Simulation of water transport in the soil-plant-atmosphere system

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Simulation of water transport in the soil-plant-atmosphere system

Guo, Yimei, Ph.D.
Iowa State University, 1992
Simulation of water transport in the soil-plant-atmosphere system

by

Yimei Guo

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Iowa State University
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1992
TABLE OF CONTENTS

LIST OF FIGURES v
LIST OF TABLES vii
LIST OF SYMBOLS ix

GENERAL INTRODUCTION 1

1. Why Modeling? 1
2. Soil-Plant-Atmosphere System 2
3. Model Studies 4
4. Explanation of Dissertation Format 7

PAPER 1. SIMULATION OF WATER TRANSPORT IN THE SOIL-PLANT-ATMOSPHERE SYSTEM. I. MODEL DEVELOPMENT 8

ABSTRACT 10

INTRODUCTION 11

MODEL DESCRIPTION 15

1. Plant Water Transport 16
   1.1 Root extraction 18
   1.2 Transpiration 21
   1.3 Leaf resistance 22
   1.4 Leaf water potential 25

2. Soil Water and Heat Flow 26
   2.1 Soil water flow 26
   2.2 Soil heat flow 27
3. Energy Budgets
   3.1 Radiation components
   3.2 Sensible heat flux
   3.3 Vapor flux
   3.4 Soil surface energy balance
   3.5 Aerodynamic resistance

NUMERICAL SOLUTION

MODEL RESULTS AND CONCLUSIONS

REFERENCES

PAPER 2. SIMULATION OF WATER TRANSPORT IN THE SOIL-PLANT-ATMOSPHERE SYSTEM. II. MODEL VALIDATION AND SENSITIVITY STUDIES

ABSTRACT

INTRODUCTION

METHODS AND MATERIALS

MODEL VALIDATION

SENSITIVITY STUDIES
   1. Soil Moisture Conditions
   2. Atmospheric Conditions
   3. Root Resistances
   4. Soil Resistance
   5. Soil Types
   6. Plant Water Capacitance

DISCUSSION AND CONCLUSIONS

REFERENCES
# PAPER 3. SIMULATION OF LEAF RESISTANCE RELATED TO ENVIRONMENTAL FACTORS AND LEAF WATER POTENTIAL

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>93</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>94</td>
</tr>
<tr>
<td>MODEL DEVELOPMENT</td>
<td>98</td>
</tr>
<tr>
<td>MODEL VALIDATION</td>
<td>102</td>
</tr>
<tr>
<td>DISCUSSION AND CONCLUSIONS</td>
<td>105</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>108</td>
</tr>
<tr>
<td>GENERAL SUMMARY</td>
<td>120</td>
</tr>
<tr>
<td>ADDITIONAL WORK</td>
<td>122</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>123</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>127</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>128</td>
</tr>
<tr>
<td>APPENDIX B</td>
<td>161</td>
</tr>
<tr>
<td>APPENDIX C</td>
<td>163</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Paper 1.

Figure 1. Scheme of the soil-plant-atmosphere system 47
Figure 2. Analogue of water and heat transfer in the soil-plant-atmosphere system 48
Figure 3. Initial and simulated soil moisture profiles 49
Figure 4. Root density and simulated root extraction accumulation on the 4th and 9th day 50
Figure 5. Initial and simulated soil temperature profiles 51
Figure 6. Simulated energy partition of the canopy and the soil surface
- \( R_{nc}, R_{net} \): net radiation for the canopy and the soil surface
- \( \lambda E_T, \lambda E_g \): latent heat from the canopy and the soil surface
- \( H_f, H_g \): sensible heat from the canopy and the soil surface
Figure 7. Simulated diurnal pattern of the temperatures
- \( T_a, T_{af}, T_f, T_g \): are temperature of the atmosphere, the canopy air, the leaf, and the soil surface
Figure 8. Simulated diurnal variation of the vapor pressures
- \( e_a, e_{af}, e_f, e_g \): are vapor pressure of the atmosphere, the canopy air, the leaf, and the soil surface
Figure 9. Variation of leaf water potential, soil water potential, transpiration and evaporation over a 9-day simulation
- \( \psi_l, \psi_s \): leaf and soil water potential
- \( E_T, E_g \): transpiration and evaporation rate
Figure 10. Simulated effect of plant water capacitance (\( C_p = 10^{-5} \) m m\(^{-1} \))
- a. Daily variation of leaf water flux
- b. Daily variation of transpiration and root extraction
Figure 11. Description of a feedback process of leaf water response to atmospheric stress
- \( \psi_l, \psi_s \): leaf and soil water potential
- \( E_p, E_T \): potential and actual transpiration
- \( r_l \): leaf resistance

Paper 2.

