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Total Energy Budget of the Plant Canopy and Its Relationship to Evapotranspiration From Corn

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THE TOTAL ENERGY BUDGET OF A PLANT CANOPY

Essentially all energy is derived either directly or indirectly from the sun. This includes the energy required by chemical and biological processes in the production of plants. The solar energy received by a section (1 sq. mile) of land during a summer day is equivalent to the energy of nearly a thousand tons of coal or to the output of hydro-electric energy during one-half day from Hoover Dam.

Only a small percentage of this solar energy is used in the production of carbohydrates and sugars to build plant tissues. Even for large yields of dry matter, such as of 10 tons per acre, less than 2 per cent of the energy from the sun is used by the biological process which converts carbon dioxide to carbohydrates (photosynthesis). Apparently the maximum use of energy by plants in the production of carbohydrates is 8 to 12 per cent of the solar energy, and this high rate persists for short periods of time and only with special plants.

This bulletin concerns the dissipation or utilization of the remaining 90 to 99 per cent of the energy received from the sun by processes other than the production of carbohydrates by plants. Clearly some of this energy is used to warm the atmosphere and earth, but it will be demonstrated that a larger segment of this energy is directly linked to the water balance of the biosphere and atmosphere. Because of its influence on the water balance, the energy from the sun becomes important in determining the rate of water use by plants.

THE ROLE OF WATER IN HEAT BUDGET OF THE SURFACE

Energy Requirement for Evaporation

Besides the importance of water in sustaining life with its associated economic importance to industrial growth and food production, water is involved with the energy balance at the earth's surface and in the atmosphere. Unlike most common substances, water exists under natural conditions in all three phases, i.e. as a solid, liquid, and gas.

Energy is either required or liberated when a change in phase occurs, so water changing from a liquid to a vapor in the evaporation process utilizes large amounts of energy. This energy is released upon the condensation of water vapor back to the liquid phase. Thus, heat is required for water to evaporate from plant, soil, or water surfaces; and this energy is subsequently released into the atmosphere when condensation occurs during cloud formation.

Water follows a definite cycle of movement. First, evaporation occurring from the oceans, other bodies of water, and vegetation transfers water into the atmosphere as vapor. In humid and subhumid regions large quantities of water are condensed in the atmosphere and deposited on the surface of the earth through the rain and snow.

In Missouri, the annual precipitation averages approximately 40 inches a year. The amount ranges from areas in the northwest part of the state that receive only 34 inches to portions of southeast Missouri that average as much as 47 inches per year. A portion of the water falling in Missouri moves over and through the earth's surface, returning to the large permanent water bodies which form the ocean and seas. A larger part of the water intercepted by the surface in Missouri moves directly back to the atmosphere by evaporation from inland water, soil, and plant surfaces.

The cycle of water movement from the oceans, to the atmosphere, to the land and back to the atmosphere is, similarly, a cycle of heat transfer. Heat is required by the evaporation process at the surface and it is released through condensation in the atmosphere.

Evapotranspiration From a Plant Surface

The combined amounts of water evaporated from soil surfaces and transpired by plants into the atmosphere are defined as the "evapotranspiration." Wide adoption of this term justifies its use when considering the total vapor movement from soil and vegetative cover. It has similarly become common to use the term "potential evapotranspiration" to refer to the maximum possible loss of water vapor by a plant cover for any set of weather conditions. Potential evapotranspiration occurs from a complete and actively growing canopy of plants with an optimum supply of soil water.

Under conditions of an incomplete plant canopy, a stage of development during which the plants are not actively growing or at a time when the quantity of soil water is limiting growth, the actual evapotranspiration is less than the potential. In general, the potential evapotranspiration from a vegetative cover is less than that occurring from a free-water surface. Vapor flow from the surface of the soil is retarded by the soil particles which are often dry near the surface. Similarly, the stomatal apertures of the plant tissue are not open continuously, so the plant forms a barrier to vapor flow.

Mechanism of Transport of Water Vapor From the Surface

The mechanism of evapotranspiration involves the mixing of gaseous water molecules from the surface of the soil and plants by air turbulence into the atmosphere. Penman (10) and Sutton(14) present excellent reviews of the essential features of the theory for turbulent transport of water vapor. However, the determination of the amount of evapotranspiration by relationships dealing with the turbulent transport is complicated by many instrumentation and theoretical difficulties. Decker (3) showed that extremely sensitive measurements with complex instrument systems are required if the turbulence theory is to be used for quantitative estimates of the amount of evapotranspiration.

Perhaps a more practical method of evaluating the mechanism of evapotranspiration and determining the amount of evapotranspiration is through an examination of the heat budget of the plant and soil surfaces. This relation is presented in equation (1).

$$R_n = Q + LE + S + --- \qquad (1)$$

Where:

R_n is the net radiation or the energy remaining at the surface after all radiative processes have occurred, i.e. it is energy available for physical and biological processes at the earth's surface;

Q is the sensible heat transfer to the atmosphere;

S is the sensible heat transfer to the soil;

LE is the heat used in the evapotranspiration process.

Determining the amount of evapotranspiration from the energy budget has an advantage over the use of the turbulent transport phenomena because the instrumentation is not so complex and expensive.

EVALUATION OF THE TERMS OF THE ENERGY BUDGET

Net Radiation Measurements

Since the net radiation at the surface is defined as the difference between the downward and upward streams of radiation, it may be expressed as presented in equation (2):

$$R_n = I - aI - L_n \qquad (2)$$

Where:

I is the amount of visible or short wave energy reaching the surface from the sun and sky;

a is the albedo of the surface, the fraction of the short wave energy reflected from the surface;

L_n is the net exchange of long wave (infrared) radiation from the earth's surface; i.e. the difference between the energy radiated from the earth's surface and the long wave radiation received by the earth's surface from the atmosphere.

