

Estimation of internal crop water status from meteorological and plant parameters

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Crop water status can be expressed directly in terms of the water potential of plant material or indirectly in terms of the partitioning of energy received by the crop. The water status of a crop must be evaluated to develop crop, soil, and water management techniques that can be applied to practical agroclimatological problems. Any estimate of crop water status should consider the plant response to environmental conditions and characterization of these conditions. Plant and meteorological parameters that can be evaluated in agronomic crops form a basis for arriving at estimates of the crop water status. Therefore, the objective of this paper will be to review some of the meteorological tools and techniques and to consider how they can be combined with certain plant parameters for arriving at estimates of crop water status. The emphasis will be on indirect expression of the water status rather than a detailed approach to measuring water relations of plant tissue. The review will include research using meteorological techniques, research using plant parameter measurements, and combinations of the two approaches. Some aspects of micrometeorological modelling will be discussed.

METEOROLOGICAL APPROACH

Meteorologists have used an approach for evaluating the water status of plant communities based on the balance of energy at plant and soil surfaces. The approach considers the radiation exchange at the earth's surface, and the airflow processes controlling the exchange of mass and momentum at the earth's surface. From the diurnal cycle of aerodynamic exchange processes and the energy balance, the source and sink intensity of latent heat flux, sensible heat flux, and photochemical energy flux have been assessed. The patterns of the flux components during the day illustrate the coupling between the meteorological elements and physiological functions of the plant.

Since the partitioning of the energy received by a crop depends on the water status of the crop, the evapotranspiration rate of a crop is an indirect measure of the crop water status. The measurement of evapotranspiration as a meteorological element has received considerable attention (for reviews see Jensen, 1966; Hagan *et al.*, 1967). Evapotranspiration is measured on several scales—from seasonal estimates based on empirical methods to short time periods by energy balance methods or precision lysimetry. Tanner (1967) discusses some of the measuring techniques and comments on the advantages of micrometeorological methods. When applicable, micrometeorological methods can measure evapotranspiration over very short time periods (a few minutes), can provide flux measurements of entities other than evapotranspiration (CO_2 , heat), and can provide additional information (temperature, humidity) that can be related to short-term physiological response.

Begg *et al.* (1964) studied the diurnal energy exchange as well as the relative plant water content, stomatal aperture, and photosynthetic activity of a crop of bulrush millet. The study included measurements of leaf area, total dry matter production, and soil water. The soil water level at the time of this study was approaching the wilting stage. The decrease in transpiration and the increase in sensible heat flux corresponded to stomatal closure during the middle of the day and demonstrated the coupling between climatic elements and plant response. As the radiation intensity decreased in the afternoon, transpiration actually increased as a result of additional energy being extracted from the air and increasing transpiration from lower layers in the crop. This study demonstrates the value of an integrated plant physiological-micrometeorological approach, and how this becomes more useful as a tool that can be used for prediction of responses than any of the observations would have been separately.

Brown and Covey (1966) used an energy balance approach to evaluate the fluxes of sensible heat and latent heat by layers in a fully grown corn crop. They found the transpiration rate of the crop to be related to three micrometeorological parameters, net radiation, saturation-water vapour pressure deficit of air, and a leaf-to-air transfer coefficient; and two plant parameters: leaf wetness and leaf area density. They defined a "leaf wetness" parameter as a "lumped" factor for the plant transpiration regulatory processes. This parameter is related, in a physiological sense, to the stomatal resistance to vapour loss and to the resistance of movement of water within the plant. The calculated values of the wetness parameter through the day agreed with the expected patterns of stomatal behaviour. No direct measurements of plant water status or stomatal aperture were made, but the water status of the crop was implied from the analysis of the energy balance measurements.

PLANT PARAMETERS

The types of plant parameters that can be used to evaluate the water status of a crop under field conditions have been referred to briefly, i.e., leaf area, leaf water potential, and stomatal aperture. Very little reference has been made to direct measurement of water status of the plant tissue in the field. A detailed review of the various techniques will not be made, since several recent works are available (Slatyer, 1967; Slatyer and Shmueli, 1967; Barrs, 1968).

The direct measurement of internal water status of crops growing in the field remains a difficult task. The development of thermocouple psychrometers capable of measuring the water potential of intact leaves in the field is still being perfected (Hoffman and Herkelrath, 1968; Rawlins *et al.*, 1968; Calissendorff and Gardner, 1969). Until the design problems are overcome, indirect measures of the water potential of the crop will still be used (Barrs, 1968).

Kramer (1969) contends that the only reliable method of evaluating plant water stress is by direct measurement on experimental plants. This is particularly important if we are to study the mechanisms of operation of water stress. However, the correlation between indirect measures of water status and the crop response can be useful in developing management practices for dealing with agroclimatic problems.

Certain plant responses have been implied from meteorological analyses. Shinn and Lemon (1968) evaluated plant water status directly in conjunction with measurement of evapotranspiration by meteorological techniques over a corn (*Zea mays*) field. The variation in leaf water potential at different heights in a corn crop was studied during a period of increasing soil water tension. The upper leaves exhibited a bimodal fluctuation in the water potential, whereas the lower leaves exhibited a more constant water potential

through the day. There was no evidence that evapotranspiration decreased, even though plants showed visible signs of wilting. A similar bimodal trend could be expected in stomatal closure. Since evapotranspiration for the crop was not bimodal, it was concluded (a) that stomatal closure was ineffective in reducing transpiration, or (b) that the transpiration decrease from the upper leaves due to stomatal closure was compensated by the evapotranspiration from the lower leaves where potentials apparently did not reach values to induce stomatal closure. Stomatal aperture was not measured in their study.