Figure 1. Fitted soil water retention curves using measurements from Mason et al. (1980) and parameters in Table 2 78
Figure 2. Soil moisture profiles of July 31, Aug. 3 and 8, for .25 and 1.0 m rows

Figure 3. Diurnal variation of soil water potential ($\psi_s$), leaf water potential ($\psi_l$), transpiration ($E_T$) and evaporation ($E_g$) for the 9-day simulation

Figure 4. Comparison of measured and simulated leaf water potential
a. 0.25 m rows; b. 1.0 m rows

Figure 5. Comparison of measured and simulated evapotranspiration
a. 0.25 m rows; b. 1.0 m rows

Figure 6. Comparison of measured and simulated soil moisture profiles
a. 0.25 m rows; b. 1.0 m rows

Figure 7. Simulated and measured leaf water potential on a cloudy day

Figure 8. Effect of soil moisture on leaf water potential
(soil water potential $\psi_s =-12$, -27, and -55 m)

Figure 9. Effect of soil moisture on canopy resistance
(soil water potential $\psi_s =-12$, -27, and -55 m)

Figure 10. Effect of soil moisture on transpiration
(soil water potential $\psi_s =-12$, -27, and -55 m)

Figure 11. Effect of atmospheric demand on leaf water potential
(potential transpiration $E_p = 2.4$, 4.6, and 9.7 mm day$^{-1}$)

Figure 12. Effect of root radial resistivity on leaf water potential
(root radial resistivity $P_r = 1 \times 10^{11}$, $5 \times 10^{11}$, and $1 \times 10^{12}$ m s$^{-1}$)

Figure 13. Effect of soil type on leaf water potential
(sand, loam, and clay)

Figure 14. Effect of soil type on transpiration
(sand, loam, and clay)

Figure 15. Effect of plant water capacitance on leaf water flux
(plant water capacitance $C_p = 1 \times 10^{-6}$, $5 \times 10^{-6}$, and $1 \times 10^{-5}$ m m$^{-1}$)

Figure 16. Diurnal variation of leaf water potential, root extraction and transpiration for a large leaf water capacitance $C_p = 10^5$ m m$^{-1}$

Figure 17. Diurnal variation of leaf water potential and transpiration for zero leaf water capacitance
Figure 18. Effect of leaf water capacitance on leaf water potential (plant water capacitance $C_p = 1 \times 10^{-6}$, $5 \times 10^{-6}$, and $1 \times 10^{-5}$ m m$^{-1}$, soil water potential $\psi_s = -26$ m)

Paper 3.

Figure 1. Comparison of simulated and measured leaf resistance related to irradiance under high water potential (measured data adapted from Turner and Begg (1973))

Figure 2. Comparison of simulated and measured leaf resistance related to leaf water potential under high irradiance (measured data adapted from Turner (1974)).

Figure 3. Diurnal variation of radiation (adapted from Choudhury and Idso (1985))

Figure 4. Diurnal variation of leaf water potential (adapted from Choudhury and Idso (1985))

Figure 5. Comparison between simulated and measured diurnal variation of leaf resistance (measured data adapted from Choudhury and Idso (1985))

Figure 6. Effect of irradiance on leaf resistance for different levels of leaf water potential

Figure 7. Effect of leaf water potential on leaf resistance for different levels of irradiance

Figure 8. Effect of soil water potential on canopy resistance
LIST OF TABLES

Paper 2.

Table 1. Soil physical properties of Ida silt loam, Castana, Iowa 75
Table 2. Parameters for calculating the soil water retention and hydraulic conductivity 76
Table 3. Root length density distribution (104 m m$^3$) 77
Table 4. Climate data for Castana, Iowa 78
Table 5. Parameters used for model validation 79
Table 6. Comparison between soil and root resistances 80

Paper 3.