Fig. 1—An instrument used in this study to measure the net radiation above the experimental area used.

The magnitude of R_n has been estimated by many techniques. One method, suggested by Brunt(1) estimates the terms of the equation (2) from empirically derived relationships between the radiation components and cloudiness, vapor content of the atmosphere, and air temperature near the surface. In recent years, instruments have been designed for measuring directly the net radiation and in this research R_n was measured by a ventilated radiometer. This instrument was obtained commercially. The theory of the measuring device has been described by Gier and Dunkle (6) and by Suomi, Franssila and Islitzer (13). Figure 1 shows this instrument as exposed above a corn field.

Energy Sinks for Net Radiation

The terms of the total energy budget shown in equation (1) may be evaluated by measuring all or part of the components as in the Lake Hefner study (15) for a water surface and studies by Suomi and Tanner (12), Graham and King (7), and Fritchen and Shaw (4) for various crop canopies. Similarly, the components of equation (1) may be evaluated from mathematical models involving the temperature, vapor pressure, and wind gradients as the models proposed by Halsted (8) and Suomi (11).

A major contribution to the evaluation of the heat budget was made by Penman (9) in England during 1948. Basically, Penman's model partitions the net radiation into the energy used in the latent (LE) and sensible heat (Q) transfer. In the model the heat transfer to the soil is neglected, but Gerber and Decker (5) modified the relationship to account for the heat transfer to the soil. This modification of the Penman relationship is given in equation(3):

$$LE = \frac{\Delta (R_n - S) + \gamma LE_a}{\Delta +} \qquad (3)$$

Where:

LE is the energy used in the latent heat transfer;

R_n is the net radiation just above the corn canopy;

S is the transfer of heat to the soil;

Δ is the slope of the vapor pressure-temperature curve at the air temperature;

γ is the psychrometric constant ($\gamma = .27$) when temperature is measured in degrees Fahrenheit and vapor pressure in millimeters mercury);

LE_a, is a convenient term which may be considered as the evaporation occurring from a surface with an average temperature equal to that of air.

The term, LE_a, is derived from an empirical relationship between the vapor pressure deficit and the air movement as shown in Equation (4).

$$LE_a = 0.35\ (e_a - e_d)\ (0.5 + u/100) \qquad (4)$$

Where:

e_a is the saturated vapor pressure at the air temperature; e_d is the actual vapor pressure of the atmosphere; u is the miles of wind travel per day at 2 meters above the surface.

The advantage of the relationship in equation (3) over a more rigorous treatment is that the components of the heat budget may be estimated in terms of readily measurable quantities. The units of the estimated LE will be determined by the constants employed and these units are usually expressed in calories per square cm surface area per day. The number of calories may be converted to the equivalent depth of evaporated water through dividing by 1500, the number of calories required to evaporate an inch of water from a one square centimeter surface area.

MEASUREMENT OF COMPONENTS OF THE ENERGY BUDGET FOR CORN

Experimental Area

The experimental area on which energy budget experiments were conducted during 1959, 1960, and 1961, is at the Midwest Claypan Station near McCredie, Mo., which is approximately 30 miles east of Columbia. The experimental area was an approximately 10-acre block of land situated on a south-facing slope of about 2 to 4 per cent. The layout of the plot in which five terraces divide the experimental area into approximately two-acre segments is shown in Figure 2.

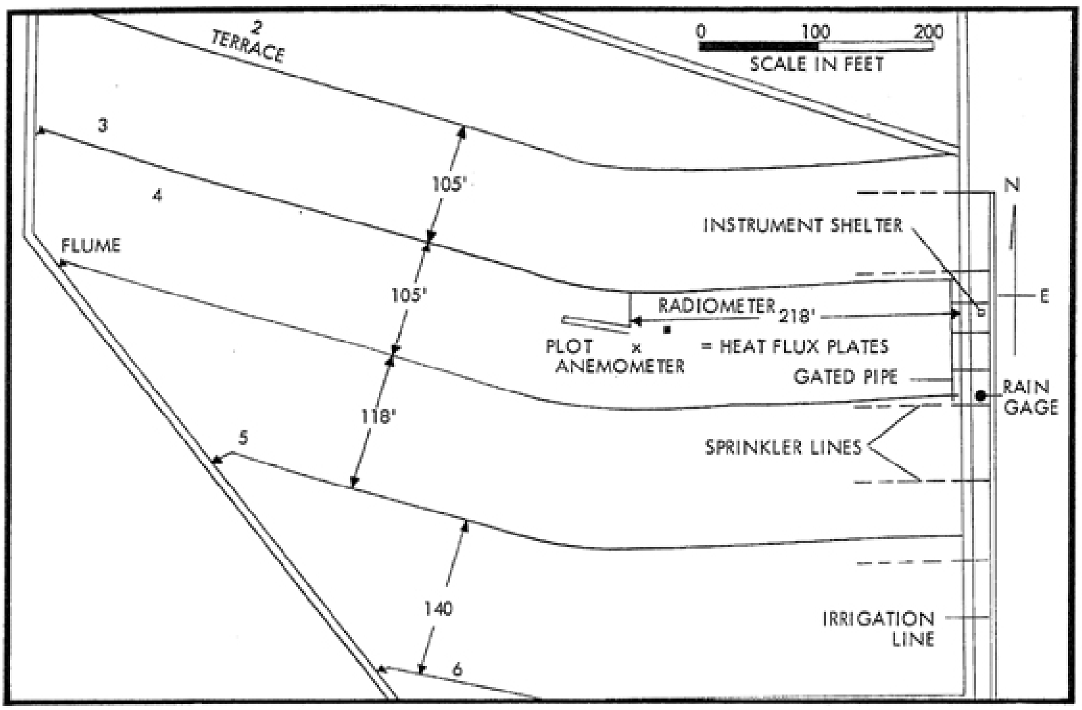

Fig. 2—A diagram of the five terraces which comprised the experimental area. The site of the experiment was near the center of Terrace 4.

