Relative Importance of Reradiation, Convection, and Transpiration in Heat Transfer from Plants

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Summary. For a plant of average spectral properties and average diffusion resistance (2 sec/cm), diurnal variations in the energy dissipated by reradiation, convection, and transpiration have been explicitly calculated and plotted for certain environmental conditions as measured at St. Paul, Minnesota. These conditions represent the environments of characteristic types of days and of characteristic types of leaves. In all situations reradiation is overwhelmingly the dominant mode of heat transfer.

A new method for the calculation of Bowen's ratio is also presented which gives results in very good agreement with older procedures. For certain individual leaves the energy dissipated by convection is found to be greater than that dissipated by transpiration. For a crop as a whole, however, transpiration is found to be far the most important.

In recent years the physical environment and its effects upon plant processes have come to be looked upon more and more from the viewpoint of energy exchange. Heat transfer in plants has been shown to control to a very great extent leaf photosynthetic activity and plant productivity (4,7,8,9). It thus becomes important to know how energy is exchanged between a plant and its environment and how the relative effectiveness of the various modes of energy exchange compare.

To begin with, a basic understanding of the 3 chief modes of heat transfer to and from plants is required. These modes are radiation, convection, and transpiration or condensation. Briefly, radiation is the transfer of energy through space by electromagnetic waves, convection is the transfer of energy by the mass movement of a fluid such as air, and transpiration is the evaporation of water from the walls of the substomatal cavity of a plant leaf and its subsequent diffusion out through the stomatal opening, whereby the latent heat of evaporation is removed from the plant. Condensation of dew on a plant leaf has the opposite effect of conveying heat to the plant. For a much more complete discussion of these and other more minor processes as they occur in relation to plants, see the review by Idso, Baker, and Gates (9).

For a plant leaf, each of these 3 modes of heat transfer may be both a source of energy and a means of energy dissipation. The main source of the heat load of a plant leaf is radiation: direct short wave radiation from the sun, diffuse short wave radiation (skylight), reflected short wave radiation from the ground, long wave radiation from the atmosphere, and long wave radiation from the ground. More minor sources are convection and condensation. As for the role of each in disposal of energy, that is the major concern of this paper and will be dealt with quantitatively in a later section. To bring us to that point we must briefly review the methods by which leaf temperature is calculated from a knowledge of the energy environment, for leaf temperature is essential to the calculation of the energy dissipated by each of the 3 chief modes of heat transfer.

Materials and Methods

Energy Balance of a Leaf. The temperature of a leaf in a given environment is obtained from a solution of the equation expressing the balance between the energy absorbed by the leaf and that removed from it. For a single horizontal leaf this equation as written by Idso and Baker (8) is

\[ a_s(1 + r)S/2 + a_t(1 + r)s/2 + a_t(R_o + R_s)/2 - a_oT^4_{L} \pm C \mp E = 0. \]

where: \( S \) = direct solar radiation, cal/cm²/min; \( s \) = diffuse skylight, cal/cm²/min; \( R_o \) = long wave thermal radiation from the ground, cal/cm²/min; \( R_s \) = long wave thermal radiation from the atmosphere, cal/cm²/min; \( r \) = reflectance of the ground.

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to direct solar radiation and diffuse skylight:
\[ a_s = \text{absorptance of leaf to direct solar radiation}; \]
\[ a_t = \text{absorptance of leaf to diffuse skylight}; \]
\[ a_i = \text{absorptance of leaf to long wave thermal radiation}; \]
\[ \sigma = \text{Stefan-Boltzmann constant, } 7.92 \times 10^{-11} \text{ cal/cm}^2/\text{min}^{-1}/^\circ\text{K}^4; \]
\[ T_i = \text{leaf temperature, } ^\circ\text{K}; \]
\[ C = \text{energy gained or lost by conversion, cal/cm}^2/\text{min}; \]
\[ LE = \text{energy gained by condensation or lost by transpiration, cal/cm}^2/\text{min}. \]

This equation as it stands cannot be solved directly for the temperature of the leaf, however, because the quantities \( C \) and \( LE \) appear as unknowns. Expressions are thus needed which also relate these quantities to the leaf temperature. One such expression written by Gates (4) for the energy dissipated by transpiration is

\[ C = 6.0 \times 10^{-3} \left( \frac{\Delta T}{L} \right)^{0.4} \Delta T \]  

