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ABSTRACT

These materials were designed to be used by life science students for instruction in the application of physical theory to ecosystem operation. Most modules contain computer programs which are built around a particular application of a physical process. This report introduces two models of the thermal energy budget of a leaf. Typical values for environment variables and leaf parameters are discussed and simple calculations are made to see how radiation, convection, and transpiration affect leaf temperature. A graphical method of analysis is used to present a more detailed energy budget model. A problem set and an accompanying computer program called TRANS permit the student to explore the consequences of the models. Algebra and some knowledge of heat transfer physics are prerequisites. (Author/CS)

TRANSPIRATION AND LEAF TEMPERATURE

by

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February 1979

PREFACE

The reasoning behind the simple, heat energy budget of a leaf is developed in this module into a detailed explanation of leaf transpiration. Although the mathematical model is conceptually simple, seven independent variables prevent easy exploration of the consequences of the model. The accompanying computer program provides the student with a tool to concentrate his efforts on the biology of heat and water balance of a leaf rather than time-consuming numerical calculations. Algebra and some knowledge of heat transfer physics are prerequisites.

CONTENTS

INTRODUCTION

Water is essential to life as we know it on earth. Water acts as a medium for carrying nutrients, ions, and suspended particles from the soil into a plant and as a conducting system within a plant. Most organic tissue is permeable to water and when the external water vapor pressure is less than that inside a plant, water will evaporate from it. Plant leaves have evolved stomates or pores through which to take in carbon dioxide from the surrounding air, but since the water molecule is of lighter molecular weight than the carbon dioxide molecule, it tends to escape readily from the leaf through the stomates. Normally the air in the intercellular spaces within a leaf is at or near saturation. This process of water evaporation from a plant is known as transpiration. Energy is required to convert liquid water to vapor. As a consequence of transpiration, energy is lost by a leaf and the temperature of the leaf is reduced.

Temperature is extremely important to the physiological processes within a leaf including photosynthesis, respiration, growth, cell enlargement and division, protoplasmic streaming, and translocation. Most chemical and biological processes are temperature-dependent and as a general rule, they proceed slowly at relatively low temperatures, speed up in reaction with increased temperature, and at high temperatures become limited or terminated by adverse reactions such as the denaturation of proteins and the breakdown or dissociation of molecules. A typical biological response with temperature is illustrated in Figure 1 for net photosynthesis. Many temperature zone plants have a maximum rate of photosynthesis at about 25 to 30°C while plants of arctic or alpine habitats have an optimum temperature of about 15°C and some plants of extremely hot regions have

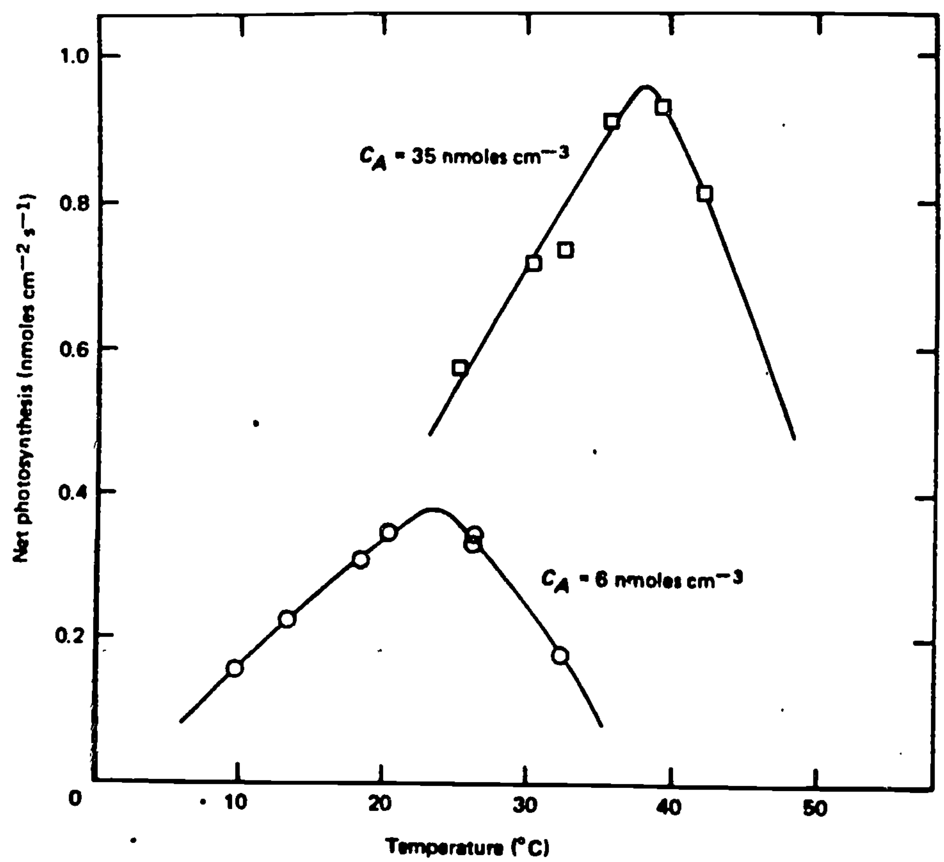


Figure 1. Net photosynthesis versus leaf temperature at high and low carbon dioxide concentration. From Lommen et al. 1975. P. 41.

optima near 40 or 45°C (e.g., Lange et al. 1975, Bjorkman et al. 1972, Billings et al. 1971). When a plant of a cool habitat is functioning optimally at a particular temperature, a plant of a warm habitat will scarcely function at all at that same temperature. Many plant leaves undergo irreversible thermal damage when their temperatures exceed 45 to 48°C while some will not be damaged at 50 or even 55°C and others will be severely denatured at 42°C. Therefore, the temperature of a leaf is always of enormous significance to the viability of it. However, when one wishes to know the temperature of a plant or, in particular, the temperature of a leaf, it is important to ask why and with what accuracy. Is it necessary to know the leaf temperature to an accuracy of 0.1, 0.5, or 1°C, and why? The answer to this question will often determine the method of measurement and the precision necessary, or it will guide one with respect to the detail required in an energy budget calculation.

The temperature of a leaf is the result of energy flow between it and its surroundings. A leaf exchanges energy by the basic physical processes of radiation, conduction, convection, and evaporation, all of which go on simultaneously. If a leaf takes in more energy than it puts out, its temperature increases and if it loses more than it gains, the temperature will decrease. When energy in equals energy out, the leaf will maintain a constant temperature.

Once the processes by which a leaf exchanges energy are recognized, it is straightforward to identify the properties of the environment which must be known. In fact, there are only two ways by which an environment interacts with an organism, including a plant leaf, and that is by energy flow or mass flow. In this module, we are dealing with both since the exchange of heat is an energy flow process and the diffusion of water vapor is a gas exchange process which also involves the transport of energy.

The remainder of the module is devoted to developing and analyzing simple models of how a leaf exchanges thermal energy with the environment. Although our knowledge of leaf morphology and physiology is more detailed than what is included in the models, the level of description here is sufficiently general to provide valuable insights.

In the following pages, the reader is formally introduced to the leaf energy budget. Typical values for environment variables and leaf parameters are discussed. Some simple calculations are then made to see how radiation, convection and transpiration affect leaf temperature.

The graphical method of analysis used by Gates (1968) is then employed to understand a more detailed energy budget model. Problems with accompanying solutions are followed by an appendix on symbols, units and dimensions. Finally, a second appendix outlines how the student could use a computer program called TRANS to answer problems and explore consequences of the second model.

LEAF ENERGY BUDGET

Radiation incident upon a leaf includes shortwave radiation in the form of direct sunlight, skylight and reflected light, and longwave radiation emitted by the atmosphere and clouds, or by the surfaces of ground, nearby plants, and other objects.

A plant may absorb 40 to 80 percent of incident sunlight and skylight and it will absorb 96 percent of incident longwave thermal radiation. A plant leaf redistributes this absorbed radiation by emitting a substantial amount of it as longwave radiation from the leaf surface. The remainder is partitioned into convective and evaporative heat exchange and a very small amount is utilized for photosynthesis. Only certain wavelengths of light are effective for photosynthesis. The amount of energy converted to biomass is very small (a few percents of the incident sunlight at most) and may be neglected in considerations of the energy budget of a leaf. The amount of radiation emitted by a leaf is proportional to the fourth power of the absolute temperature of the leaf surface. This phenomenological relation is known as the black body radiation law and is written $R = \sigma[T+273]^4$.

The flow of heat by convection is proportional to the temperature difference between the leaf and the air. Convective heat transfer is proportional to the wind speed and varies inversely with the characteristic dimension of the leaf which affects the boundary layer thickness. Because of the viscosity of air, there is an air layer which adheres to any surface, including that of a leaf known as a "boundary layer." When the wind blows, the boundary layer of viscous air represents a transition zone between zero air flow at the leaf surface to free air flow at some distance from the leaf. A temperature difference may exist across a boundary layer of air and it is across this that heat moves from the leaf to the air by conduction and convection. The larger a leaf, the thicker the boundary layer of air adhering to the surface. A small leaf will have a boundary layer about 1 mm thick and a large leaf, like a banana leaf, will have a boundary layer of 1 or 2 cm thickness. It happens that for broad flat leaves the rate of heat transfer by convection is proportional to the square root of the ratio of wind speed to leaf dimension. Increase wind speed fourfold and the rate of convective heat exchange will increase twofold or increase leaf dimension fourfold and convection will decrease twofold. The characteristic dimension is approximately the average width of the leaf. Although the length of a leaf affects convection in the interest of simplicity, a single characteristic dimension given by the leaf width is used here. The more complex relationship involving leaf width and length is introduced later.

The transpiration rate is determined by the water vapor pressure or density difference between leaf and air. This relationship is described in more detail in the next two sections. Energy is required to convert liquid water to vapor and the amount of energy is known as the latent heat of water. It is temperature-dependent but at 30°C its value is 2.43×10^6 J kg^{-1}. Each of the environmental variables affect the leaf energy status simultaneously. They are radiation, air temperature, wind speed, and water vapor pressure, density, or relative humidity. A plant leaf responds to these by assuming a certain temperature and by losing water at a particular rate depending upon the properties of the leaf. Once the energy budget relationship is written, the student will see how it is that each of these environmental variables enter the common energy pool for the leaf.

The steady state energy budget for a leaf is

Thermal energy gained = Thermal energy lost

Absorbed radiation = Reradiation + Convection + Evaporation

$$Q_a = \varepsilon\sigma\ T_\ell + 273\ ^4 + k_1 \left(\frac{V}{D}\right)^{\frac{1}{2}} [T_\ell - T_a] + L(T_\ell)E \qquad (1)$$

where

Q_a = total amount of radiation absorbed in W m^{-2},

ε = emissivity of leaf surface to longwave radiation,

σ = (Stefan-Boltzmann constant) 5.67×10^{-8} W m^{-2} K^{-4},

T_ℓ = leaf temperature in °C,

k_1 = 9.14 J $m^{-2} s^{-\frac{1}{2}}$ °C^{-1},

V = wind speed in m s^{-1},

D = leaf width in m,

T_a = air temperature in °C,

$L(T_\ell)$ = latent heat of vaporization of water in J kg^{-1} as a function of leaf temperature and is equal to 2.43×10^6 at 30°C and 2.50×10^6 at 0°C,

E = transpiration rate in kg $m^{-2} \times s^{-1}$.

For any given value of E, a specific value of T_ℓ will balance Equation (1), provided all other quantities are known. However, E depends on a unique set of environmental variables. It is seen in the next paragraphs that E is a function of T_ℓ. Therefore, it is possible to determine E and T_ℓ simultaneously. If the air temperature is warmer than the leaf temperature, heat is gained by convection rather than lost and this term becomes negative on the right-hand side of the energy budget equation.

Resistance to Water Loss

There are three requirements for the loss of water from a leaf. There must be water available in the leaf, there must be energy available to convert liquid water to vapor, and finally, there must be a vapor pressure or density gradient along which water vapor may flow from inside to outside the leaf beyond the bounday layer of air which adheres to the leaf surface. Liquid water at the mesophyll cell walls within the leaf is vaporized and from the intercellular spaces, this water vapor passes out of the leaf by diffusion through the stomates or through the leaf cuticle. Usually, the cuticle is coated with a wax layer which is relatively impervious to water and as a result most of the water lost from a leaf is through the stomates. As with fluid passing through any tube or pipe, there is resistance to vapor flow by viscous drag with the walls. The resistance to water vapor diffusion through the substomatal and stomatal spaces with the leaf is r_ℓ in s m^{-1} and represents an average value for the entire leaf. In addition, the water vapor must diffuse across a boundary layer of air adhering to the leaf surface and this offers a resistance r_a given in s m^{-1}. The boundary layer resistance is affected by the wind speed across the leaf. In fact, the greater the wind speed the thinner the boundary layer thickness; and hence, diffusion resistance is greater on large leaves than on small leaves. Experimental results show that the boundary layer resistance varies directly as the square root of the leaf dimension (width) D and inversely with the square root of the wind speed V, a relationship which is precisely the inverse of the influence of wind speed and leaf dimension on the exchange of heat by convection. Therefore, the boundary layer resistance r_a is given by

$$r_a = k_2 \left(\frac{D}{V}\right)^{\frac{1}{2}}. \qquad (2)$$

Although there are complexities concerning air flow about a leaf which cause k_2 to change its value for leaves of characteristic dimension less than 0.005 m, we shall use a single value here for all leaf dimensions. $k_2 = 200\ s^{\frac{1}{2}-1}m^{-1}$ when D is in m and V is m s^{-1}. Since the ratio of D/V is involved here, nothing is changed if D is in cm and V in cm s^{-1}.

Transpiration Rate

The rate at which water vapor will diffuse out of a leaf will depend directly on the difference in water vapor density inside and outside the leaf, just as the rate at which water will flow downhill depends on the difference in height between the top and bottom of the hill.

For the moment, it is assumed that the air in the intercellular air spaces inside the leaf is at saturation at the temperature of the leaf and has a saturation density ${}_s d_\ell(T_\ell)$. The air outside the leaf and beyond the boundary layer has a water vapor density equal to [r.h.] × ${}_s d_a(T_a)$, where r.h. is the relative humidity and ${}_sd_a(T_a)$ is the saturation water vapor density of the air as a function of the air temperature. The relative humidity is, by definition, the ratio of the actual water vapor density of the air to the saturation density. Usually, it is given in percent, but as used here, it is a decimal fraction. The rate of water loss from a leaf per unit area per unit time is equal to the gradient for water vapor density divided by the resistance to water vapor movement and is given by

$$E = \frac{{}_sd_\ell(T_\ell) - [\text{r.h.}]\,{}_sd_a(T_a)}{r_\ell + r_a} \tag{3}$$

where r_a is given by Equation (2). Here, if ${}_sd_\ell(T_\ell)$ and ${}_sd_a(T_a)$ are given in kg m^{-3} and r_ℓ and r_a in s m^{-1}, then E is in kg m^{-2} s^{-1}.

COMPLETE ENERGY BUDGET

By substituting Equation (3) into Equation (1), and including the expression given by Equation (2) in Equation (3), one gets for the full expression of the leaf energy budget the following:

$$Q_a = \varepsilon\sigma[T_\ell + 273]^4 + k_1\left(\frac{V}{D}\right)^{1/2}[T_\ell - T_a] + L(T_\ell)\,\frac{{}_sd_\ell(T_\ell) - [\text{r.h.}]\,{}_sd_a(T_a)}{r_\ell + k_2\left(\frac{D}{V}\right)^{1/2}} \tag{4}$$

Here all environmental variables which affect the energy status of the leaf act simultaneously. They are Q_a, T_a, ε, D, and r_ℓ, while the absorptivity of the leaf surface to radiation is buried in the term Q_a. When all the environmental variables and appropriate leaf properties are known, a unique value of T_ℓ will balance this equation.