The work reported by Shinn and Lemon (1968) in corn is contrasted, in general, to the work reported by Begg *et al.* (1964). The latter work showed advective energy transport increased transpiration from the lower leaves, and also how stomata responded to a more negative water potential in the upper leaves to reduce transpiration. The results from the corn field, in a more humid area where advection was less likely, suggest that stomata were ineffective in reducing transpiration, if in fact, they did close at all in response to the more negative water potentials. The continued increase in transpiration suggests that stomata may be insensitive to decreases in water potential until some critical water potential is reached. If this is so, the critical water potential is likely to be different for different crop species. In the case of the bulrush millet, the stomatal closure indicated that the critical water potential in the upper leaves was reached. The issue is not settled since stomatal aperture was not measured in the corn field study.

Stomatal aperture has been implied as a plant parameter that can be used to evaluate the response of plants to changes in plant water status. Complete reviews of the mechanism of stomatal action are available (Heath, 1959; Ketellapper, 1963; Meidner and Mansfield, 1968; Zelitch, 1969). Based on these reviews, it can be concluded that the predominant environmental factors influencing stomatal behaviour are light intensity, CO₂ concentration of the air surrounding the leaf, leaf water status, and temperature. Separating the mechanisms by which each factor operates becomes very difficult because the influence of one factor often consists of interaction with another.

Slatyer (1969) concluded that the direct impedance of the CO₂ supply and the resulting increase in leaf temperature, upon stomatal closure, may be the primary mechanism by which water stress leads to reduce net photosynthesis under natural conditions. Assuming that stomata act as the first order influence on photosynthesis and transpiration, stomatal aperture can be used as a parameter for evaluating the crop water status.

Quantitative measurements of this plant parameter will, therefore, enhance the usefulness of various models involving the microclimate of the crop. The separation of light intensity and water potential effects on stomatal diffusion resistance is a logical step for evaluating the effect of water stress in various models.

The development of a porometer for field use has made possible more quantitative and rapid measurements of stomatal diffusion.

Subsequent field studies (Ehrler and Bavel, 1967; Turner, 1969; Burrows, 1969; Hurd, 1969) appear to substantiate the concept that, under most field conditions, light intensity and leaf water potential are the primary factors influencing stomatal movement. Hyperbolic relationships between stomatal resistance and light intensity have been developed under controlled conditions where water stress was unlikely (Gaastra, 1959; Kuiper, 1961; Ehrler and Bavel, 1968; Turner, 1969).

To consider the effects of decreasing water potential, the relationship of leaf resistance and leaf water potential must be known. The critical water potential concept as discussed by Slatyer (1967) and by Barrs (1968) should be evaluated in depth. The critical water potential is defined here as the water potential that the leaf tissue must reach before stomatal resistance begins to rise. Kanemasu and Tanner (1969) have examined this concept in snap beans (*Phaseolus vulgaris* L.) and found the critical water potential for the abaxial surface to be -11 bars and for the adaxial surface to be -8 bars. Ehlig and Gardner (1964) found stomata did not begin to close until leaf water potentials of -5 to -12 bars were obtained, depending on species. Dale (1961) found that the critical relative water content (RWC) of cotton was 85 per cent RWC, or about -12 bars. If one considers the diurnal change of leaf water potential, stomata may be viewed as an on-off switch for transpiration depending on the critical potential.

MODELLING APPROACH

The examples cited in this review show how meteorological techniques and measured plant parameters have been used to evaluate the partitioning of energy received by the crop and indirectly to evaluate the crop water status. One objective of this work is to be able to predict the crop water status and to use this prediction in application of soil and water management practices. To achieve this objective it is necessary to combine the approaches in some systematic way. The mathematical model tries to do this by fitting all the available information that can be described mathematically into a system of equations for simulation of processes in the plant community. Obviously all interactions are not known to the extent that they can easily be included in the model. Certain assumptions must be made until information from experimental work delineates the interactions.

Microclimate models are used to calculate the exchange of energy within and above the plant community and to calculate the vertical profiles of humidity, temperature, wind, and radiation in the canopy. Several models of this type, with variations as to the emphasis and assumptions, have been developed (Philip, 1964;

Denmead, 1964; Cowan, 1968; Waggoner and Reifsnnyder, 1968; Waggoner *et al.*, 1969). One of the main differences in the models has been the way the leaf properties have been included. Leaf resistance was first assumed to be uniform in the canopy (Philip, 1964) and then, as the response to light and the effectiveness of leaf wetness were demonstrated (Brown and Covey, 1966), the effects of changing the minimum resistance in the canopy were used in the simulation of the crop climate (Waggoner and Reifsnnyder, 1968). Cowan (1968) used a combination of the energy balance model for calculating fluxes and the momentum balance model for determining the ventilation characteristics of the canopy. He included a variable leaf resistance as an input to his model.

