ENERGY BUDGET MEASUREMENTS OVER IRRIGATED ALFALFA

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Introduction

Irrigated crops flourish in the warm, semi-arid region of the southwestern United States. Consumptive use is high, and the water requirements of crops have been studied extensively in attempts to develop rational irrigation practices. However, these studies are mostly based upon long-term water balances. More sensitive methods have been developed such as energy budget evaluations, lysimeters, and even soil moisture budgets, but there have been few attempts to apply these sensitive methods in Arizona in order to determine precise evaluations of crop water use on a short-term basis. Such studies have proven useful elsewhere in examining water use differences between various species and varieties, in comparing management practices, in evaluating the effects of water stress on growth and yield, and in studies of the evaporation process (see, for example, Baldocchi et al., 1981; Blad, et al., 1981; Hipps and Hatfield, 1981).

Irrigated alfalfa in central Arizona appears to use about 9 or 10 mm of water per day in mid-summer. Van Bavel (1967) reported maximum rates of 12.2 mm/day near Phoenix, based on measurements with the energy budget method. Rosenberg and Verma (1978) found even higher water use rates in Nebraska, where irrigated alfalfa consistently used 8 to 12 mm/day on clear days, and the maximum use reached 14.2 mm/day as measured with a lysimeter. The Nebraska summer climate has less extreme temperatures and atmospheric vapor pressure deficits than are found in central Arizona, but wind is an important factor there, and the higher use rates were associated with clear, windy weather conditions that provided a substantial advective energy component.

This study reports evapotranspiration measurements made with the Bowen ratio energy budget method over irrigated alfalfa during four days in June, 1980. The study sought: (1) to test a new, dual-mast measurement system; and (2) to develop baseline data of evapotranspiration losses from a standard crop (irrigated alfalfa) under the warm, dry environmental conditions that characterize summer in southern Arizona.

The Bowen Ratio Model

The theoretical basis and application techniques of the energy budget and the Bowen ratio model are well known and thoroughly documented (see, for example, Bowen, 1926; Tanner, 1963; Webb, 1965). While details of the derivations need not be repeated here, some aspects of the model should be noted for reference during later discussions.

The model is based upon the one-dimensional energy budget of a volume beneath a horizontal plane of infinite extent:

$$Q^* + G + LE + H = 0 \qquad (1)$$

where Q^* is the net exchange of radiation, G is the rate of heat storage in the volume beneath the plane, LE is the exchange of latent energy and H is the exchange of sensible energy (convection) across the plane. The fluxes of Q^*, LE, and H are positive in the downward direction (to the plane) and the storage term G is positive when stored energy is released to the plane (i.e., when the level of thermal energy stored with the volume decreases). The energy budget can be evaluated periodically in order to provide an average over the desired time period.

The fluxes Q^* and G are readily measured directly with a net radiometer and a soil heat flux disc, respectively. The fluxes LE and H can be expressed in terms of measured temperature and vapor concentration gradients if Equation (1) is first divided through by LE and then solved to yield the Bowen ratio model,

$$LE = -(Q^* + G)/(1 + \beta) \qquad (2)$$

where β (Bowen's ratio) can be expressed as

$$\beta = H/LE = \lambda P(K_h/K_e)(\Delta\theta/\Delta z)/(\Delta e/\Delta z) \quad (3)$$

$$= 0.646\ \Delta\theta/\Delta e \text{ at sea level,}$$

with λ ($\lambda = 0.000646/^{\circ}C$) being the psychrometric constant, P (mb) is atmospheric pressure at the site, K_h and K_e are the turbulent diffusivities for sensible energy and for vapor (K_h/K_e is normally assumed to equal 1.0), $\Delta\theta/\Delta z$ (°C/m) is the gradient of potential temperature above the plane, and $\Delta e/\Delta z$ (mb/m) is the gradient of vapor pressure. Both gradients are measured over the same vertical distance Δz.

Equation (3) requires that measurements of $\Delta\theta$ and Δe be made in the air above the evaporating surface. Since the gradients are often rather small, a high degree of precision is needed in order to evaluate LE with Equation (2). The basic applicability of the model has been well established by comparisons with lysimeter measurements (see Tanner, 1963). Note that the assumption that $K_h/K_e = 1.0$ appears to hold reasonably well, except for recently raised questions concerning measurements made during strongly advective conditions (Verma, _et al._, 1978).