(II)

for free or natural convection and

\[ C = 5.7 \times 10^{-3} \left( \frac{I'}{L} \right)^{0.6} \Delta T \]  

(III)

for forced convection, where
\[ \Delta T = \text{temperature difference between the plant leaf and the ambient air (} T_i - T_i \text{), } ^\circ\text{K or } ^\circ\text{C}; \]
\[ L = \text{characteristic dimension of the leaf, cm}; \]
\[ I' = \text{wind speed, cm/sec}. \]

An expression for the energy dissipated by transpiration due to Lee and Gates (10) is

\[ LE = \frac{L}{R} \left( e - r.h. \right) \]  

(IV)

where \( e \) is the water vapor density of the air next to the mesophyll cell walls at the temperature of the leaf \( T_i \), gm/cm\(^2\); \( r.h. \) is the relative humidity of the air at temperature \( T_i \); \( L \) is the latent heat of vaporization, about 600 cal/gm at 20\(^\circ\); \( R \) is total resistance of the diffusion pathway, min/cm.

These equations taken together give a set of 3 equations in the 3 unknowns as \( a_s T_i, C, \) and \( LE \), each of which is uniquely determined if \( T_i \) is known. Thus, this set is solvable.

**Methods of Leaf Temperature Calculation.**

Even though the set of equations presented in the previous section is solvable, it is an extremely time consuming process to do so by ordinary hand methods. The first major breakthrough in reducing this computational burden was the development of a graphical method of solution by Gates (2), usually referred to as the energy diagram solution method. It is explained in detail in Gates (4) and in Idso, Baker, and Gates (9). As this method is used in these references, however, the variation of \( LE \) throughout the day is not explicitly solved for, but rather a reasonable constant value is assumed throughout the major portion of the daylight hours.

Since the variation throughout the day of \( LE \) is one of the quantities we are interested in obtaining, a modification of the energy diagram solution method is thus necessary. This modification has been developed and used by Idso and Baker (7), and their results obtained with it will be discussed shortly. In essence it consists of an iterative process whereby \( LE \) is calculated from equation (IV) by guessing a leaf temperature variation for the day; then \( T_i \) is calculated by means of the energy diagram using this newly calculated daily variation of \( LE \); \( LE \) is then recalculated using this value of \( T_i \); and etc. The process converges quite rapidly to give accurate daily variations of both leaf temperature and the energy dissipated by transpiration. It is also easily adapted to use by a computer for rapid calculation of many values.

**Experimental Situations.**

The experimental situations for which an analysis of the relative importance of the different modes of energy dissipation will be carried out will be situations for which the leaf temperature calculations by the modified energy diagram solution method have already been made. These situations have been reported on by Idso and Baker (7, 8), and the full mechanics of the leaf temperature calculations may be found worked out there. These situations in the order in which they will be considered here are: 1) a single horizontal leaf located over a surface of bare soil on a) a clear, cool day; b) a clear, warm day; c) a cool, cloudy day; d) an intermittently clear-cloudy, warm day, and; 2) a typical leaf from each of 4 characteristic leaf types into which a crop such as soybeans growing in a field situation may be considered to be divided, namely, a) an upper peripheral leaf; b) a lateral peripheral leaf; c) north facing; ii) south facing; iii) east facing; iv) west facing; c) a lower peripheral leaf; d) an interior leaf.

The meteorological parameters pertinent to the analysis as they existed in these experimental situations are relative humidity, air temperature, wind speed, and the various radiant energy fluxes making up the heat loads of the leaves. By assuming values for \( a_s, a_t, \) and \( a_i \) which are averages of values for many different plants as reported by Gates, et al. (5), the total energy absorbed by a plant leaf in each of the experimental situations is easily calculated from the measured radiant energy fluxes reported in Idso and Baker (7, 8). Results of these calculations for \( a_s = 0.55, a_t = 0.65, \) and \( a_i = 0.97 \) are shown in figures 1 and 2. Also, the other meteorological parameters (relative humidity, air temperature, and wind speed) are shown in figure 3. Then, to provide the last pieces of working data for our analysis, the results of the leaf temperature calculations for these situations are shown in figures 4 and 5.

