac{Lysimeter\ area}{Field\ spacing\ area} \qquad [3]$$

or the ET_c of the lysimeter could be adjusted as:

$$ET_c = ET_c(Lysimeter) \times \frac{Lysimeter\ area}{Field\ spacing\ area} \qquad [4]$$

With drip irrigation, the ET_c adjustment is possible since the soil area outside of the lysimeter, which is part of the field spacing area, is always dry except after precipitation and for all practical purposes was a negligible adjustment under the present weather conditions. These adjustments are shown on the right ordinate axis of Figure 3 for ET_c and on the right ordinate axis of Figure 4 for the K_c. Since vine and tree spacings are rarely uniform, presenting ET_c and K_c results based on the lysimeter area seems justified. Another approach could be to convert ET_c to water volume, V, per tree and use this information accordingly:

$$V = ET_c(Lysimeter) \times Area\ of\ Lysimeter \qquad [5]$$

Monthly 1989 results for grape vines are given in Table 1 and summarized rainfall, lysimeter ET_c, reference ET_o, lysimeter K_c, the number of irrigations applied and the mean soil matric potential (ψ_m) at 20, 60, 100, and 150 cm depths.

Table 1. Monthly summary of 1989 evapotranspiration and soil matric potential measurements for the grape vines grown in the lysimeter at Parlier, CA. K_c is based on a 4 m^2 soil area per vine.

Month	Rain (mm)	LYSIMETER ET_c (mm)	CIMIS ET_o (mm)	LYSIMETER K_c ($\lvert ET_c/ET_o \rvert$)	Number of Irrigations	Mean Soil Matric Potential (J/kg) 20 cm	60 cm	100 cm	150 cm
Jan	9	14	32	0.46	0	-0.22	-0.45	-0.37	-0.36
Feb	30	25	41	0.61	0	-0.26	-0.50	-0.42	-0.32
Mar	48	45	75	0.60	0	-0.20	-0.53	-0.40	-0.23
Apr	1	52	135	0.39	12	-0.52	-0.43	-0.38	-0.09
May	15	161	176	0.91	68	-0.63	-0.49	-0.69	-0.09
Jun	0	222	207	1.07	100	-0.45	-0.56	-0.97	-0.16
Jul	0	288	218	1.33	119	-0.13	-0.14	-0.98	-0.11
Aug	2	164	184	0.89	84	-1.64	-1.85	-1.72	-0.46
Sep	22	107	127	0.85	42	-0.33	-0.17	-2.73	-0.24
Oct	10	46	91	0.51	17	-0.01	0.83	-2.28	-0.19
Nov	10	16	55	0.28	3	-0.02	0.93	-2.04	-0.28
Dec	0	11	26	0.43	0	0.08	-0.89	-1.81	-0.30
Total	145	1153	1366		445				

Figure 3 shows daily ET_c and ET_o during 1989 and Figure 4 illustrates K_c for years 1988, 89, and 90. In 1989, each vine in the lysimeter used approximately 4612 l of water and had an ET_c of 1153 mm based on an area of 4 m^2. Reference ET_o was 1366 mm. There were 445 irrigations, totaling 804 mm of applied water and 145 mm of rainfall. No drainage was collected from the lysimeter. The two vines in the lysimeter grew to a size approximately equal to the size of the vines in the surrounding field. The sum of irrigation and rainfall 949 mm and was 204 mm short of the 1153 mm of ET_c. The difference of 204 mm between ET_c and total water applied (irrigation + rainfall) was extracted from the soil profile after irrigation was terminated. The large drop in the 1989 K_c after the maximum during the week of July 13th (day 200) was partially due to an electrical outage on July 18 and mechanical failure of the lysimeter's irrigation system. The two vines in the lysimeter did not receive water for a period of one week following that period and extracted water from the soil. This adversely affected water use of those vines for the next three weeks.

In 1989, the maximum yield obtained was 31.4 t/ha for Treatment 5. This treatment had received 61% of the water used by the lysimeter vines. The vines in Treatment 1 (no applied water) had a yield of 24.7 t/ha (11.0 tons/acre). Lack of yield response beyond irrigation Treatment 5 was probably due to the fact that all vines were irrigated at 100% of ET_c during the previous year. In 1990, yield increased almost linearly from 0 to 100 percent of the water applied in the lysimeter. Yields ranged from 12 to 51.4 t/ha. These results confirm the validity of this irrigation scheduling technique.

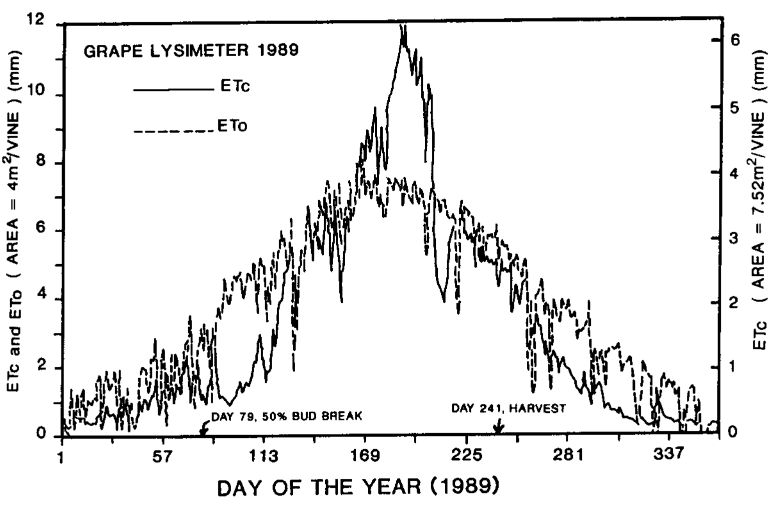

Figure 3. Daily evapotranspiration of grapevine (Area = 4 m^2/vine, left axis or 7.52 m^2/vine, right axis) and reference evapotranspiration of grass calculated by the CIMIS equation.

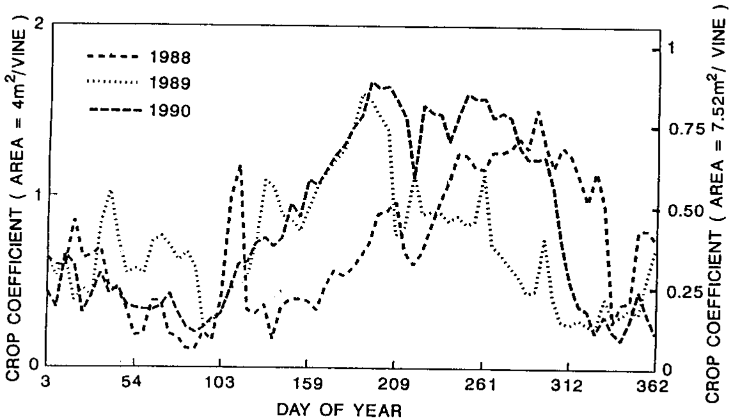

Figure 4. Daily crop coefficient (K_c) for maturing grapevines irrigated by surface drip irrigation (Area = 4 m^2/vine, left axis or 7.52 m^2/vine, right axis) and grass reference ET_o.

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