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THE SOIL—PLANT—ATMOSPHERE MODEL AND SOME OF ITS PREDICTIONS*

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ABSTRACT

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A general description of the soil—plant—atmosphere model (SPAM) is given. Emphasis is made as to the logical sequence of the operation of the model by use of various submodels depicting the soil, plant, and climatic interactions. Examples of the testing of the model are discussed. Some simulation studies are given to show how the model can be used in setting priorities on those variables that have the greatest influence on plant responses.

INTRODUCTION

A search for an understanding of the basic relationships between plants and their environment has kept man occupied for centuries. Man has learned to use his knowledge of these basic relationships to his advantage for increasing crop production. As the supply of resources becomes limiting he must begin to measure output against input and seek ways to optimize this efficiency ratio without sacrificing the total amount produced. The basic premise of this symposium is that we can modify plants and plant communities to reduce wasteful use of water while retaining acceptable levels of production. The acceptance of this premise implies that we know how the soil—plant—atmosphere system works. Although much is known about the operation of this system, the search for greater understanding of this system continues.

The role of modeling in this search is an attempt to bring all factors involved in the system together in order that we may simulate various cause

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and effect relationships. The rate at which experiments could be conducted would be increased. This, of course, assumes that the models constructed for this purpose are correct.

In a previous symposium sponsored by the Great Plains Agricultural Council, Lemon (1969) outlined some ways of manipulating the soil—plant—atmosphere continuum (SPAC) for more efficient use of resources. Three broad areas of research effort were suggested: (1) physiology and genetics, or the search for ways of increasing the inherent photosynthetic efficiency of plants; (2) structural, or changing the plant canopy architecture and the soil environment to help minimize the effects of stresses and to maximize photoenergy conversion relative to latent heat conversion; and (3) to understand the whole SPAC as a system in order to manage as well as predict output from input.

The soil—plant—atmosphere model (SPAM) is basically geared to point (3) above. The need for models does not have to be emphasized, but the scope or scale of models does need clarification as more models are developed. There are various types of models that are geared to the prediction of a single factor over a wide area. Several models of this type for predicting *ET* were discussed in the Great Plains Agricultural Council Publication No.50 (Anonymous, 1970). There are also the so-called growth models that predict the growth of a particular crop. Recent examples are reported by DeWit et al. (1970) and Baker et al. (1972). Still another type of model deals with basic plant and environmental interactions on a short term basis. It is in this latter area that SPAM fits.

Models of this scope have treated plants and plant communities as energy exchange systems. A quantitative understanding of the energy exchange processes in plant communities is important in the study of large-scale meteorological processes as well as local climate. The major plant processes are solar-energy driven. Generally, the largest share of the energy used is in latent heat conversion or evaporation, but the relative amounts of energy partitioned into various forms depends largely on the water supply.

The common practice in earlier modeling was to model separate components of the energy exchange system. Examples are the various models for the evaporation from soil and plant surfaces (Penman, 1948; Van Bavel, 1966; Tanner and Fuchs, 1968). Various models have treated the latent and sensible heat exchange in plant canopies (Philip, 1964; Denmead, 1964; Cowan, 1968; Waggoner and Reifsnyder, 1968). Models of the photosynthetic component of the energy balance have also been developed (DeWit, 1965; Duncan et al., 1967). One approach to building a complete model would be to combine the latent and sensible heat flux models with the photosynthesis models. In treating all components as energy exchange systems an aerodynamic term for the carbon dioxide exchange must be included (Lemon, 1967). In addition, models of assimilation, transpiration, and respiration on the scale of individual leaves must also be considered if a comprehensive model of plant community and environmental interactions is to be constructed.

Waggoner (1969a) described such a model and showed how this model could be combined with energy exchange models for simulating the microclimate of a crop and responses of the crop to environmental manipulation (Waggoner, 1969b).

Stewart (1970) compiled a model that included characteristics of all the models discussed. It takes advantage of computer simulation and numerical analysis techniques where a tremendous number of interaction calculations and iterations are made. Stewart's model had an advantage over other models in that the building of the model was carried out in conjunction with extensive field measurements for testing the model. A look at the model, its nature, capabilities, testing, and its predictions follow.

THE SOIL—PLANT—ATMOSPHERE MODEL (SPAM)

The details of the model development are given by Stewart and Lemon (1969) and Stewart (1970). Several individuals were involved in testing the model and using it to simulate plant responses (Shawcroft, 1970, 1971; Lemon et al., 1971, 1973; Allen et al., 1971). The following discussion includes the logical sequence of SPAM and includes its predictions, boundary conditions and submodels. The logical sequence is: (1) to define the response of leaf and soil surfaces to a given microclimate; (2) to calculate the immediate microclimate of the leaf and soil surfaces from the gross meteorological boundary conditions; (3) to calculate the specific response of leaf and soil surfaces to this immediate microclimate; and (4) to sum this response from the soil surface to the top of the crop, layer by layer to obtain the response for the whole crop. The essential components and predictions of the model are shown in Fig.1, and the logical sequence of the model is shown in Fig.2 as a flow diagram.

To emphasize what SPAM can and cannot do, we discuss the predictions first. These are depicted in the box in Fig.1. The lower portion of the box shows how the microclimate in the crop community has been calculated based on the defined response characteristics of the crop and the external climatic conditions. The microclimate of the crop is shown here as profiles of wind, light or radiation, carbon dioxide, water vapor, and temperature. This defines how the concentration and intensity of these components change within the crop canopy. These profiles in effect define the climate at leaf surfaces at any particular level in the canopy. The time scale depicted here is important. The profiles shown here are the steady-state, mean values for a period on the order of one hour, and are typical examples for a corn crop at midday. As shown in the flow diagram (Fig.2), SPAM calculates new profiles for successive periods as new boundary conditions are defined.