Values of the Leaf Parameters

Leaves are of many sizes from 1.0×10^{-3} m by 2.0×10^{-2} m for a Douglas fir needle to 0.3 m by 1.5 m for a banana leaf. Some leaves will have lengths very nearly equal to their widths. Internal diffusion resistances of leaves vary from less than 100 s m^{-1} to infinity but with commonly occurring values between 200 and 2000 s m^{-1}. Most leaves will have an absorptivity to shortwave radiation of about 0.6, but it may vary from 0.4 to 0.8. Longwave absorptivity will equal the longwave emissivity of 0.96. The total amount of radiation absorbed by a leaf will vary from about 400 to 800 W m^{-2} but higher and lower amounts may be encountered.

Values of the Environmental Variables

It is relatively easy for any of us to visualize the range of values for air temperature. A leaf is likely to encounter freezing when the air temperature is 0°C. Maximum air temperature for hot desert conditions, for example, would be about 45°C. Relative humidity is also easy to visualize as a result of common experience. For example, humid air would have a relative humidity of about 70% or greater and for very dry air r.h. = 30% or less. It is easy for one to look up in tables the water vapor density of saturated air at any particular temperature. Values range from 1.289 kg m^{-3} at 0°C to 1.068 kg m^{-3} at 45°C. Wind speeds are a part of common experience. Still air usually has very slight air movement which we arbitrarily put at 0.1 m s^{-1}. A gentle breeze is 1.0 m s^{-1} (2.2 mph) and a moderate wind is 10 m s^{-1} (22 mph). Radiation is the least familiar of all of the environmental variables and yet it is the most significant of them.

INFLUENCE OF ENERGY COMPONENTS ON LEAF TEMPERATURE

It is useful to evaluate the major components separately of the leaf energy budget in order to get a feeling for their values and influence.

If a non-transpiring leaf is in a vacuum, its temperature is determined solely by radiative exchange and its energy budget is

$$Q_a = \varepsilon\sigma[T_\ell + 273]^4. \tag{5}$$

Let $\varepsilon = 0.96$. If $Q_a = 800$ W m^{-2}, $T_\ell = 75.2°C$; 600 W m^{-2}, $T_\ell = 51.1°C$; and $Q_a = 400$ W m^{-2}, $T_\ell = 19.8°C$. A leaf temperature of 75°C is very warm indeed and no plants as we know them would survive such a temperature. Even at 51°C, most plants would sustain serious heat damage. However, plants live in air, a fluid, which flows about the plant and takes away excess heat by convection. Just as a plant loses heat by radiation, it must lose heat by convection as well, and this it cannot avoid. We shall now determine the extent to which a plant leaf may have its temperature influenced by convection.

If the non-transpiring leaf is placed in air, the leaf temperature is significantly affected by the air temperature. If the ratio V/D is large, convection becomes very significant and the leaf temperature is tightly coupled to the air temperature. Large V/D suggests high wind speeds or small leaf dimension. If V/D is small, the leaf temperature is less strongly affected by the air temperature, but still it is significantly influenced. The energy budget is given by

$$Q_a = \varepsilon\sigma[T_\ell + 273]^4 + k_1 \left(\frac{V}{D}\right)^{\frac{1}{2}} [T_\ell - T_a]. \tag{6}$$

If the air temperature is 30°C, one can determine the exact numerical relationship between Q_a and T_ℓ for any given ratio V/D. For example, we will determine values of T_ℓ for $Q_a = 800$, 600, and 400 W m^{-2} for V/D = 1.0, 10.0, and 100. These values are listed in Table I. The easiest way to solve Equation (6) is to put in values of V/D, T_ℓ, and T_a,

Q_a ($W\ m^{-2}$)	Radiation only	Radiation and convection V/D(s^{-1})			Radiation, convection, and transpiration V/D(s^{-1})		
		1.0	10.0	100.0	1.0	10.0	100.0
800	75.2	61.5	39.7	33.5	36.8	31.8	30.3
600	51.1	39.1	34.0	31.2	30.4	28.5	28.7
400	19.8	26.1	28.3	29.4	23.0	24.9	27.1

Table 1. Leaf temperature in °C for various amounts of absorbed radiation exchanged by radiation only, by radiation and convection, and by radiation, convection, and transpiration. Values of variables used are T_a=30°C, r.h.=50%, and r_ℓ = 100 s m^{-1}. The addition of convective exchange to the energy budget will decrease the difference between leaf temperature and air temperature compared to the leaf temperature computed when only radiation is included. As the ratio V/D increases, the magnitude of the difference between leaf temperature and air temperature decreases. Note that if absorbed radiation levels are above black body value (for Q_a=800 and 600 W m^{-2} because here black body level is $Q_a = \sigma T_a^4 = 5.67\times10^{-8} \times (273+30)^4 = 478$ W m^{-2}). $T_\ell - T_a$ is positive and if Q_a is below the black body value $T_\ell - T_a$ is negative. If transpiration is included, it will reduce all leaf temperatures from the values computed when only radiation and convection transfer are included.

determine Q_a and then plot T_ℓ versus Q_a at fixed ratios of V/D and a fixed value of T_a; in this case $T_a = 30°C$.

For V/D = 1.0, simply placing the non-transpiring leaf in air of temperature 30°C dropped the leaf temperature from 75.2 to 61.5°C at $Q_a = 800$ W m^{-2}, a decrease of 13.7°C. Clearly, convection may play a very strong role in influencing leaf temperature. If V/D = 10.0, the decrease is, of course, even more dramatic. At $Q_a = 800$ W m^{-2} and $T_a = 30°C$, T_ℓ = 39.7°C, there is a decrease of 35.5°C from the pure radiation regime. If V/D = 100 and $Q_a = 800$ W m^{-2}, the leaf temperature is 33.5°C with convection, a change of 41.7°C.

We tend to forget the significance of convection in the ordinary world but when we make comparisons of this kind to show what would happen to leaf temperature without convective cooling, the influence of convection becomes very clear. At lower amounts of absorbed radiation, the influence of convection is less strong, but still important until the leaf temperature is equal to the air temperature. Then, when the quantity of absorbed radiation is very low, which will occur for an exposed leaf on a clear night, the leaf temperature is below the air temperature and convection will deliver heat to the leaf, thereby, warming it. This is seen in Table I for $Q_a = 400$ W m^{-2}; when, without convection, the non-transpiring leaf had a temperature of 19.8°C, and the in air at 30°C, the leaf temperature increased to 26.1, 28.3, and 29.4°C, respectively, at V/D = 1.0, 10.0, and 100.0.

The influence of transpiration is now readily seen by including the transpiration term in the full energy budget expression as given in Equation (4). Now one must decide on a value for the internal resistance of a leaf and the relative humidity of the air. Let $r_\ell = 100$ s m^{-1} and r.h. = 50%. It is more difficult to solve Equation (4) then it is to solve Equations (5) or (6). Graphical methods are possible although cumbersome. It is far easier to use a calculator or a computer and this is now done. The values are listed in Table I.

At Q_a = 800 W m^{-2}, T_ℓ = 36.8, 31.8, or 30.3°C for V/D = 1.0, 10.0, and 100.0, respectively. Hence, transpiration has reduced the leaf temperature by 24.7, 7.9, and 3.2°C for the three ratios of V/D, as shown by comparing the values listed in columns 6, 7, and 8 with those in columns 3, 4, and 5. These temperature reductions caused by transpiration are quite striking and would be significant in terms of photosynthetic and respiration rates. At lower levels of absorbed radiation, the influence of transpiration if reduced, since there is less energy available for the evaporation of water. Transpiration always produces leaf temperatures lower than the case of radiation and convection only.

MORE DETAILED ENERGY BUDGET

So far, the energy budget equation has contained only the leaf width as the characteristic dimension for convective heat transfer and gas diffusion. Such a simple expression is only strictly correct for leaves which are nearly square; however, realtively few leaves are of this form. Most leaves have a long dimension which is considerably greater than the narrow dimension. Some years ago, Gates (1968) reported investigations of the heat and water vapor transfer from simulated leaves of blotting paper of a variety of lengths and widths. He found if D is the characteristic dimension of the leaf in the direction of air flow and W is the dimension transverse to the wind, that the energy budget is given by

$$Q_a = \varepsilon\sigma[T_\ell + 273]^4 + k_1 \left(\frac{V}{D}\right)^{\frac{1}{2}} [T_\ell - T_a]$$

$$+ L(T_\ell) \frac{{}_s d_\ell(T_\ell) - r.h.{}_s d_a(T_a)}{r_\ell + k_2[D^{0.30}W^{0.20}]/V^{0.50}} \qquad (7)$$

where

$$k_1 = 9.14 \text{ J m}^{-2} \text{ s}^{-\frac{1}{2}} \text{ °C}^{-1} \qquad \text{and} \qquad k_2 = 183 \text{ s}^{-\frac{1}{2}} \text{ m}^{-1}.$$

Gates elected to include W in the evaporation term only since the amount of data was not sufficient to reveal the functional relationship in both the convective and evaporative terms simultaneously. Equation (7) is more realistic than Equation (4), which, nevertheless, is a good approximation. If the wind is blowing across the leaf in the direction of the leaf width, then, the characteristic dimension D is the average leaf width and W is the average length. If, on the other hand, the wind is blowing along the length of the leaf, then, D is the average length and W is the average leaf width.

ANALYSIS OF A MORE GENERAL MODEL

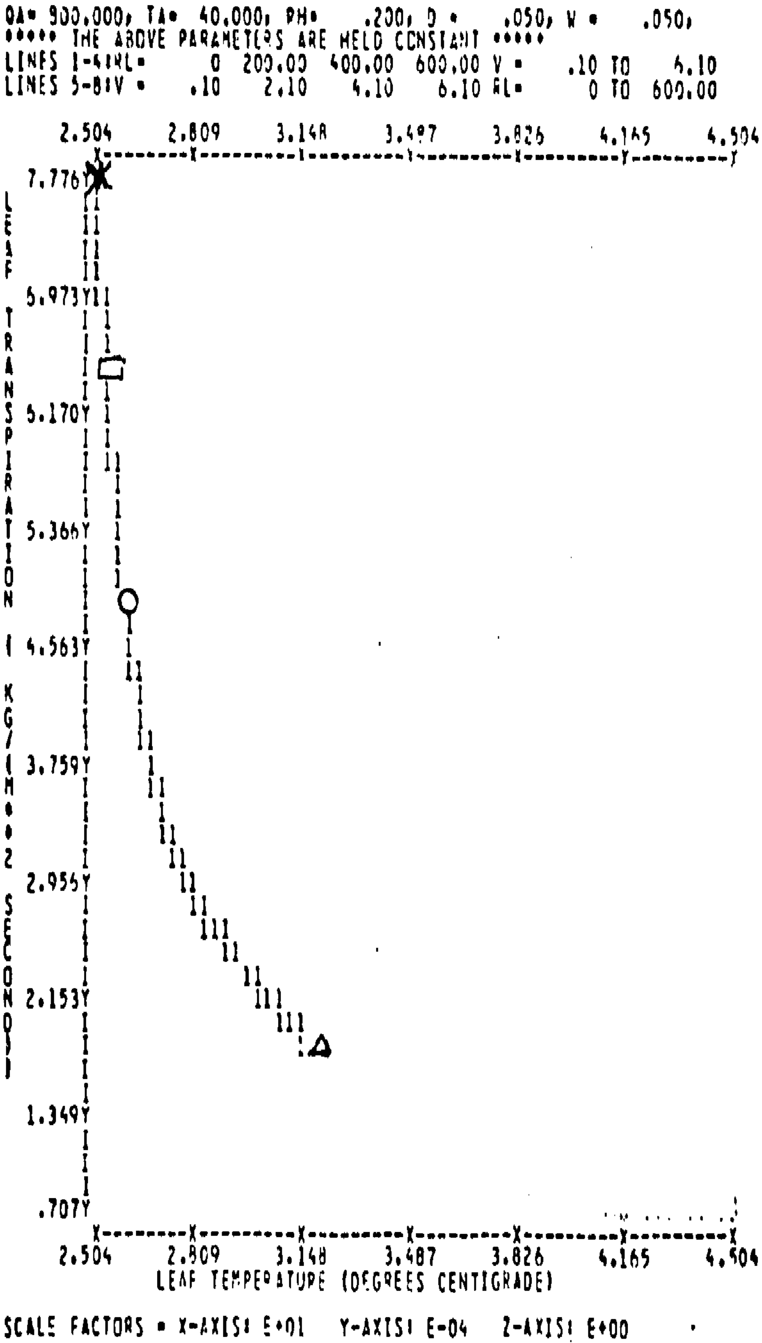
Computer Leaf Temperatures and Transpiration

It is straightforward to obtain values of the two dependent variables, leaf temperatures and transpiration rate, as a function of any conceivable combination of values of the independent variables and leaf parameters which appear in Equation (7). The four independent variables used are radiation absorbed, air temperature, relative humidity of the air, and wind speed; and the three leaf parameters are characteristic dimension, leaf width and internal resistance. Gates and Papian (1971) published a tabulation of leaf temperatures and transpiration rates for various sets of values of the dependent variables and leaf parameters. Similar plots are shown in a paper by Gates (1968). These plots have proved useful in understanding Equation (7), and therefore at this time we will undertake an explanation of how they are produced.

Let us begin by specifying $Q_a = 800$ W m^{-2}, $T_a = 40°$C, r.h. = 0.20, D = 0.05 m, W = 0.05 m, r_a = 0.0, s m^{-1} and V = 0.10 m s^{-1}. Now all the parameter values of Equation (7) are known except leaf temperature. Using numerical techniques or a trial-and-error procedure one can find T_ℓ. Once T_ℓ is known, the transpiration rate is calculated using the last term of Equation (7). It is then possible to plot this point (as a triangle) in Figure 2a. If V is changed to 2.1 m s^{-1} and the other variables are held constant, we get another pair of transpiration and leaf temperature points to plot shown by a circle in Figure 2a. If V = 4.1 m s^{-1} and 6.1 m s^{-1}, the square and star points respectively can be computed in the same fashion.

These four points are then connected as in Figure 2a with 1's. This line describes all the pairs of leaf temperature and transpiration rate points with the fixed conditions specified above and wind speed varying from 0.10 m s^{-1} to 6.1 m s^{-1}.

It is also possible to fix wind speed and let leaf resistance vary. As an example, assume the same conditions as at the beginning of the previous paragraph but let V = 2.1 m s^{-1} and r_ℓ vary continuously from 0.0 to 600 s m^{-1}. The result is the line of 6's shown in Figure 2b. Using this procedure, a series of eight lines is generated for each plot. If the plots look confusing, simply locate a point of intersection of two lines and ask what are the parameter values. It is then easy to find out which parameter is varying for any given line.



