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Experiments in Predicting Evapotranspiration by Simulation With a Soil-Plant-Atmosphere Model (SPAM)[1]

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ABSTRACT

From extensive field study, we have introduced a comprehensive mathematical model that acts like a plant community. It is based upon the conservation of energy. Our understanding and deficiencies have been gauged by testing model forecasts of local climate and community processes against real world experience with a simple system—a corn field (*Zea mays* L.). Microclimate prediction is biologically good enough, but reveals inadequacies of understanding airflow fluid dynamics within the vegetation stand. The inability to measure or predict the degree of wetness of the soil surface hampers correct forecast of evaporation. Probably the most difficult problem to resolve is the biological one of predicting how leaf pores (stomates) open and shut under drouth stress, thus affecting both evaporation and photosynthesis in leaves. Additional serious problems will arise in the future modeling of nonuniform or more complex systems especially in forecasting the distribution of wind, momentum, and radiation within the foliage stand.

INTRODUCTION

A little over 10 years ago, the U. S. Department of Agriculture joined with Cornell University in extensive field studies to understand how plant communities interact with the environment. It was a team effort to study first the component parts of physical and physiological processes under field conditions. Once there was sufficient knowledge and expertise, the team was able to study simultaneously the component parts all together. A suitable computer model was developed to simulate the plant community—both its

[1]Contribution of the Northeastern Region, Agricultural Research Service, U. S. Department of Agriculture in cooperation with the New York State Agricultural Experiment Station at Cornell University, Ithaca, N. Y. Agronomy Department Series Paper no. 970.

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environment and its interaction—then it was tested against the integrated field measurements. The work was done in a corn field (*Zea mays* L.) in Ellis Hollow, New York, 8 km (5 miles) east of the University. We report here the status of progress and unresolved problems.

Primarily, we have aimed at answering agricultural problems of water conservation and crop production. We wished to know, for example, what plant shape or crop architecture would best use a given climate for net photosynthesis and efficient water use. While such questions are no less important today in a world of expanding population and increased demands for fresh water, other significant applications have developed from society's growing awareness of environment-related problems.

Our work has had meteorological application because solar energy exchange at land surfaces is under direct control of plant and soil characteristics. Evidently knowledge of how solar radiation, absorbed at the earth's surface, is parcelled to heat air and evaporate water is needed to understand not only large-scale meteorological processes but local climate formation. Since evaporation of water plays such an important role in the hydrologic cycle, forecast of its "use" is also of interest to foresters, hydrologists, irrigationists, and water resource planners.

Our study of carbon dioxide exchange of growing crops is of geophysical interest. Calculations indicate that green plants growing on the land dampen present increases in atmospheric carbon dioxide due to fossil fuel burning. Now we recognize, in addition, how local plant communities "air condition" the air, removing noxious contaminants and adjusting temperature and humidity.

It makes sense to treat crops as energy exchange systems because the major plant processes are also solar energy driven. Photosynthesis uses sunlight energy to fix carbon dioxide into carbohydrate materials. When carbon dioxide and oxygen gases are transferred across wet interfaces to an aerial environment in both photosynthesis and respiration, water is unavoidably lost in energy use by a water transfer process called transpiration. In fact, transpiration accounts for large shares of the water lost from the land and the energy transformed from absorbed solar radiation when water is plentiful. If one makes an energy balance based on the energy conservation law, the portions of net absorbed solar radiation going to various energy forms for summertime eastern United States might be: 1 to 5% to photosynthesis; 40 to 90% to evaporation; 10 to 60% to heat air; and 5 to 10% to minor storage terms. How these forms are proportioned largely rests on water supply.

Many workers have quantitatively predicted individual components of the energy balance. Evaporation formulae are examples. Variants of one developed by H. L. Penman in 1948 are probably the most sound physically and most popular today (19, 36, 51, 56). Net photosynthesis models based only on absorbed sunlight are numerous (8, 11, 30, 34, 41). Recent net photosynthesis models adding aerodynamic carbon dioxide terms have appeared (10, 22, 31, 32, 54). Nevertheless, prediction modeling of all the surface energy exchange processes has proven, until now, too complex a problem to define quantitatively in terms that are reasonably sound, physically and physiologically. Interaction has been the chief difficulty in the modeling machinery.

Within the past 2 years, several comprehensive plant community-environmental interaction models based upon the energy balance have appeared in the literature (18, 27, 33, 42, 46, 47, 58). All of them take advantage of computer simulation techniques where a tremendous number of interaction calculations and iterations are made. Only one of them has had sufficient field testing to pinpoint areas of needed research for future model evolution. We look at this model and its testing next.

THE SOIL-PLANT-ATMOSPHERE MODEL (SPAM)

The computer simulation model SPAM was developed by Stewart (25, 43, 44, 45, 46, 47, 48) while its testing involved a team of several individuals.

Figure 1 gives the essential ingredients of the model and its predictions. Let us take up the latter first to stress what the model can and cannot do. SPAM can answer questions in two general areas: (i) it can forecast the microclimate in a community and at soil and leaf surfaces with various leaf and community traits and external climates, and (ii) it can predict activity of leaves or of the community, such as, respiration, photosynthesis, evaporation and transpiration, heat dissipation, and noxious gaseous absorption.

Some predicted climate properties, which can change vertically through a plant community during midday, are pictured in Fig. 1 as "profiles" in the lower portion of the prediction box. One sees from left to right profiles of wind (u), light (Lt), carbon dioxide (C), water vapor (e), and air temperature (T). These are forecasts of steady-state mean values on a time scale of 1 hour. They define living conditions for plants and other organisms at any given level in the community, such as, walking animals, flying bugs, or "creeping" fungi living on a leaf.