The evapotranspiration measurements and the environmental measurements were taken at a site near the center of Terrace 4. This site, along with the location of the instrument, is shown in Figure 2. The two acres comprising Terrace 4 were irrigated during the three years of this experiment by furrows between the rows. During 1959 and 1960, approximately 80 per cent of the remaining portion of the experimental area was irrigated, using the sprinkler system, but during 1961 only Terrace 4 was irrigated. Water for all irrigation treatments was supplied from a nearby 15-acre lake.

Figures 3 and 4 show the diagrammatic layout of the experimental site within the terrace. It will be noted that a wooden walk-way was constructed in the plot, which permitted movement through the plots during periods when the soil was wet. This walk-way may have interfered some with vapor diffusion; however, soil compaction would have been a greater detriment to the experiment.

The soil type of the experimental area is Mexico silt loam. This planosol has a heavy claypan in the B horizon and a leached, grey silty A_2 horizon. The A horizon has been disturbed by erosion and land leveling with many places showing complete removal. Prior to each cropping season, basic applications of fertilizer and limestone were made to correct deficiencies in soil fertility. Ample quantities of nitrogen and starter fertilizer were used to produce 100 to 150 bushels

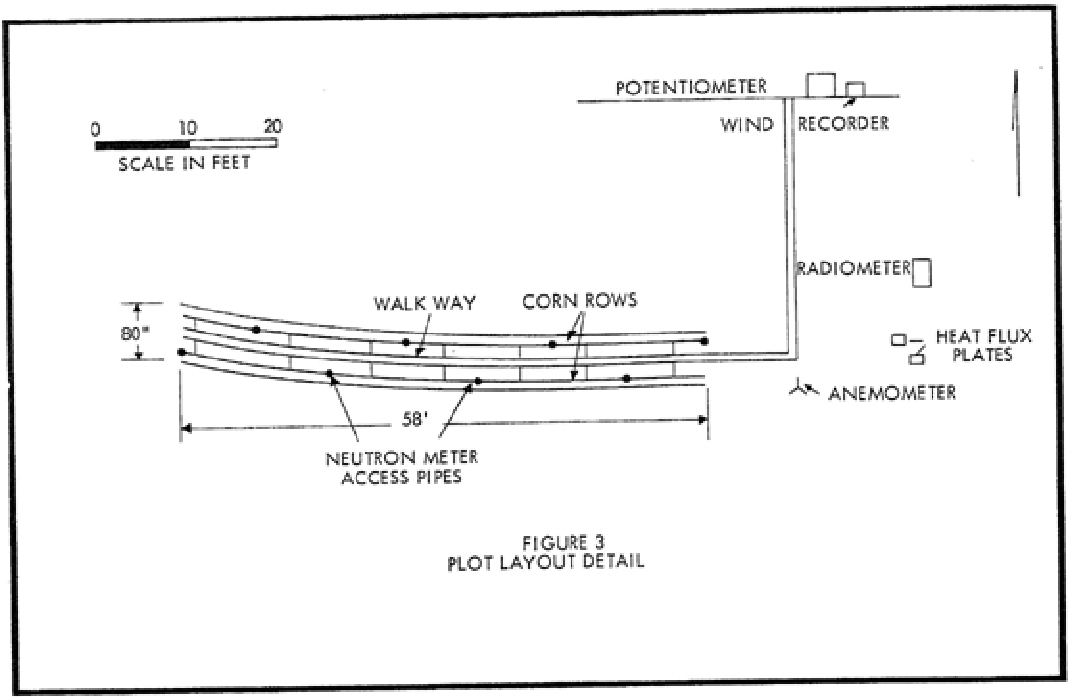

Fig. 3—A detailed diagram of the experimental site near the center of the experimental area.