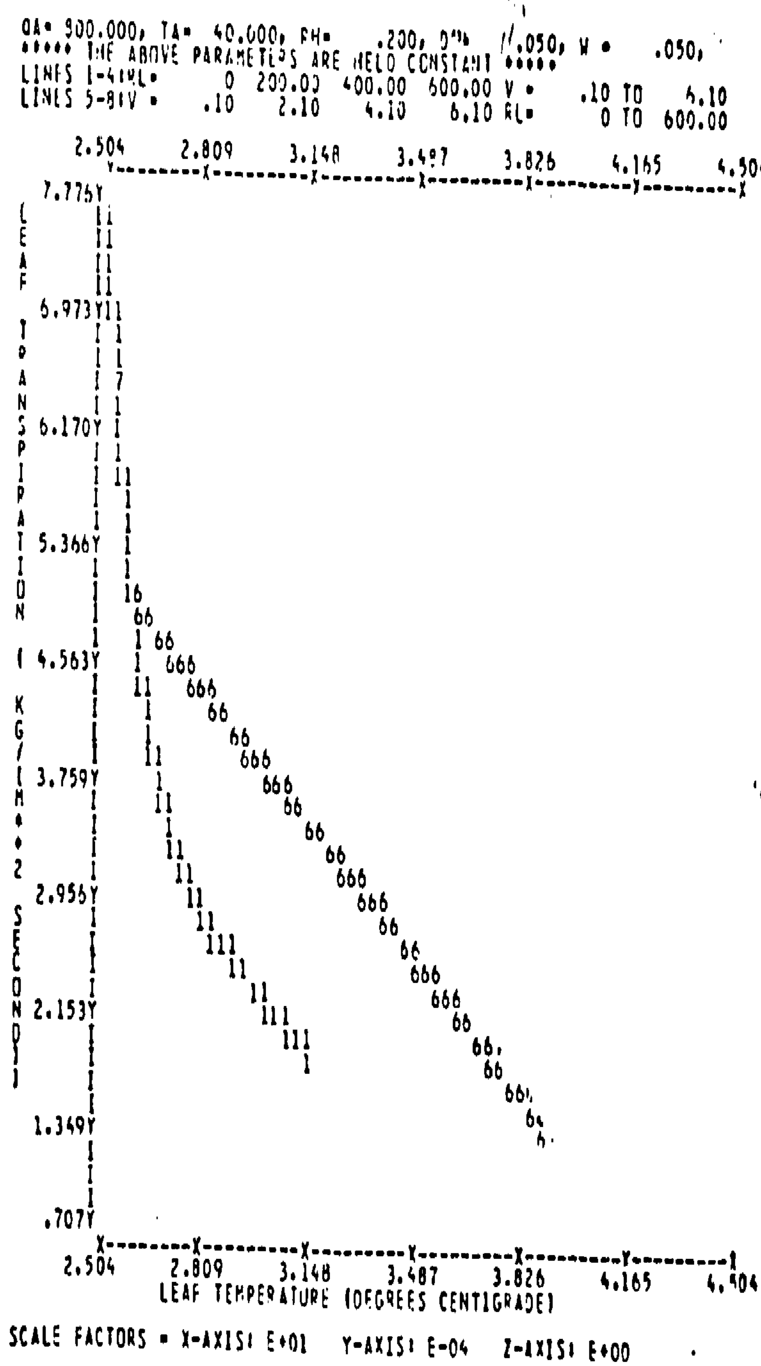


Figure 2a. Plot of transpiration versus air temperature using the energy balance equation (7) from the text, with Q_a=800 w m^2, T_a=40°C, D=0.05 m, W=0.05 m, and r_ℓ=0.0 s m^{-1}. For V=0.10, 2.1, 4.1 and 6.1, m s^{-1} symbols Δ, o, □ and * are used. The line of 1's is of V varying continuously from 0.10 to 6.1 m s^{-1}.

Figure 2b. Same as 2a except that the line of 6's is for V=2.1 m s^{-1} and r_ℓ varying from 0.0 to 600 m s^{-1}.

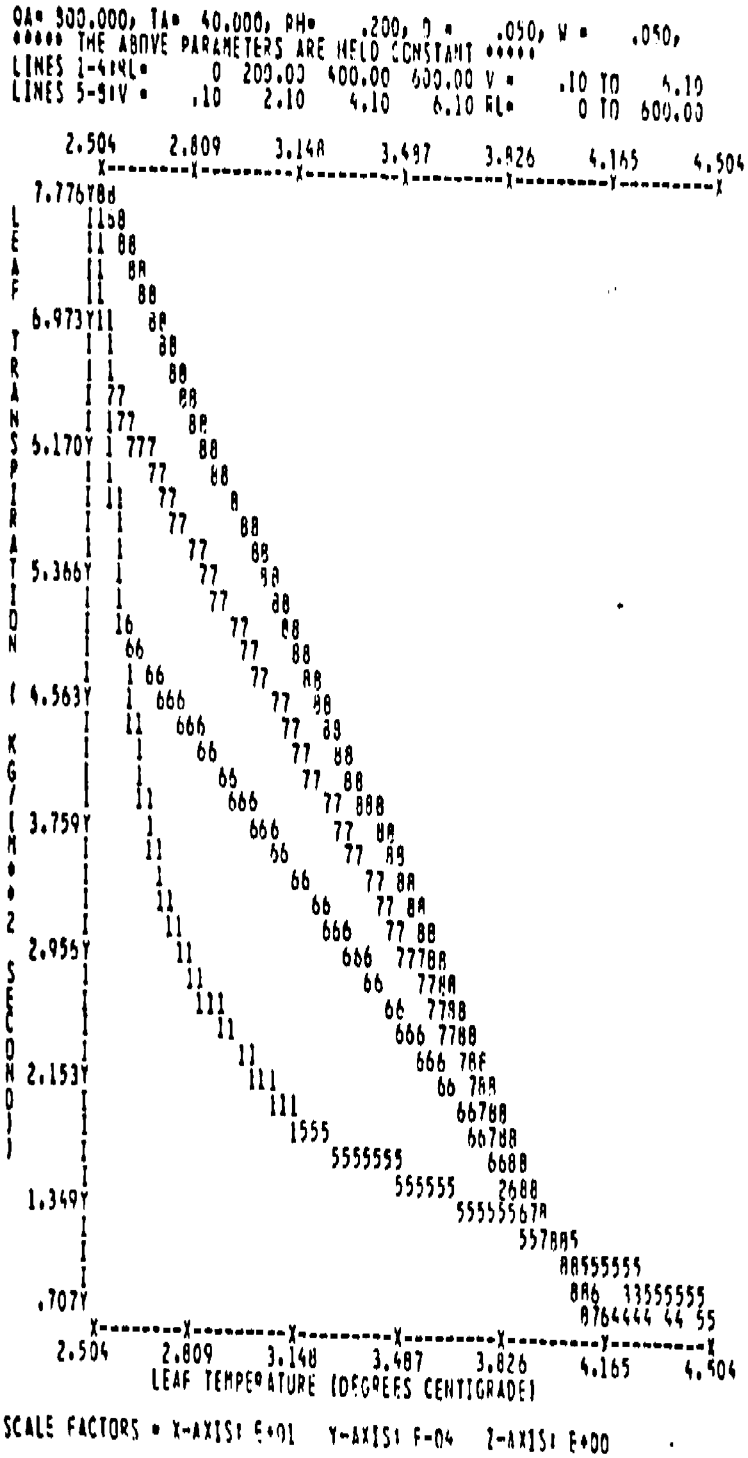
Sample Plots of Transpiration and Leaf Temperature

It is possible to select as changing variables in the graph any two of the following independent variables and leaf parameters: amount of radiation absorbed, air temperature, wind speed, relative humidity, leaf dimensions, and diffusion resistance. For our first example, we shall use, as changing variables, wind speed and internal diffusion resistance. Let wind speed values by 0.1, 2.1, 4.1, and 6.1 m s^{-1}, and internal diffusion resistance values be 0, 200, 400, and 600 s m^{-1}.

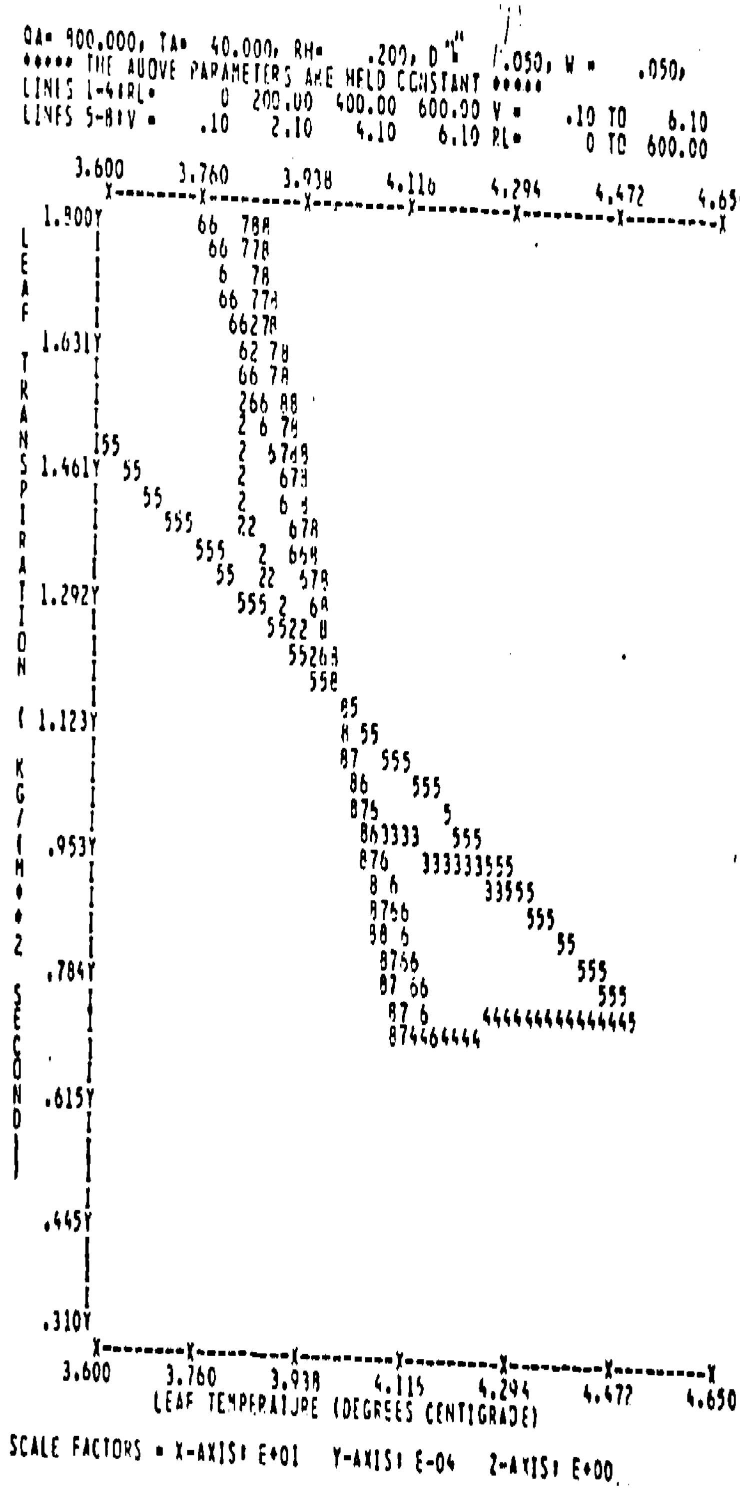
A leaf size of 0.05 x 0.05 m is selected for the first examples. Plots are generated for the following conditions:

3) Q_a = 800 W m^{-2}; T_a = 40°C; r.h. = 0.20
4) Q_a = 700 W m^{-2}; T_a = 30°C; r.h. = 0.20
5) Q_a = 700 W m^{-2}; T_a = 30°C; r.h. = 0.80
6) Q_a = 300 W m^{-2}; T_a = 10°C; r.h. = 0.50.

Plot 3a has many interesting features. It is characteristic of a hot, dry, high intensity radiation environment, such as one finds in a desert. In still air, represented by $V = 0.1$ m s^{-1}, a leaf with a high diffusion resistance becomes very warm. For $r_\ell = 600$ s m^{-1}, $T_\ell = 45$°C, but if $r_\ell = \infty$, T_ℓ is nearly 15°C above the air temperature of 40°C. This can only be obtained by extrapolating the straight line for $V = 0.1$ m s^{-1} to where it intersects the temperature axis at zero transpiration. (The 5's line. It would be easiest to see this if one enlarged the scale of plot and let the ordinate begin at 0.0 transpiration rate.) It is evident that all the constant wind speed lines intersect and cross over at $T_\ell \approx T_a = 40$°C. Note the small decrease in transpiration rate for $r_\ell = 600$ s m^{-1} when $T_\ell < 42$°C and the wind speed has increased to $V = 2.1$, 4.1, and 6.1 m s^{-1}. This is an interesting phenomenon and should be



Plot 3a. Leaf transpiration versus leaf temperature with leaf resistance r_ℓ and wind velocity V varying.



Plot 3b. Enlarged 3a.

understood by the reader. Look at Equation (7) and consider the effect of increased wind speed. An increase of V, when the leaf temperature is above the air temperature, produces a decrease of leaf temperature by convective cooling. The increased wind speed also diminishes the thickness and resistance of the leaf boundary layer. This, by itself, would cause the transpiration rate to increase. However, the convective cooling of the leaf caused the water vapor pressure inside the leaf to drop and that produces a reduction of transpiration. In effect, what happens is that there is a greater reduction of the numerator in the evaporation term of Equation (7) (the driving force) than there is of the denominator (the resistive force). This phenomenon shows up at relatively high values of internal leaf resistance. At lower leaf resistance values, of 400 s m^{-1}, when the wind speed increases the transpiration rate increases and the line of constant internal leaf resistance turns upward with wind speeds greater than about 1 m s^{-1} (see Figure 3b, line 3).

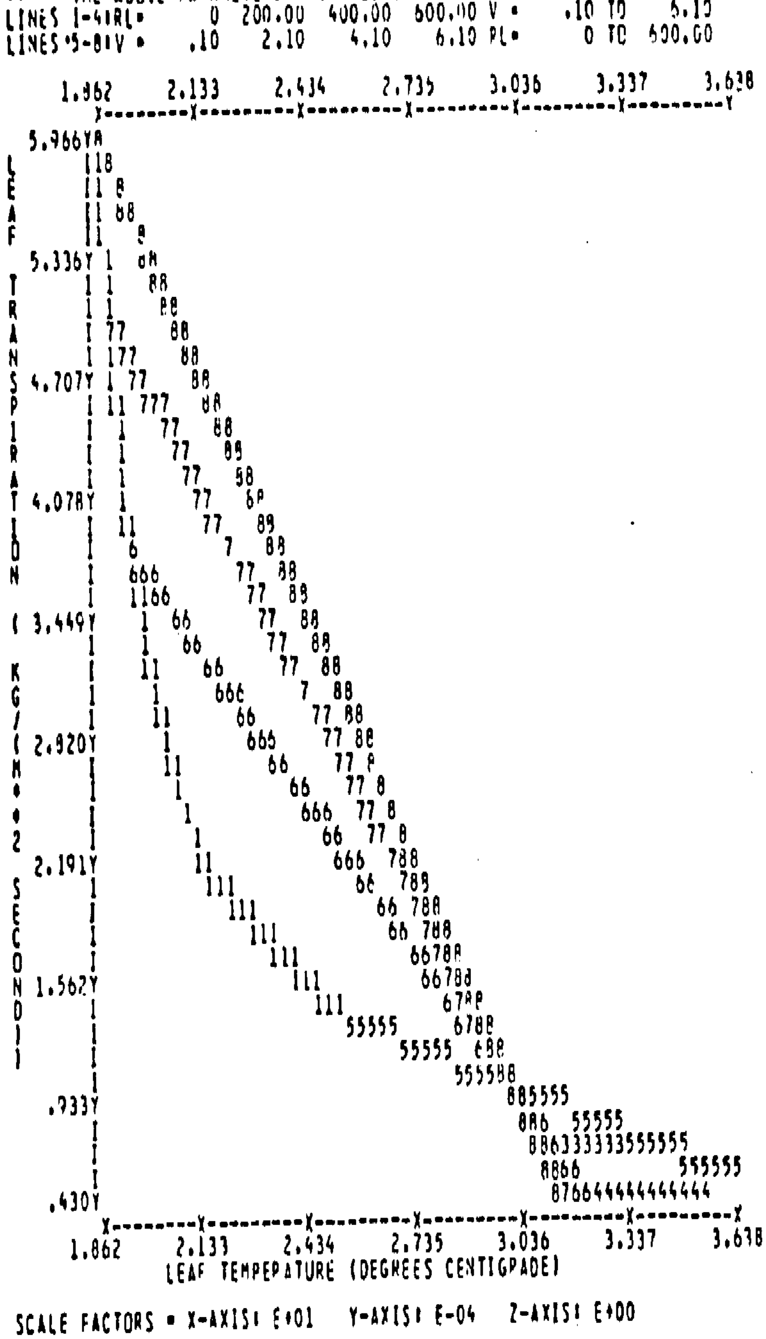
Now consider what happens when the leaf diffusion resistance is small, e.g., 200 sm^{-1}. Here in Plot 3b, the line at constant r_ℓ = 200 s m^{-1} is doubled valued in E for certain T_ℓ. The line curves back on itself as wind speed increases. At first, as the wind speed increases from 0.1 m s^{-1} to about 1.0 m s^{-1}, the leaf temperature decreases as the transpiration rate increases, but at higher wind speeds; although the transpiration rate continues to increase, the leaf temperature begins to increase. At very high wind speeds, it would approach the air temperature because convection is transferring heat to the leaf since the air is warmer than the leaf. A general feature of Plot 3b is that for hot, dry, high radiation conditions, a leaf is warmer than the air temperature if the internal diffusion resistance is above a certain value--here, estimated at about 300 s m^{-1}. If the leaf resistance is less than this value, the leaf temperature is below the air temperature.