From this calculated microclimate and the plant response submodels, the activity of the crop is predicted. The predictions are shown in the upper box of Fig.1 as the source or sink intensities at any plane in the canopy or the vertical flux or flow density across any horizontal plane. The flux density

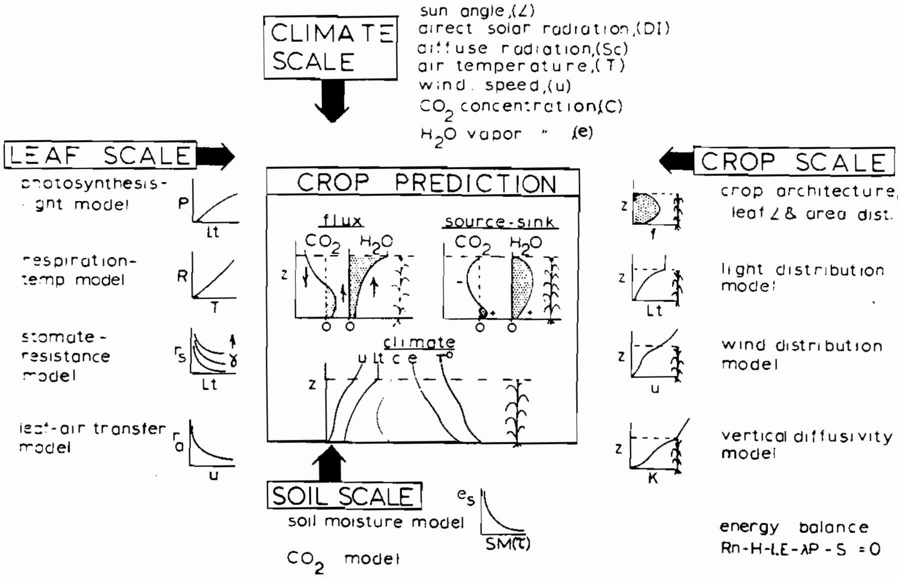

Fig. 1. Schematic summary of a mathematical soil—plant—atmosphere model (SPAM) giving required inputs, submodels, and representative daytime predictions of climate and community activity (that is, water vapor and carbon dioxide exchange). Abbreviations: height (z), wind (u), light (Lt), concentration of carbon dioxide (C), water vapor (e), air temperature (T°), surface vapor pressure (e_s), surface soil moisture or water potential $SM(\tau)$, photosynthesis (P), respiration (R), leaf temperature (T), stomate resistance (r_s), minimum stomate resistance at high light intensities (γ), gas diffusion resistance (r_a), leaf surface area (f), vertical diffusivity (K), net radiation (R_n), sensible heat (H), latent heat (LE), photochemical energy equivalent (P), and soil heat storage (S).

and source and sink intensity for carbon dioxide and water vapor are shown. The same intensities of radiation, latent, sensible and photochemical energy, and momentum can also be depicted in this manner. The water vapor flux density expressed as units/time/ground-area increases steadily from the soil surface to the top of the crop. The carbon dioxide flux is downward from the atmosphere to actively photosynthesizing leaves and upward from respiring soil and lower leaves. A positive source intensity shown for water vapor shows the position in the canopy of the most intense transpiration, and similarly a negative sink intensity shows the most intense absorption of carbon dioxide. The source and sink intensities are in units/time/volume. Both flux and source-sink intensities are mean, steady-state values for a time scale of one hour.

The prediction of other entities can also be calculated from the basic outputs just described. For example, the short-term water-use efficiency defined as the ratio of the photochemical energy flux to the latent heat flux (or grams CO_2 fixed per unit evapotranspiration) can be calculated. Because of its time scale SPAM provides an instantaneous water-use efficiency and can be used to test the feasibility or sensitivity of changes in individual factors on

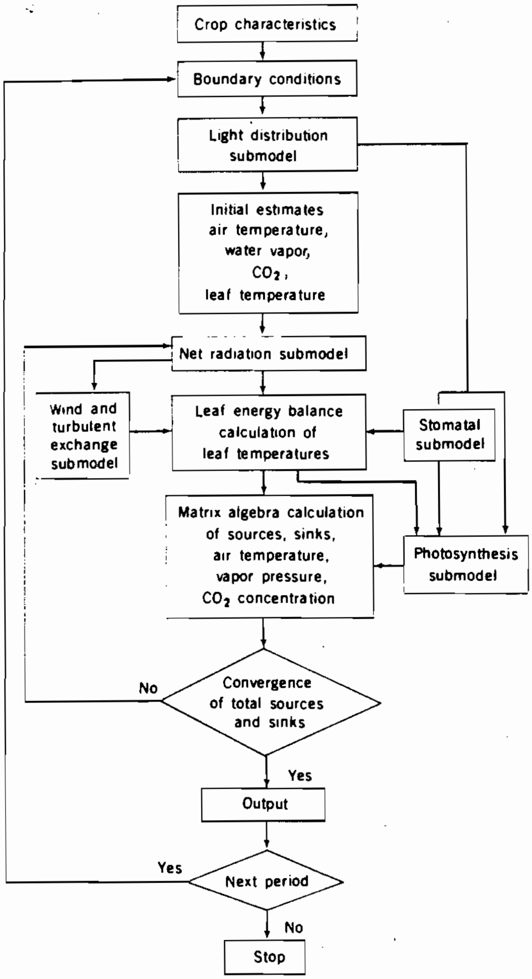

Fig.2. The general procedure of SPAM, given as a flow diagram.

water-use efficiency. Some factors that could be tested are leaf area index, leaf angle distribution, photosynthetic response to leaves, or changes in the stomatal response with stress. SPAM should be considered more as a tool for testing the sensitivity of certain factors as opposed to a model for predicting growth or yield. It could be considered a submodel for a larger growth or yield model.