In predicting activity, SPAM gives community processes in terms of source and sink intensities at any horizontal plane or vertical flux or flow densities across any horizontal plane. They can be defined for mass (i.e., water vapor and carbon dioxide), energy (radiation, latent and sensible heat, and photochemical energy equivalent), or momentum (wind shear). We picture activity of carbon dioxide (CO_2) and water vapor (H_2O) in the top portion of the prediction box. On the left, one sees that CO_2 flows both up and down in the midday case. Carbon dioxide diffuses upward from respiration in the soil and from poorly lit bottom leaves. It diffuses downward from the atmosphere to well-lit photosynthesizing upper leaves of the canopy. By convention, flux upward is plus and downward is minus. For water vapor, daytime upward flow steadily increases from the soil surface through to the top of the plant stand. Flux densities are often in mass or energy units per time per ground area.

Source and sink activity of CO_2 and H_2O are shown as source plus and sink minus. Thus, soil and plant respiration gives off CO_2 in the base of the stand as source and photosynthesis in the upper canopy is the CO_2 sink. Water vapor from soil evaporation is the source at the base, and transpiration is the water vapor source in the canopy. Source and sink intensities are usually in mass or energy units per time per volume. Again, the quantities are for mean steady state on a time scale of 1 hour.

Forecast of evaporation has many areas of application. In agriculture, water conservation aims at more effectively using water in unavoidable evaporation and transpiration. SPAM can help design crops and cropping schemes to do this. It can improve irrigation planning and scheduling, too. However, we are learning from big cities paved with concrete that, in the broader sense, evaporation and transpiration are desirable for proper air conditioning. Thus, in agriculture, we do not want to stop evaporation, just obtain the most effective use from it.

In forecasting net photosynthesis, SPAM can help the plant breeder and agronomist select more efficient plant shapes and planting patterns. Questions can be answered about crop adaptation to new lands and new crops or new cropping sequence in established areas undergoing social and economic change. Farmer harvest schedules for forage crops can be optimized. With manipulation of the submodels within SPAM, questions about feasibility, desirability, and sensitivity of factor changes on final outcome can be tested. For example, you can determine whether changing the leaf angle of a crop has as much influence on net photosynthesis as changing the individual leaf photosynthesis response to light.

We need to stress that while SPAM can predict net photosynthesis or dry matter gain, it is not a plant growth or crop yield model. While net photosynthesis is a major building block to growth and yield, it is but one of several processes involved. C. T. de Wit (8) of the Netherlands is a leader in complex growth model development.

Ideally, SPAM should be able to answer questions of community environment and activity for systems of any size, shape, or external climate. It cannot. It gives reasonable answers only for systems that are (i) simple or uniform in structure, (ii) large enough in extent to avoid horizontal climate variation, and (iii) under steady-state or slowly changing conditions. Extensive dense and vigorous agricultural crops approach conditions (i) and (ii). Clear or cloudy days approach condition (iii) except near sunrise and sunset.

Boundary Conditions

Now we turn to inputs of SPAM, then see how it operates. SPAM has two boundaries like a large horizontal slab with a top and bottom. The top is a plane in the airstream, 1 to 4 m above the stand. The bottom is the soil surface. At the top, external climate is defined by solar radiation, wind, temperature, carbon dioxide, and humidity. At the soil, we need to know heat storage, carbon dioxide evolution, and soil surface wetness, *SM*. From the

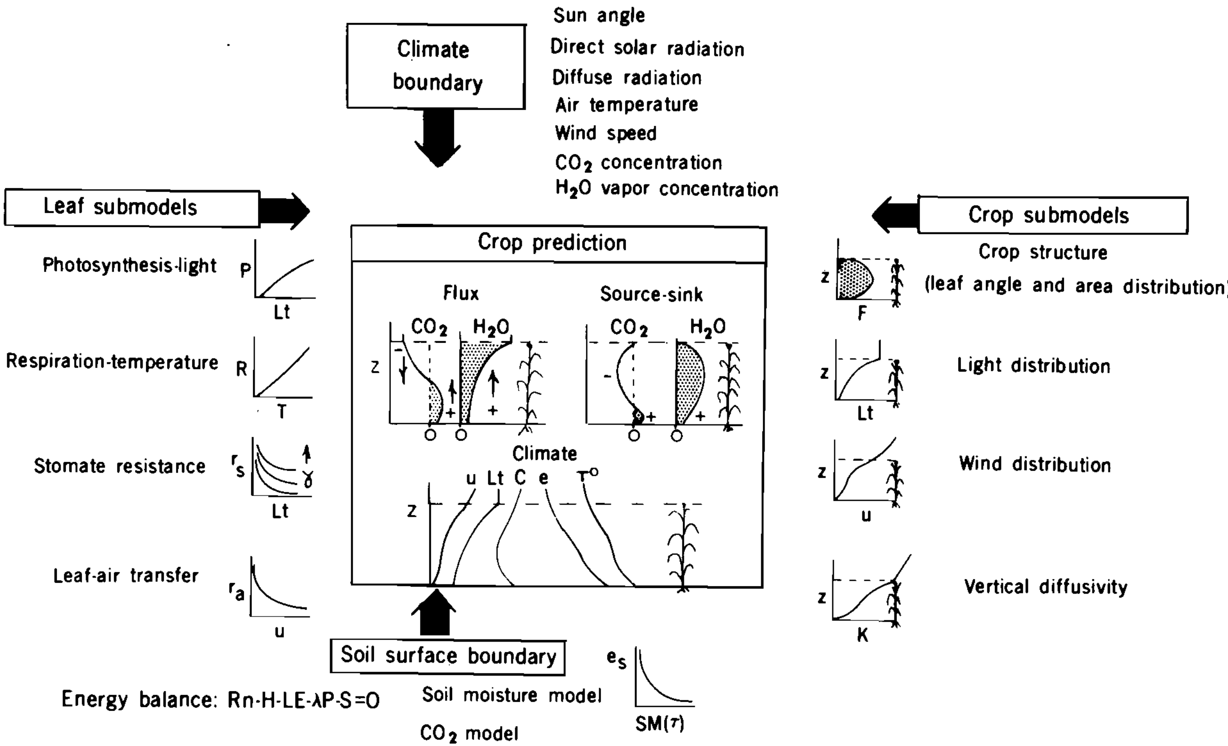

Figure 1. Schematic summary of a mathematical soil-plant-atmosphere model (SPAM) giving required inputs, submodels, and representative daytime predictions of climate and community activity (that is, water vapor and carbon dioxide exchange). Abbreviations: height (z), wind (u), light (Lt), concentration of carbon dioxide (C), water vapor (e), air temperature (T°), surface vapor pressure (e_s), surface soil water potential [SM (τ)], 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 (λP), and soil heat storage (S).

latter, SPAM calculates in a submodel the apparent surface vapor pressure, e_S. Later, we see this item is more important to forecast evaporation from the soil and one of the most difficult to obtain.