Plot 4 represents leaf temperature and transpiration rates for warm, dry, moderate radiation conditions, with V and r_ℓ as changing quantities. Only leaves with relatively low internal resistance have temperature less than the air temperature (line of 1's). Leaves with resistances of about 200 s m^{-1} or greater will be from 0 to about 8°C above air temperature, depending on the wind speed (lines of 2's, 3's, and 4's, Plot 4b). Where does the line of zero internal diffusion resistance show up in this plot or is it beyond the scale used?

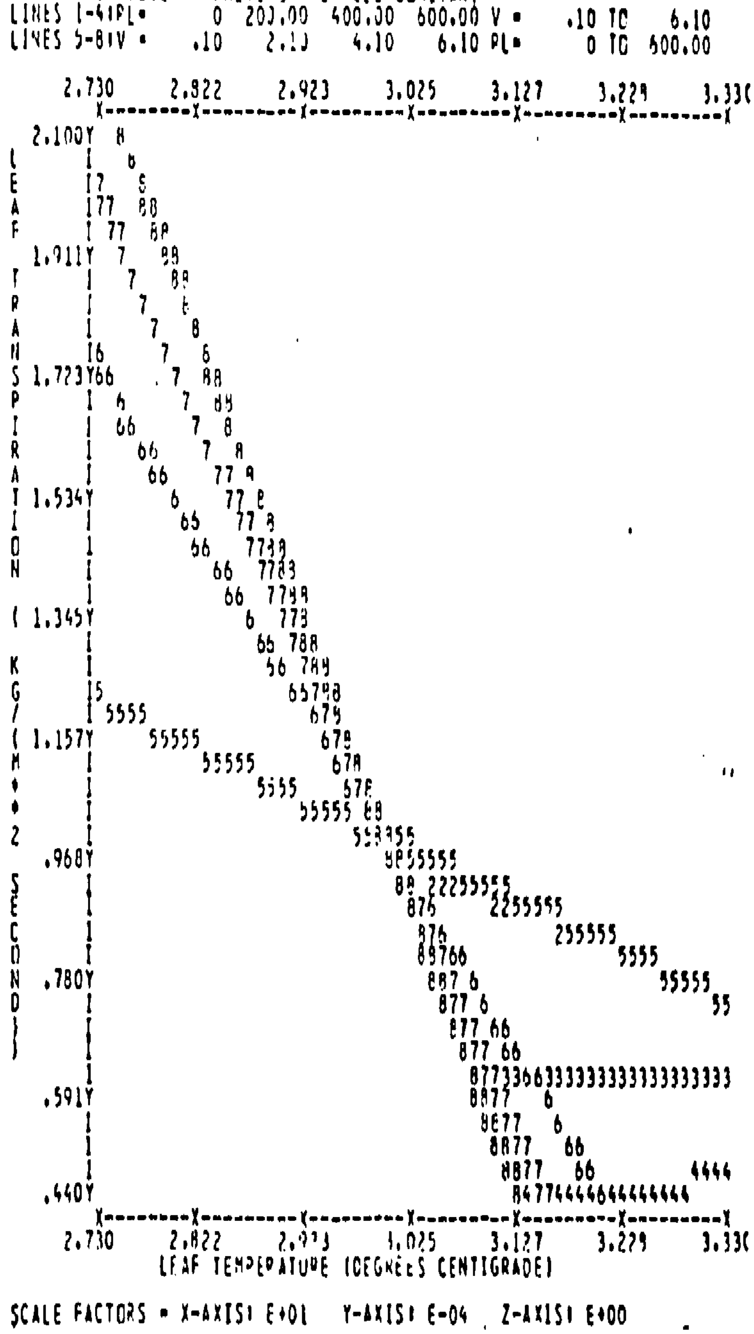
Plot 5 is for warm, humid, moderate radiation intensity conditions such as occur in many tropical situations and during moist, summer temperate region days. Transpiration rates are generally low, since the vapor density difference between leaf and air is not very great. Now the leaf temperatures are always above the air temperature for all realistic values of r_ℓ.

Plot 6 represents cool, moderately humid, low radiation conditions and exhibits some interesting features. All leaf temperatures are below the air temperature. An increase of wind speed always warms the leaf and, at constant internal leaf resistance, produces a small increase of transpiration. Generally, the transpiration rates are very low because of the limited amounts of energy available. The line of zero leaf resistance constant is well displayed here. The reader should ask if the conditions used here, e.g., Q_a = 300 W m^{-2}, T_a = 10°C, and r.h. = 0.50 are realistic and, if so, when and where will they occur.

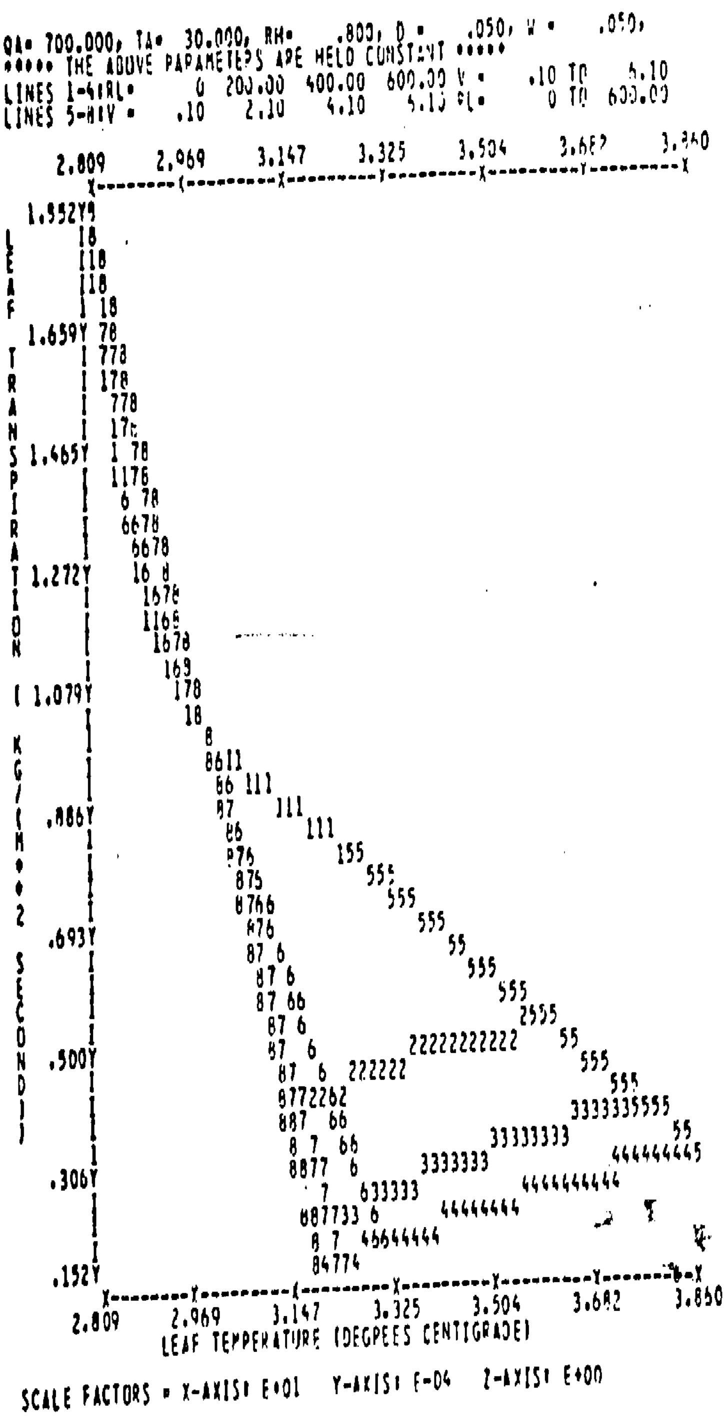
Now it is possible to explore other dimensions of the transpiration-leaf temperature plot. Let the changing variables be air temperature and



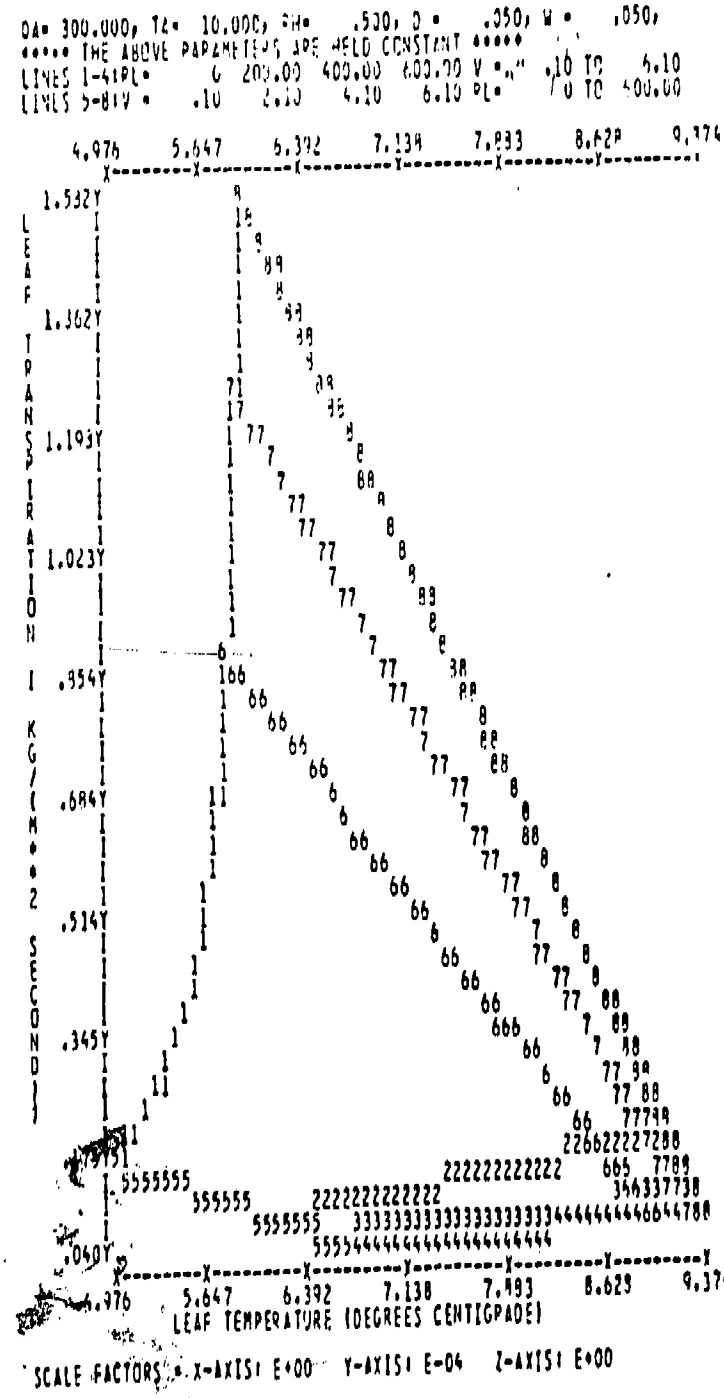
Plot 4a. Leaf transpiration versus leaf temperature with leaf resistance r_ℓ and wind velocity V varying.



Plot 4b. 4a enlarged.



Plot 5. Leaf transpiration versus leaf temperature with leaf resistance r_ℓ and wind velocity V varying.



Plot 6. Leaf transpiration versus leaf temperature with leaf resistance r_ℓ and wind velocity V varying.

internal diffusion resistance. Use air temperature of 10, 20, 30, and 40°C and resistance of 0. 333, 667, and 1000 s m^{-1}. The leaf size is 0.05 x 0.05 m as before. Plots are generated for the following conditions:

7) Q_a = 700 W m^{-2}; V = 0.1 m s^{-1}; r.h. = 0.20

8) Q_a = 700 W m^{-2}; V = 0.1 m s^{-1}; r.h. = 0.80

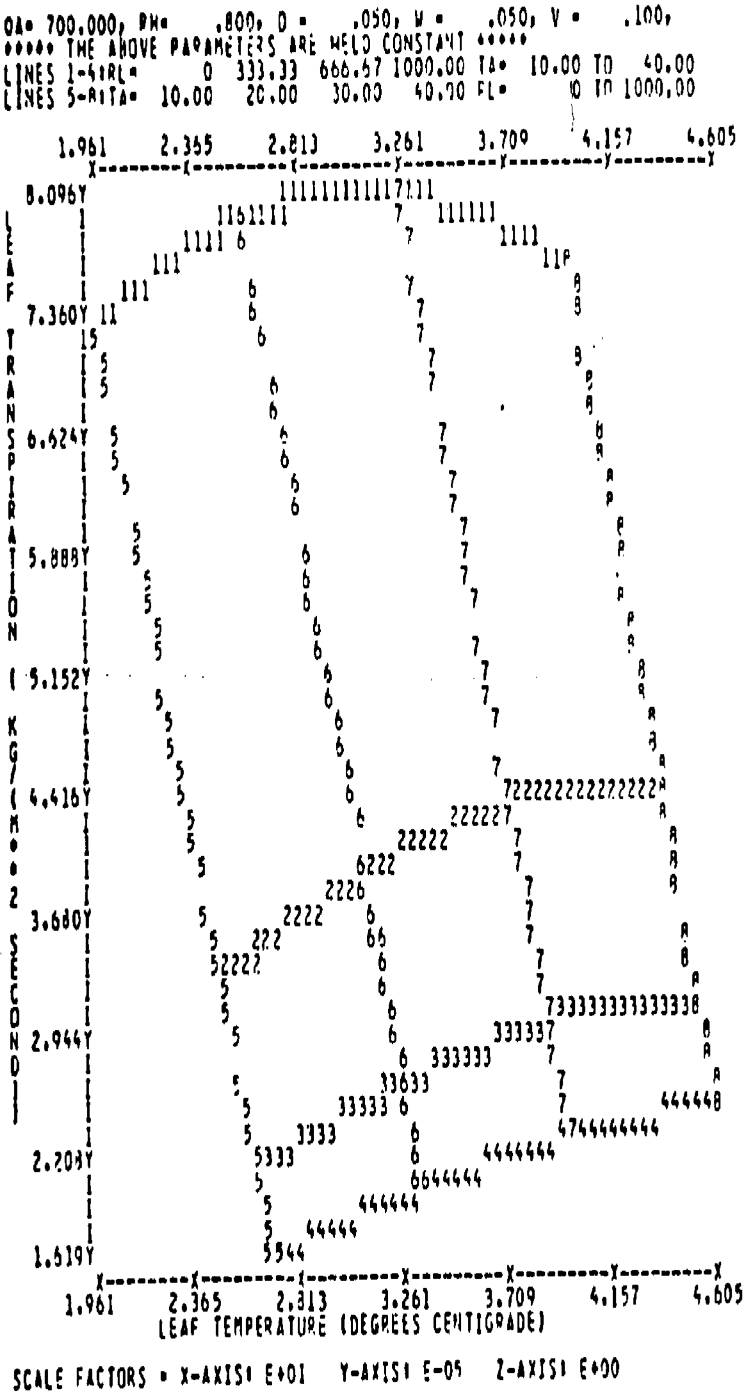
9) Q_a = 700 W m^{-2}; V = 2.0 m s^{-1}; r.h. = 0.50

10) Q_a = 300 W m^{-2}; V = 0.1 m s^{-1}; r.h. = 0.50.