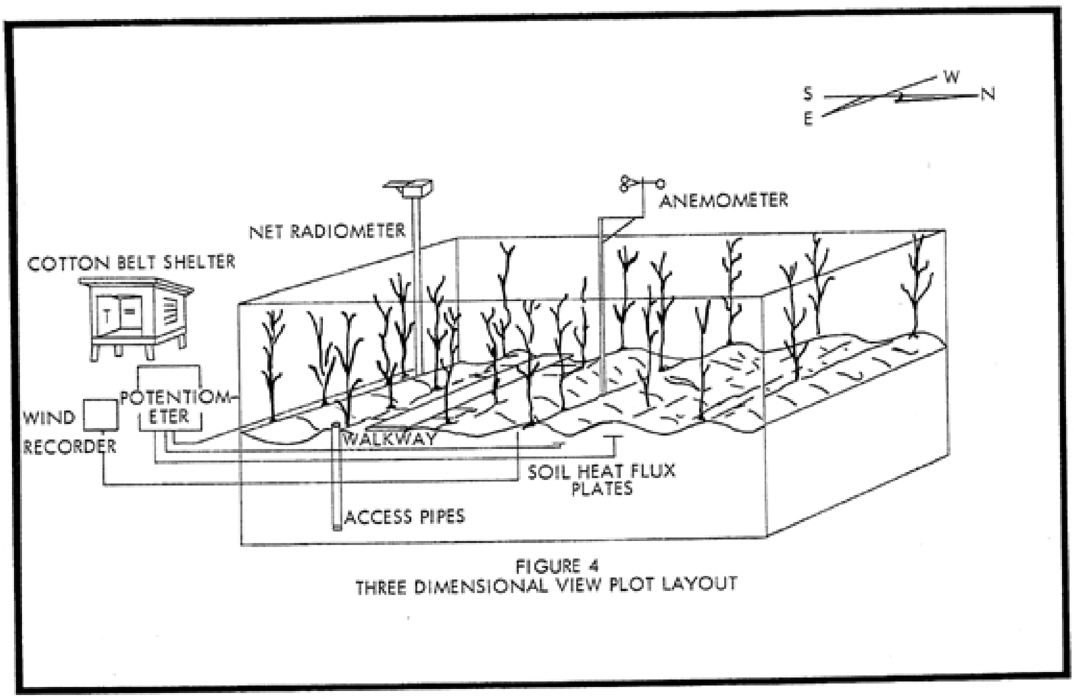

Fig. 4—A three dimensional view of the experimental site.

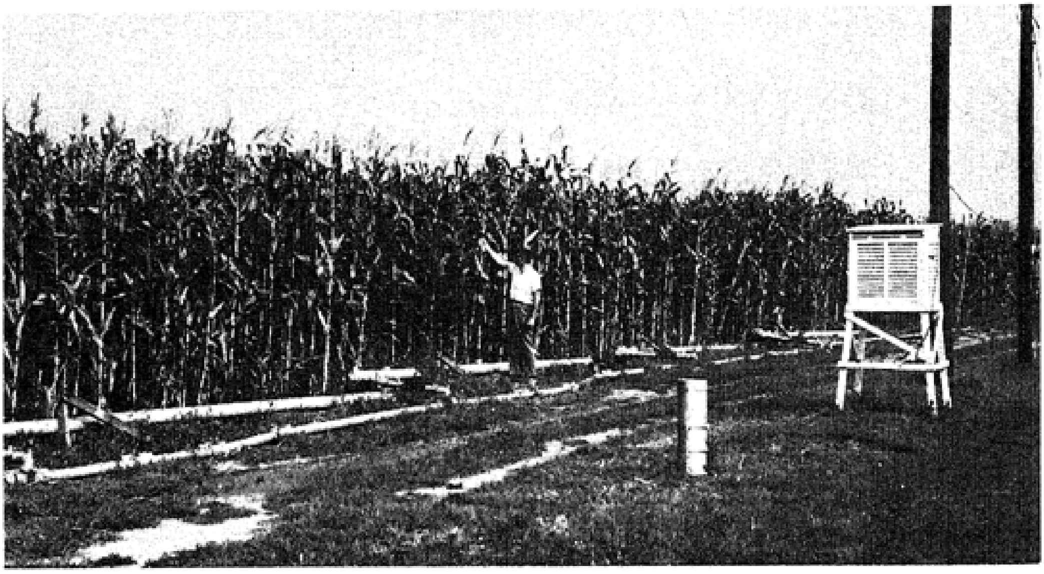

Fig. 5—A view of the corn field showing the abundant growth which resulted from the irrigation and fertility treatments.

per acre. A view of the field showing the quantity of growth is shown in Figure 5. The corn variety used during the first two years was Dixie 33, but a Missouri adapted hybrid was planted during the last year. A high rate of planting was attempted and during 1959 and 1960 about 18,000 plants per acre resulted, but in 1961 the stand consisted of only 10,000 plants per acre.

Water Balance Measurements to Estimate Evapotranspiration

To obtain the water balance, runoff measurements were taken from Terrace 4 by an H-type flume located in the terrace outlet. These runoff measurements provided estimates of the average water loss from the entire two-acre terrace and did not actually represent the runoff from the experimental site located near the center of the terrace. During the first two years of the experiment this procedure seemed quite satisfactory so far as rainfall was concerned, but during the last year erratic runoff measurements were obtained. For all years the runoff measurements did not appear to yield realistic results when associated with irrigation. It appears that the amount of water retained at the experimental site under conditions of irrigation was different than for the Terrace as a whole.

Pipes which are shown schematically in Figures 3 and 4 were placed vertically into the soil in each of the two rows of corn which defined the experiment site. These access pipes consisted of 1.5-inch rigid, thin-wall electrical conduit, and were placed in the ground to an approximate depth of 5.5 feet. A probe from a neutron meter was lowered into the pipes for measuring the quantity of soil water. The neutron probe resting on one of the access pipes is shown in Figure 6. With

Fig. 6—The soil moisture measurements were taken under the corn by use of the neutron probe on the right and the scalar in the foreground.

Fig. 7—A view of the net radiometer and anemometer above the corn in the experimental site.

the measurement of rainfall (P), runoff from rainfall (R), and change in quantity of soil water (Δ M), the water balance could be estimated. From this balance the evapotranspiration (LE) was measured using equation (5):

$$LE = P - R - \Delta M \quad (5)$$

Other Environmental Factors and the Components of the Energy Budget

An attempt was made to measure environmental factors important to the energy budget of the corn field as given in equation (1). This included the measurement of R_n, the exchange of net radiation above the corn crop, and S, the heat transfer into the soil. The instruments for measuring wind and net radiation are shown in Figure 7. There were no direct measurements of the heat transfer to the atmosphere through sensible heat, Q. The estimate for this quantity of the energy budget was obtained by solving for the residual in equation (1).

RESULTS OF THE ENERGY BUDGET MEASUREMENTS FOR CORN DURING 1959, 1960, AND 1961

Magnitude of the Net Radiation Above a Surface Covered With Corn

It has been noted that the energy available for such physical processes as warming the atmosphere and soil and for biological processes such as transpiring water and photosynthesis is derived from the net radiation term. It is of interest to note what portion of the incoming energy from the sun becomes available as net radiation and is used by the physical and biological processes within the crop. These data are summarized for the periods used in this study in Table 1.