These models deal only with the exchange of sensible and latent heat, and further refinements are necessary for including photosynthesis and respiration of the plant community. One approach is to combine the microclimatic models with radiation models. Radiation models define the photosynthetically active light régime in the canopy and consider the direct and diffuse light, leaf angle distribution, light scattering and solar elevation (Wit, 1965; Duncan *et al.*, 1967).

A third type of model that is necessary for complete simulation is a model for leaf assimilation and respiration of CO_2 . Waggoner (1969a) describes such a model and includes the relationship of stomatal resistance to concentration of CO_2 inside the stomatal cavity and to light intensity. In another paper, Waggoner (1969b) summarizes how the photosynthesis-respiration models can be coupled with microclimatic models to act as a crop simulator and predict profiles of temperature, vapour pressure, and CO_2 .

The complete plant community models can be used to test the response of the plants to a variety of factors. In attempting to evaluate the water factor, the response of the plants to changes in water status must be included in these models. It must be reiterated that estimation of the internal crop water status from meteorological and plant parameters, as discussed thus far, is not designed to predict what the plant water potential might be under a certain set of conditions; but, rather, it is designed to predict certain plant processes that are an integration of all the factors that are interacting, including the internal crop water status. Such processes as evapotranspiration and photosynthesis of plant communities are used in this sense as indirect measures of the internal water status of the crop.

The next section of this paper will be concerned with relevant studies with which we have been closely associated. A plant community model will be used to simulate plant processes. Included in the model will be a submodel evaluating the stomatal response to changing plant water status. Results are compared with flux measurements determined by the energy balance method.

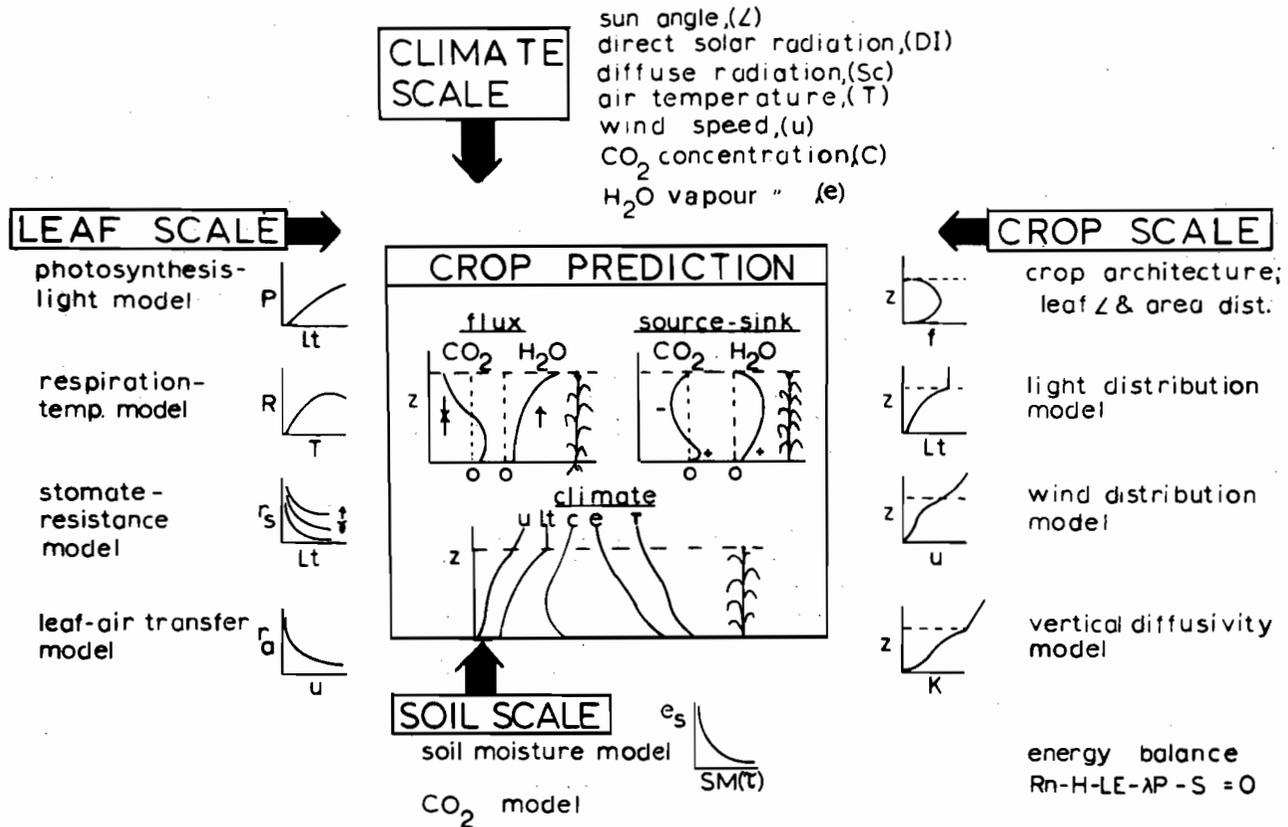


FIG. 1. Schematic representation of soil-plant-atmosphere model (SPAM) showing the sub-model inputs and predicted crop climate.