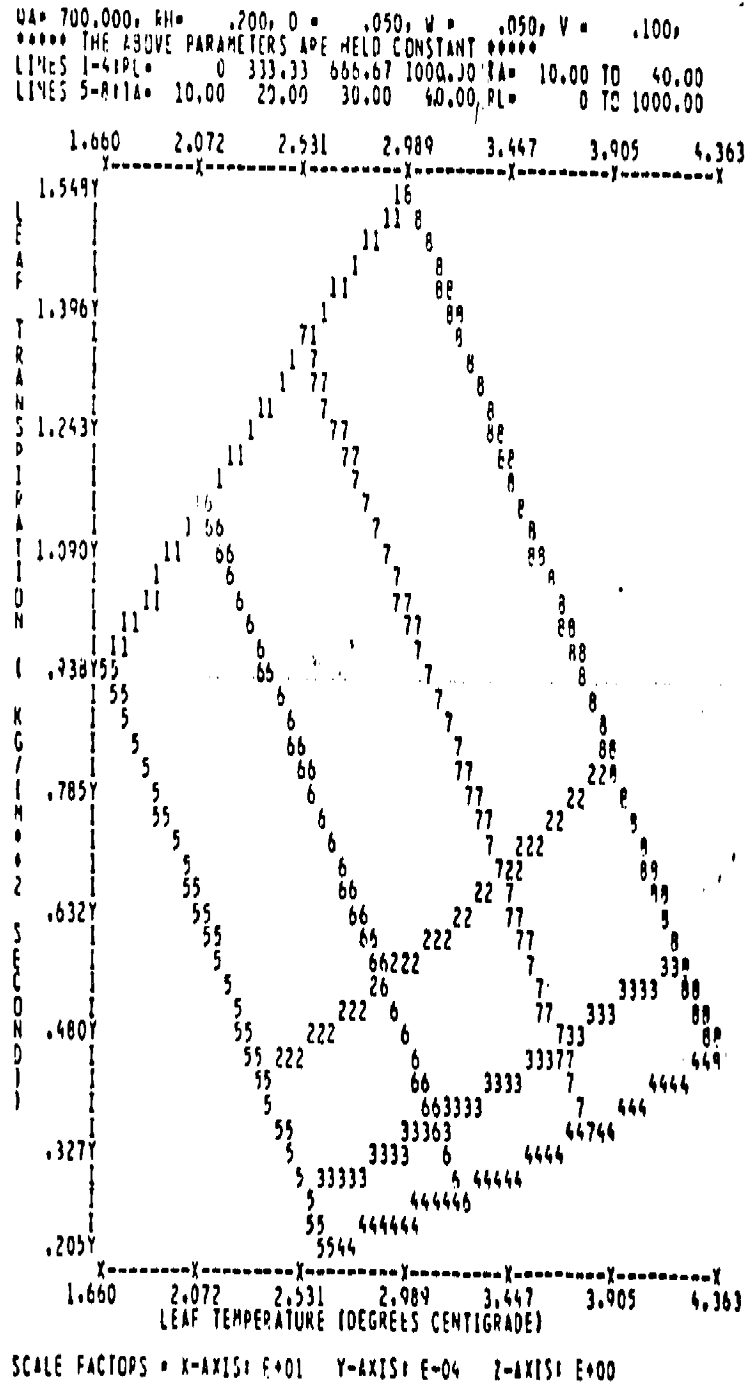
Plot 7 represents an environment of no wind, moderate radiation intensity, and very dry air. There are lines of constant air temperature. Note where it is in the plot that $T_\ell > T_a$ and $T_\ell < T_a$. Locate the transition point on the air temperature lines and draw a light line connecting these.

Plot 8 is for an environment of no wind, moderate radiation intensity and high humidity. Compare this with Plot 7. Notice the change in slope of the constant temperature lines and the curvature of the constant resistance lines. It is seen there is an optimum temperature for the freely evaporating surface with zero internal resistance. Why? As the air temperature increase from 10 to 20 to 30°C along a constant resistance line, the leaf temperature is increasing but at the same time the difference $T_\ell - T_a$ is getting smaller. Since the term for radiation emitted by the leaf increases with the fourth power of T_ℓ, it is taking up a disproportionate amount of the available energy which is constant at Q_a = 700 W m^{-2}. Not only is there less energy available for convection, but less for evaporation of water. Also, as T_a increases, the vapor density difference in the evaporation term of Equation (7) becomes less and the driving force to remove moisture from the leaf diminishes.

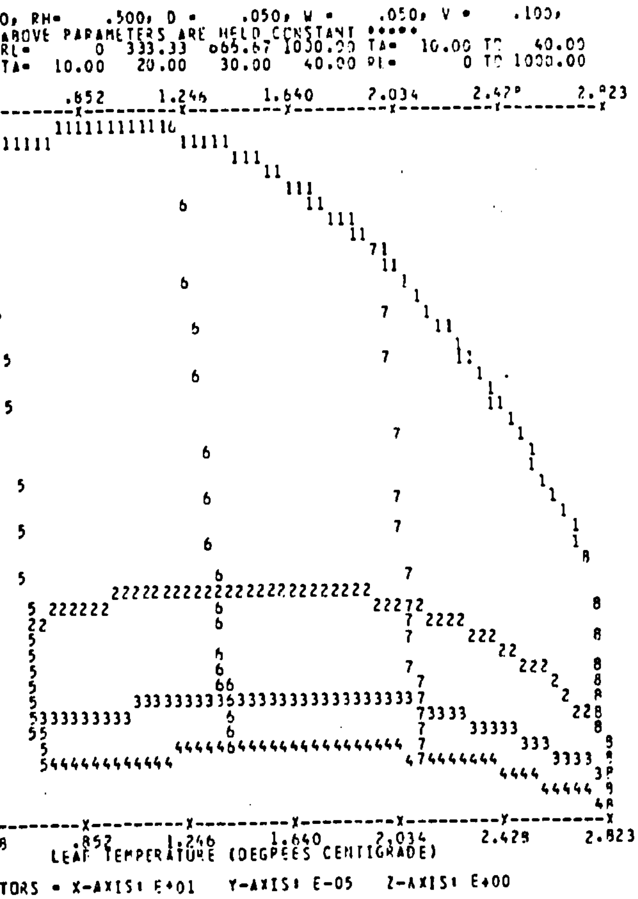
Plot 9 is for conditions of moderate radiation intensity, moderate humidity, and light wind. The rate of transpiration has increased over that



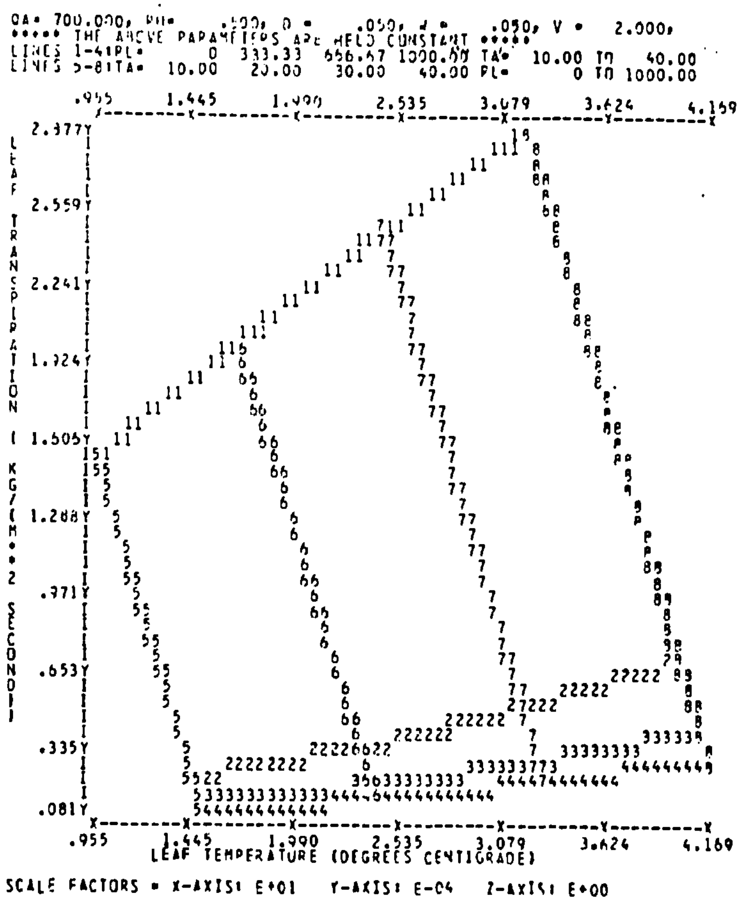
Plot 7. Leaf transpiration versus leaf temperature with leaf resistance r_ℓ and air temperature T_a varying.



Plot 8. Leaf transpiration versus leaf temperature with leaf resistance r_ℓ and air temperature T_a varying.



ot 9. Leaf transpiration versus leaf
mperature with leaf resistance r_ℓ and air
mperature T_a varying.



Plot 10. Leaf transpiration versus leaf
temperature with leaf resistance r_ℓ and air
temperature T_a varying.

in Plots 7 and 8. Here the leaf temperature is above air temperature for high resistance values, but for low resistances it is below; whereas in Plot 8, it was above air temperature for nearly all of the graph.

Plot 10 is for a low amount of absorbed radiation, no wind, and moderate humidity. The constant air temperature lines are very steep and the leaf temperature is always less than the air temperature. Note that for each constant resistance line, there is an optimum air temperature for which transpiration is a maximum. Why does transpiration diminish at high air temperatures? Are the environmental conditions realistic throughout the graph? Is the amount of radiation absorbed by the leaf consistent with the air temperature regime throughout the plot? If not, draw a line on the graph demarking a region of real environments from unreal ones.

CONCLUSION

In this module, two simple models of the thermal energy budget of a leaf have been introduced. Radiation, convection and evaporation, the most important heat transfer processes, are included in the models (note that conduction of heat along the leaf stem is not included). Because of the multidimensionality of the models, a graphical analysis was used. The models show that

1. leaf temperature can be above or below air temperature,
2. the larger the difference between absorbed radiation and the black body level of radiation, the larger the difference between leaf temperature and air temperature,
3. the greater the wind speed, the smaller is the difference between leaf temperature and wind speed, and
4. increasing evaporative water loss via transpiration always decreases leaf temperature.

In this formulation, the plant "can control" leaf temperature or transpiration by its size (D and W) and by its physiology (k_2 and r_ℓ).

There are, however, a number of leaf characteristics which have not been explicitly or implicitly included in the leaf energy budget. These include stomata size and shape, wax cuticle properties, leaf orientation and leaf absorptivity to shortwave radiation.

Finally this work has help lead to research in related areas. Scientists have developed equations to model (1) photosynthesis which couples the interchange of water vapor and CO_2 (Lommen et al. 1975; Tenhunen, Yocum and Gates 1976; Tenhunen et al. 1976), (2) whole-plant water transport (Farnum 1977), and (3) optimal leaf form (Taylor 1975; Parkhurst and Loucks 1972; Givnish and Vermeij 1976).

PROBLEMS

1. Using the example of a leaf with dimensions .05 m by .05 m, Dr. Gates shows in his paper that under certain circumstances an increase in wind speed will increase transpiration while in other cases an increase in wind speed will decrease transpiration. Find examples of these two cases for a Douglas fir needle with D = .001 m, W = .02 m.
2. Your light plane has just been forced down at 5000 feet in the Andes mountains. It is a hot (35°C), still (wind speed = 0.1 m sec^{-1}), and dry (r.h. = 20 percent) day in late summer. To pass the time until you are rescued, you look at the surrounding flora and become interested in leaf sizes. The sun is shining brightly and you guess that, without as much atmosphere to absorb the radiation, the plant leaves must be absorbing about 1045.6 W m^{-2} of radiant energ . You also note that the ground is dry so you surmise that the plants are water-stressed and must have internal diffusive resistances of about 2000 s m^{-1}. Assuming that these are the conditions which determine plant survival in this area, and assuming that plant leaves cannot tolerate temperatures in excess of 45°C for extended periods, what are the shape and size of the largest leaves you expect to find?
3. Equation (7) in the module indicates how a leaf dissipates the radiant energy it absorbs. The three terms on the right-hand side of (7) correspond to reradiation; loss of sensible heat by convection; and loss of latent heat through transpiration. For each of the three situations listed below, find the relative contribution of each of these mechanisms to the dissipation of the incident radiant energy.
   (a) In Figure 3, the situation indicated by the intersection of the RL = 200 sec m^{-1} and V = 0.1 m sec^{-1} lines,

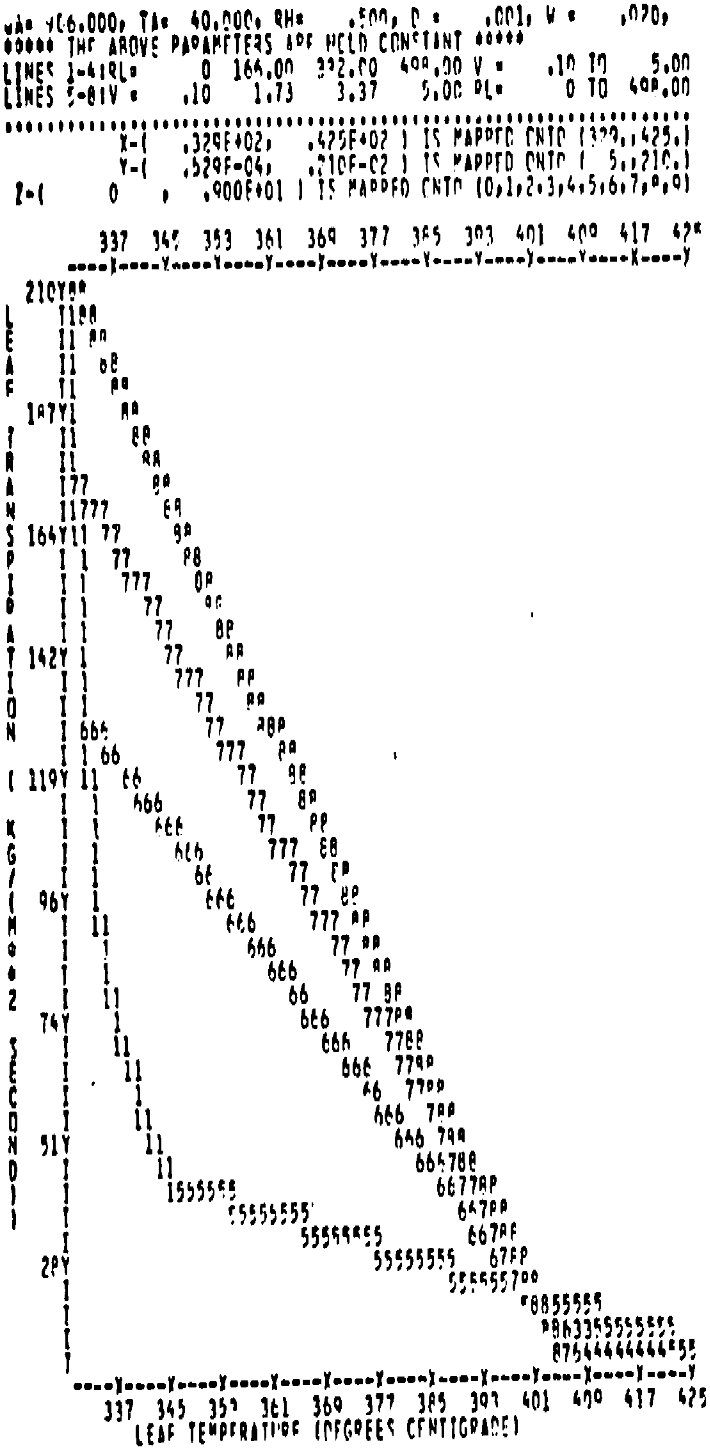
(b) In Figure 3, the situation indicated by the intersection of the RL = 0 sec m^{-1} and B = 2 m sec^{-1} lines.