The logic of SPAM is to (i) define on a leaf scale at many levels in the canopy, how each level, or the soil surface, will act in response to a given immediate climate; (ii) calculate from meteorology what that climate is; (iii) calculate the leaf and soil response to it, then; (iv) add up the leaf and soil responses, layer by layer for the whole stand. An energy balance is made on each layer, then on the stand as a whole by computer iteration. To do all this, certain information is needed both on the leaf scale and the stand scale.

Leaf Scale Submodels

Leaf scale submodels are on the left in Fig. 1. For photosynthesis response (P) of individual leaves to incident light (Lt), Chartier's model (6) has been modified to incorporate a stomate control mechanism. Carbon dioxide response is included in the photosynthesis submodel. For respiration response (R) to temperature (T), Waggoner's approach is used (57).

Kuiper's stomate opening relationship (20) is pictured in the leaf scale submodel defining the stomate resistance to gas diffusion (r_S) in response to light (L_t). Stomates are little valves on leaf surfaces controlling the passage of water vapor, carbon dioxide, and oxygen between wet inside membranes and dry outside air. With no water stress, stomates open in daylight and shut at night. However, as stress develops under water shortage, stomates close in daylight as a protective measure to water loss. Carbon dioxide diffusion is also cut. Shawcroft (43, 44) has modified Kuiper's model to include drouth effects, shown by a family of curves for increasing stress, gamma. This improvement is an empirical one for a very complex process. Lack of quantitative knowledge here is perhaps the weakest biological link in SPAM. The status of stomates rigidly controls transpiration and photosynthesis, and thereby, the whole energy balance. We cannot overstate this fact.

The final leaf scale submodel deals with the gas diffusion resistance (r_a) through the film of still air on the leaf surface. For this, Pohlhausen's formula, as derived by Gebhart (12) has been modified to account for natural field turbulence. Our experiments indicate a sizeable reduction in r_a with increasing windspeed (u) in turbulent air (46, 47, 49).

Crop Scale Submodels

Next, crop or community scale structure and submodels are pictured on the right in Fig. 1. The submodels deal with meteorological processes once the crop structure or architecture is defined.

The description of crop structure in quantitative terms is important and difficult (4, 28, 32, 34, 35). It is expressed in terms of plant surface area (F), distributed in height (z), and how it is displayed. Leaf size, leaf angle, and azimuth are all required. An adequate definition can only be made of simple stands where area distribution is uniform horizontally and reasonably uniform vertically. Nonuniformity, where clumping and vegetation gaps occur, creates special problems for light models predicting light distribution in the canopy.

To forecast light (Lt) with height in the stand (z), Duncan's model is used (11, 49). With modifications, infrared portions of the solar spectrum are predicted. Finally, thermal radiation is assessed from surface temperatures. The latter hinges on energy balance iteration. All three radiation regimes are needed to give net absorbed radiation for energy balance.

Because wind must diffuse gases and heat by turbulent motion, SPAM has to calculate windspeed distribution, u vs. z, and vertical turbulence diffusivity, K vs. z. Windspeed profiles above the stand first are generated by a method of Swinbank (50) knowing stand aerodynamic roughness traits as well as energy balance components. Profiles of wind in the stand are next predicted. This rests on distributing the wind drag on plant surfaces from the top of the stand downward into the canopy using a method of Perrier (37). Vertical diffusivity (K) is calculated by using a constant relation between it and the predicted wind in the stand as Cowan (7) has done.

Finally, the whole scheme must obey the energy balance in which energy sources must equal energy sinks. In this case (see Fig. 1), the net absorbed radiation is the driving source. The sinks are sensible heat, latent heat, photochemical energy equivalent, and soil heat storage (22). In the computer program, the energy balance is solved for each leaf layer and soil surface as well as for the entire system.

Solving the equation of any given part of SPAM is dependent on solving the equation of some other part. This interdependence requires the use of successive approximations in order to solve all of the equations simultaneously. The converging solutions thus give final answers for the complete system. Figure 2 gives the general procedure as a flow diagram.

THE TESTING OF SPAM

An experimental test of a mathematical model is an indispensable part of its proper development. We choose our best data to test SPAM for its weakness. On 18 August 1968, we took all the data needed in a 10-ha corn field in Ellis Hollow. 'Cornell M3' (*Zea mays* L.) is an ideal crop with leaves randomly oriented and relatively uniformly distributed in size and display. We planted it in a hexagonal array like an orchard so that all plants occupied equal space of 6 plants/m^2 land area. The crop was fully grown with a leaf area index (LAI) of 3.6 m^2 leaf area/m^2 land area. It was healthy but under mild water stress. The test day was prefectly clear with ideal growing season weather.