Field Measurements

The alfalfa field site was located about 50 km northwest of Tucson in the Avra Valley Irrigation District, at an elevation of about 650 m. The instruments were sited in a field approximately 12 ha in area; fetch to the desert and to the west and northwest was about 300 m, and fetch to adjacent fields to the south and east was about 270 m and 80 m respectively. The recently irrigated alfalfa was vigorous, dense, and about 0.5 m tall. Measurements were taken on June 11 and 12, just before cutting began on June 14, and again on June 27 and 28, after the canopy was re-established.

The system used for the energy budget measurements is similar to that described by Gay (1979a). The key features are: a precision data acquisition system, a microprocessor calculator for on-line data analysis, precisely calibrated ceramic wick psychrometers (Hartman and Gay, 1981), and an exchange mechanism that interchanges psychrometers between observations. The system employs two masts in close proximity (about 10 m apart here) so that two independent Bowen ratios can be obtained in order to provide a check on measurement precision. The two net radiometers (one on each mast) were averaged for areal net radiation and one soil heat flux disc was used to estimate thermal storage changes in the soil. The data acquisition system and microprocessor are housed in a mobile van, and the system operates from a generator in the field.

The pair of psychrometers used on each mast are vertically separated by 1 m. The psychrometers on each mast are interchanged every 6 minutes so that unbiased Δt and Δe means can be obtained for the Bowen ratio model every 12 minutes, using the averaging approach described by Sargeant and Tanner (1967). The Δt's are corrected for the adiabatic lapse rate to yield $\Delta\theta$'s. The mean gradients are then calculated from 15 samples made during the second 3 minutes of each 6 minute period (sensors are achieving equilibrium during the first 3 minutes at the new level). The exchange mechanism used here is described in detail by Gay and Fritschen (1979).

The exchange mechanisms were oriented to the north and placed on the masts with the lower psychrometer about 0.5 m above the alfalfa canopy. The net radiometers extended to the south at a height of 1.5 m above the alfalfa. The soil heat flux disc was placed in a representative location at a depth of about 10 mm. In addition to the data obtained for the basic energy budget, measurements were made of incident and reflected solar radiation, and wind speed and direction.

Results

The daily energy budget results are obtained from two periods with quite different thermal regimes: (1) the daytime period, characterized by large and cyclic variations in the inputs and outputs of energy; and (2) the night time period, with rather uniform, low intensity inputs and outputs of energy. Further, there were unexpected difficulties in obtaining night measurements, as the data acquisition system, which was unmanned at night, was frequently interrupted by problems in the data processing equipment and/or generator. The generator was also routinely shut down for service at dawn and again at sunset each day. The data were obtained with virtually no trouble during the four daytime periods, however. The daytime energy budget results will therefore be emphasized because of their great magnitude, and because of the excellent quality of the data.

Energy Budget Analyses

The daytime period of analysis actually conforms to the time that net radiation (Q*) is positive, rather than to the period between sunrise and sunset. Net radiation lagged about 30 minutes behind solar radiation in the morning, becoming positive about 30 minutes after sunrise, and it went negative again about 30 minutes before sunset. This timing conforms to general results reported for a variety of surfaces elsewhere (Gay, 1979b).

The flux densities of the energy budget components (in W/m^2) are illustrated in Figure 1 for the daylight period of positive net radiation on June 11 (approximately 0636-1836 hours). The points upon which the curves are based were obtained at intervals of 12 minutes throughout the day. The curves on this day are quite similar to those obtained on the other three days of measurement. The soil heat flux (G) shown in Figure 1 is based upon a single sensor, while the measurements of net radiation and sensible heat are averaged between the two masts ($\overline{Q^*}$, $\overline{H}$). The flux of latent energy is of primary interest in this study, and these estimates are shown individually for the two masts (LE1, LE2) to provide a visual check on the relative precision of measurement. This precision will be discussed further in a subsequent section of this paper.

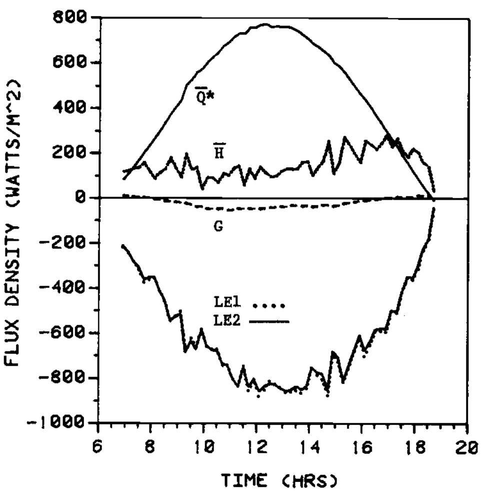

Figure 1. Energy budget components over irrigated alfalfa on June 11, 1980. Symbols identified in the text.