(c) In Figure 8, the situation indicated by the intersection of the RL = 5000 sec m^{-1} and TA = 0°C lines.

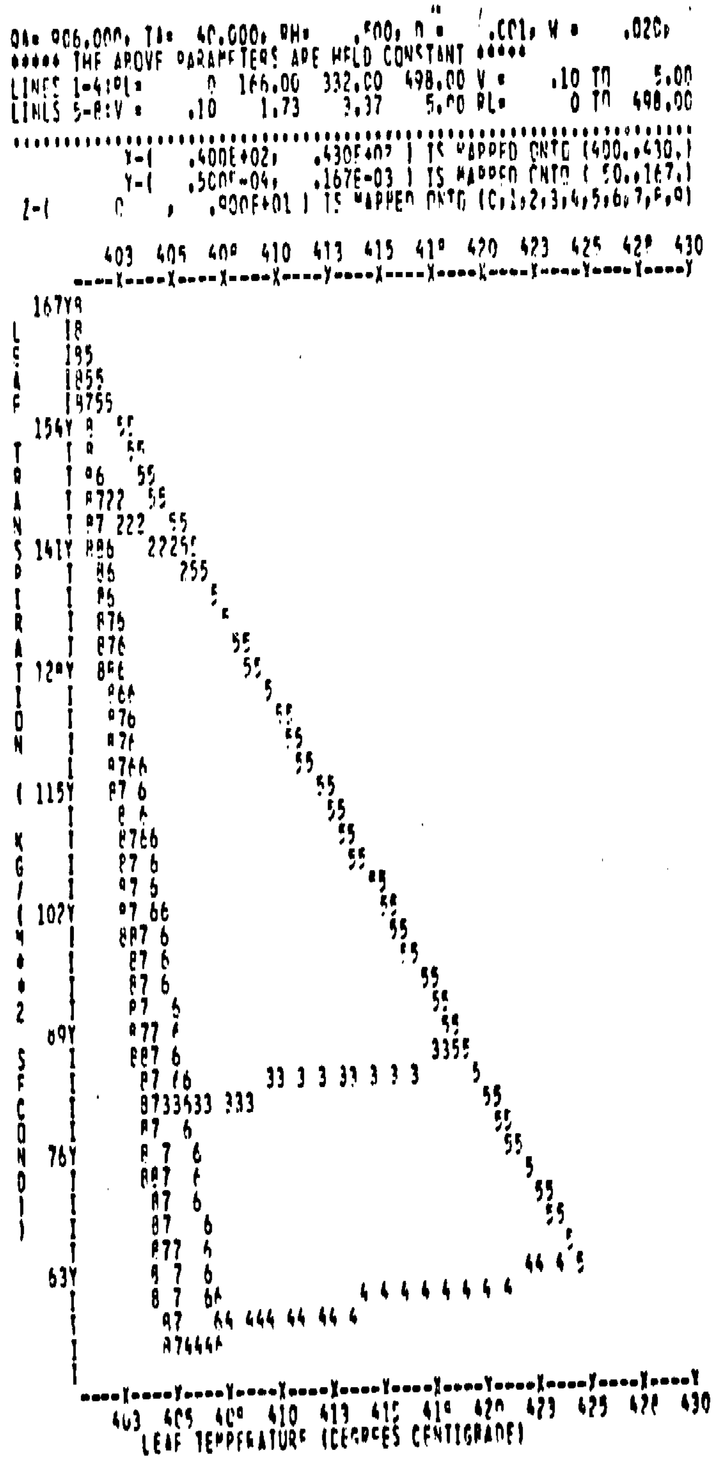
PROBLEM SOLUTIONS

1. Transpiration increases with wind speed for lines 1 and 2, i.e., RL = 168 s m^{-1}, but decreases with wind speed for lines 3 or 4 (see Plots 11a and 11b).
2. The leaves will be long and thin so that their dimension in the direction of the wind is always small. They must be less than about .007 m wide, and are essentially unlimited in length (see Plot 12).
3.

T_ℓ Leaf Temperature (°C)	E Transpiration (kg m^{-2} s^{-1} × 10^{-5})	Q_a Absorbed Radiation (W m^{-2})	$\varepsilon\sigma T_e^{\ 4}$ Reradiation (W m^{-2})	C Convection (W m^{-2})	LE Latent Heat Transfer (W m^{-2})
43	1.1	800	540	46	255
32	40	800	470	-580	950
5	0.17	697	330	360	7

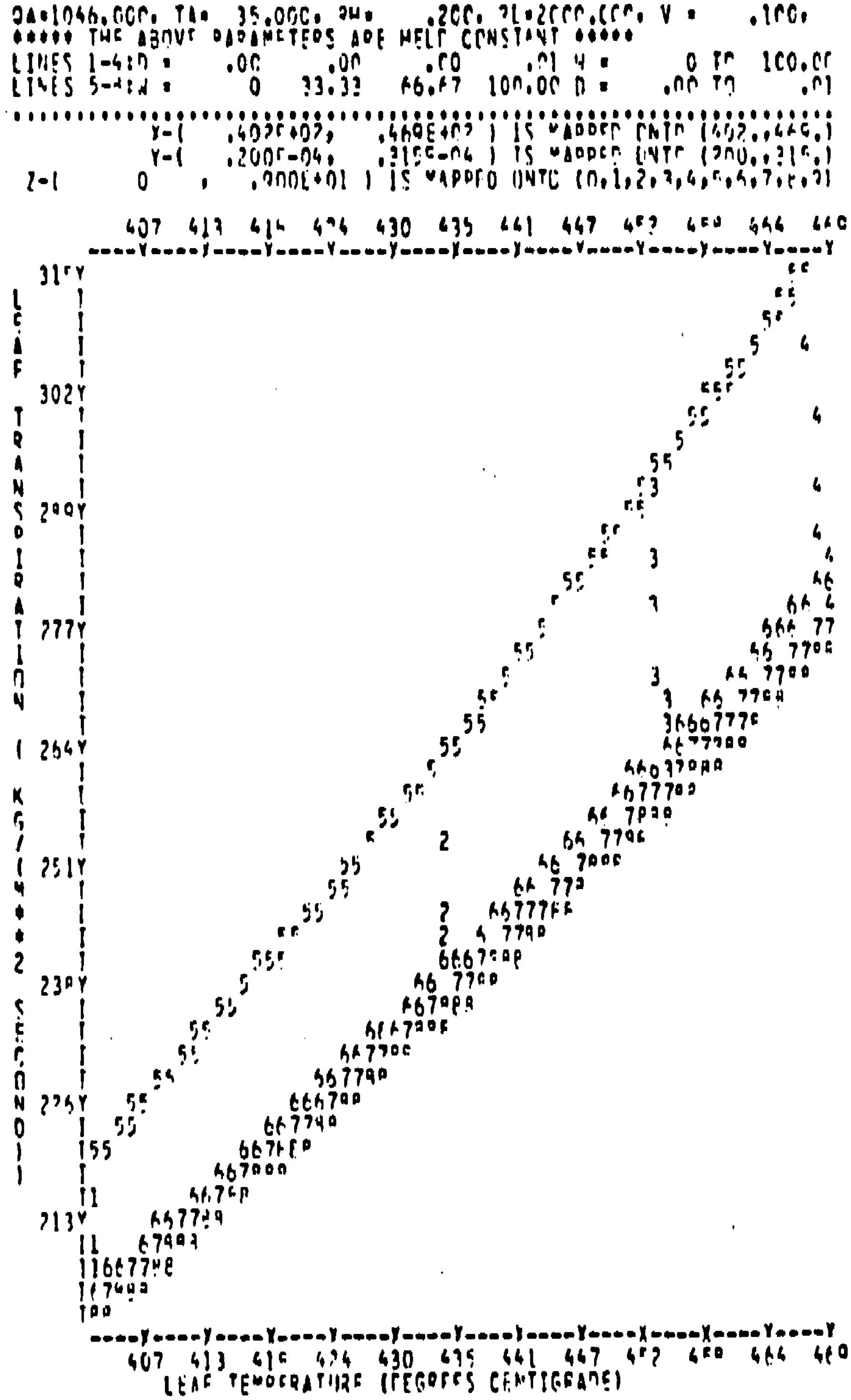


Plot 11a. Leaf transpiration versus leaf temperature for Problem 1.



FOR

Plot 11b. Leaf transpiration versus leaf temperature. The lower right-hand corner of Plot A is blown up to show lines 2, 3, and 4.



Plot 12. Leaf transpiration versus leaf temperature for Problem 2. Diameters above 0.0067 m make the leaf temperature raise above 46°C.

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TRANSPIRATION AND LEAF TEMPERATURE

APPENDIX 1. Symbols, Units, and Dimensions

Symbol	Quantity	Units	Dimension
D	Leaf dimension parallel to the wind direction	M	L
$s^d{}_a$	Saturation density of the air	$kg\ m^{-3}$	ML^{-3}
$s^d{}_\ell$	Saturation density of the leaf	$kg\ m^{-3}$	ML^{-3}
E	Transpiration rate	$kg\ m^{-2}s^{-1}$	$ML^{-2}\ T^{-1}$
k_1	Convection coefficient	$9.14\ J\ m^{-2}s^{-1/2}{}^{o}C^{-1}$	$MT^{-2.5}\Theta^{-1}$
k_2	Boundary layer resistance coefficient	$s^{1/2}m^{-1}$	$T^{1/2}L^{-1}$
L	Latent heat of vaporization of water	$J\ kg^{-1}$	L^2T^{-2}
Q_a	Total radiation absorbed	$W\ m^{-2}$	$HL^{-2}T^{-1}$
R	Black body radiation	$W\ m^{-2}$	$HL^{-2}T^{-1}$
r_a	Resistance to water diffusion across the boundary layer of air	$s\ m^{-1}$	TL^{-1}
r_ℓ	Resistance to water diffusion within the leaf	$s\ m^{-1}$	TL^{-1}
r.h.	Relative humidity	--	--
T	Temperature	^{o}C	Θ
T_a	Air temperature	^{o}C	Θ
T_ℓ	Leaf temperature	^{o}C	Θ
V	Wind speed	$m\ s^{-1}$	LT^{-1}
W	Leaf dimension perpendicular to the wind direction	m	L
ε	Emissivity of the leaf surface	--	--
σ	Stefan-Boltzmann constant	$5.67\text{x}10^{-8}\ W\ m^{-2}\ K^{-4}$	$HL^{-2}T^{-1}\Theta^{-4}$

L = length
M = mass
T = time
Θ = temperature
H = ML^2T^{-2}

USER'S GUIDE FOR PROGRAM TRANS

Identification

TRANS - A Program which Displays the Relationship between Leaf Temperature and Transpiration Rate

Authors - Suzanne Miller, Larry Gales, Peter Farnum, Graham Carey, Center for Quantitative Science in Forestry, Fisheries and Wildlife, University of Washington, Seattle. March, 1977.

Purpose

Program TRANS is the computer supplement to the module "Transpiration and Leaf Temperature" by David M. Gates (which is based on Gates, 1968). This paper stresses the relationship, through the leaf energy budget, between the transpiration rate and temperature of a leaf and the independent variables of the climate and plant (radiation absorbed, air temperature, internal diffusive resistance, leaf dimension, relative humidity, and wind speed). The computer program is based on this analysis and enables the student to create figures similar to those in the paper for any combination of independent variables he wishes to specify. Thus the paper gives the student a theoretical understanding of the relationship between leaf temperature and transpiration and the associated program helps him assimilate that knowledge by applying it to particular situations of interest.

Operation

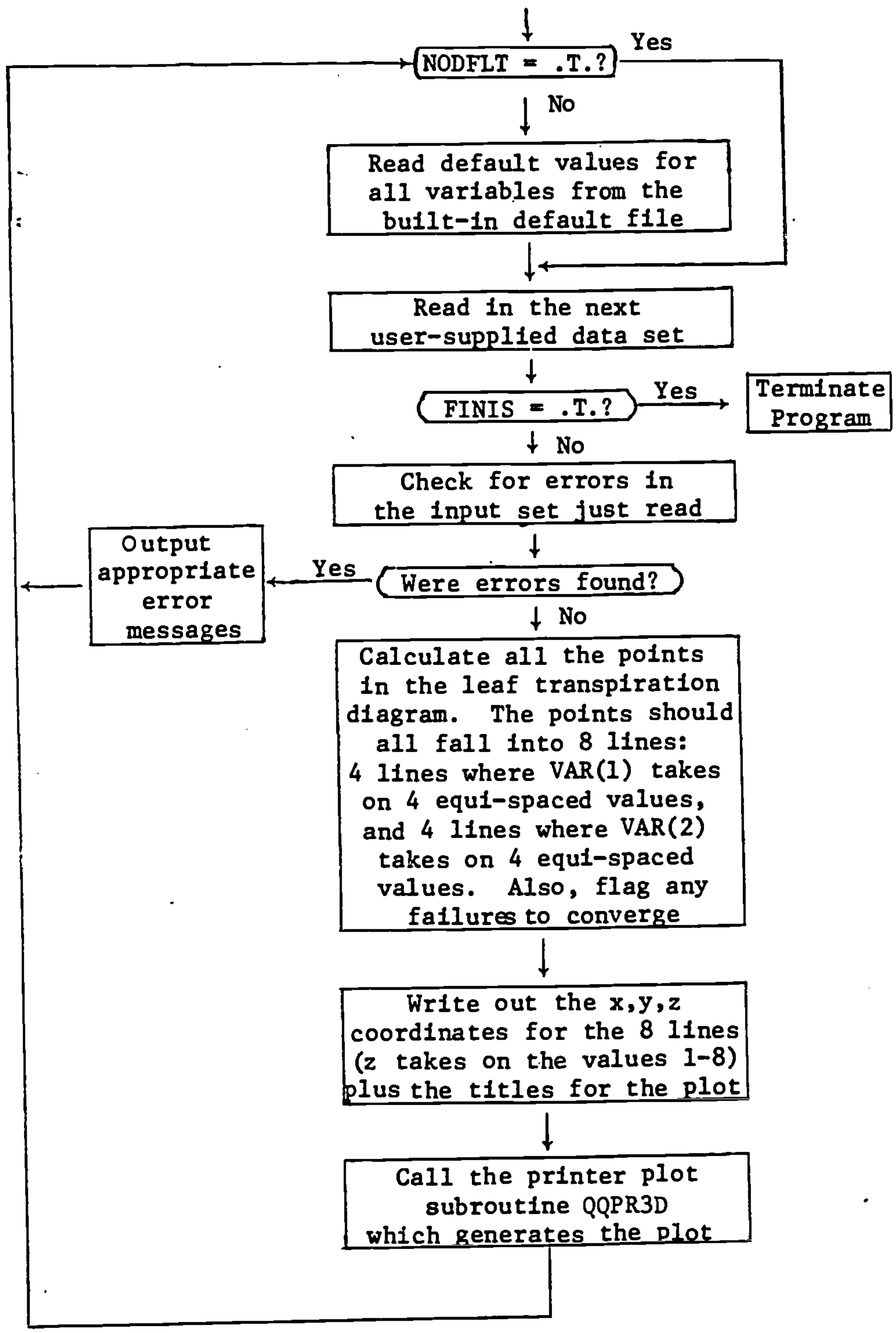
The user specifies values for five of the seven independent variables and ranges for the other two (called changeable variables). The value of the first changeable variable is fixed at the lower end of the specified range while the value of the other changeable variable changes continuously over its range. For each point in the independent variable space the energy budget equation (#7 in the module) is solved for leaf temperature using Newton's method, and then the transpiration rate is computed using this leaf temperature (from the last term in Equation (7)). This process generates a curve of transpiration versus leaf temperature for the five constant independent variables and the minimum of the first changeable variable as the value of the second changeable variable changes over its range. The value of the first changeable variable is then incremented to its minimum plus 1/3 of the range and the process is repeated to generate a second curve.