COMBINATION OF METEOROLOGICAL AND PLANT PARAMETERS

The plant community model (Stewart, 1970) and the stomatal-water stress model (Shawcroft, 1970) were developed and tested concurrently with energy balance measurements and other microclimatic measurements as part of the Microclimate Investigations Project at Ithaca, New York.

Stewart (1970) compiled a model that includes characteristics of all the models discussed. The soil-plant-atmosphere model (SPAM) is represented schematically in Figure 1. The model consists of a series of sub-models of the climate, crop, leaf, and soil scale. These are combined in a computer programme that, by means of numerical analysis and iterative techniques, calculates the climate in the crop, the flux of various components into or from the crop canopy, and the source-sink intensity of various components. The radiation model considers the leaf area density, leaf angle, solar angle, and light scattering in the canopy and is an improvement in that no extinction coefficients need

to be assumed for penetration of visible and net radiation. The model calculates the various crop climate elements using measured values at a reference height above the crop. The model was tested by comparison with measurements in the crop canopy. The calculated profiles of CO₂ and water vapour agreed quite closely with the measured profiles. The largest difference occurred near the ground where the calculated temperatures were as much as 0.5° lower than the measured temperatures. In Stewart's preliminary testing of the model, sensible heat flux was underestimated and latent heat flux was overestimated, when compared with similar components measured by the energy balance technique. The calculated values were sensitive to changes in stomatal resistance, and to temperature and vapour pressure at the immediate soil surface. The stomatal resistance-water stress sub-model was included as a means of simulating the effects of water stress.

Field data collected during 1967 and 1968 enabled the leaf resistance-light intensity relationships of Figure 2 to be constructed. The measured resistance values plotted in Figure 2 are from intact leaves at various positions in the canopy and at various times of the day

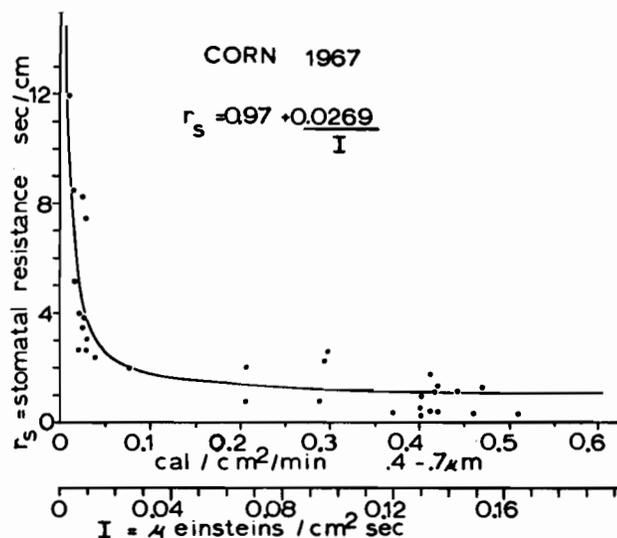


FIG. 2. Light intensity-stomatal resistance relationship for unthinned stand.

on cloud-free days. Relative water contents (RCW) of leaves on the same days were above 94 per cent.

A hyperbolic equation was fitted to the data points in order to obtain a mathematical expression of the relationship. The general equation for this relationship is:

$$r_s = \gamma_0 + \frac{\beta_0}{I} \quad (1)$$

where γ_0 and β_0 are constants having the units of sec/cm and $\mu\text{einsteins}/\text{cm}^2 \text{ sec}$ and I is the light flux density in $\mu\text{einsteins}/\text{cm}^2 \text{ sec}$. The values of γ_0 and β_0 , as determined from the regression analysis, were calculated to be 0.97 and 0.0269. The shape of the curve agrees well with similar measurements on beans by Kuiper (1961) and on corn by Turner (1969) and by Ehrler and Bavel (1968). The absolute values of the resistances and light at which resistance increases rapidly also compare well with the same points as reported in the work cited. The main feature of this relationship is that, over a large range of light intensity up to full sunlight, the leaf resistance changes very little. Assuming this same relationship holds for all active leaves in the canopy, light intensities at lower layers in the canopy would have to be at low levels to cause stomatal closure.

The relationship shown in Figure 2 was used to calculate the leaf resistances at lower depths in the canopy. The calculated values were slightly higher than the measured resistances. The light intensity value used was a mean value and it is likely the leaf was actually seeing some instantaneous value of higher intensity. This relationship (equation 1) is concluded to be a reasonable approximation of the response of stomata under field conditions to changes in light intensity and under conditions free from water deficits. It is subsequently to be used in the development of a model that includes the influence of water deficits.

From the field data, two generalizations can be made. Firstly, stomata of corn open in accordance with the well-known response to increasing light intensity in the morning hours. The aperture continues to increase until some maximum aperture is obtained. This maximum aperture (or minimum resistance) is related to the degree of water stress prevailing for any particular day, with the minimum resistance decreasing as stress decreases. Secondly, decreasing (more negative) water potential has little effect on stomata until some critical water potential is reached. Once this critical potential is reached, resistance values increase sharply, even though there is an improvement in the water balance of the plant. The overriding influence of the water potential over the light response can occur even under relatively adequate soil water conditions.

