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Using Weighing Lysimeters to Develop Evapotranspiration Crop Coefficients

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Abstract

Weighing lysimeters provide an accurate means of measuring evapotranspiration (ET), the evaporative loss of water from growing crops. Two weighing lysimeters were installed at a research site near Kimberly, ID, and have been used during the past 20 years to measure the ET of the major irrigated crops of the region. Results were used in developing functional relationships and coefficients for use with the reference ET-crop coefficient approach for estimating crop ET from meteorological, crop and soil data. Examples of the use of meteorologically determined alfalfa reference ET and lysimetrically measured crop ET for the development of mean and basal crop coefficients are presented. Encountered problems and some successfully used solutions are discussed.

Introduction

Presently, weighing lysimeters provide the most exact means of continuously measuring the transfer of water vapor from the crop and soil system to the atmosphere, often spoken of as evapotranspiration (ET) or total evaporation (TE), throughout the cropping period. However, since the utilization of weighing lysimeters is largely a scientific endeavor, the "reference ET-crop coefficient" approach has evolved during the past two decades to expedite the estimation of crop ET from available data on crop, soil, and weather conditions. Estimates of crop ET have practical application in the scheduling of irrigations, the modelling of crop yield in relation to crop water use, and in irrigation project planning and management. The reference ET-crop coefficient approach centers on the utilization of an empirical crop coefficient to relate total crop evaporation to a reference evaporation. Generally, formulae based on meteorological parameters are used to characterize the reference ET, and the empirically derived crop coefficients are used to account for specific crop conditions. Weighing lysimeters are useful in the development or verification of reference ET techniques and in the development of specific crop coefficient curves.

This paper briefly reviews the use of weighing lysimeters during the past 20 years in the development of crop coefficient curves for the major irrigated crops of the arid, irrigated region near Kimberly, ID. Weighing lysimeters were used firstly to provide

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data for the development of procedures for calculating daily alfalfa reference ET from meteorological data and secondly to provide data for the development of crop coefficient curves for specific cropping situations. Examples of results are reported and some problems encountered during this research are briefly discussed.

Theoretical

The equations used in the development of ET crop coefficients are briefly repeated here for clarity, but without discussion, for brevity. Detailed definitions and discussions of the principles of the reference ET-crop coefficient approach, relevant to the research reported here, were discussed by Wright (1981, 1982, 1985, and 1988) and Wright and Jensen (1978) and were well discussed in general by Allen et al. (1989), Doorenbos and Pruitt (1977), and Jensen et al. (1990).

The reference ET-crop coefficient approach is based on the fundamental definition of the general crop coefficient given by:

$$K_c = E_{tc}/E_t \text{ (reference)} \qquad [1]$$

where K_c is the dimensionless daily crop coefficient, E_{tc} is measured daily crop ET (mm/day) and E_t (reference) is daily reference ET (mm/day) estimated or measured. The distribution of K_c with time throughout the season forms the "ET crop coefficient curve." When applicable crop coefficients and E_t (reference) are available, crop ET can be practically estimated when Eq. [1] is solved for crop E_{tc}.

To account for effects of soil water status, the crop coefficient can be factored by:

$$K_c = K_{cb} K_a + K_s \qquad [2]$$

where K_{cb} is a basal crop coefficient and K_a and K_s are relative coefficients related to available soil water and surface soil wetness, respectively. Wright (1982) defined K_{cb} to represent conditions when the soil surface was visually dry so soil evaporation was minimal but soil water availability did not limit plant growth or transpiration. A mean crop coefficient (K_{cm}) which averages the effects of K_s, is given by:

$$K_c = K_{cm} K_a \qquad [3]$$

In practice, E_t (reference) is usually estimated from meteorological data in some manner because direct measurements are rarely available. Alfalfa reference ET, (E_{tr}), has been used for arid climates (Jensen et al. 1971, 1990; Wright and Jensen 1972, 1978; Wright 1981, 1982) and is defined as the daily ET of an actively growing alfalfa crop covering an extensive area, at least 30 cm tall and standing erect, and well watered so that soil water availability does not limit ET. A modified form of the Penman combination equation (Jensen et al. 1990) is often used to estimate E_{tr} from meteorological data:

$$E_{tr} = \left[\frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma} W_f (e_s - e_d)\right] L^{-1} \qquad [4]$$

where R_n is net radiation, G is soil heat flux, W_f is a wind function dependent on daily wind travel (U) and the nature of the selected reference surface, (e_s - e_d) is the mean daily saturation vapor pressure deficit, Δ is the slope of the saturation vapor pressure - temperature (T) curve, γ is the psychometric constant, and L is the latent heat of evaporation. Measured R_n, G, U, e_s, e_d, T and E_{tr}, in appropriate units, are used to evaluate W_f as a function of U for the respective reference surface.

Lysimeter Field Site

Two lysimeters, similar in design to that of Ritchie and Burnett (1968), were installed in adjacent open fields at a site about 1 km south of the USDA, Agricultural Research Service, research facility near Kimberly, Idaho. The lysimeter fields were surrounded by irrigated agricultural fields typical of the area. The research site, at latitude 42° 33'N, longitude 114° 21' W, elevation 1207 m, was in the interior of a large irrigated region. The Portneuf silt loam soil at the site was about 4 m deep and was underlain by fractured, basalt bedrock.

The first weighing lysimeter (Lys. 1) was installed in 1968 near the center of a rectangular field, of 2.6 ha, while the second (Lys. 2) was installed in 1971 in a nearly square field of 2.2 ha which was immediately west of the Lys. 1 field. The fields surrounding the lysimeters provided at least 75 m of fetch in the prevailing wind direction. The basic lysimeter design is shown in Fig. 1. The steel lysimeter soil bin rested on a mechanical floor stand scale. A 1-cm wide air gap separated the soil bin and the outer retaining wall. A pliable, nylon reinforced rubber seal covered the air gap between the inner and outer walls without interfering with the movement of the soil bin.

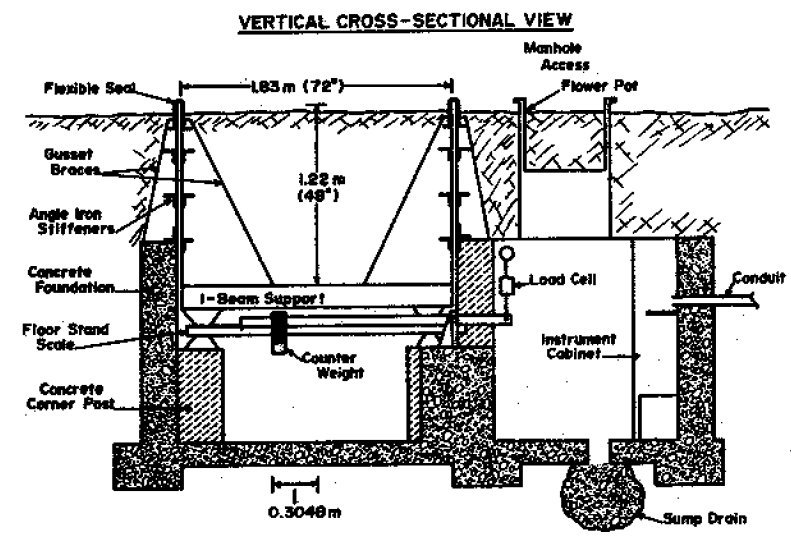

Figure 1. Cross-sectional view of the construction of the weighing lysimeter.

The resulting rim, about 2.5 cm wide, had an exposed cross-sectional area of about 5.6% of the surface area of the soil bin. This rim surface was mostly shaded by overhanging plants when they were growing on the lysimeter.

