COMPARISON OF SIMULATED AND ACTUAL EVAPORATION FROM MAIZE AND SOIL IN A LYSIMETER

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ABSTRACT


Evaporation from maize and soil in a pair of lysimeters in a maize crop, ventilation and net radiation above the crop canopy, temperature and humidity above and below the canopy, and leaf area and stomatal resistance in six strata of the canopy were observed during 12 one-hour periods. The measured evaporation was mimicked by an algebraic simulator of energy exchange in six canopy strata plus a seventh stratum occupied by bare stems and the soil surface when the observed stomatal resistance or a resistance that varied realistically with radiation was specified. If a constant stomatal resistance was specified, the simulation was inaccurate. Accurate simulation of evaporation from the soil required that diffusivity be decreased more rapidly within the lower canopy than the observed decrease in horizontal wind.

INTRODUCTION

Analysis of the exchange of energy within a canopy of leaves has turned out to require both meteorological and botanical observations, while the observations extant have been of one sort or the other. Thus when simulators of energy exchange that incorporated the obviously necessary parameters were devised (e.g., Waggoner and Reifsnyder, 1968), some of the parameters, notably the leaf area and stomatal resistance, were lacking in the sets of observations available for testing the simulators. Further, although direct observations of energy exchange by radiation were generally available, direct observations of exchange of potential energy, i.e., evaporation, were generally lacking. Thus because of missing items in sets of simultaneous meterological and botanical observations, the simulators have been inadequately tested. The present report employs 12 sets of simultaneous observations of weather, foliage and evaporation to test a simulator.

The simulator tested (Waggoner et al., 1969b) differs from those of Cowan (1968) and Denmead (1966) in that the former conceives the canopy as strata and employs algebra while the latter conceive the canopy as a continuum and employ calculus. As it turns out the answers from both types of simulators are about the same but the algebraic simulator does not require successive approximation.
A more significant difference between the simulators is found, however, in the boundary conditions. That is, the algebraic model requires specification of temperature and humidity below the canopy, which are easy things to observe, while the continuous models require specifications of the exchange of vapor and sensible heat between air and soil, which make the calculus easy. Since temperature and humidity near the soil, not fluxes in and out of the soil, were measured in the present observations, the algebraic, stratified simulator of energy exchange is tested here.

THE SIMULATOR

The simulator of the exchange of energy within a canopy, and by the soil beneath, has already been presented (Waggoner and Reifsnyder, 1968; Waggoner et al., 1969b), and only its essential features need be presented here to aid the reader.

The canopy is conceived as six strata that absorb $S_i (1 \leq i \leq 6)$ thousandths of a calorie of radiation of all wavelengths per cm$^2$ of land per second (mly/sec) as pictured in Fig. 1. The ground absorbs $S_g$. At steady state these radiant currents are balanced by currents of evaporation $V$ and sensible heat $H$, providing six linear equations. A seventh is provided by the balance of $S_g$ against the sum of $V_g$, $H_g$ and the gain $G$ of energy by the ground.

![Diagram of energy exchange within a canopy of leaves](image)

Fig.1. The conception of energy exchange within a canopy of leaves. For explanation, see text.

The horizontal resistances to the left are the boundary layer resistances near each leaf, and the vertical resistances are integrals of the diffusivity of the bulk air divided into height. Using the simple rules of direct electrical currents, one can write seven linear equations relating products of these resistances and the currents $H_i$ or $H_g$ to differences between $T_0$ and $\theta_1$, $\theta_1$ and $\theta_2$, ..., $\theta_6$ and $T_g$. The $\theta_i$ are the leaf temperatures,
and $T_o$ and $T_g$ are temperatures at the boundaries. This provides another seven linear equations.

The resistances to the evaporative flux (right side of Fig. 1) are the same as the resistances to sensible heat with the addition of stomatal resistance. Since vapor pressure beneath the stomata is essentially saturated, the vapor pressure differences are functions of $\theta_i$, $e_o$, and $e_g$, where $e_o$ and $e_g$ are vapor pressures above and below the canopy. Thus seven more linear equations can be written in terms of $V_i, V_g, e_o, \theta_i, e_g$ and the resistances.