Certain basic assumptions in some of the submodels place limitations on the types of systems to which SPAM can be applied. It cannot be applied indiscriminately to all systems, but is limited to steady-state or slowly changing conditions for systems that are relatively simple and uniform in structure and free from horizontal variation in climate. These limiting conditions are approached by large, dense agricultural crops and forests and on clear and cloudy days. SPAM becomes difficult to apply to small areas where horizontal advections might occur or under conditions of intermittent clouds or at sunrise and sunset where conditions are changing rapidly.

In terms of actual programming techniques the translation of SPAM from "fortran to english" or vice versa requires an extensive report in itself and is not attempted here. The flow diagram in Fig.2 shows the basic logic of the actual calculations. The interdependence of the solution of one set of equations on the solution of another makes the use of successive approximations and iterations necessary for simultaneous solutions. The final answers are a result of the convergence of the solutions. Assemblying SPAM could not have been possible without a large, high-speed computer, and both the programming and the theory have required intensive effort.

We have shown what SPAM does, and in order to understand how this is done we must look at the inputs, namely, the boundary conditions and the leaf and crop submodels and how these are tied together as an energy balance system. The lower boundary is the soil surface. Important considerations here are the exchange of heat, carbon dioxide, and water vapor. The submodel for determining the apparent surface vapor pressure from the soil temperature and the apparent surface soil water potential is important in determining the evaporation from the soil. As will be shown later, the testing of the model showed that the exact definition of the apparent soil surface properties is most difficult.

The above-crop boundary conditions are depicted in Fig.1 as the gross external climate within the boundary layer for a field. For most agricultural crops this is from 1 to 4 m above the crop. The above-crop wind speed, temperature, radiation, and CO_2 and water vapor concentrations define this boundary. The geophysical parameters of solar time and latitude are used in calculating the sun angle and azimuth.

The leaf submodels depicted in Fig.1 are in four basic areas: (1) the photosynthetic response to changing light intensity; (2) the relationship of respiration to temperature; (3) stomatal response to light and water stress; and (4) the leaf-to-air transfer resistance in relation to the air movement around the leaf. Details of submodels (1) and (2) are given by Stewart and Lemon (1969). Submodel (1) is basically a modification of models of the photosynthetic response to light developed by Lake (1967) and Chartier (1970). These models were modified to include a variable stomatal resistance. The respiration-temperature relationship similar to Waggoner (1969) was also incorporated. The net photosynthesis submodel becomes a function of light, CO_2 concentration, and temperature.

The leaf to air transfer or the leaf boundary layer resistance was determined by using the heat transfer equations for a flat plate. Stewart (1970) used the Polhausen similarity solutions for a two-dimensional flat plate (Gebhart, 1961), and concluded from experiments in a wind tunnel with natural leaves and from the degree of natural turbulence under field conditions, that the leaf boundary layer resistances, (r_a, for two surfaces) can be determined as a function of the wind speed at the height of any particular leaf and as a function of a leaf width factor:

$$r_a = h(L/u)^{1/2} \tag{1}$$

where L is leaf width, u is wind velocity, and h is the slope of the line with r_a plotted against $(L/u)^{1/2}$. The h value used in SPAM to simulate field conditions was 0.6 sec$^{1/2}$/cm. The value of h for heat transfer from two sides of a flat plate in a nonturbulent wind tunnel is 0.6. An h value for a leaf in a bluff body position in a wind tunnel without induced turbulence was 2.3 times larger than 0.6, and approached the value for a flat plate in streamline position. Parlange et al. (1971) found that turbulence enhanced leaf-to-air transport by about 2.5 times. Pearman et al. (1972) using metal plates under natural turbulence found the heat transfer coefficient for turbulent flow to be from 1 to 3 times greater than that theoretically predicted for laminar flow. Monteith (1965) summarized several sources of data and concluded that h = 0.65 would be representative of leaves in open air. The choice of an h value of 0.6 is in basic agreement with other values reported for conditions of natural turbulence.

The submodel for the stomatal response to light and water stress will be explained in more detail since examples of simulations with changing stomatal resistances are discussed in the next section of the paper. The stomatal submodel is shown in Fig.1 as a family of hyperbolic curves showing the change in stomatal resistance as light intensity increases. The model is described in detail by Shawcroft (1970, 1971). The hyperbolic relationship is based on stomatal resistance and light intensity measurements made in a corn crop under conditions free from water stress. These measurements are shown in Fig.3, with a hyperbolic equation fit to the data of the form:

$$r_s = \gamma_0 + (\beta_0 / I) \tag{2}$$

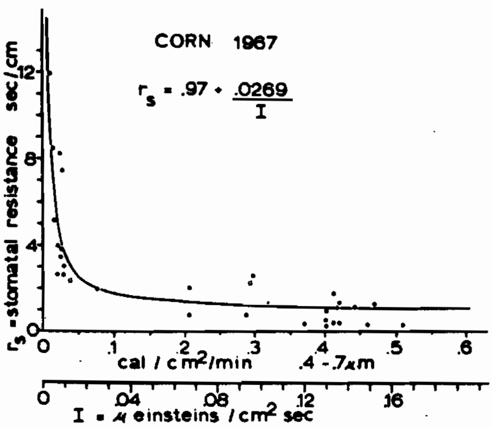

Fig.3. Light intensity—stomatal resistance relationship for corn leaves under low water stress conditions.