The lysimeter scale was basically a commercially available floor stand scale, with precision grinding of the fulcrums. The lever-arm ratio was 30:1. The scale was equipped with an adjustable counter balance which was set so that only about 10% of the total mass of the system was effective in translating force to the single electronic load cell mounted to measure tension. The 22.68-kg (50 lb) load cell provided a sensible total mass change of about 680 kg, equivalent to a loss or gain of about 200 mm water depth over the entire surface of the lysimeter. This amount of water was equivalent to a volumetric water content change of 16%, or about 50% of the field capacity of the soil. The scale and recording system had a combined sensitivity which permitted the resolution of a total mass change of 50 g, equivalent to 0.015 mm of water depth. Considering the effects of system hysteresis, non-linearity, and wind, the net daily system accuracy was about 250 g, equivalent to 0.07 mm of water depth, which was about 1% of midsummer daily ET.

The soil bin was filled with a reconstituted soil profile since the lysimeter project was designed for research on the ET of well-watered crops and the effects of a disturbed soil profile were not expected to affect ET. An array of sintered stainless steel candles was installed in the bottom of the soil bin to permit removal of drainage water. The performance of the weighing mechanism and the accuracy of the calibration factors were periodically checked with lead bricks of known mass added to or removed from the soil bin.

During the growing season, the load cell signals were continuously recorded with strip chart recorders and at 20-min intervals with an automatic data system. The chart records were used to monitor lysimeter performance and to correct data for the effects of irrigation, precipitation, harvest, and cultural operations. Load cell data were analytically converted to an equivalent water depth per unit area assuming a water density of 1 g cm^{-3} and an effective surface area (mid-rim to mid-rim) of 3.44 m^2. Daily ET was calculated from midnight to midnight.

Development of Crop Coefficients

Crops were planted and managed according to recommended agronomic practices. Tractors were used in the field, but all cultural operations on and immediately around the lysimeter were performed manually. Traffic was minimized near the lysimeter so that the crop and soil conditions would be representative of the bulk of the surrounding field. Irrigations were scheduled so that plant available soil water (ASW) within the crop root zone would not be less than 50% ASW (70% ASW for potato) to assure that transpiration rates would be independent of soil-water status. Fields were generally furrow irrigated except when, in a few cases, a solid-set sprinkler system was used. During furrow irrigations, water was pumped onto the lysimeter surface from a nearby furrow, with a small submersible pump, to bring the lysimeter to the desired water content. The amount of water added was calculated from the change in mass of the system.

Meteorological data from a National Weather Service (NWS) weather station were used in the computation of reference ET so that the developed procedure would be generally useable by those with access to the NWS data, whereas the lysimeter site meteorological data would not be similarly accessible. The NWS weather station was

located about 0.8 km north of the lysimeter field site, near the USDA-ARS laboratory complex, in a 45- by 35-m irrigated, clipped grass plot surrounded by irrigated field plots planted to various crops each year.

Alfalfa lysimeter ET and meteorological data from the NWS site were firstly used to derive an alfalfa wind function for use with Eq. [4]. Data were selected for periods when the alfalfa crop satisfied the reference criteria (see Wright and Jensen 1972; Wright 1982; Allen et al. 1989). Secondly, daily crop coefficients were computed by Eq. [1] using lysimetrically measured daily E_{tc} and alfalfa E_{tr} computed by Eq. [4] using the functional relationships developed for alfalfa.

Basal crop coefficient curves were fitted to the seasonal K_c curves to represent conditions when the soil surface was visibly dry. For such periods, by Eq. [2], $K_e = 0$ and $Ka = 1$ so that $K_{cb} = K_c$. Mean crop curves were also fitted to the daily K_c curves using Eq. [3] by which $K_{cm} = K_c$ when $Ka = 1$.