TABLE 1 - SOLAR RADIATION AND NET RADIATION FOR AN IRRIGATED CORN FIELD BY SEMI-MONTHLY PERIODS

Growing Period	I Solar Energy cal/cm^2/day	R_n Net Radiation cal/cm^2/day	Ratio R_n/I
July 1-15	672	473	.70
July 16-31	529	354	.67
Aug. 1-6	520	367	.71
Aug. 16-31	504	342	.68
Sept. 1-15	486	288	.59

Here the incoming energy was measured at the Columbia Municipal Airport some 30 miles west of the site from which the net radiation was measured. Because the cloud cover over the two areas is nearly identical over the period of a day, it is doubtful that the incoming energy totals were greatly different at the airport and at the experimental farm.

During the period from July 1 through August 31, about 70 per cent of the incoming energy becomes part of the net radiation term in the energy balance relationship. When early July is compared with late August there is a 25 per cent reduction in both the amount of energy received from the sun and net radiation. However, the amount of energy available as net radiation decreases more rapidly during the first half of September than the incoming energy from the sun. This seems to indicate that either a change in color and, therefore, reflectivity of the corn occurs during early September, or the reflectivity is increased by the lower sun angles of September. The latter appears more likely since there was no noticeable change in the color of the corn during the early September period.

Heat Budget Measurements

The average energy budget as presented in Equation (1) for periods of three to five days length were measured from corn grown with abundant fertility and moisture during 1959, 1960, and 1961. In 1959, measurements of the energy budget were begun during the first days of July and continued until mid-September. A total of 81 days were included in the measurements. During 1960 the measurements were begun in mid-July and were terminated late in August, a total of 25 days. Because of instrumental difficulties the experiment did not begin until mid-August of 1961, it was continued into mid-September for a total of 21 days.

Daily measurements of the energy budget for the corn were impossible. The precision for measuring the latent heat component, LE, was not great enough for daily observations. As a result, the measurements were taken for periods ranging from 2 to 6 days in length. Table 2 shows the data for all periods during the three years of observations.

All energy components are given in terms of the calories per square centimeter of surface per day.

From these data it is apparent that there is wide variability from period to period in the components of the energy budget. The net radiation varied from nearly 500 calories per sq. cm. per day to a low of about 200 calories per sq. cm. per day. The transfer of heat to the soil, S, is relatively high during early July and becomes negative during the latter part of the growing season. This negative quantity indicates the heat stored in the soil early in the summer is delivered by the soil to the surface. On the other hand, the heat transferred to the atmosphere as sensible heat, Q, is greater during the late portion of the growing season.

The component of the energy budget indentified as LE or the energy required in evapotranspiration is of prime interest to the agriculturist. There is a wide variability in the amount of heat used in the evapotranspiration process, LE. Although extremes of the observations occurred during 1959, this does not mean that it was necessarily an

TABLE 2 - THE ENERGY BUDGET OF A CORNFIELD DURING 1959, 1960, AND 1961 FOR PERIODS OF TWO TO SIX DAYS LENGTH

Year	Period	Length of Period	Net Radiation R_n	Latent Heat LE	Heat Transfer to soil S	Heat Transfer to Air Q
1959	July 3-6	3	428	300	112	16
	6-8	2	488	428	30	30
	8-10	2	495	285	30	180
	10-13	3	488	330	30	128
	15-17	2	218	165	30	23
	17-20	3	398	345	38	15
	20-22	2	420	300	38	82
	22-24	2	360	285	38	37
	24-27	3	338	188	22	128
	27-29	2	398	360	52	-14
	29-31	2	352	390	22	-60
	31-Aug. 3	3	405	398	15	-8
	Aug. 3-5	2	368	338	45	-15
	5-7	2	240	188	-8	60
	7-10	3	338	180	-45	203
	12-14	2	420	435	8	-23
	14-17	3	255	232	0	23
	17-19	2	412	300	30	82
	19-21	2	382	278	15	89
	21-24	3	262	98	8	156
	24-26	2	368	368	-8	8
	26-31	5	345	233	-8	120
	31-Sept. 2	2	210	270	-52	-8
	Sept. 2-4	2	382	180	-60	262
	4-7	3	382	218	15	149
	7-9	2	202	202	-8	8
	9-11	2	248	135	-90	203
	11-14	3	315	82	-75	308
	14-16	2	345	142	-38	241
	16-18	2	135	82	-82	135
1960	July 11-13	2	441	270	14	157
	22-27	5	257	248	8	1
	27-29	2	433	338	-26	121
	29-Aug. 1	3	370	202	-15	183
	Aug. 5-8	3	405	315	-5	95
	12-15	3	366	308	1	57
	17-19	2	262	180	-6	88
	19-22	3	313	255	2	56
	22-24	2	389	232	10	147
1961	Aug. 11-16	5	382	150	-2	234
	16-21	5	349	300	-18	67
	24-29	5	380	120	-8	268
	Sept. 5-11	6	321	135	-13	199

anamolous year so far as evaporation and transpiration were concerned. These extremes are indicative of the large number of observational periods during 1959. In addition, most of the periods during 1959 were only 2 and 3 days in length, giving a minimum to the effect of averaging over a longer period. The greatest average evapotranspiration occurred July 6 through 8 and August 12 through 14 of 1959, when 0.28 inch per day of water was evaporated from the corn cover. The smallest amount of evapotranspiration occurred during mid-September when 0.05 inch per day of water was lost through evapotranspiration. In determining the significance of this latter quantity, it should be remembered that the corn was still green and turgid during September.