**Calculation of Energy Dissipated by Reradiation, Convection, and Transpiration.** The results of the
Fig. 1. Energy absorbed by a horizontal leaf located over a surface of bare soil as calculated for the radiant energy regimes as measured on 4 different characteristic types of days at St. Paul, Minnesota.
Fig. 2. Energy absorbed by characteristic types of leaves for the energy environment conditions of July 22, 1966, at St. Paul, Minnesota.
Fig. 3. Relative humidity, air temperature, and wind speed as measured concurrently with the radiant energy regimes.
modified energy diagram solution method for the leaf temperature have already given the daily variations in the energy dissipated by transpiration, as shown in figures 4 and 5 of the previous section. From the daily variations of leaf temperature shown there the energy dissipated by reradiation is given directly by $\alpha a T^4$. Then, by observation of the energy balance equation (1), it is seen that the energy dissipated by convection is $C = \text{energy absorbed} - \alpha a T^4 - I.E$. Thus, these calculations are easily carried out, with the results as shown in figures 6 and 7.

Results and Discussion

The first conclusion to be drawn from these figures is that reradiation is by far the most effective mode of energy dissipation. In all situations reradiation dissipates more than twice as much energy as either convection or transpiration. Also, it is the only infallible mode of heat transfer, which under any set of environmental conditions will always be found to be functioning.

Figure 6 brings out many interesting effects of environmental conditions upon transpiration and convection. First of all, high relative humidities are seen to curtail transpiration quite effectively, as is shown by the results for September 6 and August 24. Also, cool air temperatures are seen to do the same. On September 6 the cool air acts together with a high relative humidity to produce an almost negligible transpiration rate, while on August 28 it acts to keep transpiration low in spite of quite low relative humidity in the afternoon. Conditions of high air temperature and low relative humidity, very favorable to transpiration, obtained on August 14; and in accordance with the dependency of transpiration upon these 2 factors, transpiration that day was twice as great as on any other day.

Convection, on the other hand, is not so much related to either relative humidity or air temperature. Rather, it is enhanced by high wind speeds
and large temperature differences between the leaf and the air. Thus, on clear days when leaves are exposed to intense radiant heat loads and leaf temperatures can rise a good deal above air temperature, conditions are prime for a sizeable convective heat loss. See, for example, both August 28 and August 14, along with the sunny conditions of August 24. Air temperature differs quite a bit among these days, and yet the rates of heat loss by convection are almost identical during the day.

The cloudy conditions of September 6, however, reduce the effectiveness of convection quite drastically, as leaf temperature cannot rise much above air temperature at all.

The results in figure 7 for the different characteristic leaf types are interpreted in much the same way as those of figure 6, for the different leaves illustrate the effects of different environments just as much as the different days do. For instance, upper and lateral peripheral leaves may

![Graphs showing leaf temperature and energy dissipation](image)

**Fig. 5.** Iterative calculations of plant leaf temperature and the energy dissipated by transpiration for the different characteristic types of leaves.
Fig. 6. Energy dissipated by reradiation, convection, and transpiration as calculated for 4 different characteristic types of days.

Fig. 7. Energy dissipated by reradiation, convection, and transpiration as calculated for the different characteristic types of leaves.
be subjected to intense radiation; and when each of them is, convection is quite high. Interior and lower peripheral leaves, on the other hand, are never subjected to the direct rays of the sun, and they will not vary far from air temperature. In fact, in the situation illustrated here, interior leaf temperature is a little lower than air temperature, with the result that heat is added to the leaves by convection. Also, in the interior of the plant canopy the relative humidity is higher than that of the free air over and between the rows, and transpiration is thus accordingly reduced there too.

Bowen's Ratio. A quantity of some interest in many applications is the ratio of sensible heat transfer or heat transfer by convection to that by transpiration. This ratio of $C$ to $LE$ has been given the name Bowen's ratio (1) for the man who first posed it as an important parameter in the exchange of heat and moisture over a lake, where of course $LE$ then represented evaporation. Bowen's ratio has been computed for the various experimental situations considered here and is presented in table I. These values were arrived at by the integration of the areas under the curves of figures 6 and 7 and the subsequent formation of the ratio $C$ to $LE$.