Results and Discussion

The weighing lysimeters have performed well providing measurements of daily crop ET for all the major irrigated crops of the region. Procedures for estimating alfalfa E_{tr} were developed from 3½ seasons of data obtained with the cultivar 'Ranger' grown on Lys. 1 (see Wright 1982, 1988; and Wright and Jensen 1972). Lysimetrically measured daily E_{tc} data were also obtained for the following crops, with the number of seasons of study as indicated: 'WL-312' alfalfa, 4; alfalfa/orchard grass mix, 1; garden bean, 2; dry bean, 1; sweet corn, 1; field corn, 1; garden pea, 1; garden pea with new alfalfa, 1; oat for hay with new alfalfa, 1; spring wheat, 1; spring barley, 1; winter wheat, 2; potato, 2; sugar beet, 2; clipped rye grass, 3; clipped fescue grass, 4; and fescue grass hay, 1. The basal and mean crop coefficients developed from these data have been reported for many of the crops (Burman et al. 1980; Jensen et al. 1990; Wright 1981, 1982). A severe hail storm in early August damaged the crops of sweet corn and field corn during one season.

The agreement between lysimeters was mostly studied with alfalfa. In 1982 both Lys. 1 and Lys. 2 had an established crop of 'WL-312' alfalfa, planted from the same seed lot. This provided an opportunity to assess the agreement between daily E_{tc} measured with Lys. 1 and Lys. 2 for full-cover conditions and also the agreement between measured 'WL-312' ET and alfalfa E_{tr} computed with the procedures developed from the earlier 'Ranger' alfalfa data. In 1982, E_{tc} for full cover conditions was generally less for Lys. 2 (about 6.9% overall) than for Lys. 1, with the difference increasing during the season. The mean and standard deviation (SD) for E_{tc} measured by Lys. 1 and Lys. 2 and computed E_{tr}, all in mm/d, were, respectively (n = 80): 5.68 ± 1.62, 5.29 ± 1.48, and 6.07 ± 1.70. The corresponding standard error of the estimate (SEE) was: 0.440 for Lys. 2 vs. Lys. 1; 0.591 for E_{tr} vs. Lys. 1; and 0.525 for E_{tr} vs. Lys. 2.

Lower ET on Lys. 2 than on Lys. 1 in 1982 was similar to results of an earlier period when 'Ranger' alfalfa was grown on both lysimeters (see Wright 1988). In that case, it was concluded that some of the differential response might have been due to possible genotypic differences between the two alfalfa crops, since different lots of seed were involved. However, the 1982 differential response would have been due to other factors since the two crops originated from the same seed lot. Recent comparisons of the soil within the two lysimeters indicated that Lys. 2 had about 50% less topsoil than Lys. 1 because the Lys. 2 site was located in an area of the field that

had had top soil removed during levelling operations. The forage yields from Lys. 2 and its field were consistently less than those from Lys. 1 in both cases.

The analysis of the 1982 alfalfa data also showed that the mean E_{tc} for Lys. 1 was generally less (about 10% overall) for full cover periods than E_{tr}. This difference was likely due to morphological differences between cultivars since forage yields of 'WL-312' were equal to or greater than those obtained with the earlier 'Ranger' crops. The 'WL-312' cultivar had finer stems, smaller leaves, and tended to lodge more easily than did the 'Ranger' crop used in the development of the E_{tr} functional relationships. While the mean E_{tc} for Lys. 1 and Lys. 2 was less than for E_{tr}, the SEE's were similar for all three comparisons (see data listed above). This indicated that the daily differential response of the two lysimeters to causative factors was only slightly less variable than the differential response between either of the lysimeters and the estimating procedures.

The nature of daily lysimeter ET is illustrated in Fig. 2 where daily measured E_{tc} for a crop of spring wheat is plotted along with the daily computed alfalfa E_{tr} during 1979. The spring wheat was planted on day of year (DOY) 101, reached effective full cover (EFC) on DOY 171 and was harvested on DOY 233. Daily wheat E_{tc} ranged from a low of 0.5 mm/d, after planting when the soil surface was dry, to about 10 mm/d during the peak ET period. The effects of a wet soil surface, prior to EFC, are evident in Fig. 2 when E_{tc} was nearly equal to E_{tr} for a short period following the irrigation on DOY 121. Similar but less pronounced effects were evident following the second irrigation on DOY 158 and during final maturation of the crop following rain on