STOMATAL MODEL

Assuming no water stress conditions, the light intensity-leaf resistance relationship given in equation (1) can be considered as the "ideal" no-stress case. Consider γ_0 and β_0 constants for the ideal case. In order to have r_s remain finite at some very low light intensity, i.e. $I \rightarrow 0$, a minimum light intensity, I_0 , is introduced that corresponds to some maximum, finite resistance r_c . This resistance is taken to be constant and can be considered as the cuticular resistance or some maximum resistance when the stomata are closed. Expressing this similarly to equation (3) gives:

$$r_c = \gamma_0 + \frac{\beta_0}{I_0} \approx r_s \quad (2)$$

with r_c as a constant and γ_0 and β_0 as constants, I_0 can be calculated. From equation (1), the minimum r_s for the day, r_{min} , approaches γ_0 at high light intensities. Following the suggestion from experimental measurements, imposing a water stress condition will cause the minimum resistance, r_{min} , to increase. One can think of a family of curves of the general shape as the ideal case, but with changing γ as water stress increases. A schematic representation of this is given in Figure 3. Then for some stress condition, i.e. RWC decreasing:

$$r_c = \gamma + \frac{\beta_0}{I} \quad (3)$$

$$r_s = \gamma + \frac{\beta_0}{I + I_0} \quad (4)$$

Note that I_0 is added to I in equation (4) to maintain r_s at some finite value (r_c) when I becomes zero. The water stress influence is introduced by considering $\gamma = f(\text{water stress})$.

Stewart (1970) included equation (4) in the plant community model as a means of estimating the stomatal resistance at various levels in the canopy once the light flux densities at leaf surfaces of different leaf

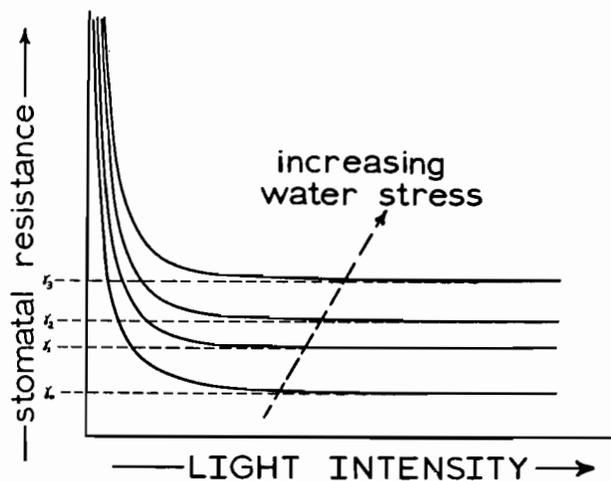


FIG. 3. Schematic representation of light intensity-water stress interaction on stomatal response.

angles were calculated. The model takes various reference parameters that are mean values measured over one-half-hour periods as inputs and calculates profiles and energy flux values for this half hour. In order to vary the stomatal resistance in the computer model, the value of γ for each half hour must be included as an input. The γ value can be approximated from the minimum stomatal resistance, since, from equation (1), r_{min} approaches γ at high light intensities. For example, r_{min} equals 1.08 sec/cm if I is taken at mid-day value of 0.23 $\mu\text{einstein}/\text{cm}^2 \text{ sec}$ with a γ of 0.97. The appropriate γ can be estimated from measured resistances. The γ value for any half-hour period sets limits on the minimum resistance value. The vertical distribution of the resistances in the canopy will be determined by the same light intensity-resistance relationship and will depend on the calculated light attenuation in the canopy. If several half-hour periods throughout the day are chosen for testing, the γ value may change according to the measured resistance values. For example, the ideal "no-stress" case would imply that the γ would be the same for all periods through the day and would be the minimum γ value, i.e. γ_0 .

PLANT COMMUNITY MODEL TESTING

The approach used for testing the model was to select, for a given day, five half-hour periods beginning at 08.00, 10.00, 12.00, 14.00, and 16.00 hr. The reference input data for three periods were obtained from measurements in the field for corresponding time periods.

There is a need for an independent check of the model. The measurements necessary for applying the energy balance technique described by Lemon (1967) were made. A modification of this technique using the Bowen

ratio was used to determine the total flux from the canopy. The Bowen ratio, $B = k\Delta T/\Delta e$, (where k is the psychrometer constant and ΔT and Δe are the differences in temperature and absolute humidity over the same height interval), was determined by plotting measured values of T against e and taking the slope of this line. The slope of the T - e curve can be used to determine B above the crop, since the flux above the crop is constant and T and e are linearly correlated. Once the Bowen ratio is known, the total flux components can be calculated using the energy balance relationship and the assumption that the diffusivities of heat, water vapour, and CO_2 are equal (Fritschen, 1966). The energy balance flux values are used as a standard for comparison with the model.

The model is a system of equations that describes the turbulent transport of heat, momentum, and mass from some reference height above the crop surface to the individual leaf surfaces. There are two boundaries to the system (the reference height and the soil surface) and conditions at both boundaries must be known or defined. In this model, the soil surface is defined in terms of the heat flux into the soil, which is measured directly using heat flux plates near the surface, and the surface soil water tension, which can be estimated from soil water tension measurements at various depths in the soil. The model uses these two surface soil inputs to determine the effective vapour pressure at the soil surface and the soil temperature and, subsequently, the flux of latent and sensible heat from the soil surface. The difficulty of predicting a mean or effective surface soil water tension is apparent if the relationship between soil water tension and percentage soil water is examined. For the soil in Ellis Hollow, the soil water characteristic curves show that the soil water potential changes from -50 bars at 6 per cent water by volume to less than -10,000 bars at 3.5 per cent. The soil at the immediate surface was in the percentage range where the soil water tension changes drastically. The large soil water tensions used as inputs in the model should not be confused with the effective soil water tension in the root zone which will be in the range for plant growth.