Bowen's ratio for single leaves over bare soil is much greater than that for leaves in a true field situation (table I). This, of course, is due to the modification of the energy environment of the leaves in the field situation by the other leaves of the same plant and those of adjacent plants. Gates (3) has shown that even naturally occurring leaves can have quite high values of Bowen's ratio, however. In making calculations of instantaneous values of the Bowen's ratio from measured transpiration losses and calculated convection losses, he found the Bowen's ratio for an exposed but oak leaf growing near the lower perimeter of a tree surrounded on 3 sides by other trees to be as high as 6.00 when the leaf was at a temperature of 46.9°, about 15° above air temperature. Thus, values like those for the different days are not unlikely to be found in some situations.

For most applications, however, it is not the Bowen's ratio of single leaves which is important, but that for the crop as a whole; and for well watered crops the Bowen's ratio characteristically averages about 0.1 (6, 11, 12). To compute the Bowen's ratio for the crop we have been considering, it is necessary to know what fraction of the total number of leaves each leaf type comprises. From an analysis of the crop geometry of soybean-like plants, Idso and Baker (7) have worked out these fractions for the time of 50% cover. For the two situations of east-west and north-south row orientation, they found interior and lower peripheral leaves to comprise 0.70 of the total and each of the other 3 types to comprise 0.10 of the total. Multiplying the Bowen's ratio of each characteristic leaf type by the fraction of the total number of leaves which it comprises and adding together these partial sums, the total average Bowen's ratio for the crop as a whole is obtained. This calculation of the average Bowen's ratio is presented in tabular form in table II.

Bowen's ratio for the crop as a whole for both row orientations is practically zero, which is quite close to the characteristically observed values of about 0.1 (table II). The small deviation below this value is probably due to the fact that the condensation of dew was not measured or taken into account in the calculations. Its inclusion would have slightly decreased the denominator of the Bowen's ratio with the result that the final average value would be shifted closer to 0.1. In

<table>
<thead>
<tr>
<th>Day</th>
<th>Bowen's ratio</th>
<th>Leaf type</th>
<th>Bowen's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug. 28</td>
<td>2.44</td>
<td>Upper peripheral</td>
<td>0.646</td>
</tr>
<tr>
<td>Aug. 14</td>
<td>0.885</td>
<td>Interior and lower</td>
<td>-0.196</td>
</tr>
<tr>
<td>Sept. 6</td>
<td>3.36</td>
<td>Lateral peripheral</td>
<td></td>
</tr>
<tr>
<td>Aug. 24</td>
<td>1.78</td>
<td>North facing</td>
<td>0.161</td>
</tr>
<tr>
<td>Clear</td>
<td>1.40</td>
<td>South facing</td>
<td>0.590</td>
</tr>
<tr>
<td>Cloudy</td>
<td>1.59</td>
<td>East facing</td>
<td>0.289</td>
</tr>
<tr>
<td>Avg.</td>
<td></td>
<td>West facing</td>
<td>0.512</td>
</tr>
</tbody>
</table>

Table II. Calculation of Bowen's Ratio for the Crop as a Whole

<table>
<thead>
<tr>
<th>Leaf type</th>
<th>Fraction of total no of leaves</th>
<th>Bowen's ratio</th>
<th>(Fraction) × (Bowen's ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>East-west row orientation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>North-south row orientation</td>
</tr>
<tr>
<td>Upper peripheral</td>
<td>0.10</td>
<td>0.646</td>
<td>0.065</td>
</tr>
<tr>
<td>Interior and lower peripheral</td>
<td>0.70</td>
<td>-0.196</td>
<td>-0.137</td>
</tr>
<tr>
<td>Lateral peripheral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North facing</td>
<td>0.10</td>
<td>0.161</td>
<td>0.016</td>
</tr>
<tr>
<td>South facing</td>
<td>0.10</td>
<td>0.590</td>
<td>0.059</td>
</tr>
<tr>
<td>East facing</td>
<td>0.10</td>
<td>0.289</td>
<td></td>
</tr>
<tr>
<td>West facing</td>
<td>0.10</td>
<td>0.512</td>
<td></td>
</tr>
<tr>
<td>Total avg Bowen's ratio</td>
<td></td>
<td></td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.008</td>
</tr>
</tbody>
</table>
either event, the results must be considered in very good agreement with other established procedures.

By comparing the results of the Bowen's ratio calculations with the actual plots of energy dissipation, however, it can be seen that the Bowen's ratio cannot distinguish between cases where convection and transpiration are either both great or small together. Thus, explicit plots of energy dissipation by each of the modes of heat transfer are in many cases more helpful and enlightening.

**Literature Cited**