By observing temperature and humidity above ($T_o$ and $e_o$) and below ($T_g$ and $e_g$) the canopy, $S_i$ and $S_g$ and the resistances, we can then calculate 21 variables: six $\theta_i$, seven $V_i$, seven $H_i$ and $G$. Since the lysimeter indicates the sum of the six $V_i$ in the canopy and, when the soil is exposed, the $V_g$ as well, the lysimeter provides a test of our calculations. Further, since $G$ must be a gain in the morning as the soil is warmed and a loss later in the day as the soil cools, $G$ provides a further test.

MATERIALS AND METHODS

The crop

The study was conducted in a half hectare field of maize (Zea mays L. variety Pa. 602-A) at the Lockwood Farm, Mt. Carmel, Connecticut. On August 5, 6 and 7, 1970, the dates of the study, the leaf area index (LAI) of the two plants in each lysimeter was distributed among six strata as shown in Table I.

The stomata

Stomatal resistances were observed by means of a ventilated diffusion porometer (Turner and Parlange, 1970). Within each hour of observations, the upper and lower epidermal resistances from two leaves per stratum were measured. One leaf was on a plant in a lysimeter and one on a plant adjacent to the lysimeter. The average resistances are shown in Table I.

The lysimeters

The evapotranspiration per hour was measured on a pair of weighing lysimeters that have been described by Waggoner et al. (1969a). In essence a drum, 85 cm deep and 56 cm in diameter, filled with soil 28 months previously and containing two maize plants, was weighed by a beam balance with flexible pivots. The exchange of 0.02 mm of water or 0.3 mly/sec for 1 hour can be detected. The loss of water, as potential energy, is shown in Table II opposite the beginning of the hour of observation. The occasions when the soil was covered by a 0.1-mm thick black plastic film are noted in the table.

The relation between evaporation from the two lysimeters is shown in Fig. 2. Since the evaporations from the two lysimeters are about equal when the soil of the east is covered
TABLE 1

The leaf area index (LAI) on the two lysimeters and the stomatal resistance averaged between upper and lower epidermes on a plant on a lysimeter and another plant nearby (height as top of 30-cm strata)

<table>
<thead>
<tr>
<th>Height (cm)</th>
<th>LAI east</th>
<th>LAI west</th>
<th>Stomatal resistance (sec/cm)</th>
<th>5 August</th>
<th>6 August</th>
<th>7 August</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11h45</td>
<td>12h45</td>
<td>08h00</td>
<td>09h00</td>
<td>10h00</td>
<td>11h00</td>
</tr>
<tr>
<td>210</td>
<td>0</td>
<td>0.46</td>
<td>2.8</td>
<td>2.4</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>180</td>
<td>0.43</td>
<td>0.71</td>
<td>2.7</td>
<td>3.0</td>
<td>1.9</td>
<td>2.0</td>
</tr>
<tr>
<td>150</td>
<td>0.88</td>
<td>0.44</td>
<td>3.6</td>
<td>5.2</td>
<td>4.6</td>
<td>2.9</td>
</tr>
<tr>
<td>120</td>
<td>1.54</td>
<td>0.90</td>
<td>2.8</td>
<td>8.9</td>
<td>7.7</td>
<td>6.4</td>
</tr>
<tr>
<td>90</td>
<td>0.94</td>
<td>0.74</td>
<td>7.4</td>
<td>14.1</td>
<td>12.8</td>
<td>16.7</td>
</tr>
<tr>
<td>60</td>
<td>0.62</td>
<td>0</td>
<td>11.8</td>
<td>13.3</td>
<td>14.5</td>
<td>35.8</td>
</tr>
</tbody>
</table>
### TABLE II