R. B. Musgrave took the needed leaf scale measurements of the photosynthesis submodel for us (17) while a team of several individuals made field

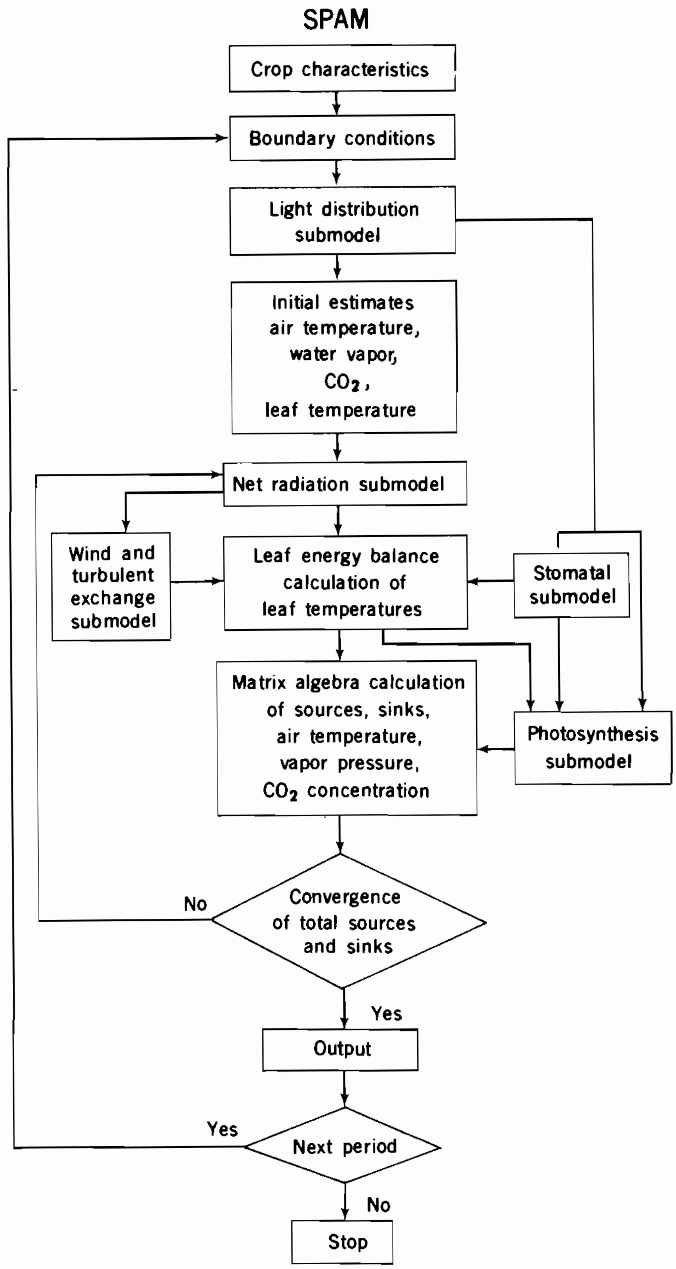

Figure 2. The general procedure of SPAM, given as a flow diagram.

measurements of climate profiles along with vertical fluxes to compare with model calculations. All of the SPAM requirements such as, structure, optical and fluid dynamic properties, and stomate response were measured on the

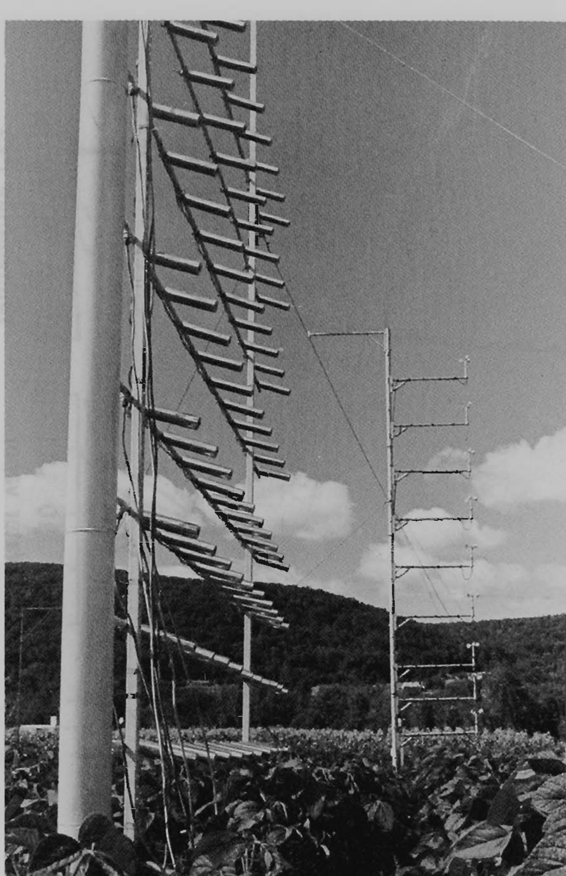

Figure 3. Equipment used to measure air temperature, water vapor, carbon dioxide concentration, and wind speed at various heights in and above uniform agricultural crops (soybeans shown here). Measurements are used to calculate items (photosynthesis, transpiration, and sensible heat exchange) in the energy balance, where the source is solar radiation.

same crop. Figure 3 shows some of the equipment used (in a field of soybeans) to measure the climate profiles in corn.

Theory vs. test is shown in Fig. 4, 5, and 6. Figure 4 compares forecast climate as solid and dotted lines against dashed lines drawn through data points. Size of error in data points is about equal to circle diameters. All data are 0.5-hour means spanning noon. Leaf area density, F, is given on the leaf and a scaled plant on the right for reference. All profiles have been adjusted to data points at the 240-cm height, judging this to be the best reference level. On this basis, SPAM undershoots temperature about 0.25C through most of the stand and overshoots water vapor about 0.5 g/m^3. It comes close to the mark on wind and CO_2 except near the soil.