Note that $\overline{H}$>0 throughout the day confirming that there was a continuous advection of sensible energy from the warm desert to the cool, transpiring alfalfa field. Also, there are short period fluctuations of about ±50 W/m^2 that are superimposed upon daily cycles of convective latent energy. Both masts show the same fluctuations in LE1 and LE2, leading to the conclusion that these flucuations are probably associated with atmospheric transport changes as affected by wind speed.

The energy flux densities have been totaled for the periods of measurements and the totals are presented in Table 1. The individual days are quite similar. The flux totals for the daylight periods are (in MJ/m^2): $Q^* = 19.8$; $G = -0.7$; $\overline{H} = 7.8$; and $\overline{LE} = 26.9$. The latent energy mean is equivalent to the daily evaporation of 10.4 mm depth of water.

The night period totals shown in Table 1 are based on measurements made through the single night of June 12-13. The basis for the night period estimates requires further explanation. The measurements revealed that nocturnal conditions in this semi-arid climate place exceptional demands upon the Bowen ratio model. The clear skies, dry air and resulting steady loss of longwave radiation at night contribute to rapid surface cooling and to the formation of a strong inversion over the alfalfa field (temperature gradient increases with height). At the same time, the distribution of water vapor from the irrigated field is apparently affected by the stable inversion conditions, and we observed strong water vapor gradients (decreasing vapor concentrations with height above the field). The positive temperature gradients and negative vapor gradients were of a magnitude to produce Bowen ratios that approached negative one ($\beta \rightarrow -1$). The Bowen ratio model in Equation (2) becomes undefined when $\beta = -1.0$. This can only happen when $Q^* + G = 0$, according to Equation (1), and thus it occurs only during periods of very low energy flux. When the Bowen ratio is close to negative one, however, extraordinarily high precision is needed in measurements of $\Delta\theta/\Delta e$ in order to make consistent estimates of LE. The application of the Bowen ratio to these nocturnal periods in semi-arid conditions is under further study and will be reported on in a future paper.

In the meantime, we have estimated the nighttime fluxes from the measured values of Q* and G, by assuming that all of the longwave losses (Q*) are supplied by positive soil heat flux (G) and positive convection of sensible heat from the air (H). Latent energy

Table 1. Energy budget components over irrigated alfalfa. Energy units are MJ/m^2; ET units are mm/day.

Date 1980	←--- $\overline{Q^*}$	G	H1	MJ/m^2 H2	LE1	LE2 ---→	mm ET
11 June (0636-1836)	20.52	-0.84	6.54	6.33	-26.22	-26.01	10.45
12 June (0636-1836)	21.08	-0.97	6.12	5.88	-26.23	-25.99	10.44
27 June (0648-1848)	18.35	-0.49	7.14	6.63	-25.00	-24.49	9.90
28 June (0648-1848)	19.10	-0.58	8.21	7.70	-26.73	-26.22	10.59
Daytime Mean	19.76	-0.72	7.00	6.64	-26.05	-25.67	10.35
Night 12-13 June (1836-0636)	-1.81	1.22	.59	.59	0	0	0
24-hour Mean	17.95	0.5	7.69	7.23	-26.05	-25.67	10.35

was therefore set equal to zero at night. Forcing LE = 0 is consistent with the closure of stomata at night, but any evaporation from the soil surface is ignored. Since soil evaporation is likely to be low because of the closed crop canopy, we feel that little error is introduced by this simplification given the low levels of energy exchange at night. Likewise, the use of a single night to represent all four nights should cause few problems, given the similar conditions that prevailed during the four days of measurement.

Combining the night time estimates with the daytime averages reduces the daily total of Q* by nearly 10 percent, from 19.8 to 18.0 MJ/m^2. The positive night time flux G, which supplied most of the night radiative loss, more than compensated for the daytime "loss" of G, so the daily total becomes slightly positive. The flux H is increased slightly, and daytime LE remains unchanged over the 24-hour period. The mean Bowen ratio $\bar{\beta} = \overline{H}/\overline{LE} = -0.29$ for the 24-hour day, and there is little variation from this value from day to day.

Clearly, the most significant feature of the energy budgets measured over the alfalfa is the advection of sensible heat from the surrounding desert. More than 25 percent of the evaporation that took place was derived from this source, which served to substantially augment the energy available from the net exchange of radiation. The consequence of the desert warming of the air is clearly shown in Figure 2, which illustrates the mean hourly temperature and vapor gradients over the alfalfa field on June 11. The gradients are averaged between masts, as well as within each hour, to smooth out the random flucuations in the air. Note the air temperature gradient was about +1°C/m during the mid-day hours, and the vapor gradient was about -2 mb/m during the same period. The positive temperature gradients and the negative vapor concentration gradients indicate that sensible heat was directed towards the surface (advection) and water vapor was moving away from the surface (evaporation).