Weather and evaporation on 5, 6 and 7 August 1970

<table>
<thead>
<tr>
<th>Date and hour</th>
<th>5 August</th>
<th>6 August</th>
<th>7 August</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11h45</td>
<td>12h45</td>
<td>08h00</td>
</tr>
<tr>
<td>Temperature, °C*1</td>
<td>22.5</td>
<td>22.6</td>
<td>22.9</td>
</tr>
<tr>
<td>Vapor pressure deficit, mm Hg*2</td>
<td>6.8</td>
<td>6.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Radiation, mly/sec</td>
<td>4.4</td>
<td>5.5</td>
<td>11.1</td>
</tr>
<tr>
<td>Wind, cm/sec</td>
<td>53</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>Diffusivity, cm²/sec</td>
<td>1700</td>
<td>2000</td>
<td>5000</td>
</tr>
<tr>
<td>10-cm Temperature, °C*2</td>
<td>-0.8</td>
<td>-0.4</td>
<td>-1.3</td>
</tr>
<tr>
<td>10-cm Vapor pressure, mm Hg*2</td>
<td>2.1</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Evaporation, mly/sec</td>
<td>East lysimeter</td>
<td>3.5*3</td>
<td>3.3*3</td>
</tr>
<tr>
<td>West lysimeter</td>
<td>3.2*3</td>
<td>3.6*3</td>
<td>6.5</td>
</tr>
</tbody>
</table>

*1 At top of canopy
*2 Relative to temperature or humidity at canopy top
*3 Soil covered by a thin, black, plastic film.
and since evaporation from the east is somewhat greater than from the west when the
soil of both is uncovered, evaporation from the soil must have been of some consequence.
The change in the data from east covered to both uncovered suggests evaporation from
the soil is 1 to 2 mly/sec at midday.

![Graph showing evaporation from two lysimeters](image)

**Fig. 2.** Evaporation from the two lysimeters. Black circle: both soil surfaces covered; half-black circle:
east soil surface covered; open circle: neither soil surface covered.

**Temperature and humidity**

Twice during each hour of observation these parameters were measured at 10 and 210
cm height by means of a ventilated wet-bulb psychrometer. The mercury-in-glass thermometers
of the psychrometer were shielded in white plastic tubes.

**Radiation**

The net flux density of radiation of all wave lengths was measured above the canopy
by means of a Gier and Dunkle (1951) radiometer. During the days of observation the
meter was calibrated twice by shading it, and an Eppley pyrheliometer, from direct
insolation and setting equal the change in the two instruments.

Specifying the radiation absorbed in each stratum, however, requires observation
within as well as above the canopy. A Weston selenium photocell showed that illumination
was extinguished as \( \exp(-0.9 \text{ LAI}) \)

Since net radiation is extinguished less rapidly than light, the coefficient of 0.6,
obtained for net radiation in maize by others (Brown and Covey, 1966), was employed
instead of the 0.9 for light.

**Ventilation**

Casella T16112 anemometers were mounted 27, 249, 341, 418 and 509 cm above the
ground. The diffusivity at canopy top was calculated from a least-squares regression of
wind speed \( U \) on the logarithm of height:

\[
U = \left[ - \frac{U_*}{k} \ln(z_0) \right] + \left[ \frac{U_*}{k} \ln(z - 25) \right]
\]
where $U_*$ is friction velocity, $k$ is Von Karman's constant, $z_0$ is roughness length, and $z$ is height. The 25 is an assumed zero-plane displacement. The diffusivity at canopy top was taken as $kU_* z$ where $z$ is 210 cm, the height of the crop.

On 20 occasions when the anemometer at 27 cm started, the ratio of wind at 27 to that at 250 cm was 0.09 to 0.44 with an average of 0.20. The ratio was not correlated with wind speed. Uchijima (1962) has shown that wind speed and diffusivity decrease into the canopy approximately as $U/U_H = \exp \left[-a(z/H - 1)\right]$ where $H$ is the height of the canopy. The ratio of 0.20, therefore, corresponds to an $a$ of 1.6.