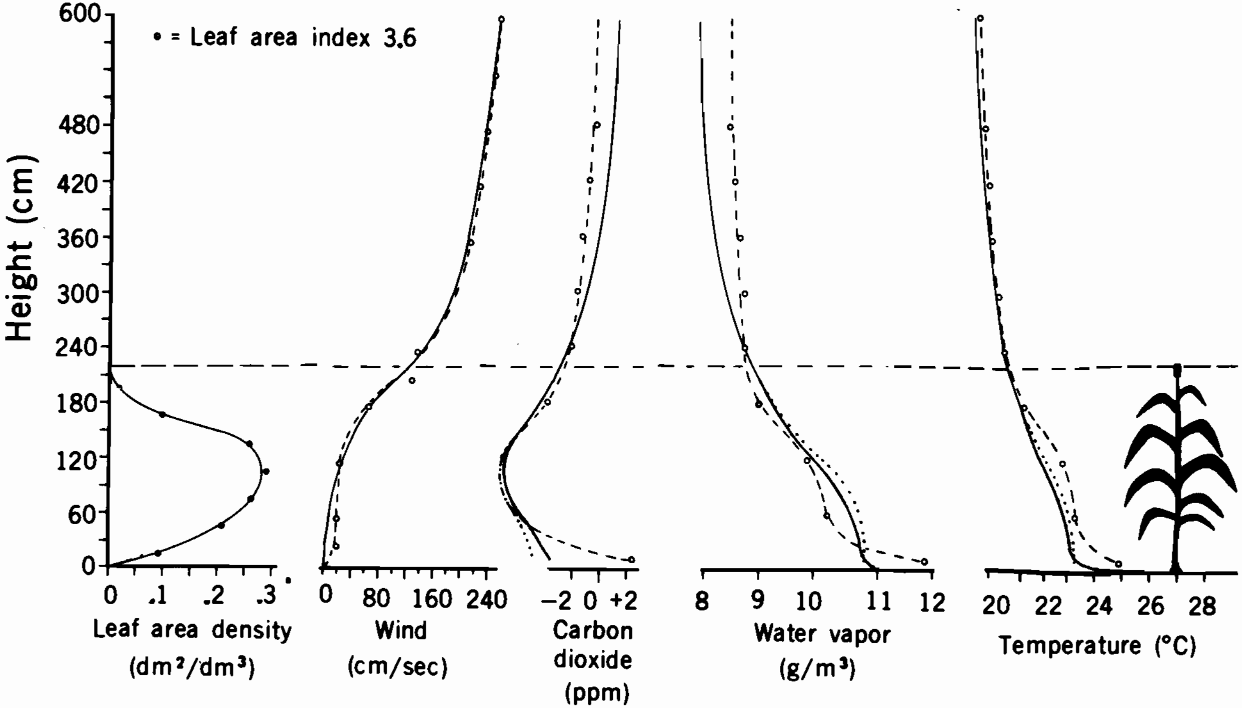

Figure 4. Measured (circles and dashed lines) and predicted (solid and dotted lines) profiles of climate factors in and above a corn field, with the field's vertical leaf area density constructed profile shown. Profiles are 0.5-hour mean values. (18 August 1968; 1145 to 1215 hours, Eastern Standard Time.)

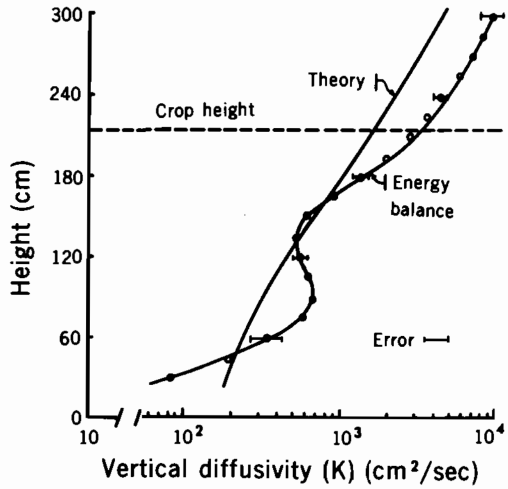

Figure 5. Measured energy balance profiles of vertical diffusivity (K) (circles and solid line) and model prediction (solid line) from momentum balance. (18 August 1968; 1145 to 1215 hours, Eastern Standard Time.)

The serious spread between predicted and measured water vapor and CO_2 above the stand raises questions about theory despite good wind and temperature profiles. Since we are confident of our data, we wonder about site and aerodynamic theory. Downwind fetch over the crop to sensors ran about 200 to 250 m, adequate for a boundary layer of 2 to 3 m over the stand. We question more seriously if classical fluid dynamic theory for boundary flow is applicable to tall vegetation that is porous and flexible. We suspect that troubles may start within the canopy since we cannot explain airflow deep in the stand. In Fig. 4, you can see in the real wind profile an almost constant wind from the densest part of the stand down to near the soil. This is indicative of no wind drag on the vegetation in the bottom half of the stand, which is physically impossible. Evidently some aerodynamic mechanism adds entrained air at the base of the stand for more airflow. To see if this explains other profile differences, we plug real wind into SPAM and reforecast the dotted profiles. Changes are slight. Next, we look to the vertical diffusivity (K) for answers. Vertical diffusivity is defined as an eddy diffusion coefficient. It is arrived at by assuming that transport of heat and water vapor can be expressed as (i) diffusion equations of time-averaged flux, gradients, and a coefficient (diffusivity) in the energy balance, or (ii) as time-averaged flux of momentum, wind gradients, and coefficients (diffusivity) in the momentum balance theory used in SPAM. The application of diffusion equations in both cases can be questioned if vertical mass flow occurs in the canopy. The additional entrained air in the base of the canopy suggests that mass flow does occur; now turbulent diffusivity values arrived at by either method will not account for the two transport mechanisms. Fortunately, from an operational point of view, our lack of understanding, and the incor-