There does appear to be a marked seasonal variability in the evapotranspiration from the corn canopy. The average components of the radiation balance by semi-monthly periods through the summer are listed in Table 3. Both net radiation and heat used in the evapotranspiration process (latent heat) decrease as the summer progresses.

TABLE 3 - AVERAGE ENERGY BUDGET OF IRRIGATED CORN AND EVAPOTRANSPIRATION BY SEMI-MONTHLY PERIODS.

Growth Period	Heat Budget ($cal/cm^2/day$)				
	Net Radiation	Latent Heat	Sensible Air	Heat Soil	Evaportranspiration* (inches/day)
July 1-15	473	332	92	48	.22
July 16-31	354	280	58	17	.19
Aug. 1-15	367	277	89	1	.18
Aug. 16-31	342	233	109	0	.16
Sept. 1-15	288	157	171	-40	.10

* Latent Heat/1500 = Evapotranspiration

At the same time the transfer of heat to the atmosphere increases in late summer and early fall, while the heat transfer to the soil reaches zero in late August and is negative during early September. The values shown in Table 3 are demonstrated diagrammatically in Figure 8.

The portion of the net radiation used in evapotranspiration is between 70 and 80 per cent during most of the summer with nearly all of the remaining available energy being transferred to the atmosphere. Since these two components of heat budget (evapotranspiration and warming the atmosphere) account for more than 90 per cent of the net radiation, it is often customary to neglect the energy transferred to the soil. It is informative to speak of the portion of net radiation used by the components of the energy budget; the fractions of the net radiation used by all of the components are shown in Table 4.

Late in the growing season the amount of energy used for warming the atmosphere becomes greater with a corresponding decrease in that used in the evapotranspiration process. This reduction in energy use

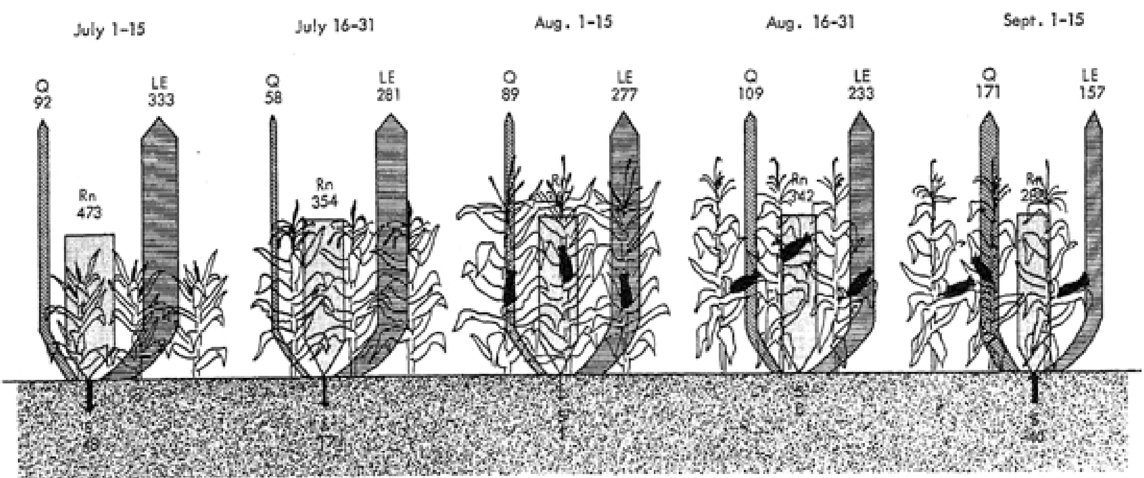

Fig. 8—A diagramic presentation of the energy budget of corn by two-week periods through the growing season.

TABLE 4 - RATIOS OF ENERGY FOR IRRIGATED CORN BY SEMI-MONTHLY PERIODS

Growing Periods	Fraction of Net Radiation Used in: Evapotrans-piration	Warming Atmosphere	Warming Soil	Bowens Ratio Q/LE
July 1-15	.70	.20	.10	.28
July 16-31	.79	.16	.05	.21
Aug. 1-15	.75	.25	*	.32
Aug. 16-31	.68	.32	*	.47
Sept. 1-15	.54	.60	-.14	1.09

in evapotranspiration is associated with the decline of biological activities of corn during late August and early September when final translocation of dry matter to the ear is taking place. On the other hand, the increase in relative importance of the transfer of heat to the atmosphere as sensible heat results from a greater frequency of cool air mass penetrations into Missouri during late August and early September.

The ratio between the transfer of heat to the atmosphere and that used in evapotranspiration is important. This ratio, which is called Bowen's ratio, is presented for the five periods during the growing season in Table 4. This ratio appears to be reasonably constant during the mid-portion of the corn growing season, with an average value of 0.27. The ratio increases in size as the season progresses and attains a value greater than one during early September.

ESTIMATION OF EVAPOTRANSPIRATION FOR CORN FROM ENERGY BUDGET CONSIDERATIONS

Variability in Evapotranspiration

Of the components in the heat budget in equation (1) the one with greatest practical interest is the energy used in latent heat or evapotranspiration. Corn does not evaporate water at the same rate each day. Not only is there a systematic variation in the evapotranspiration through the season, but there is a variability during the same portion of the growing season from one year to another. Plotted in Figure 9 is a histogram showing the frequency distribution of average daily evapotranspiration for the three- to five-day periods during 1959, 1960, and 1961. There is a tendency for this distribution to be skewed toward the smaller values of evapotranspiration. The average of all the observations is 0.17 inch per day, while the median quantity is 0.18 inch per day and the modal value is 0.20 inch per day. The dis-