Two surface soil water tensions were assumed as inputs to the model: -600 bars as the "wet" surface and -8,000 bars as the "dry" surface. The -600 bars tension results in a vapour pressure of 20.5 millibars at 25°C and 63.7 millibars at 45°C. The -8,000 bars tension corresponds to an extremely dry surface with vapour pressure values of 0.1 millibars at 25°C and 0.4 millibars at 45°C surface temperature. The surface soil in the experimental field contains over 50 per cent by volume of large flat stones. Although the -8,000 bars tension leads to low vapour pressure values, it is not unrealistic when the high percentage of the surface consisting of the dry, flat, stones is considered.

As a systematic approach to the testing the approximate minimum stomatal resistant ($\gamma \approx r_{min}$) was first assumed constant throughout the day. The results of

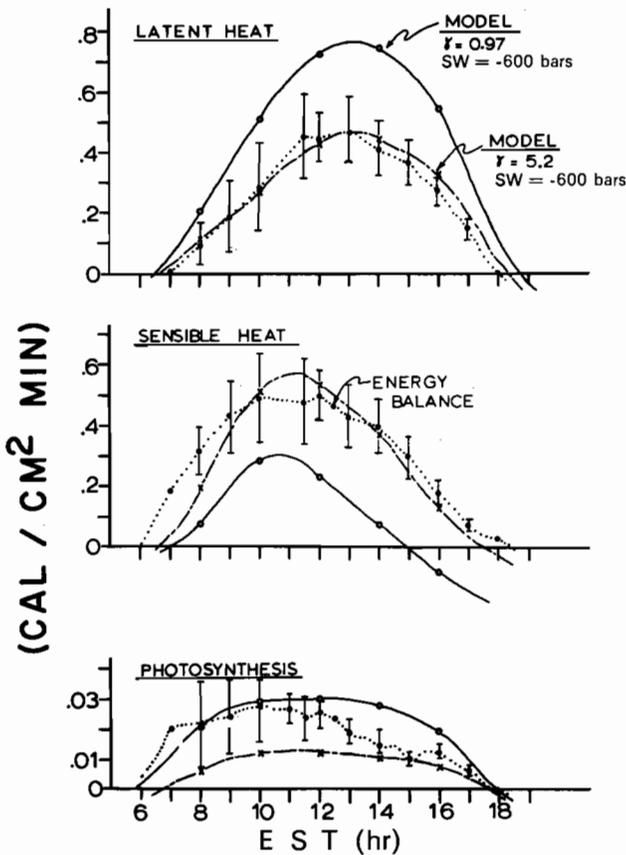


FIG. 4. Latent heat, sensible heat, and photochemical energy flux determined by the energy balance method and calculated by the model with two values of minimum stomatal resistance, $\gamma = 0.97$ and $\gamma = 5.2$, each taken as constant values through the day. Surface soil water tension (SW) held constant at -600 bars for each value of γ . (Corn, unthinned, 18 Aug. 1968.)

the model testing with $\gamma = 0.97$ sec/cm and with $\gamma = 5.2$ sec/cm are shown in Figure 4. The surface soil water potential (SW) was held constant at -600 bars. The latent heat, sensible heat, and photochemical energy flux calculated by the model were compared with the flux values determined by the energy balance technique.

The γ value of 0.97 sec/cm, taken at each hour through the day, simulates a condition where stomata are at their maximum opening throughout the day. With this condition the latent heat flux calculated by the model was much larger than the energy balance method, and the sensible heat flux was much less. The photochemical energy flux as determined by the energy balance method shows an increase in the morning hours, but declines sharply in the afternoon. The model, with $\gamma = 0.97$ sec/cm, calculates photosynthesis values that were close to the energy balance values in the morning, but overestimated photosynthesis in the afternoon. When γ was increased to 5.2 sec/cm, the latent and

sensible heat flux values calculated by the model agreed more closely with the energy balance method. However, the calculated photosynthesis with $\gamma = 5.2$ sec/cm was considerably below the energy balance value except at points late in the afternoon.

Although the calculated sensible heat and latent heat flux values with $\gamma = 5.2$ sec/cm agreed closely with the energy balance method, the energy balance photosynthesis indicated that stomata were open in the morning, corresponding more closely to the no-stress case of $\gamma = 0.97$ sec/cm. This suggested that some factor other than stomata was involved.