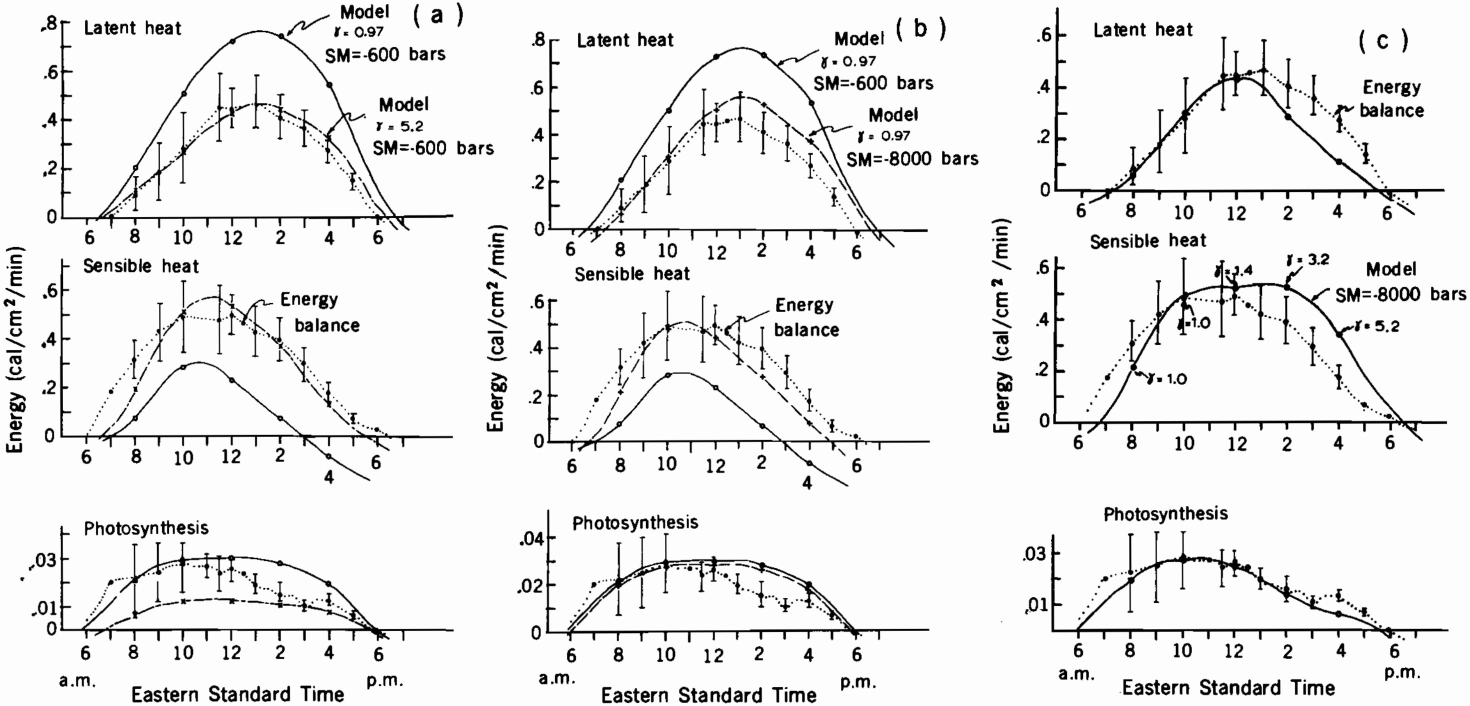

Figure 6. Predicted (solid and dashed lines) and measured (dotted lines) energy fluxes from a corn field during a clear summer day. (*a*) Fixed constant soil surface water [$SM = -600$ bars (wet)] and two constant minimum stomatal resistances ($\gamma = 0.97$ and 5.2 sec/cm). (*b*) Two fixed constant soil surface water conditions [$SM = -600$ bars (wet) and -8000 bars (dry)] and constant minimum stomatal resistance ($\gamma = 0.97$ in sec/cm). (*c*) Fixed constant soil surface water [$SM = -8000$ bars (dry)] and measured minimum stomatal resistance (γ is measured in seconds per centimeter). (18 August 1968; length of bar denotes margin of error.)

rectness of the estimates of vertical diffusivity have little effect on outcome in a uniform crop. However, it is serious in a multistory forest (13, 24).

Figure 5 compares the vertical diffusivity predicted by SPAM and values computed from measurements of energy balance (14, 15, 16, 23, 53, 59). The latter's odd variation with height is dictated by the measured constant temperature and water vapor in midstand, as well as by the measured added airflow at the base. However, we have already shown that the additional mean airflow at the base does not appreciably alter the other predicted profiles. Thus, unexplained traits of fluid dynamics are at work both in the midcanopy and at the bottom (1, 3, 9, 21, 38, 52, 55, 59, 60).

At the base of the canopy, errors in the temperature and water vapor profiles are traceable to a relatively small error in predicting net radiation and to a large error in predicting soil surface water potential. Although we have measured soil water beneath the surface, we have not been able to predict soil surface water in Ellis Hollow. Over 50% of the soil surface is occupied by flat stones which create an abnormally hot, dry surface in the daytime despite adequate and measurable water below the surface.

However, stones are only part of the problem. SPAM estimates vapor pressure at the soil surface from the apparent surface water potential of the soil, in a range where vapor pressure is substantially less than saturation. In this situation, the vapor flux is influenced by the dynamic time and space distributions of the heat and water fields below the surface. We have not as yet incorporated enough theory into SPAM to be able to deal with this complexity. Error in estimating CO_2 evolution at the base of the canopy has little effect on the outcome (2).

Despite inadequacies in theories of fluid dynamics and soil water, the prediction of the stand's climate is probably sufficient from a biological point of view.

Figure 6 gives corn crop activity on the ideal day, comparing SPAM output fluxes from the whole stand to energy balance fluxes from real data. In parts (*a*) and (*b*), we do a sensitivity test for wet and dry soil, as well as stress and no stress stomates, plugging into SPAM two fixed *SM* and two fixed gamma values for the whole day. Part (*c*) has real gamma values in SPAM but a fixed *SM* input. Comparing a wet case, $r_S = 0.97$ sec/cm, when the corn stomates are wide open, to a mild stress case where stomates are partially closed, $r_S = 5.2$ sec/cm, the latent heat flux is reduced for the day from 350 cal/cm^2 to 200 cal/cm^2 or 43%. One sees (in Table 1) that sensible heat increased from 57 units to 204 units, and net photosynthesis was reduced 37%. By drying the soil surface from a damp −600 bars to a dry −8000 bars, latent heat flux is reduced 38% and net photosynthesis 6%. Sensible heat flux increased from 57 units to 171 units.