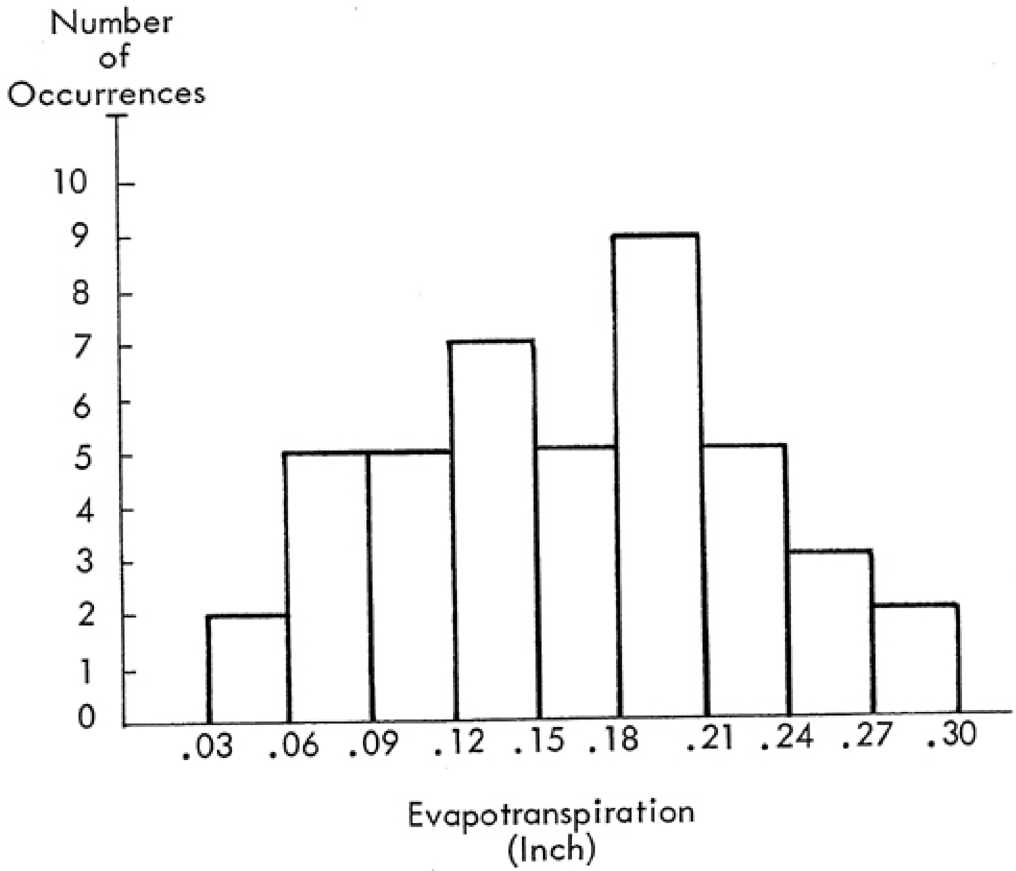

Fig. 9—The histogram showing the frequency of the average daily evapotranspiration from corn for 3- to 7- day periods during 1959, 1960, and 1961.

tribution is quite flat, which indicates a tendency for rather large deviations from the mean. One-fourth of the observations of evapotranspiration were 0.12 inch or less, while one-fourth were greater than .21 inch.

Although the absolute magnitude of the variation is small, there is considerable percentage variability. The difference between high and low values of evapotranspiration is extremely important in the depletion of soil water over a period of a few days or a week.

Estimation of Evapotranspiration from Weather Observations

For many years it has been the objective of agriculturalists, hydrologists, and climatologists to estimate the rate of evapotranspiration from concurrent weather data. Should a successful method for estimating evapotranspiration be found, the necessity of observing the water balance in the soil would be removed, making the task of accounting for the water balance in the soil easier.

The method suggested by Penman for estimating evapotranspiration from weather information was discussed earlier in this bulletin. This method is often selected by investigators because it has the elegance of being based upon the energy budget relationship of equation(1). Gerber and Decker (5) have reported an investigation in which the relationship between the observed evapotranspiration and that estimated by the Penman method were compared. Their results suggest that the data should be partitioned into those cases with a dry soil surface and those with a wet surface. A correlation coefficient of 0.85 was obtained between the measured evapotranspiration and that estimated by the Penman relationship when the soil's surface was wet. A lower, but significant, correlation coefficient was obtained through the relationship of the estimated and measured evapotranspiration for cases where the soil's surface was dry. In addition, the investigators reported a difference between the slopes of regression lines obtained from the relationship between the observed evapotranspiration and the estimated value from the Penman method.

The 1959 data included in this bulletin are the same as those used in the regression analysis for the study reported by Gerber and Decker. It now appears that they may have arrived at a false premise when analyzing the 1959 data. An examination of Table 3 shows a seasonal distribution in the amount of evapotranspiration. The majority of the dry cases included in the report by Gerber and Decker occurred during September, and the reduction in evapotranspiration could have been due to the stage of development of the corn plant at this time of year rather than to the impedence of moisture flow through the surface by the dry soil layer. It is now suggested that a seasonal correction be applied to the estimated quantities of evapotranspiration by the Penman method to account for this decline in evapotranspiration during the late summer season.

During the period from July 16 through August 15, when corn has reached its maximum vegetative growth, 75 to 79 percent of the net radiation was used in evapotranspiration (Table 4). This monthly period was taken as the base with an average of 77 per cent of net radiation used in evapotranspiration; a correction to the estimated evapotranspiration was made for the remaining three periods, based on the proportion of net radiation used in the evapotranspiration process. By this token the period July 1 through 16 had a correction of 0.91 (70/79) while the August 16 through 31 period used a correction of 0.88 (68/77), and the period from September 1 through 16 employed the correction 0.70 (54/77). These correction factors were multiplied by the estimated evapotranspiration obtained from the Penman method. It will be noted that these corrections reduced the estimated evapotranspiration during the latter part of the growing season, and to some degree during early July prior to the time when the corn growth was at its maximum.