Table 7. Parameters in equation (11) (from Figures 1 and 2) 119
LIST OF SYMBOLS

c, heat or moisture transfer coefficient in the canopy.

c_{Hc}, c_{Hg}, heat or moisture transfer coefficient above the canopy and underneath the canopy.

C_l (m m^{-1}), leaf water capacitance.

C_p (J kg^{-1}C^{-1}), specific heat capacity.

c_s (J m^{-2}C^{-1}), soil heat capacity.

d (m), distance of displacement.

D (m^2 s^{-1}), soil hydraulic diffusivity.

e_a, e_{af}, e_s, e_l (kPa), vapor pressure of the atmosphere, the canopy air, the ground, and the leaf.

e_{aat}, e_{aat} (kPa), saturated vapor pressure of the ground and the leaf.

E_a, E_t, E_g (m s^{-1}), vapor flux rate from the canopy to the atmosphere, leaf transpiration rate, and surface evaporation rate.

h_a (kg m^{-3}) absolute air humidity.

H_a, H_t, H_g (W m^{-2}), sensible heat from the canopy air, leaf, and the ground.

g (m s^{-2}), gravitation acceleration.

I_R, I_{R_{max}} (W m^{-2}), irradiance and maximum irradiance.

K, K_s (m s^{-1}), soil hydraulic conductivity, and saturated soil hydraulic conductivity.

L, L_i, L', total leaf area index, leaf area index for a canopy strata, and downward accumulated leaf area index.

L_h (J kg^{-1}), specific latent heat.

L_r (m m^{-3}), root length density.

m_c, clay fraction.

P (kPa), atmospheric pressure.

P_a (s m^{-3}), P_r (s m^{-1}), root axial resistivity and root radical resistivity.
\( q_a, q_i (kg \ kg^{-1}) \), specific humidity of the atmosphere and the leaf.

\( q_{la}, q_{ri}, q_{sl} \) and \( q_{kr} (m \ s^{-1}) \), water flux from leaf to the atmosphere, from roots to the leaf, from soil to the leaf, and from soil to roots.

\( r_a, r_i, r_g, r_l, r_r, r_s, r_{sl} \) and \( r_x (s \ m^{-1}) \), resistance of atmosphere, canopy air, canopy, air underneath the canopy, leaf, root, soil, soil surface and xylem.

\( r_{max}, r_{min}, r_{wmax} (s \ m^{-1}) \), maximum, minimum \( r_i \) without water stress, and maximum \( r_i \) with water stress.

\( R (J \ kg^{-1} \ °C^{-1}) \), ideal gas constant.

\( R_i \), Richardson number.

\( R_{lg}, R_{hb} (W \ m^{-2}) \), longwave radiation at the ground and at the top of the canopy.

\( S_i (m \ s^{-1}) \), root water extraction rate from the cross sectional area of the \( i \)th soil layer.

\( S_g, S_h (W \ m^{-2}) \), shortwave radiation at the ground and at the top of the canopy.

t (s), time.

\( T, T_a, T_{st}, T_g, T_l (°C) \), temperature of the soil, atmosphere, canopy air, soil surface and leaf.

\( u_a, u_{st} (m \ s^{-1}) \), wind speed above the canopy and within the canopy.

\( W_l (m) \), leaf water content.

\( z_o (m) \), degree of roughness.

\( z_l (m) \), depth of the mid point of the \( i \)th soil layer.

\( \alpha_i, \alpha_g \), albedo of the canopy and the ground.

\( \Delta z (m) \), soil depth increment.

\( \delta \), solar elevation.

\( \epsilon_c, \epsilon_g \), emissivity of the canopy and the ground.

\( \theta, \theta_i \), and \( \theta_s (m^3 \ m^{-2}) \), soil water content, residual soil water content, and saturated soil water content.

\( \lambda (W \ m^{-1} \ °C^{-1}) \), soil heat capacity.
\( \rho_a, \rho_w \) (kg m\(^{-3}\)), density of dry air and liquid water.