This process is repeated to generate two families of four curves each of leaf temperature versus transpiration rate. For both families one changeable variable is fixed at its minimum, its minimum plus 1/3 of its range, its minimum plus 2/3 of its range, and its maximum value while the value of the other changeable variable changes continuously over its range.

> Example: let the two changeable independent variables be air temperature and wind speed and let their specified ranges be 10 to 40°C and 0.1 to 3.1 meters sec^{-1}. Then one family of four curves consists of transpiration versus leaf temperature for air temperature equal to 10, 20, 30 and 40 degrees while wind speed varies continuously from 0.1 to 3.1 meters sec^{-1}. The other family contains four curves for wind speed equal to 0.1, 1.1, 2.1, 3.1 meters sec^{-1} while air temperature varies continuously from 10 to 40°C.

Program Organization

The program is organized according to the following flow chart:



Input

All input is handled by the format free input package (Gales and Anderson, 1978) which permits a user to assign values to variables by a "name=value" convention. Not all variables need be explicitly assigned by the user, however, as unassigned variables automatically assume default values. The input consists of any number of data sets, each of which is terminated by a dollar sign ($). Each data set generates a separate printer plot.

The input for TRANS is divided into three classes: (a) variables having biological significance: VAR, VARMIN, VARMAX, QA, TA, RH, RL, D, W, and V; (b) variables which control certain program operations, such as program termination or the handling of default input: IPRINT, ECHO, NODFLT, and FINIS; and (c) variables which control the printer plots (default values are in parentheses): XMIN (0), XMAX (0), YMIN (0), YMAX (0), ZMIN (0), ZMAX (9), XRICH (0.1), YRICH (8E-6), DFAULT (0), OVPRNT (.F.), AVE (.F.), INT2D (.F.), NX (60), NY (45), and ZMAP (0,1,2,3,4,5,6,7,8,9). The variables in the first two classes are explained in the following INPUT TABLE, whereas the printer plot variables are explained in the user's guide for PRNT3D (Gales, 1978).

INPUT TABLE

Name	Type and Dimensions	Range Limits	Description
VAR	Integer (2)	1,7	Number codes for the first and second changeable variables. Default values are: VAR(1)=4, VAR(2)=7
VARMIN	Real (2)	Depends on VAR	Minimum values for the first and second changeable variables specified by VAR (1) and VAR(2). Default values are: VARMIN(1)=0, VARMIN(2)=0.1
VARMAX	Real (2)	Depends on VAR	Maximum values for the first and second changeable variables specified by VAR(1) and VAR(2). Default values are: VARMAX(1)=1002, VARMAX(2)=5
QA (=#1)	Real	200,1200	Radient energy absorbed by leaf, in watts/meter^2. Default value is: QA=815. (Note: the code number for QA is 1.)
TA (=#2)	Real	0,50	Air temperature (°C). Default value is: TA=40 (Note: the code number for TA is 2.)
RH (=#3)	Real	0,1	Relative humidity (as a fraction). Default value is: RH=0.5. (Note: the code number for RH is 3.)
RL (=#4)	Real	0,10000	Diffusive leaf resistance, in sec meter^{-1}. Default value not specified as RL is a changeable variable by default. (Note: the code number for RL is 4.)

Input Table (cont.)

Name	Type and Dimensions	Range Limits	Description
D (=#5)	Real	$0 < D \leq 2$	Leaf dimension parallel to wind in meters. Default value is: D=0.05 (Note: the code number for D is 5.)
W (=#6)	Real	0,10	Leaf dimension transverse to wind, in meters. Default value is: W=0.05 (Note: the code number for W is 6.)
V (=#7)	Real	$0 < V \leq 10$	Wind speed, in meters sec^{-1}. Default value is not specified as V is a changeable variable by default. (Note: the code number for V is 7.)
IPRINT	Logical	.F., .T.	A Logical value which causes the current values for <u>all</u> input variables (default as well as current user input) to be printed. Default value is: IPRINT = .F.
ECHO	Logical	.F., .T.	A Logical value which causes the user's input to be echoed if ECHO=.T., or suppresses echoing if ECHO=.F. Default value is: ECHO=.T.
NODFLT	Logical	.F., .T.	A Logical value which suppresses the input of default values if NODFLT=.T. Default value is: NODFLT=.F.
FINIS	Logical	.F., .T.	A Logical value which causes program termination if and only if FINIS=.T. Default value is: FINIS=.F.

The last four variables deserve special mention.

1. The logical variable IPRINT controls the output of all input variables which are currently in effect (default values as well as those specified in the current input set). Setting IPRINT=TRUE (or T or .T.) displays the input variables; setting IPRINT=FALSE (or F or .F.) suppresses the display.
2. The logical variable ECHO controls the echoing of the input cards. Setting ECHO=TRUE causes the <u>subsequent</u> input set to the echoed; setting ECHO=FALSE suppresses the echo for the <u>subsequent</u> input set.
3. The logical variable NODFLT can be used to inhibit the automatic assignment of default values to input variables. If NODFLT is set TRUE in the <u>current</u> input set, then the current input set is assigned default values as usual, but all <u>subsequent</u> input sets merely accumulate more input values. In effect, the input values which exist after the i-th input set is read, become the default values for the (i+1)-th input set. The standard default values may then be restored by setting NODFLT=FALSE, but, again, the effects of this change are delayed until the next input set is read. To a limited extent, NODFLT permits a user to set up his own default values and can be very useful for executing a number of input sets which differ only in a few parameters. Consider the following example in which a user wishes to view the same plot in a variety of ways by "zooming in" on various parts of it. Since the calculations are the same for all plots, only the viewing coordinates need be changed:

```
/INPUT SET 1:  THE FOLLOWING VALUES BECOME THE DE FACTO/
/DEFAULTS FOR ALL SUBSEQUENT INPUT SETS:              /

   NODFLT = TRUE,     XRICH = 0.05, YRICH = 2E-6,
   VAR = 4, 7,  QA = 700,  TA = 30,  RH = 0.2,  D = 0.05,  W = 0.05,
   VARMIN = 0, 0.1,  VARMAX = 6.1, 600,   $

/INPUT SET 2:  ZOOM IN (SEE RUN NO. 2 IN SAMPLE RUNS):/

   XMIN = 27.3, XMAX = 33.3, YMIN = 4.296E-5, YMAX = 21E-5,  $

/INPUT SET 3:  ZOOM IN ON ANOTHER PART OF THE PLOT:/

   XMIN = 20, XMAX = 27, YMIN = 8E-5, YMAX = 14E-5,  $

/INPUT SET 4:  ZOOM IN ON YET ANOTHER PART:/

   XMIN = 25, XMAX = 28, YMIN = 40E-5, YMAX = 50E-5,  $

/INPUT SET 5:  STOP/

   FINIS = TRUE,  $
```

4. The logical variable FINIS controls program termination. The user should add the card:

   ```
   FINIS = TRUE,  $
   ```

   as the very last input set. If FINIS is not set, the program will terminate abnormally.

Output

TRANS produces sets of plots, via subroutine PRNT3D, which are similar to those in the paper by Gates. Each plot contains a title, legend, x and y axis annotation, and printer plot lines. The title displays the values, and ranges of values, for the variables used to generate a plot and is best explained by an example. Consider the plot in the first sample run, whose title reads:

```
QA=700.000  TA = 30.000  RH=.200  D=.050  W=0.50
***** THE ABOVE PARAMETERS ARE HELD CONSTANT*****
LINES 1-4:  RL=.00  200.00  400.00  600.00  V=.10 TO 6.10
LINES 5-8:  V=.10  2.10  4.10  6.10  RL=.00 TO 600.00
```

The plot contains eight lines with line 1 indicated by a string of 1's, line 2 by a string of 2's, ... , and line 8 by a string of 8's.

For this particular plot, the variables QA, TA, RH, D, and W are held constant at their stated values for all eight lines. The values for RL and V, however, are allowed to vary. For lines 1 through 4, RL is held fixed at a given value (0 for line 1, 200 for line 2, 400 for line 3, and 600 for line 4) while V varies continuously from 0.1 to 6.1. For example, line 3 features RL fixed at 400 while V varies from 0.1 to 6.1. For lines 5 through 8, the situation is reversed, and V is held constant at a given value (0.1 for line 5, 2.1 for line 6, 4.1 for line 7, and 6.1 for line 8) while RL varies continuously from 0 to 600. The user can select which variables are held fixed and which are allowed to vary.

The plot legend, in conjunction with the numbers along the x and y axes, allows users to interpret the plot numerically. For example, the first line of the plot legend for the first sample run (page 51) reads:

SCALE FACTORS = X-AXIS:E+01, Y-AXIS:E-04, Z-AXIS:E+00

hence the point (x=2.133, y=4.707) [this is among a group of points marked with an "8" near the upper left corner of the plot] is interpreted as ($x=2.133 \times 10^1$, $y=4.707 \times 10^{-4}$) = (21.33°C, 0.0004907 kg/m^2-sec). The next two lines in the plot legend indicate the number ("-9" means "more than 99") of points mapped to each z-axis level.

The plot in run 1 also illustrates the problem of low resolution which often plagues printer plots. The lines near the lower right corner of the plot are so crowded together that it is difficult to distinguish them (for example, line 2 contains only one visible point). The "zoom in" feature of PRNT3D is invaluable here in that it permits users to blow up selected regions of the plot into as much detail as is desired. For example, in run 2 the user input the coordinates

$$(XMIN=27.3,\ YMIN=4.296\text{x}10^{-5})\ ,\ (XMAX=33.3,\ YMAX=21\text{x}10^{-5})$$

of a rectangular window which enclosed the region he wished to see, and the computer responded with a full page blow up of the specified region. Zoom in and other features of PRNT3D are discussed in more detail in its user's guide.

Restrictions

The user must restrict all input variables according to the range limits listed in the input table, in order to avoid unrealistic physical values.

Error Messages

There are four types of errors which may occur when attempting to execute program TRANS:

1. Syntax errors in the user's input
2. Range check errors
3. Convergence errors
4. Plot parameter errors

For type 1 and 2 errors, the program flags the error, skips the calculations and plotting, and then reads the next input set. For type 3 errors, the program continues with the calculation and plotting after outputting an error message. For type 4 errors, the program suppresses plotting, outputs the error message, and reads the next data set. For a complete description of type 1 and type 4 error messages and actions, refer to the user's guides for the format free input package and printer plot package, respectively.

Range check errors occur if the range limits set for input variables are exceeded. These messages are of the form:

----- ERROR NO. x IN SUB. INCHK -----

yy...y OUT OF RANGE

yy...y = dd...d

where x is an error number ranging from 1 to 11, yy...y describes the variable in question, and dd...d is the input value. The correspondence between error numbers and variables is as follows:

Error No.	Associated Variable
1	QA
2	TA
3	RH
4	RL
5	D
6	W
7	V
8	VAR(1) or VAR(2)
9	VARMIN(1) or VARMIN(2)
10	VARMAX(1) or VARMAX(2)
11	VAR(1) and VAR(2)

Convergence errors occur when the values of combinations of input variables, which escaped the range checks, cause the iterative solution for leaf temperature to fail to converge. These messages are of the form:

----- ERROR NO. 1 IN SUB. TLEAF -----

CONVERGENCE REQUIRES MORE THAN d...d ITERATIONS

QA = dd...d

V = dd...d

D = dd...d

```
LEAF TEMPERATURE =   dd...d

NEWTON-S INCREMENT = dd...d


----- ERROR NO. 2 IN SUB. TLEAF -----

SLOPE = ZERO AT ITERATE = dd...d
```