Using these corrections, estimates of the evapotranspiration were made and compared with the measured quantities. The comparison is shown graphically in Figure 10. The least squares regression line is plotted on this figure along with the line corresponding to a 1.1 relationship between the observed and the expected. Not only is the least squares line significantly different from zero, but it is also significantly different from the theoretical line; that is, the line with a slope of 1 passing through the origin. The correlation coefficient is 0.70.

There are several interesting points to be made concerning Figure 10. Of most importance is the fact that the evapotranspiration estimated by the mathematical model tends to estimate quantity nearer the overall mean than is observed. For example, the lowest estimated quantity of evapotranspiration for a day is 0.09 inch, while values as low as 0.05 were measured. Similarly, the highest value estimated by the heat budget model and its adjustment, is 0.25 inch, while amounts were observed as high as 0.29 of an inch. A standard error of estimates of 0.0010 inch was obtained using these data.

To further emphasize the tendency of the estimated quantity to lie near the median or mean evapotranspiration, it is noted that all of the points (eight observation periods) with measured evapotranspiration above 0.22 are below theoretical line in Figure 1, while all of the measured evapotranspiration quantities below 0.13 inch (nine points are involved) lie above the theoretical line. This fact has been observed before and was reported by Decker (2). It is important to note that the method based on mean temperatuve, e.g. Thornthwate's, for estimating evapotranspiration, estimated amounts near the over-all mean an even greater percentage of the time than the method of Penman.

It is this tendency for mathematically derived models to estimate near the mean that makes these models useful under average conditions.

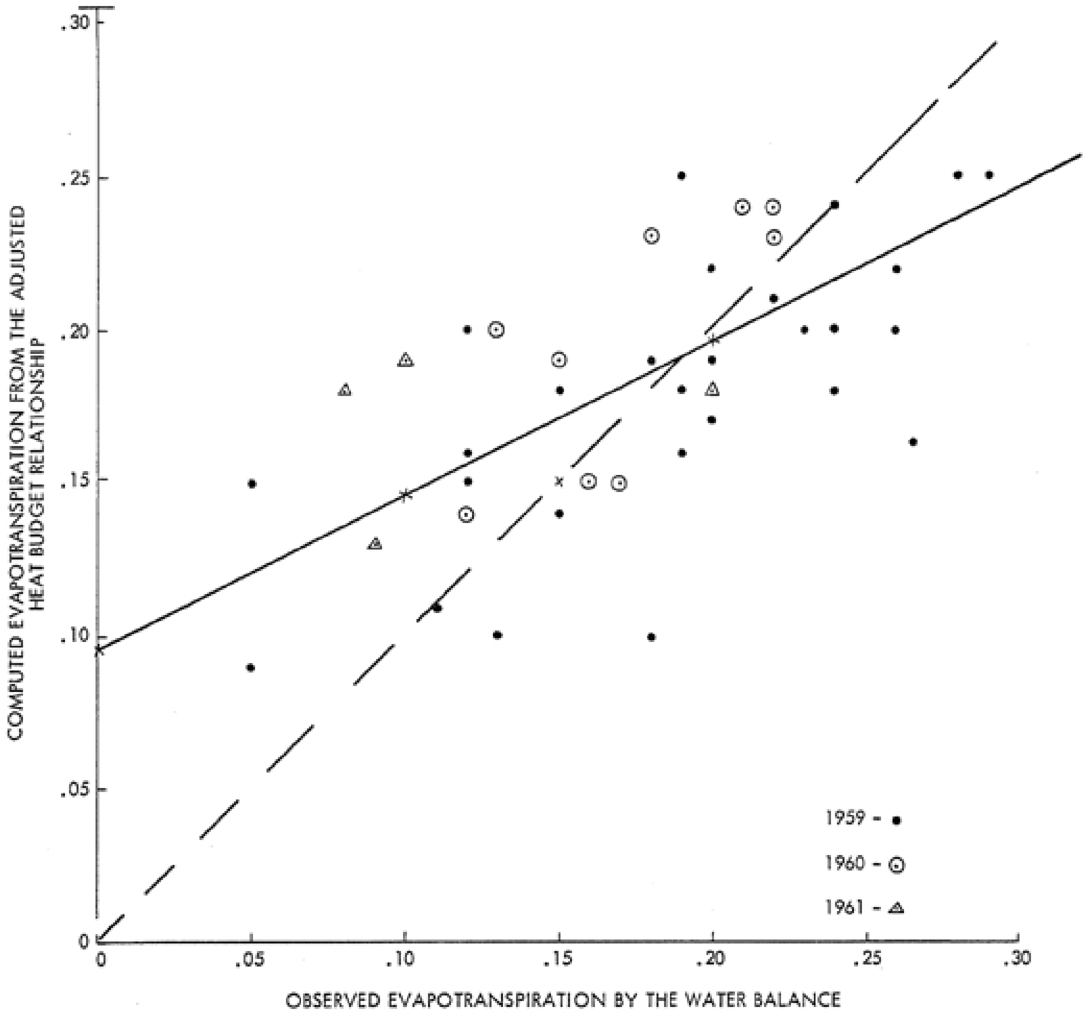

Fig. 10—The relationship between estimated and measured evapotranspiration where the estimated quantity is from the Penman model as corrected for the portion of the net radiation used in the evapotranspiration process.

At the same time, this tendency of estimating toward the central values encourages investigators to modify proposed methods of estimation in an attempt to obtain more precise estimates of high or low evapotranspiration.

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