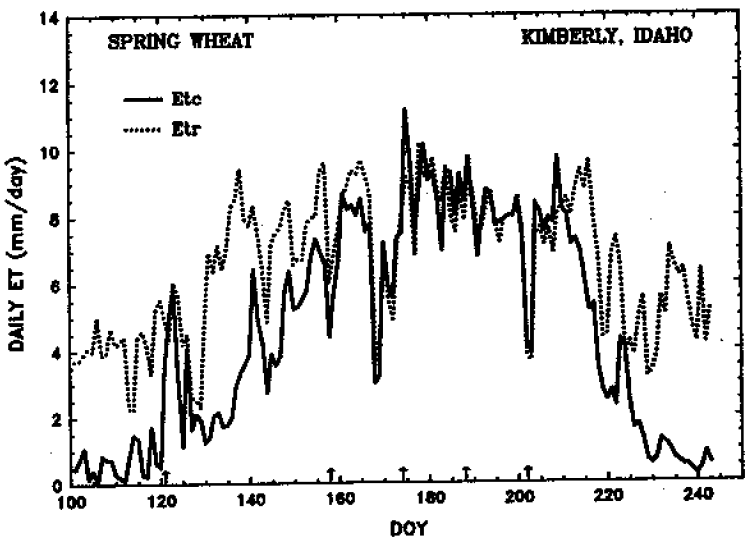

Figure 2. Daily values of alfalfa reference ET and lysimetrically measured ET of wheat during the season with irrigations indicated (↑).

DOY 222. The three irrigations applied during the full cover period had little noticeable effect on E_{tc}.

Daily K_c data computed from E_{tc} and E_{tr} data of Fig. 2, by Eq. (1), are shown in Fig. 3 along with smoothed basal K_{cb} and mean K_{cm} curves developed from the daily K_c data. The smoothing was accomplished by manually linearizing segments of the seasonal accumulative E_{tc} and E_{tr} curves. For the period extending from DOY 160 through DOY 210, daily K_{cm} varied between 0.85 and 1.20 and averaged 1.00. For the period from DOY 170 through DOY 210 mean E_{tc} = 7.96, SD = ± 1.57 mm/d; and mean K_c = 1.03. The SEE between daily E_{tr} and E_{tc} during this 40-d period was 0.644 mm/d, which was about 8% greater than the SEE of 0.591 obtained in the comparison of 1982 alfalfa E_{tr} and Lys. 1 E_{tc}, as discussed above.

General Observation

Results of periodic calibration checks showed that the lysimeter calibration factors calculated from the factory provided load cell calibration, the lever arm ratio and the surface area of the lysimeter were always within the statistical range of the calibration factors obtained during the tests. Load cells were damaged several times during lightening storms. Consequently, at least one replacement load cell was maintained on inventory to minimize down time. Eventually, a 45.36-kg (100 lb) load cell was installed on Lys. 1 because of difficulty in obtaining the smaller 22.68-kg (50-lb.) load cell. This change had relatively little effect on the overall accuracy of the system because of the overriding effects of wind, crop uniformity, and other such

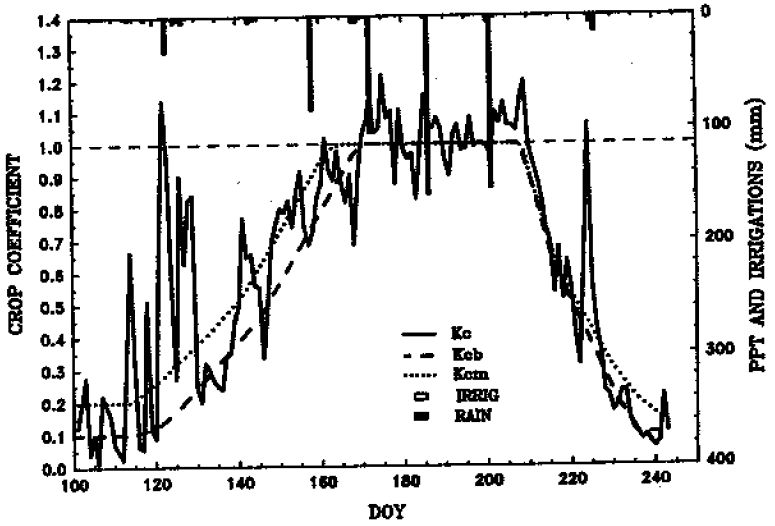

Figure 3. Daily ET crop coefficients for spring wheat throughout the season with irrigations and rainfall as indicated.