where r_s is stomatal resistance in sec/cm, γ_0 and β_0 are constants, and I is the incident light intensity (expressed as the visible radiation in terms of the photon response and has units of μE cm^{-2} sec^{-1}). This hyperbolic curve is similar to the stomatal response of beans reported by Kuiper (1961) and on corn reported by Turner (1969) and by Ehrler and Van Bavel (1968). The γ_0 in eq.2 can be considered as some minimum stomatal resistance at high light intensity. From field measurements of the stomatal resistance—light intensity relationship on days with varying degrees of water stress (the degree of water stress was determined by leaf relative water content measurements) it was observed that the minimum stomatal resistance increased as the degree of water stress increased. This generalization led to the family of hyperbolic curves with γ increasing as water stress increases. The equation as used in SPAM was generalized as:

$$r_s = \gamma + [\beta_0/(I + I_0)] \tag{3}$$

where γ is some minimum resistance at high light intensity and a function of water stress; I_0 is a minimum light intensity that corresponds to some maximum, finite resistance, r_c. This maximum finite resistance can be considered the cuticular resistance. Note that I_0 is added to I in eq.3 to maintain r_s at some finite value r_c when I approaches zero. As the incident light intensity at the leaf surfaces is determined from a light penetration submodel, the stomatal resistance profile is determined from eq.3 with γ entered as some known input factor related to water stress.

It must be emphasized that gamma is an empirical innovation to describe a complex biological process, and should not be construed as the exact relationship. The lack of a quantitative expression of the complex, feedback, response of stomata is a major weakness in SPAM. Stomata regulate the partitioning of the components of the energy balance system, and more exact linkage of this biological system to the physical processes of energy exchange must be sought.

The crop scale submodels are shown on the right in Fig.1. Four basic submodels that are related to the crop canopy architecture are involved: (1) the leaf angle and leaf area distribution; (2) the light distribution within the canopy; (3) the wind distribution; and (4) the vertical diffusivity of turbulence. Detailed measurements of leaf surface area and the distribution of leaf area with height and with angle are necessary inputs to SPAM. At present, the submodels assume a random azimuthal distribution, but modifications may be necessary in view of recent work by Lemeur (1973) who showed that azimuthal distribution of leaves may not be random. The assumption of random distribution limits the application of SPAM to stands free from clumping and gaps in the vegetative structure.

The light penetration submodel developed by Stewart (1970) was patterned after those of Duncan et al. (1967) and DeWit (1965). The light penetration model is extended to include the visible and infrared portions of the solar spectrum. The thermal radiation portion is determined as a function of leaf temperature. These are combined to find the net absorbed radiation for each leaf layer. The light penetration model accounts for direct and diffuse radiation as well as the radiation that is unabsorbed and scattered. The unabsorbed radiation is redistributed as diffuse radiation by successive iterations. The light and radiation penetration submodel is extremely important since several of the other models use the incident light as a major variable in the calculation of other components.

The transport equations for heat, water vapor, and CO_2 are written as a gradient times an eddy diffusion coefficient. The distribution of this eddy diffusion coefficient with height in the canopy is needed to calculate the flux densities at each layer. Wind speed above the crop is determined from the method of Swinbank (1964) based on aerodynamic roughness of the crop and energy balance components. Wind speed profiles in the canopy are determined by the method of Perrier (1967) which is based on the wind drag on plant surfaces from the top of the canopy downward. These horizontal windspeeds are used to calculate the boundary layer resistance (leaf to air transfer model) and to calculate the vertical diffusivity coefficients using a relationship between wind speed in the canopy and the diffusivity coefficient described by Cowan (1968).

On the lower right side of Fig.1 is the energy balance equation which relates the net radiation R_n absorbed by a surface into its components of sensible heat H, latent heat LE, photochemical energy equivalent P, and soil heat storage S. This equation summarizes all the models discussed. The complete system, layer by layer or the crop as a whole, must obey the energy balance equation.

MODEL TESTING AND SIMULATION STUDIES

Profiles

To be useful, the model must be tested against accurate experimental measurements of similar values generated by the model. Detailed energy balance measurements in a 10-ha (25-acre) corn field were made. The corn was planted in a hexagonal array to meet the requirements of uniform distribution of plants. Profiles of CO_2, water vapor, temperature, wind speed, and radiation were measured, and flux and diffusivity values calculated from the profile data. In addition, individual leaves were measured for inputs to the photosynthesis submodel and the stomatal response. Crop structural parameters were also measured. Profiles calculated by SPAM (solid and dotted lines) are compared to measured profiles (dashed line drawn through data points) in Fig.4. All data are mean values for a half-hour period spanning noon. Looking at the calculated (solid) line versus the measured (dashed), SPAM underestimated the temperature within the stand by about 0.5°C, and overestimated water vapor by about 0.5 g m^{-3}. The calculated wind and

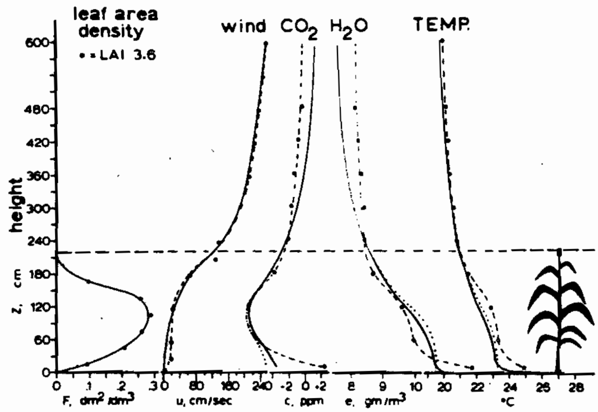

Fig.4. Measured (circles and dashed lines) and predicted (solid and dotted lines) profiles of climate factors in and above a cornfield, with the field's vertical leaf area density shown. Profiles are half-hour mean values. (18 August, 1968; 11h45 to 12h15, E.S.T.)