It is obvious now (from Table 1) that both soil surface wetness and stomate status have rigid control over the sun's energy division into sensible and latent heat. Stomates also have rigid control over net photosynthesis, but apparent soil surface wetness has only a small effect here through temperature influence on respiration.

By putting the real stomata r_S values for the day in SPAM, prediction of

Table 1. A daytime energy balance for a corn crop, 18 August 1968, Ellis Hollow, New York. (Total incident solar radiation is 696 calories/cm^2; total net radiation, 453 calories/cm^2.)

Cases	Latent heat, cal/cm^2	Sensible heat, cal/cm^2	Photo energy, cal/cm^2	Soil storage, cal/cm^2
		SM(τ)* = -600 (Fig. 6a)		
Case 1				
γ† = 0.97	350 (0.77)‡	57 (0.12)	15.0 (0.033)	33 (0.074)
γ = 5.2	200 (0.45)	204 (0.45)	9.4 (0.021)	33 (0.074)
		γ = 0.97 (Fig. 6b)		
Case 2				
SM(τ) = -600	350 (0.77)	57 (0.12)	15.0 (0.033)	33 (0.074)
SM(τ) = - 8,000	219 (0.50)	171 (0.39)	14.1 (0.032)	33 (0.075)
		SM(τ) = -8,000 (Fig. 6c)		
Case 3				
γ = measured values§	147 (0.33)	252 (0.57)	11.1 (0.025)	33 (0.074)
Measured energy balance	186 (0.41)	222 (0.49)	12.3 (0.027)	33 (0.073)
	±53	±53	±4.7	

* SM(τ) is surface soil water potential, measured in bars.
† γ is minimum stomatal resistance at high light intensities, measured in seconds per centimeter.
‡ Figures in parentheses are fractions of net radiation.
§ Measured γ are in Fig. 6c and 7.

net photosynthesis agrees with energy balance, giving us confidence that SPAM is working well. We are not as fortunate with latent and sensible heat since we cannot predict or measure soil water. By putting a fixed dry apparent surface soil water potential of −8000 bars into SPAM,[3] latent and sensible heat are close to the mark in the morning. In the afternoon, however, SPAM undershoots the mark indicative of a wetter effective surface or higher potential, −1200 bars. This makes sense because the effective vapor pressure will rise in the afternoon because of soil heating.

Despite the difficulties with soil water, the prediction of stomate status under stress, in the long run, is probably a far more difficult problem for biology. Figure 7 shows the complex trend of r_S through the moderate stress day. Under no stress, we know that r_S would follow the prediction curve. Since the leaves had undergone previous stress, they exhibited a sluggishness in early morning by not opening completely until 0.14 light units at 0800 despite ample water. Shortly after high light of 1200, the stomates gradually closed upon running low on water. Then they regained some water in the later afternoon and reopened somewhat at 0.08 light units at 1700 before sundown closure. These data are indicative of more than one complex feedback system. Several researchers (29, 40) have shown that light, water, temperature, and carbon dioxide are involved. They have reported on aging and hormonal control, as well (29, 40).

[3]The original model of SPAM had an error that made the surface soil water potential of −8000 bars reasonable for a dry soil. However, a revised version has corrected this to −2000 bars.

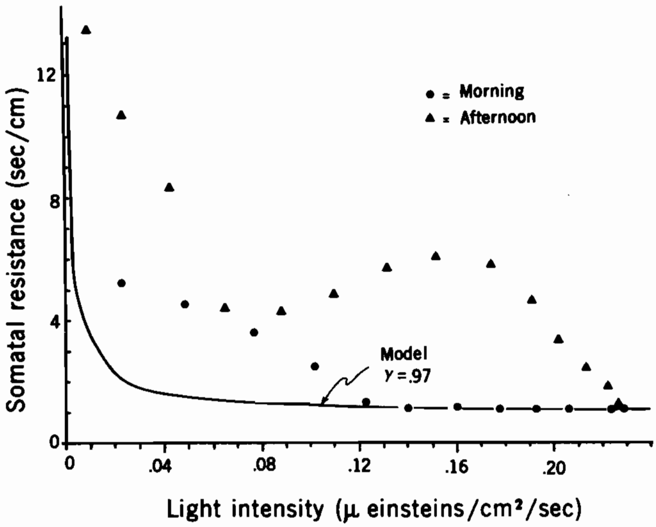

Figure 7. Stomate light response of corn leaves under mild water stress (data points). Resistance to gas diffusion through stomates is r_S (measured in seconds per centimeter). Solid line is prediction curve for the no-stress case, when corn stomates are wide open under bright sunlight [γ minimum stomatal resistance = 0.97]. Wet leaf r_S = 0 sec/cm (18 August 1968).

Can we believe SPAM's activity forecasts in Fig. 6 with the knowledge that all is not well with fluid dynamics and that errors can be hidden by our assuming soil surface wetness? Perhaps we can hazard a cautious "yes" based upon three arguments: (i) net photosynthesis comes out well while we know it is relatively insensitive to soil surface wetness; (ii) latent and sensible heat which are sensitive to soil surface wetness respond diurnally in a physically sound way to realistic *SM* inputs for a stoney soil; and (iii) the predictions are what one should expect from previous experimental experience (5, 26).

SIMULATION EXPERIMENTS OF CROP STRUCTURE AND CLIMATE EFFECTS ON EVAPOTRANSPIRATION

We have already demonstrated the sensitivity of SPAM to stomatal status and soil surface wetness and emphasized our present inability to accurately predict evaporation because of weakness in our submodels in these areas. Now we would like to demonstrate the usefulness of SPAM as an experimental tool to test the sensitivity of other aspects where the two weak submodels are given constant inputs, i.e., stomatal gamma values = 0.97 and soil surface water potential, *SM*, = −600 bars are held constant. (We would like to acknowledge many helpful suggestions of R. M. Peart during this phase of the study.)