The surface soil water tension is another variable in the model. The results of changing the surface soil water tension are shown in Figure 5, where two soil water tensions were tested with $\gamma = 0.97$ sec/cm. The calculated flux values with $\gamma = 0.97$ sec/cm and $SW = -8,000$ bars were in closer agreement with the energy balance than with $\gamma = 0.97$ sec/cm and $SW = -600$ bars. There was still an overestimation of latent heat

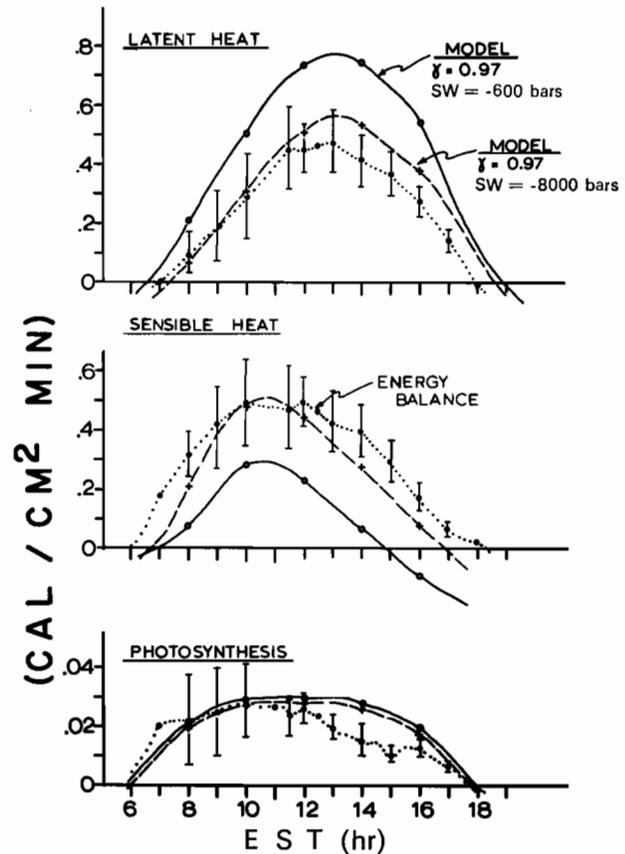


FIG. 5. Latent heat, sensible heat, and photochemical energy flux determined by the energy balance method and calculated by the model with two values of surface soil water tension (SW), -600 bars and $-8,000$ bars, each with a constant minimum stomatal resistance ($\gamma = 0.97$) through the day. (Corn, unthinned, 18 August 1968.)

TABLE 1. Total flux values obtained in a corn field, Ellis Hollow, New York, 18 August 1968. Values are cal/cm²/day, for the period between 07.00 and 19.00 hr. SW = surface soil water tension in bars. γ = approximate minimum stomatal resistance in sec/cm

	Model			Energy balance
	$\gamma=0.97$ SW = -600	$\gamma=5.2$ SW = -600	$\gamma=0.97$ SW = -8000	
Latent heat	340	196	227	182
Sensible heat	44	202	170	216
Photosynthesis	15	6	14	11

flux and photosynthesis and an underestimation of sensible heat flux by the model, as compared with the energy balance method in the afternoon hours. The results of the model testing with input parameters held constant through the day are summarized in Tables 1 and 2, where the integrated daily total flux values are shown.

Obviously there is some combination of stomatal resistance and surface soil water tension that predicts values close to those of the energy balance. There is no point in adjusting the two input parameters unless there is some criterion for evaluating their change during the day. Surface soil water tensions were the most difficult to evaluate, and the values used as input parameters are assumed values. However, the change of stomatal resistance has been measured, and the values of γ corresponding to measured resistances were used as inputs to the model along with an assumed value of surface soil water tension which was also taken to be constant throughout the day. An example of the results is shown in Figure 6.

The latent heat and sensible heat flux values are nearly identical in the morning. However the model

TABLE 2. Summary of total flux values as determined by model and energy balance techniques for period between 06.00 and 19.00 hr, 18 August 1968. Values are in units of cal/cm² day; γ determined from measured stomatal resistances

Net radiation above crop	421
Latent heat flux	
Energy balance	184
Model	142
Sensible heat flux	
Energy balance	216
Model	253
Photosynthesis	
Energy balance	11.2
Model	10.9

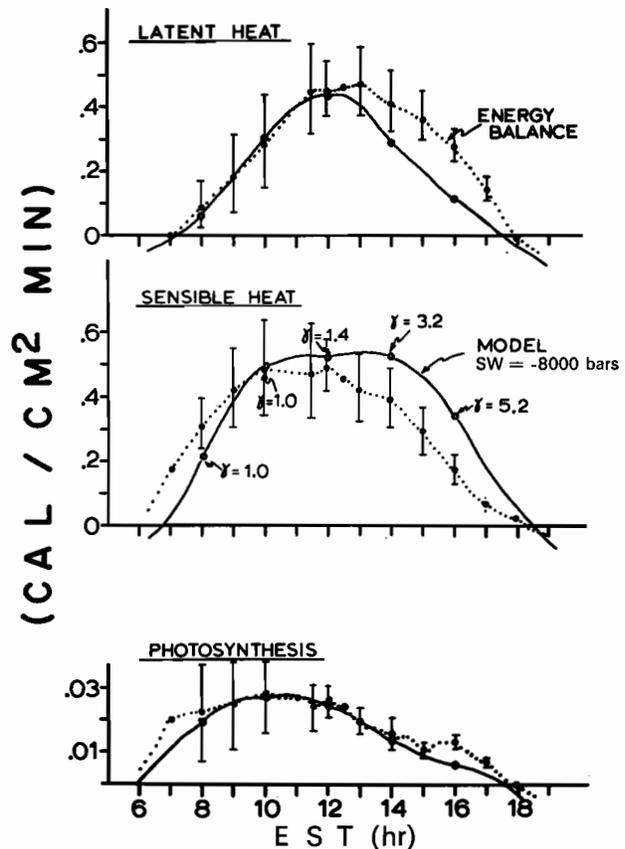


FIG. 6. Comparison of energy balance and calculated flux values using γ values determined from measured resistances. (Corn, unthinned, 18 August 1968.)