CO_2 profiles are nearly identical with the measured profiles except near the soil surface. The spread between the calculated and measured profiles leads to consideration of the applicability of dynamic theory for turbulent flow in a porous and flexible canopy. This theory is suspect in this case because the measured wind profile is nearly constant in the densest part of the canopy, indicating an absence of wind drag on the vegetation in the lower half of the canopy. This seems to be impossible and suggests added air flow in the canopy. The measured wind data was entered into SPAM, and the profiles recalculated to see if the real wind speed values could explain some of the differences in the profiles. The new calculated profiles shown as dotted lines in Fig.4, show that changes in CO_2, water vapor, and temperature profiles are very small. More detailed discussion concerning the differences in the calculated profiles and the question of vertical mass flow in the canopy as opposed to simple diffusion is given by Lemon et al. (1971). Despite these questions, the outcome of the predictions are adequate for a uniform agricultural crop and for relating the climate in the stand to biological activity.

Stomatal resistance and surface soil water potential

A more rigorous test of SPAM might be to compare the fluxes from the entire stand as well as the sensitivity of SPAM to changes suggested by the submodels.

The submodels for stomatal response and the soil surface boundary layer were discussed earlier and suggested as the weakest in theory. A test to see just how sensitive SPAM is to these submodels was conducted. The first test was to vary the minimum stomatal resistance with the apparent surface soil water potential held constant. The results of this test are shown in Fig.5. The total flux of latent, sensible, and photochemical energy using input data for August 18, 1968 is shown. The measured energy balance values are shown as the dotted line with bars showing the probable error in the flux values. The apparent soil surface water potential was held fixed at −600 bar. (More

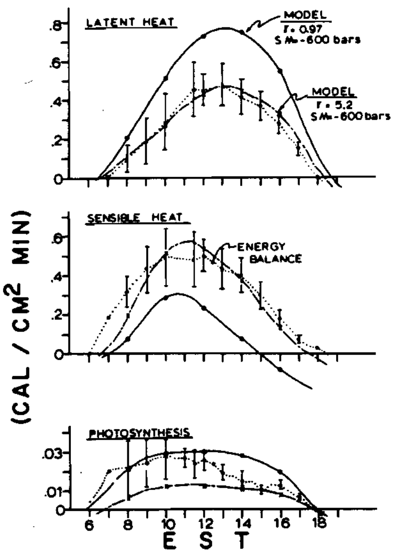

Fig.5. Predicted (solid and dashed lines) and measured (dotted lines) energy fluxes from a cornfield during a clear summer day, 18 August, 1968, with fixed constant soil surface moisture, $SM = -600$ bar (wet), and two constant minimum stomatal resistances, $\gamma = 0.97$ and 5.2 sec/cm. (Length of bar denotes margin of error.)

discussion about the surface soil water potential is given later.) With a γ = 0.97 sec cm^{-1}, which simulates a condition of wide open stomata throughout the day, the calculated latent heat flux was considerably higher than the measured, and similarly, sensible heat flux was lower. The calculated photosynthesis was very close to the energy balance values in the morning but overestimated in the afternoon. Subsequent tests with a γ = 5.2 sec cm^{-1}, which simulates a condition of partial stomatal closure, gave latent heat and sensible heat flux values much closer to the energy balance values. The calculated photosynthesis is reversed from the previous test in that it is now underestimated in the morning and closer to the measured values in the afternoon.

The second test was conducted to test the sensitivity of changing the apparent surface soil water potential (*SM*). The results are shown in Fig.6 with a fixed stomatal aperture and two values of soil water potential (*SM*) of −600 and −8,000 bar. A note of explanation for these soil water potential values is in order. These high (more negative) potentials are for the immediate soil surface and should not be confused with potential values measured in the root zone at some depth below the surface. The *SM* value is used in SPAM to calculate the apparent surface soil vapor pressure from the equation:

$$e = e_s(T_s) \exp (SM/R_v T_s) \tag{4}$$

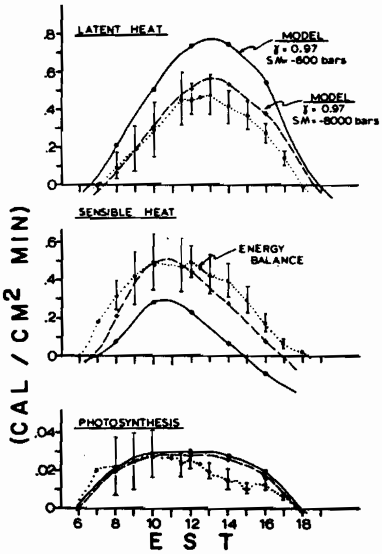

Fig.6. Same as Fig.5 except simulations are with two fixed constant soil moisture conditions, *SM* = −600 bar (wet) and *SM* = −8,000 bar (dry), and constant minimum stomatal resistance, γ = 0.97 sec/cm.

where e is the actual vapor pressure at the immediate soil surface at a surface soil temperature of T_s, and e_s is the saturation vapor pressure at the temperature T_s. R_v is the gas constant for water vapor. SPAM calculates a soil surface temperature by an iterative process of solving the soil surface energy balance. The apparent soil surface vapor pressure e is then used to determine the vapor pressure gradient in the bottom layer of the system (soil surface to 15 cm above the surface) and to calculate the latent heat flux from the soil surface. The *SM* values are "guessed" inputs at this point. It can be shown by the use of the psychrometric equation relating water potential to relative humidity that extremely high water potentials can be obtained. The equation is being applied, in this case, to a nonequilibrium, open system. There was a particular problem in estimating *SM* values for the cornfield since over 50% of the soil surface was covered with flat stones. The soil surface actually becomes a multiple system in that the water potential of dry, hot stones must be considered as well as the water potential of the exposed, evaporating soil surface. The net effect is to treat this stone-soil surface as one system and estimate a single value for the apparent surface water potential.