The diffusivity in the region between 10 cm where temperature and humidity were observed and the bottom of the canopy at 30 cm presents a dilemma. On the one hand, the wind below the canopy indicates ventilation is fully a fifth as great below as above the canopy, and a ratio of a fifth between diffusivity above and below the canopy might also be assumed. On the other hand, a diffusivity in this region that is, say, 2000 cm$^2$/sec will cause a calculated evaporation from the soil that exceeds the 2 mly/sec, the observed maximum difference between the covered and uncovered lysimeters (Fig. 2). Further, 2000 cm$^2$/sec extrapolated from diffusivity at canopy top far exceeds the 64 to 160 cm$^2$/sec that would be observed 20 cm above a smooth surface with a friction velocity of 20 cm/sec and Richardson number $R_i$ of 0 to 0.1 (Pasquill, 1962, eq.3.15). Thus the rule for obtaining diffusivity within the canopy must be modified.

This modification has a foundation in two observations. First, a current of air is often observed among stems below a canopy (e.g., Lemon et al., 1970), and this current would not necessarily be accompanied by a corresponding upward flux of matter. Second, Wright and Brown (1967) and Stewart and Lemon (1969) observed that diffusivity near the bottom of a corn crop decreased much more sharply than exponential extrapolations from diffusivity at the top of the crop.

The rule for calculating diffusivities $K$ in the canopy was, therefore, to choose the lesser of the values calculated (1) by exponential extrapolation or (2) by the following equation:

$$K = (0.4 U_* z) \cdot f(R_i)$$

This equation is explained by Pasquill (1962). The $f(R_i)$ is a function of the Richardson number, and $f(R_i)$ varies from about 0.4 in stable air to 1 in neutral stability. Since the air at the bottom was generally cooler than at the top of the canopy (Table II), $f(R_i)$ was varied from 0.4 in the stem zone to 1 in mid canopy. The $U_*$ varied from 20 to 100 cm/sec over the same range. The consequent $K$ in the middle of the stem, sixth, fifth, fourth and third strata was 64, 540, 1600, 3200 and 5400 cm$^2$/sec.

Ventilation also affects the boundary layer resistance. The boundary layer resistance of the leaves was calculated from wind speed $U$ and a leaf dimension by the Pohlhausen equation (Schlichting, 1960). The value derived from that equation was divided by 2.5, which reflects the lesser resistance encountered in nature because winds are neither steady nor laminar. This divisor makes our boundary layer resistances equal to observations summarized by Monteith (1964). A leaf dimension of 5 cm was employed.
RESULTS

Fortunately a wide range of weather was encountered, from the cloudy and humid fifth to the sunny and dry seventh of August and from turbulent midday to calm evening. Also by good fortune, the wind blew slowly over our small field. Consequently evaporation ranged from only 0.3 mly/sec to fully 17.1 among the dozen observations that we use.

The realism of the simulator can be judged by comparing simulated to actual evaporation. The first comparison is between simulated evaporation from the lysimeter where stomatal resistance was actually measured and the evaporation from that lysimeter. Since stomatal resistance was measured on both lysimeters at 10h00 on 6 August, thirteen pairs of observation and simulation are available. Stomatal resistance of the plant in the lysimeter, rather than the mean resistance (Table I), was employed. When the soil was uncovered, the simulated evaporation from the soil was added to that from the canopy. As Fig.3 shows, the simulator mimicked the observed evaporation well.

![Fig.3. Simulated and actual evaporation from a lysimeter where stomatal resistance is measured on the lysimeter.](image)

![Fig.4. The simulated evaporation from a canopy with stomatal resistance of 2 sec/cm compared to evaporation from the lysimeter where stomatal resistance was measured.](image)

The weight to be given to this evidence of realism depends in part upon whether great opportunities for error exist. An example of these opportunities is provided by examining the outcome of a fictional, constant stomatal resistance of 2 sec/cm. Simulated evaporation for the dozen times are compared to the real ones in Fig.4. Although 2 sec/cm is a reasonable stomatal resistance to assign to maize, it destroys the realism of the simulator and demonstrates the susceptibility of the simulator to erroneous values of parameters.