Sample Runs

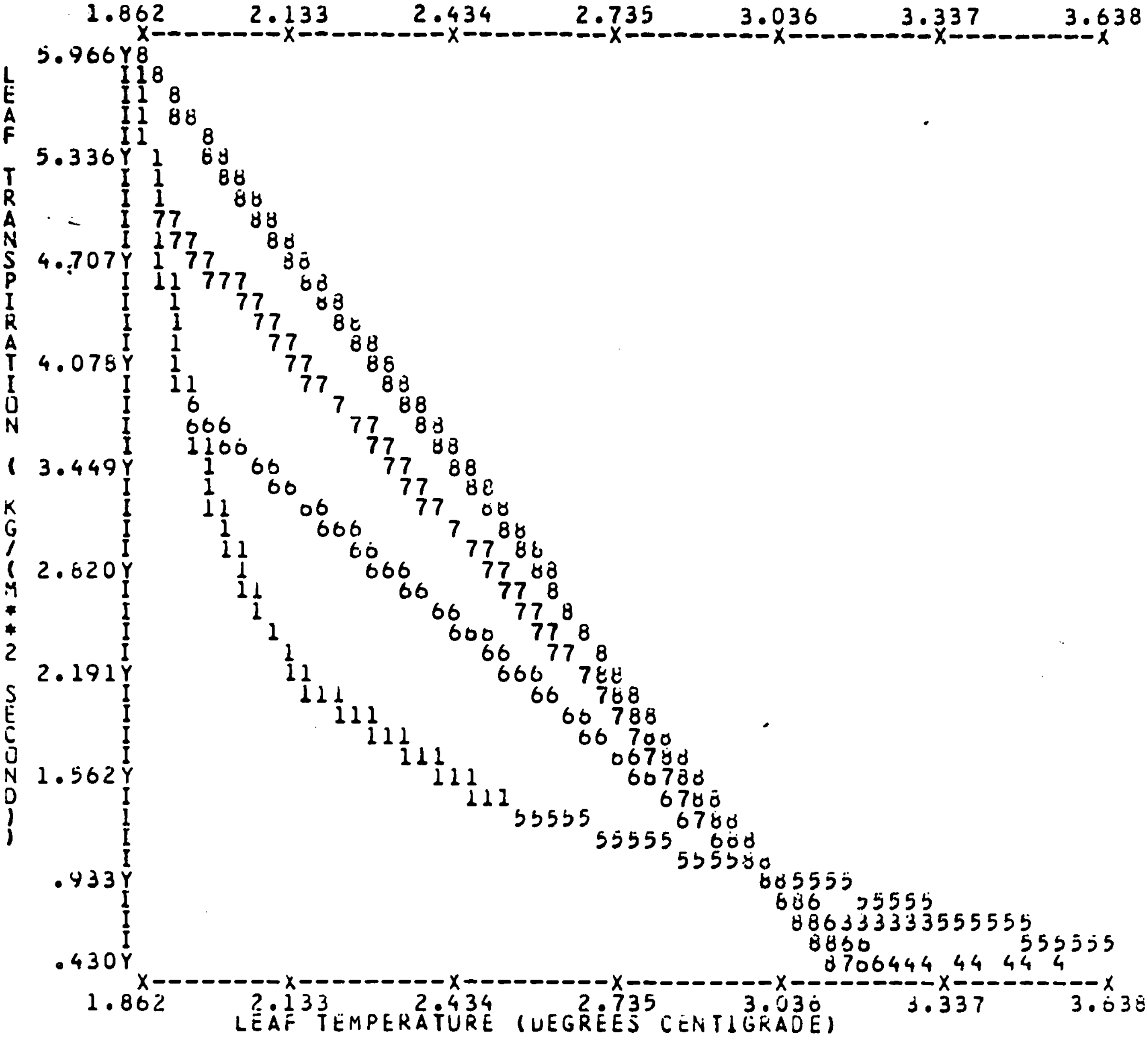
The annotated listing starting on the next page illustrates the control cards and input cards for two sample runs. Each input set is terminated by a $ and generates a one-page printer plot. These plots appear on the next few pages.

```
XTRANS,CM70000,T20.                LEAF TRANSPIRATION
ACCOUNT,XXXXXXXX,XXXXXXX,B.
COMMENT.
COMMENT.*****************************************************************
COMMENT.* THE FIRST CARD ABOVE IDENTIFIES THE JOB, SPECIFIES THE        *
COMMENT.* MEMORY REQUIREMENTS (55000 OCTAL), AND ESTIMATED CENTRAL      *
COMMENT.* PROCESSOR TIME IN SECONDS (20). THE SECOND CARD IDENTIFIES    *
COMMENT.* THE ACCOUNT AND PASSWORD.                                     *
COMMENT.*****************************************************************
COMMENT.
ATTACH,BPR3D,ID=BPR3D.
ATTACH,BFF,ID=BFF.
ATTACH,BTRANS.
COMMENT.
COMMENT.*****************************************************************
COMMENT.* THE ABOVE CARDS ATTACH THE PRINTER PLOT ROUTINE, BPR3D, THE   *
COMMENT.* FREE FORM INPUT ROUTINE, BFF, AND THE LEAF TRANSPIRATION      *
COMMENT.* ROUTINE, BTRANS. THEY ARE ALL IN BINARY FORM,                 *
COMMENT.*****************************************************************
COMMENT.
LOAD,BTRANS,BPR3D,BFF.
EXECUTE.
COMMENT.
COMMENT.*****************************************************************
COMMENT.* THE ABOVE CARDS LOAD THE ROUTINES INTO MEMORY AND CAUSE       *
COMMENT.* CONTROL TO BE PASSED TO TRANS FOR EXECUTION.                  *
COMMENT.*****************************************************************
COMMENT.
*EOR
/                                                                       /
/ THE FOLLOWING TWO PLOTS ARE SIMILAR TO THE PLOTS FOUND IN             /
/ GATES (1968), ALTHOUGH THE UNITS USED THERE WERE CGS WHEREAS         /
/ HERE, WE USE MKS.  THE SECOND PLOT IS A DETAILED VIEW OF THE          /
/ FIRST PLOT.                                                           /
/                                                                       /
/ THE FOLLOWING DEFAULT VALUES ARE ASSUMED FOR EACH OF THE PLOTS        /
/ UNLESS OVERRIDDEN BY INPUT VARIABLES                                  /
/                                                                       /
/   VAR(1) = 4, VAR(2) = 7,                                             /
/   QA = 815.8F, TA = 40, RH = 0.5, RI = 0, D = 0.05, W = 0.05,         /
/   V = .000001, IPRINT = .F.,                                          /
/   VARMIN = 0,0.1, VARMAX = 1002,5,                                    /
/   ECHO = .T., FINIS = .F., NODFLT = .F.,                              /
/   NX = 60, NY = 45, ZMAP = 0,1,2,3,4,5,6,7,8,9                        /
/   XMIN = 0, XMAX = 0, YMIN = 0, YMAX = 0, ZMIN = 0, ZMAX = 0,         /
/   XRICH = 0.1, YRICH = 1E-6, DEFAULT = 0,                             /
/   DVPRNT = .F., AVE = .F., INT2D = .F.                                /
/                                                                       /
/                                                                       /
/********************************RUN 1**********************************/
/                                                                       /
/ THE FOLLOWING VALUES OVERRIDE THE DEFAULTS FOR THE FIRST RUN          /
/                                                                       /
    QA = 700, TA = 30, RH = 0.2, VARMAX = 600,6.1,
    XRICH = 0.5, YRICH = 2E-6,     $
/                                                                       /
/********************************RUN 2**********************************/
/                                                                       /
/ THE FOLLOWING VALUES OVERRIDE THE DEFAULTS FOR THE SECOND RUN         /
/                                                                       /
```

```
    IPRINT = .T.,
    QA = 700, TA = 30, RH = 0.2,
    VARMAX = 600,6.1,
    XRICH = 0.03, YRICH = 1E-6,
    XMIN = 27.3, XMAX = 33.3, YMIN = 4.296E-5, YMAX = 21E-5,  $
/                                                                    /
/*******************************STOP**********************************/
/                                                                    /
 FINIS = .T.,     $
*EOR
*EOF
```

```
PROGRAM -TRANS- READY FOR INPUT
      /                                                                      /
      / THE FOLLOWING TWO PLOTS ARE SIMILAR TO THE PLOTS FOUND IN            /
      / GATES (1968), ALTHOUGH THE UNITS USED THERE WERE CGS WHEREAS         /
      / HERE, WE USE MKS.  THE SECOND PLOT IS A DETAILED VIEW OF THE         /
      / FIRST PLOT.                                                          /
      /                                                                      /
      / THE FOLLOWING DEFAULT VALUES ARE ASSUMED FOR EACH OF THE PLOTS       /
      / UNLESS OVERRIDDEN BY INPUT VARIABLES                                 /
      /                                                                      /
      /   VAR(1) = 4, VAR(2) = 7,                                            /
      /   QA = 815.88, TA = 40, RH = 0.5, RL = 0, D = 0.05, W = 0.05,        /
      /   V = .000001, IPRINT = .F.,                                         /
      /   VARMIN = 0,0.1, VARMAX = 1002,5,                                   /
      /   ECHO = .T., FINTS = .F., NODFLT = .F.,                             /
      /   NX = 60, NY = 45, ZMAP = 0,1,2,3,4,5,6,7,8,9                       /
      /   XMIN = 0, XMAX = 0, YMIN = 0, YMAX = 0, ZMIN = 0, ZMAX = 0,        /
      /   XRICH = 0.1, YRICH = 1E-6, DFAULT = 0,                             /
      /   OVPRNT = .F., AVE = .F., INT2D = .F.                               /
      /                                                                      /
      /                                                                      /
      /**********************************RUN 1*********************************/
      /                                                                      /
      / THE FOLLOWING VALUES OVERRIDE THE DEFAULTS FOR THE FIRST RUN         /
      /                                                                      /
          QA = 700, TA = 30, RH = 0.2, VARMAX = 600,6.1,
          XRICH = 0.5, YRICH = 2E-6,    $
```

```
QA= 700.000, TA=  30.000, RH=    .200, D =    .050, W =    .050,
***** THE ABOVE PARAMETERS ARE HELD CONSTANT *****
LINES 1-4:RL=     0  200.00  400.00  600.00 V =    .10 TO   6.10
LINES 5-8:V =    .10    2.10    4.10    6.10 RL=     0 TO  600.00
```



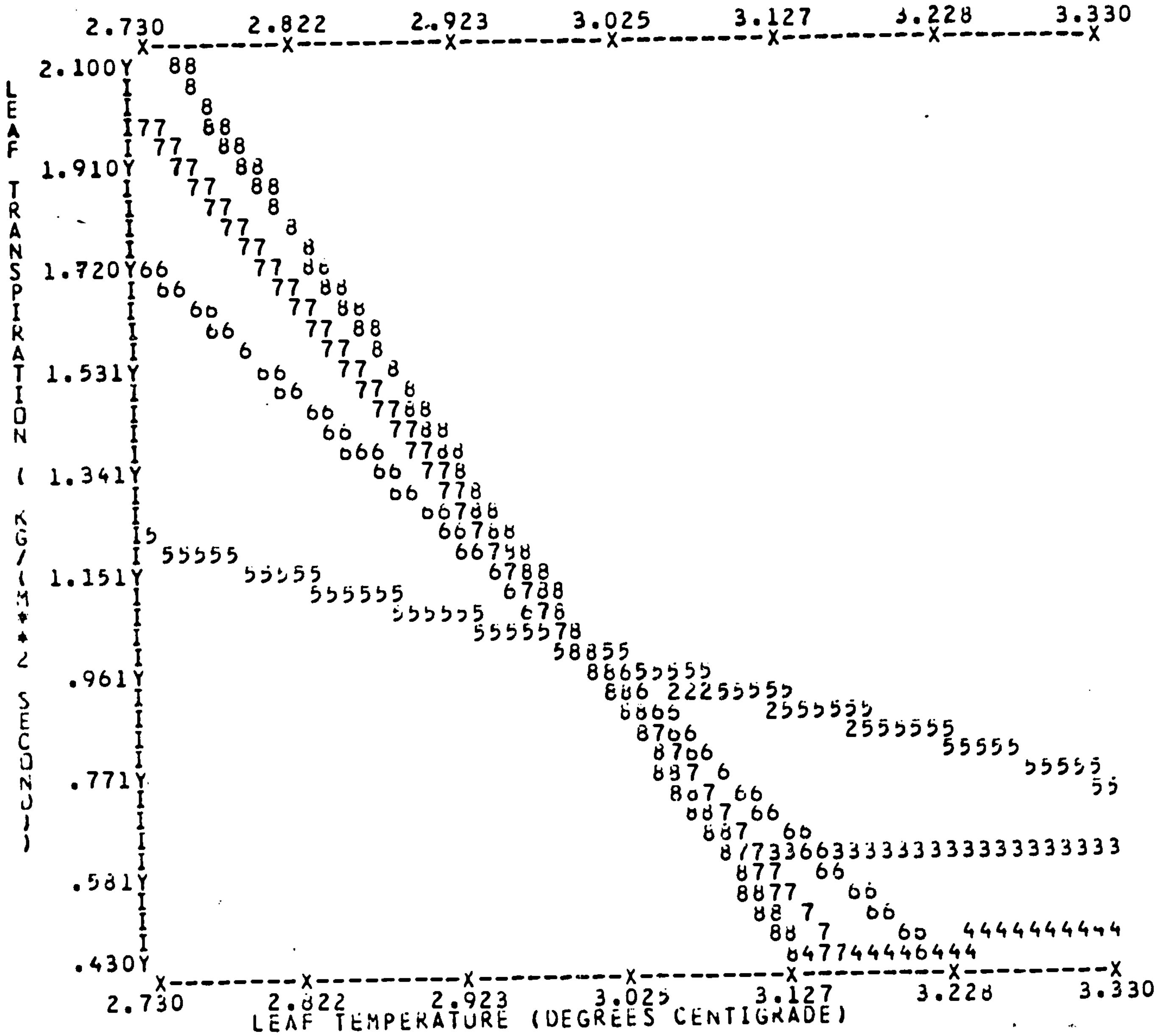

```
SCALE FACTORS = X-AXIS: E+01    Y-AXIS: E-04    Z-AXIS: E+00
Z0-Z4=      0(-9),  1.000(52),  2.000( 0),  3.000( 6),  4.000( 8)
Z5-Z9=  5.000(35),  6.000(51),  7.000(52),  8.000(81),  9.000( 0)
```

```
PROGRAM -TRANS- READY FOR INPUT
      /
      /********************************RUN 2*********************************
      /
      / THE FOLLOWING VALUES OVERRIDE THE DEFAULTS FOR THE SECOND RUN
      /
         IPRINT = .T.,
         QA = 700, TA = 30, RH = 0.2,
         VARMAX = 600,6.1,
         XRICH = 0.03, YRICH = 1E-6,
         XMIN = 27.3, XMAX = 33.3, YMIN = 4.296E-5, YMAX = 21E-5,  $
```

THE COMPLETE LIST OF THE CURRENT VALUES OF INPUT VARIABLES FOR TRANS

```
VAR     =          4,              7,
OA      =  .7000000E+03,
TA      =  .3000000E+02,
RH      =  .2000000E+00,
RL      =       0      ,
D       =  .5000000E-01,
W       =  .5000000E-01,
V       =  .1000000E-05,
VARMIN  =       0      ,  .1000000E+00,
VARMAX  =  .6000000E+03,  .6100000E+01,
ECHO    =  T,
FINIS   =  F,
NODFLT  =  F,
NX      =         60,
NY      =         45,
ZMAP    =          0,              1,              2,              3,
                   4,              5,              6,              7,
                   8,              9,
XMIN    =  .2730000E+02,
XMAX    =  .3330000E+02,
YMIN    =  .4296000E-04,
YMAX    =  .2100000E-03,
ZMIN    =       0      ,
ZMAX    =  .9000000E+01,
XRICH   =  .3000000E-01,
YRICH   =  .1000000E-05,
DFAULT  =       0      ,
OVPRNT  =  F,
AVE     =  F,
INT2D   =  F,
IPRINT  =  T,
$
```

QA= 700.000, TA= 30.000, RH= .200, D = .050, W = .050,
***** THE ABOVE PARAMETERS ARE HELD CONSTANT *****
LINES 1-4:RL= 0 200.00 400.00 600.00 V = .10 TO 6.10 .
LINES 5-8:V = .10 2.10 4.10 6.10 RL= 0 TO 600.00



SCALE FACTORS = X-AXIS: E+01 Y-AXIS: E-04 Z-AXIS: E+00
Z0-Z4= 0(-9), 1.000(0), 2.000(5), 3.000(20), 4.000(18)
Z5-Z9= 5.000(65), 6.000(59), 7.000(61), 8.000(73), 9.000(0)

```
ROGRAM -TRANS- READY FOR INPUT
     /
     /*******************************STOP************************************/
     /                                                                      /
      FINIS = .T.,
ROGRAM -TRANS- TERMINATED
R
```

References

Gates, D.M. 1968. "Transpiration and Leaf Temperature." Annual Review of Plant Physiology 19:211-238.

Gales, L.E. 1978. User's guide for subroutine PRNT3D. Center for Quantitative Science in Forestry, Fisheries, and Wildlife, University of Washington, Seattle, Washington.

Gales, L.E. and L. Anderson. 1978. User's guide for subroutine FFORM: a format free input system. Center for Quantitative Science in Forestry, Fisheries, and Wildlife, University of Washington, Seattle, Washington.