The Radiation Budget

Table 2 shows the radiation balance data for June 11, 12, 27, and 28 in terms of average flux density (W/m^2). Incident solar radiation (K↓) averaged 670 W/m^2 during the four, 12-hour daylight measurement periods. The mean shortwave albedo (ΣK↑/ΣK↓) was about 25 percent with the second study period (6/27-28) indicating slightly higher values than the first (6/11-12). Shortwave albedos in the range of 0.23 to 0.26 are typical for dense, compact canopies of crops such as the alfalfa (Monteith, 1978). The apparent difference in albedo may have been caused by partly cloudy conditions on July 27 and 28 which increased the relative contribution of diffuse radiation to the total solar radiation. Net solar radiation (K*=K↓ - K↑) averaged 505 W/m^2 during the study.

Table 2. Radiation budget components over irrigated alfalfa. Symbols identified in the text.

Date 1980	K↓	K↑	K*	L*	Q*	α
	W/m²					%
11 June (0636-1836)	714	-166	548	-73	475	23
12 June (0636-1836)	711	-166	545	-57	488	23
27 June (0648-1848)	619	-163	456	-31	425	26
28 June (0648-1848)	635	-166	459	-27	442	26
Mean	670	-165	505	047	458	25

The efficiency with which the alfalfa surface converted solar radiation (K↓) into non-radiative forms (given by Q*) can be examined by regressing Q* upon K*. Over the four 12-hour daylight periods this yields (in W/m^2).

$$Q^* = -59 + 1.02K^* \quad (4)$$

Interpretation of the coefficients "a" (intercept) and "b" (slope) have been discussed by Gay (1971). The initial net longwave, "a", represents longwave loss when K↓ = 0 (i.e., at night), so that K* must exceed approximately 59 W/m^2 before the net radiation becomes positive. The slope, "b", is 1.02, indicating an increase of 1 unit of K* will result in a 1.02 unit increase in Q*. A slope greater than unity indicates the net longwave loss increases somewhat (becomes less negative) during the middle of the day when net shortwave is greatest. This is to be expected if the surface temperature becomes relatively cooler than its surroundings (i.e., irrigated crops surrounded by desert) during periods of greater solar radiation incidence. A comparison of coefficient "a" (-59 W/m^2) and the average net longwave (-47 W/m^2) supports this interpretation. Thus, the alfalfa surface reflects a significant portion of the incident solar radiation (tending to reduce net radiation) but its relatively cool temperature moderates the longwave loss and the net result is fairly high net radiation.

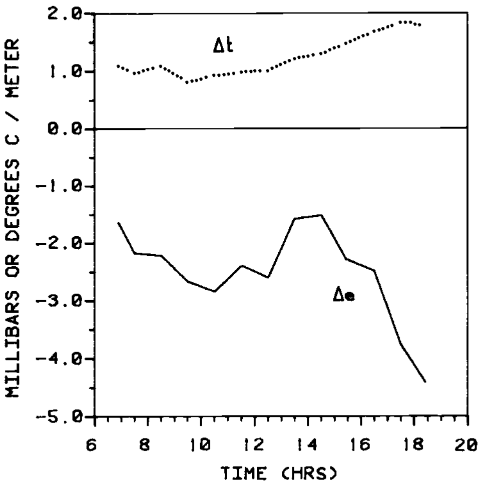

Figure 2. Mean hourly temperature and vapor concentration gradients over irrigated alfalfa on June 11.

Energy Budget Precision

The accuracy and precision of energy budget measurements have been evaluated by a variety of approaches (see, for example, Fritschen, 1965; Fuch and Tanner, 1970; Hartman, 1980; Holbo, 1973; Sinclair et al., 1976; Spittlehouse and Black, 1980; and Verma, et al. 1978). It is evident that the Bowen ratio method can yield reliable results provided it is carefully applied by competent researchers with the proper equipment. This is difficult to substantiate statistically, however, due to the adverse effects of autocorrelation which are typical of time series data such as this. A simple analysis of variance of the measured data appears inappropriate; we are attempting to quantify the effects of the autocorrelation so an analysis of variance can be properly applied. The results of those analyses will be published in a future paper.