Years of experience have, however, taught us that evapotranspiration can be estimated accurately from net radiation alone if the vegetation is dense and succulent (Penman, 1956). One might, therefore, consider the disparity between real and simulated in Fig.4 as a mark against the simulator, which includes net radiation among its parameters. The stomatal resistance employed in Fig.4 was, however, an unrealistically constant 2 sec/cm.
If instead of being constant, the stomatal resistance is caused to vary with radiation as we know it does in maize (Turner, 1969), the outcome is different. Stomatal resistance was calculated as \( r_m / \text{erf}(S/C) \) where \( r_m \) is a minimum stomatal resistance of 2 sec/cm, C is 0.01 and \( S \) is absorbed insolation per leaf area. The insolation was taken as 1.54 of net radiation at canopy top and extinguished exponentially with LAI and a coefficient of 0.9 as observed with the Weston photocell. The evaporation calculated from the simulator and this stomatal resistance mimics the real evaporation closely (Fig.5). This reconciles the simulator with the experience that has shown evaporation is correlated with net radiation, and it also suggests that the correlation of net radiation and evapotranspiration is caused by the response of stomata to radiation as well as the large role of radiation in fueling evaporation. In fact Penman (1956) himself had foreseen a role for stomata and incorporated a stomatal term in a version of his well-known equation.

Another demonstration of the realism of the simulator and the role of stomata is provided by Fig.6. Here the evaporation from both lysimeters was calculated from the mean stomatal resistance measured on a plant in one lysimeter and on another plant nearby as presented in Table I. Clearly this calculation from an average resistance does not mimic the evaporation as closely as does the simulation from the resistances of the maize in the lysimeter itself (Fig.3).

Finally the accuracy of the specification of diffusivity is tested. Since stomatal and boundary layer resistance are larger than the resistance of the bulk air within the canopy, the specification of diffusivity affects transpiration little. Thus at 11.00 h on 6 August, doubling the diffusivity from 8000 to 16000 cm\(^2\)/sec at canopy top with corresponding increases within the canopy only increased simulated transpiration from 12.26 to 12.33 mly/sec.
The diffusivity, however, greatly affects evaporation from and the gain of energy by the soil. The consequence of an error in specifying diffusivity is illustrated in Fig. 7. The evaporation and gain of heat by the soil were first calculated from the limits described under "Ventilation". The dozen cases are the same as in Fig. 4. The evaporation of 1 to 2 mly/sec (Fig. 7A) corresponds to the estimate of evaporation from the soil gleaned from Fig. 2. As expected, the soil gains heat in the morning and loses it in the afternoon. When the values, on the other hand, were calculated from exponential decrease in diffusivity throughout the canopy and a limit of 330 cm$^2$/sec in the lowest or stem stratum, the calculated evaporation was much greater than Fig. 2 indicates is real (Fig. 7B). Further, the great losses of heat from the soil during midday are improbable. Once again, the response of the simulator to faulty values of parameters has been demonstrated, and the remarkably slow vertical transport in the lowest or stem stratum is emphasized.

CONCLUSIONS

The simulator of evaporation from a plant canopy has been shown to mimic satisfactorily the evaporation from a maize crop, measured with a pair of weighing lysimeters, over a dozen hourly intervals varying markedly in evaporative conditions. The importance of stomata in regulating transpiration in a crop has been further demonstrated. Moreover, to simulate accurately the evaporation from the soil surface and obtain reasonable soil heating and cooling, the decrease in the vertical transport coefficient or diffusivity between canopy top and the region of stems and dead leaves below the leaf canopy must be greater than the corresponding decrease in horizontal wind.

REFERENCES