We report two simulation experiments of a corn crop. The first compares total evapotranspiration (total latent heat) and crop transpiration as

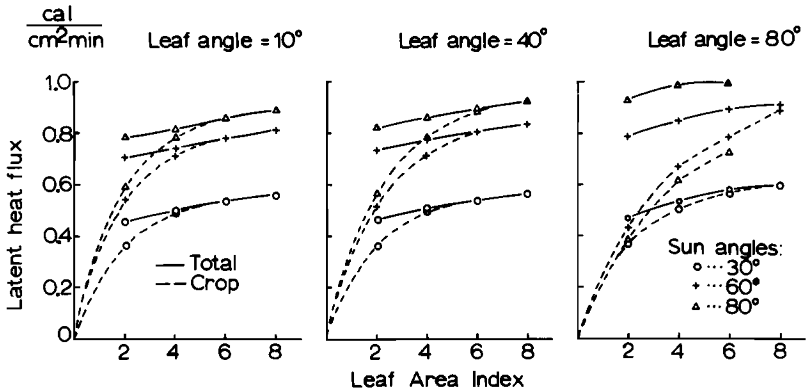

Figure 8. Simulation of corn crop leaf angle and leaf area (LAI) influence on evapotranspiration under various sun angles with other climatic conditions held constant. Climate is like that of Tampa, Florida or Corpus Christi, Texas, 28° N latitude. The broken lines indicate crop transpiration and the solid lines indicate crop transpiration plus soil evaporation.

affected by sun angle, leaf angle, and total leaf area (LAI). The second shows the influence of wind velocity, temperature, and relative humidity on total evapotranspiration and crop transpiration under constant noon-time radiation.

Figure 8 shows the results of the sun angle and crop structure interactions. Constant temperature (20.2C), relative humidity (66%), and wind speed (276 cm/sec) were assumed. Normal clear-day radiation distribution was used for a July day at 28° N, i.e., Corpus Christi, Texas and Tampa, Florida. All leaves at the three leaf angles were assumed to be uniformly and randomly distributed in space and azimuth. Also, all leaves in each angle class were assumed to be at the same angle (tilted up from the horizontal). The two assumptions about uniformity of leaf distribution in space and constancy of leaf angle are hardly realistic, especially for the higher leaf angle of 80° because row effect is not included in the model. Thus, caution must be used in interpretation, yet the analysis can be valuable if used with judgment. At the lower leaf angles, the model's assumption of random and uniform leaf placement is close to the real situation.

Figure 8 shows that the simulated total evapotranspiration increased only slightly with increasing leaf angle or increasing leaf area index (LAI > 2). In fact, the series of simulations showed an interchangeability between crop transpiration and soil evaporation. The decreased wind speed (not indicated) within the plant canopy caused by higher canopy densities should have very little effect on latent heat flux at 66% relative humidity. This conclusion can be reached from information in Fig. 9.

In Fig. 8, crop transpiration was extrapolated to a zero value at zero LAI since obviously no transpiration can occur without vegetation. Evapotranspiration was quite important at a low leaf area index (LAI = 2). As LAI increased, the canopy closed, and evaporation from the soil decreased. The

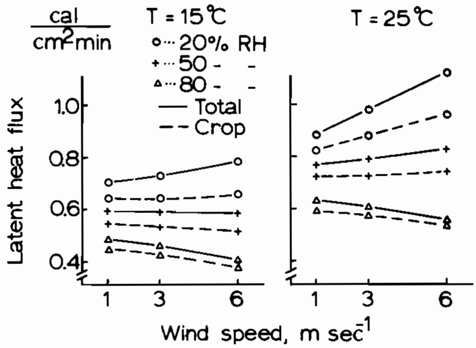

Figure 9. Simulation of varying climatic conditions on evapotranspiration of a corn crop with constant crop structure during midday radiation conditions in Ellis Hollow, New York. 18 August 1968. 42° N latitude.

figure also shows that crop transpiration actually decreased at high solar elevation angles (60° and 80°) when the leaves were erect (80°). More radiation could reach the soil under these conditions, and hence a much larger fraction of water loss came from the soil surface.

The data in Fig. 9 of the second simulation are perhaps of more significance. This arises because environmental variables are expectedly more important to evapotranspiration than is crop structure. In this simulation experiment, we used all the real corn crop data input we could for our 18 August 1968 test day at 1200 (see Fig. 4) but we varied the temperature, relative humidity, and windspeed at the upper reference boundary. As a point of interest, the 'Cornell M3' corn crop had a mean leaf angle slightly in excess of 40°. Solar radiation was 1.3 cal/cm^2 per min and net radiation was 0.96 cal/cm^2 per min. Soil surface wetness and stomatal status were held constant as in the previous simulation experiment.

In interpreting the Fig. 9 curves, one must ask whether certain combinations are likely to occur in nature, such as the high relative humidity, high wind velocity, low temperature, and clear weather. This also illustrates how easily unusual conditions can be simulated to check possibilities of environmental control in, for example, a greenhouse or with irrigation for relative humidity control. This could be especially valuable with a model accounting for water stress in plants. An interesting result shown is the different effect of increasing wind velocity at 25C and 80% relative humidity compared with 20% relative humidity. At the higher humidity, increasing wind decreased evapotranspiration, presumably by increasing the sensible heat loss from the leaves. Raschke discovered this phenomenon several years ago on single leaves (39).

All of the points shown in the last two figures total 51 computer runs and required only about 25 min of a large computer (IBM 360/65) time, a very inexpensive set of experiments. Studying such results can lead to better selection of variables for field experiments, improvement of the model itself, better understanding of the processes, and predictions of crop performance under new environments.

With caution, models are needed to solve complexity of stand structure. Their strength as a tool lies in evaluating the significance of isolated individual parameters under "controlled conditions" logistically impossible to achieve in the real world. Such information can help man order his priorities on selection traits.

ACKNOWLEDGMENT

We wish to recognize L. H. Allen, Jr. for his invaluable help in this research effort and his many suggestions in the preparation of the manuscript. Finally, we thank him for presenting this paper, substituting for the senior author, at the 1971 American Society of Agronomy symposium on Field Soil Moisture Regime, 16 August, in New York City.

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