Despite the failure of standard statistical tests, the apparent precision of the Bowen ratio measurements can be examined through a comparison of results from the two masts. The mean daily evapotranspiration from the two masts for the four days of measurements fell with ±0.7% of the mean. For the single day illustrated in Figure 1, the agreement between LE1 and LE2 is quite dramatic. The latent energy totals on this day were within 0.4 percent of their mean (LE1, LE2 in Table 1). Excellent agreement in LE1 and LE2 prevails on each of the four days. These results are in substantially better agreement than the Bowen ratio error estimates proposed for forests by Spittlehouse and Black (1980) of <15% for moist soil conditions (high ET) and 15 to 45% for dry soil conditions (low ET).

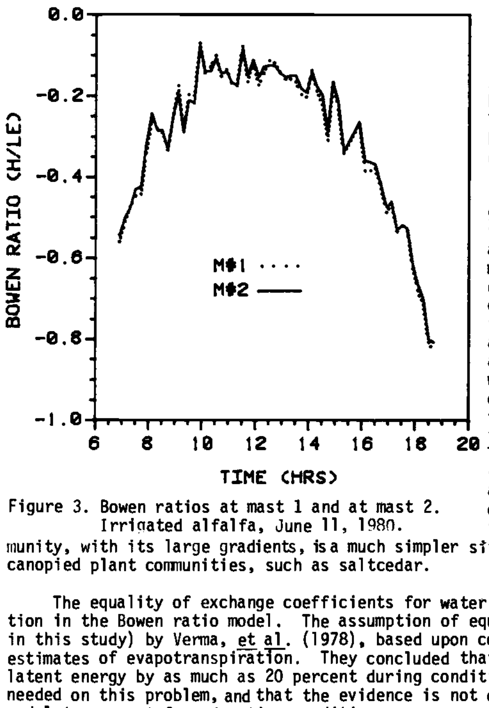

Figure 3. Bowen ratios at mast 1 and at mast 2. Irrigated alfalfa, June 11, 1980.

The difference in latent energy between masts (LE1, LE2) in Figure 1 is slightly reduced through the use of averaged net radiation. Since LE1 and LE2 in Figure 1 are not completely independent, a more appropriate test of the measurement system would be by comparison of the estimated Bowen ratios β1 and β2. The Bowen ratios estimated on June 11 are shown in Figure 3, and again the agreement is judged to be excellent.

The magnitude of the temperature and humidity gradients directly affects the precision of the Bowen ratio measurements. Obviously, when the gradients are large, the measurement system accuracy requirements are less stringent. The gradients illustrated earlier in Figure 2 over the alfalfa surface are quite large. Throughout the mid-day period, the temperature gradient fell between +0.5 and +2.0 °C/m, and the vapor concentration gradient was between -5 and -4 mb/m. In contrast, a series of measurements with the same system over freely transpiring saltcedar (Gay and Hartman, 1981) revealed that the daytime gradients were between +0.1 and +0.2 °C/m for temperature and between -0.4 and -0.2 mb/m for vapor. The two communities were transpiring at similar rates (9 mm/day for the saltcedar and 10 mm/day for the alfalfa), and the smaller gradients over the saltcedar were attributed to the role of canopy roughness in inducing mechanical mixing. Thus the alfalfa community, with its large gradients, is a much simpler site for energy budget measurements than are rough-canopied plant communities, such as saltcedar.

The equality of exchange coefficients for water vapor and heat (K_e and K_h) is an important assumption in the Bowen ratio model. The assumption of equality was questioned for advective conditions (as in this study) by Verma, et al. (1978), based upon comparisons between the Bowen ratio and lysimetric estimates of evapotranspiration. They concluded that the Bowen ratio might cause under-estimates of latent energy by as much as 20 percent during conditions of strong advection. We felt that more work is needed on this problem, and that the evidence is not conclusive enough to warrant an adjustment to the model to correct for advective conditions.

Conclusions

Bowen ratio measurements over irrigated alfalfa in southern Arizona for four days in June of 1980 indicated a mean daily evapotranspiration slightly in excess of 10 mm. Advective conditions prevailed throughout the study. The positive sensible heat flux contributed over 25 percent of the energy ultimately converted to latent energy of vaporization. The dense alfalfa canopy moderated the amount of absorbed solar radiation through a relatively high albedo (0.25). The alfalfa field remained "cool" relative to the environment, and so the net longwave loss from the alfalfa was slightly reduced during the heat of the day, and thus compensated somewhat for the high albedo.

The agreement between the latent energy estimates from the two masts is judged to be excellent, as the evapotranspiration totals for the two masts were within ±0.7% of their mean. The precision of the latent energy measurements was enhanced by the large temperature and humidity gradients over the irrigated alfalfa.

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