factors on accuracy. The larger load cell had the advantage of doubling the measurable range of mass change.

Wind produced both signal oscillation and a slight upward shift in apparent mass, particularly with a mostly bare soil surface. The signal oscillations with a frequency of about 1 cycle/s were due to fluctuations in windspeed and an induced mechanical vibration. The largest wind induced fluctuations were equivalent to about 0.66 mm ET. The signal fluctuations were initially countered with large capacitors placed across the load cell output. Later the load cell output was integrated over 10-min. periods with a scan interval of 10 s. The net upward shift in output was generally equivalent to less than 0.12 mm ET. While such a shift affected the accuracy of hourly ET, it had a lesser affect on daily ET values, partly because windspeeds at midnight were generally much less than during daytime. The wind effects were greatly reduced when crops were present on the lysimeter and field.

Perhaps the greatest challenge in obtaining reliable ET data from the lysimeters was in achieving soil moisture and crop canopy conditions on the lysimeter representative of field conditions. This was in part because even with drainage devices in the soil bin, the lysimeter surface soil tended to remain wet longer than the surrounding field in the spring after a wet winter or heavy water application. Soil salinity was occasionally checked. Flushing the soil with a large irrigation, when necessary, prevented excessive salt accumulation. This was best accomplished off season or by removing excess water in early spring following a wet winter.

Maintaining similar soil nitrogen concentration on the lysimeter and field also required careful management. The lysimeter soil tended to retain more nitrogen than the field soil due to the differences in drainage of soil water. To counter this effect and to prevent accelerated or excessive crop growth on the lysimeter, it was generally necessary to apply less nitrogen to the lysimeter than to the field.

The variation in row spacing used for the various crops also presented a challenge. After the first few years of experience in raising row crops on the lysimeters, it was decided that the best solution was to modify the row spacing for the hand planted areas, on and around the lysimeter, to provide an integer multiple of rows on the lysimeter. The spacing of plants within the row was adjusted to give equivalent plant densities on and off the lysimeter. For example, when the typically used field row spacing was 55.9 cm (22 in.), three equally spaced rows were planted on and immediately adjacent to the lysimeter with one row in the center and another row 61 cm (24 in) on either side. This located the lysimeter rim exactly midway between the outside row on the lysimeter and the first adjacent row in the field. If the desired plant spacing in the field was 10 cm, then the spacing on the lysimeter was reduced to 9.3 cm. With several of the crops, a sufficient seeding rate was used on and around the lysimeter to permit thinning the stand to the desired plant density.

Bridging was a problem if an appreciable amount of soil was allowed to extend across the lysimeter rim, such as with potato hills. While this might seem desirable from the standpoint of maintaining surface uniformity, the variability due to differential strain and stress in the soil produced unacceptable errors in the load cell output. The lysimeter rim was maintained free of soil to prevent bridging.

Excessive humidity within the pit of the lysimeter (see Fig. 1) also created problems. Even with the flexible seal across the rim of the lysimeter, some water invariably seemed to accumulate on the floor of the lysimeter pit during irrigations or

heavy precipitation events. With the resulting high humidity in the pit, water would condense on the outside of the soil bin during cooling periods and would then drip back onto the floor, creating a mini-hydrologic cycle. To prevent this, a small electrical dehumidifier was installed in each lysimeter pit, which was operated only as needed to minimize heating of the soil bin.

APPENDIX 1.--REFERENCES

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