overpredicts sensible heat and underpredicts latent heat flux in the afternoon. Using a γ value determined from the measured resistances in the model had the general result of predicting more sensible heat flux and less latent heat flux than determined by the energy balance method. This general result indicated that the effective stomatal resistance might be less than determined by an average of several individual leaf measurements. A shift in the resistance values used in the model to a slightly lower value would result in calculated values in closer agreement with the energy balance method.

Diurnal change in effective surface soil water tension and effective surface vapour pressure may be more significant than changes in stomatal resistance in accounting for the differences between the model and the energy balance values. The effective surface water tension could change throughout the day as the soil dries. Even if the soil water tension does not change appreciably during the day, the effective vapour pressure will still increase as the surface temperature increases. The latent heat flux values calculated by the model are generally less than the energy balance values, suggesting that the actual, effective, surface

vapour pressure was higher than determined by the model from the assumed input values. A soil water tension intermediate between the -600 and $-8,000$ bars value would result in a calculated latent heat flux in closer agreement with the energy balance values. The calculated photosynthetic energy flux, using measured stomatal resistances, were in much closer agreement with the energy balance values than where the resistances were held constant through the day. The same result would be likely to occur using a variable surface soil water tension through the day.

CONCLUSIONS

Since the objective of this paper has been to estimate the crop water status from plant and meteorological parameters, we need to examine how the model has been used in meeting our objectives. The sub-model for stomatal response to water deficits was developed from field measurements of stomatal resistance and relative water content. These field measurements do not give direct information about other plant processes, i.e., photosynthesis and transpiration. The energy balance method evaluates the meteorology of the crop, and shows how the energy received by the crop is being utilized. Certainly some simple correlations between a few parameters can be made, but as more parameters are measured and the interactions observed, the information gained from these correlations becomes difficult to interpret. The model is useful because it simulated the plant response to a variety of input parameters. The reasonable agreement between the model and the energy balance lends credence to the correctness of the sub-models, and makes the sub-models, by themselves, more useful as tools for predicting the crop water status. For example, if the model calculates a low photosynthesis, low latent heat flux, and high sensible heat

flux, when the reference level meteorological data for a given time period and a certain stomatal resistance are used as inputs, it would suggest that the leaf water potential had reached the critical point for inducing stomatal closure.

Evaluating the stomatal resistance of the crop will give an indication as to the water status of the crop. However, the probability that stomata do not begin to close until some critical water potential is reached makes the use of stomatal resistance as the sole measure of water status questionable unless the critical water potential for different crops has been determined. The basic relationships between stomatal resistance and the critical water potential need to be examined in greater detail and for more crop species. The question of changing sensitivity of stomata within a single species as a result of alternate dry and wet periods also becomes important if the information is to be used to plan practical management techniques.

The modelling approach has been discussed as an example of how the plant parameters and meteorological parameters can be combined in a systematic way to evaluate the plant response to a change of a large number of factors simultaneously. The model can be manipulated to arrive at "answers", but this is a dangerous procedure. The value of the exercise lies in the fact that it forces us to systematize our approach and helps identify areas where more precise information is needed. For example, the model showed the need for more information on the effective vapour pressure and effective water tension at the soil surface. The model evaluates the crop water status in terms of the over-all plant processes of photosynthesis, latent heat flux, and sensible heat flux, rather than a direct assessment of the plant water potential.

The models will be refined to include additional factors. There is still a need for precise measurement of the plant and meteorological parameters to test and improve the models.

Résumé

Estimation de l'état hydrique interne des plantes cultivées d'après les paramètres météorologiques et végétaux (R. W. Shawcroft, E. R. Lemon et D. W. Stewart)

L'état hydrique des plantes cultivées peut être estimé indirectement en mesurant la répartition de l'énergie reçue par une culture au moyen de techniques météorologiques et aussi en mesurant certains paramètres végétaux comme le potentiel hydrique foliaire, la teneur hydrique relative et l'ouverture stomatale. L'auteur examine un moyen permettant de combiner ces deux techniques à l'aide d'un modèle de communauté végétale. Un modèle simplifié de réaction stomatale aux

déficits en eau sert à introduire des données dans le modèle plus grand pour le calcul du flux d'énergie sensible, latente et photochimique de la culture. Le modèle stomatal a été mis au point à partir de mesures de la résistance stomatale et de la teneur hydrique relative effectuées dans un champ de Maïs (*Zea mays*). Les essais de ce modèle en utilisant des résistances mesurées comme entrées ont donné un accord étroit entre les composants calculés et les composants mesurés du bilan énergétique. La combinaison des paramètres météorologiques et végétaux en un modèle a l'avantage de systématiser l'étude et elle précise les secteurs où il faudrait davantage d'informations de base.

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