In the early testing of SPAM two *SM* values were estimated, −600 bar for a "wet" surface and −8,000 bar for a "dry" surface. The −8,000 bar figure was found to be in error and a more realistic figure would be about −2,000 bar for the "dry" surface. The *SM* of −8,000 bar used in the test shown in Fig.6 does show the sensitivity of the model to the extreme case. The sensitivity of the model to this input value points out a weakness in the model in that very little is known about the *SM* values of real soils. The magnitude of the soil water potential at the soil surface makes it difficult to measure directly or to estimate from measurements of soil water potential at some depth below the surface. The weakness in the use of this parameter in the model is in not knowing the actual value of this input parameter for various soils and degrees of soil wetness.

The results in Fig.6 with stomata open and a dry soil surface as inputs show SPAM predicting latent and sensible heat flux and photosynthesis values relatively close to the measured values in the morning, but in the afternoon the latent heat flux and photosynthesis are overestimated while sensible heat flux is underestimated.

Obviously, there is some combination of stomatal resistance and surface soil water potential that predicts values close to the energy balance values. There is no point in adjusting these two input parameters unless there are some criteria for evaluating their change during the day. While no known values of *SM* were available for inputs, the changes in stomatal resistance were measured and could be used as input parameters.

The flux values for the same day shown in Figs.5 and 6 are shown in Fig.7 with γ values obtained from real stomatal resistance measurements. The *SM* value was held constant. The calculated photosynthesis agreed well with

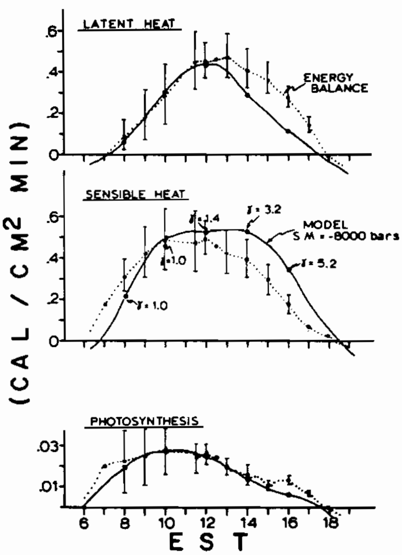

Fig.7. Same as Fig.5 except simulations are with a fixed constant soil moisture condition, *SM* = −8,000 bar, and measured minimum stomatal resistances (γ) as inputs.

the energy balance measurements. The latent and sensible heat flux values agree quite well with the measured values in the morning, but in the afternoon SPAM overestimated sensible heat and underestimated latent heat flux. The greater latent heat flux measured in the afternoon indicated that the system was actually behaving as a wetter effective surface than predicted by the model. It illustrates that a variable surface wetness would be more realistic. This is even more reasonable if the increase in effective surface vapor pressure as soil temperature increases is considered.

Tests for two additional days were made in which real stomatal resistance values with fixed surface soil water potentials were used. These additional days span conditions of high and low water stress. The results are shown for a high stress day, August 15, 1968 (Fig.8) and low stress, August 28, 1968 (Fig.9). The flux values calculated by the model on August 15 are similar in

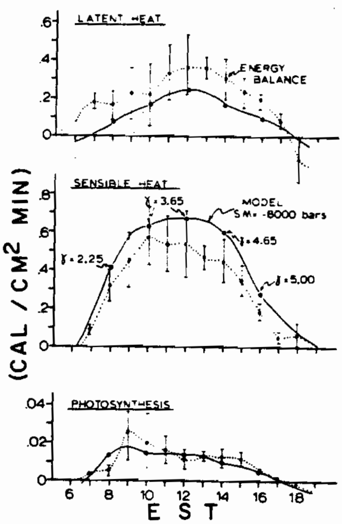

Fig.8. Predicted (solid line) and measured (dotted line) energy fluxes for a clear summer day with high water stress conditions, 15 August, 1968, with fixed constant soil surface moisture, *SM* = −8,000 bar, and measured minimum stomatal resistance (γ) as inputs.

that the real stomatal resistance resulted in photosynthesis values nearly identical with measured values while the measured latent and sensible heat fluxes implied a wetter effective surface than predicted by the model. The stress condition was simulated by the use of higher stomatal resistance values and was realistic in that net photosynthesis was lower and a greater proportion of the energy was partitioned into sensible heat rather than latent heat. The flux values for the low stress day (Aug. 28) show similar results. Two simulations are shown here at both *SM* values of −600 and −8,000 and with real stomatal resistance values. The energy balance measurements show that the effective surface wetness appeared to be near the −600 bar potential in the morning hours but somewhere in between the two potentials in the afternoon. Cloudy and clear conditions were intermittent on this day and accounted for the more irregular shape of the curves.

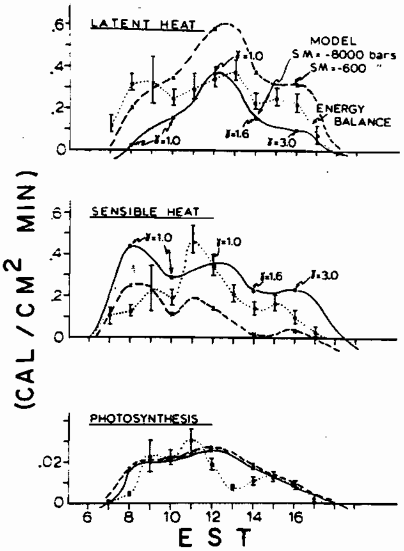

Fig.9. Predicted (solid and dashed lines) and measured (dotted line) energy fluxes from a cornfield on a day with intermittent cloud cover and low water stress conditions, 28 August, 1968, with two constant soil moisture conditions, *SM* = −600 bar and −8,000 bar, and with measured minimum stomatal resistances (γ) as inputs.

This set of simulations has shown the sensitivity of SPAM to two submodels. Both submodels may be oversimplifications. Because of the complex feedback system and the effects of aging and stress cycles, the stomatal response is most difficult to model (Meidner and Mansfield, 1968). The reliability of SPAM's predictions must be considered if SPAM is to be used as a tool for studying plant responses. Considering the limitations discussed and the problems with certain submodels, we can answer this question with a guarded "yes". The basis for this argument is the results showing: (1) net photosynthesis, which is not sensitive to surface soil wetness, was predicted quite accurately, particularly when real stomatal resistances were used; (2) latent and sensible heat, which are sensitive to soil surface wetness respond diurnally in a consistent manner; and (3) the predictions are similar to results of previous experiments (Brown and Covey, 1966; Lemon and Wright, 1969).

Crop structure and climate

Two additional simulation studies are discussed to demonstrate the way SPAM can be used as a tool for testing other parameters. In both of these simulation studies, the stomatal resistances and surface soil moisture are held constant. Two studies are discussed — one where the effects of changing the plant parameters of leaf angle and leaf area in relation to sun angle are simulated, and one where the environmental variables of temperature, humidity, and wind speed are varied with plant parameters held constant.

The results of the sun angle, leaf area index, and leaf angle simulation are shown in Figs.10 and 11. The inputs for this simulation were for noon time

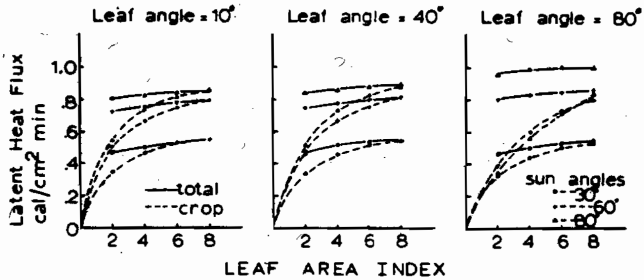

Fig.10. Simulation of corn crop leaf angle and leaf area (*LAI*) influence on evapotranspiration under various sun angles with other climate conditions held constant. Inputs for this simulation were: date 18 August, 1968; 72.97°N for 30° sun angle; 42.70°N for 60° sun angle; 21.68°N for 80° sun angle; reference height temperature, humidity, and wind speed: 20.2°C, 66% R.H., and 276 cm/sec; corn crop base level respiration rate: 15 mg CO_2 dm^{-2} h^{-1} at temperature of 302.2°K.

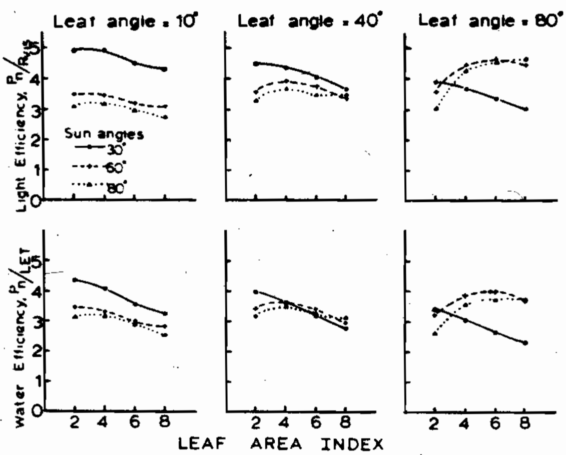

Fig.11. Light efficiency and water efficiency expressed as percentages. Inputs are the same as in Fig.10.

conditions on August 18 for the latitudes of 72.97°N for the 30° sun angle, 42.70°N for the 60° sun angle, and 21.68°N for the 80° sun angle. Reference height values of temperatures, humidity, and wind speed were assumed constant at 20.2°C, 66% R.H., and 276 cm sec^{-1}, respectively. The base level respiration rate for the corn crop, used in the leaf net photosynthesis model, was 15 mg CO_2 dm^{-2} hr^{-1} at a temperature of 302.2°K. This respiration rate may be too high for just leaves alone but may be realistic for whole plant respiration, i.e., stalks, ear and root.

Some caution in interpreting this simulation is in order since some of the combinations of variables may not exist in nature. For example, all leaves in each angle class are assumed to be at the same angle from the horizontal as well as being uniformly and randomly distributed. This is hardly realistic in nature and particularly so for the 80° leaf angle since the effects of shading from row to row has been eliminated. The lower leaf angles approach a more real situation with respect to random and uniform orientation.

The solid lines in Fig.10 are the total evapotranspiration (*ET*) while the dashed lines are the crop transpiration (*T*). The significant features of Fig.10 are that *ET* increased only slightly as leaf area index increased above on *LAI* of 2 and increased only slightly as leaf angle was increased. The sun angle caused the large difference in latent heat flux (*ET*) with all leaf angle classes. This would be expected since the net effect of increasing sun angle would be to increase the radiation load. Crop transpiration was extrapolated to zero *LAI* to show the conditions without vegetation. The comparison of total *ET* and crop transpiration as *LAI* increases shows the effects of increased radiation loads at the soil surface at low *LAI*. The increased radiation loads at the soil surface caused the soil evaporation component of the total *ET* to be large. One interesting result at the 80° leaf angle and with the higher sun angles (60° and 80°) is the decrease in crop transpiration as opposed to the crop transpiration at the leaf angle of 40°. With the vertical leaves more radiation reached the soil surface in this simulation.

In terms of efficiency of water and light utilization, shown in Fig.11 as the ratios of net photosynthesis to total latent heat flux and to visible radiation, we see that the efficiency ratios for any particular sun angle — leaf angle combination with the same *LAI* is changed by the order of 1.0 to 1.5% with a 3—5% range in efficiency values. Probably more significant is the different response between the leaf angle classes as leaf area index is increased. For the horizontal leaves (leaf angle = 10°) both water-use efficiency and light efficiency decrease as leaf area index increases. For the more intermediate leaf angle (40°) efficiencies decrease at the low sun angle, but show a peak efficiency at a *LAI* = 4.0 at the higher sun angles. The leaf angle of 40° is a realistic parameter for common agricultural crops, and the peak efficiency at *LAI* = 4.0 could be used as a significant guideline for modifying the plant canopy structure. For the more vertical leaves (leaf angle = 80°), the peak efficiencies are shifted to higher *LAI*'s at the higher sun angles. It is interesting to note that the higher water efficiency in this case was obtained even though more soil surface evaporation occurred (Fig.10). The same precaution must be used in interpreting these results since the conditions that are simulated may not be real in nature.

The simulations in Fig.12 are probably more significant in that environmental variables are probably more important in evapotranspiration than crop structural variables. In this simulation real crop and climatic data for the noon period on August 18, 1968 were used as inputs with the exception of variable temperature, wind speed, and relative humidity at the reference boundary. The real crop had a mean leaf angle of 40°. The net radiation above the crop was 0.96 cal. cm^{-2} min^{-1}, and the stomatal resistance and soil surface moisture was held constant as before. Again, some judgment must be made as to the reality of certain combinations of variables, i.e. high

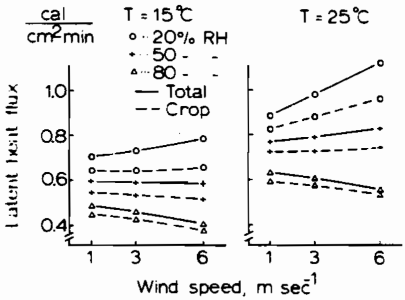

Fig.12. Simulation of varying climatic conditions on evapotranspiration of a corn crop with constant crop structure during midday radiation conditions in Ellis Hollow, N.Y., 18 August, 1968, 42°N.

humidity, high wind, low temperature, clear weather. It does illustrate the use of the model to simulate some unusual conditions that might be realized in a greenhouse, for example. The significant features of Fig.12 are the increases in both crop transpiration and total *ET* as wind speed increases with lower humidity values. A different result is observed at the high humidity value, where a decrease in evapotranspiration is observed as wind speed increases. Apparently the high humidity and high wind speed acted to reduce the vapor pressure gradient and caused greater sensible heat transfer from the leaves.

The relatively small effect of reduced wind speed on *ET* at a relative humidity of 50% relates to the minimal effect of changing *LAI* in Fig.10 (40° leaf angle, at 66% relative humidity). The decreased wind speed within the canopy as canopy density increased had very little effect on latent heat flux.

APPLICATIONS

The usefulness of the model as a tool for ordering priorities and better selection of variables for more intensive field trials is illustrated by the simulations in Figs.10, 11, 12. All points shown required 51 computer runs of the model or only 25 min of actual computer time — relatively inexpensive compared to conducting field experiments with all these variables. The emphasis should be placed on SPAM as a tool for evaluating the significant parameters that need more intensive study for better understanding. These simulations have shown how SPAM can be used to suggest possible approaches for modifying the plant and the plant community structure for increasing water use efficiency. The sensitivity of the crop response to stomatal behavior suggests a closer look at ways of controlling this response, i.e., genetic via stomatal number, size location, or chemical via antitranspirants, for example. The leaf angle, leaf area, sun angle combination show in general what might be expected in a real situation in that changing leaf angle alone does not have as great an effect as changing the leaf area for any one leaf angle.

The simulations with environmental variables — i.e., temperature, humidity, wind, and surface soil wetness — show that the idea of modifying the plant per se cannot be the only approach and that modification of the plant and the plant community must be linked together for a total system approach to increasing efficiency and maintaining high levels of production.

The model is of general nature which enables its application to any area as long as certain basic limitations, i.e. steady-state conditions, homogeneous surface, are met. Most large, dense agricultural crops in the Great Plains area would fit within these limitations. In semi-arid conditions where horizontal advection might occur, the model may be limited in application somewhat. However, this is not a serious limitation, because the model could be modified to a degree by adjusting for the added energy input from advective sources. The model would still be useful in application in semi-arid areas as a means of studying those factors that are likely to have the most important influence on evapotranspiration and water-use efficiency. It is most useful in setting a range of influence for further field studies. The example of the simulation study for LAI suggests a peak efficiency at a $LAI = 4.0$ for a corn crop with an average leaf angle of 40°. This simulation would suggest a complimentary field study with actual field parameters bracketing this range. Similar examples could be conceived for stomatal number and soil surface wetness variables.

Allen (1974) used SPAM in evaluating the net photosynthesis of a wide-row crop in conditions typical to the semi-arid area. He used the SPAM simulations to study the possible effects of different row orientations, and his use of the model offers another example of the generalized nature of the model as a tool with a wide range of application.

SUMMARY

The development and components of a comprehensive model for simulating soil—plant—atmosphere interactions have been described. Examples of testing the model for its weaknesses have been discussed, and examples of simulated plant responses that correspond to real, measured situations have been given. Serious problems exist in the modeling of the stomatal response and in placing a number on the effective wetness of the soil surface which is shown to be an important input variable for the model. The model helps focus on the priority items for more intensive research. Additional problems must be overcome in order to apply SPAM to nonuniform systems and

systems with more complex structure. SPAM is a useful tool if used with caution and judgement. It has a wide range of application in the areas of food production, conservation, climatic modification, and in increasing our quantitative understanding of basic plant—environmental interactions.

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