\( \rho_s \) (g cm\(^{-3}\)), soil bulk density.

\( \sigma_c \), canopy shading factor.

\( \Phi \), correction factor for atmospheric stability.

\( \tau \), radiation attenuation coefficient.

\( \psi_c \) (m), critical leaf water potential.

\( \psi_l, \psi_r, \) and \( \psi_s \) (m), water potential of leaf, roots, and soil.

\( \psi_{lm} \) (m), leaf water potential at which \( r \) reaches \( r_{\text{wmax}} \).
GENERAL INTRODUCTION

1. Why Modeling?

Crop production is influenced by many environmental factors, including soil moisture supply and atmospheric conditions. Two sources of information may be used for crop management. One is a field experiment, and the other is simulation results. Field measurements provide the basic information about crop response to environmental factors and management methods. However, it is very difficult to run a comprehensive field experiment because of the variation of the environmental factors and the limitation of instrumentation. Simulation, based on the field measurements, can be used to investigate the whole crop system behavior and the interaction between system components. Furthermore, a reliable and well-validated model can be used for forecasting and to provide information for crop management.

Practical utilization of a model requires validation. As pointed out by Hillel (1991), "improved procedures are greatly needed for statistical validation of models. The same degree of rigor is needed in validation as in the initial development of the models".

Field experiments provide basic information about the mechanism of each process, and models integrate the known mechanism or theory about each process and simulate the behavior of the system. However, model outputs need to be validated against field measurement. Therefore, field measurements and model simulation are each important in the sense of understanding nature.

A model (Hanks and Ritchie, 1991) is defined as a small imitation of the real thing, or as a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs. There are two primary kinds of models, descriptive and explanatory. According to Penning de Vries et al. (1989), a descriptive model defines the behavior of a system in a simple
manner. The model reflects little or none of the mechanisms that are the cause of the behavior. An explanatory model consists of a quantitative description of the mechanisms and processes that cause the behavior of a system. Explanatory models are of three types: preliminary, comprehensive and summary. Preliminary models have a simple structure because insights at the explanatory level are vague. Comprehensive models represent a system in which essential elements are thoroughly understood, and incorporate much of this knowledge. Summary models are abstractions of comprehensive models, which are easier or simplified for application. The model I developed in this work for simulating water transport in the soil-plant-atmosphere system is considered as a comprehensive model, however, with preliminary descriptions of some less understood processes and summary simplifications used when expedient.

2. Soil-Plant-Atmosphere System

Crops grow in the environment of soil and atmosphere. Soil, plant, and atmospheric conditions influence crop production. Water transport from soil through the plant and into the atmosphere is closely related to plant growth and plant response to environmental stress. Plant root extraction of soil moisture and transpiration are mostly controlled by atmospheric demand and is modified by plant factors. As stated by Hillel (1982), the loss of water vapor by plants is not in itself an essential physiological function, nor a direct result of the living processes within plants.

The driving force of plant water transport is the water potential difference between the soil, the plant and the atmosphere. As an approximation, soil water potential may be near -50 m (1 m = 9.8 kPa), leaf water potential may be -120 m, and the atmosphere water potential may be -3000 m at 30°C. This water potential gradient drives water from the soil through the plant, and into the atmosphere. Along this pathway, soil resistance, root resistances, xylem and leaf resistances
exist. Components of leaf resistance are common to water vapor loss and to carbon dioxide uptake; this is a major linkage of water loss and physiological factors.

Atmospheric conditions, including radiation, humidity, and wind speed, determine the driving force of the water transport from soil, through plants, and into the atmosphere. Under conditions of high atmospheric water demand, such as high temperature and low humidity, a large water potential gradient develops between leaves and the atmosphere inducing high rates of vapor transfer into the atmosphere. When soil water is plentiful, transpiration may keep leaf temperature near the optimum range. When soils are dry, leaf water potential may drop and stomates may close preventing further water loss into the atmosphere. This results in a leaf temperature increase and possible heat stress. Atmospheric conditions control not only the maximum rate of transpiration, but also influence plant water and temperature status.

Soil moisture is the primary water supply for terrestrial plants. Under moist soil conditions, plants seldom experience water stress. Under dry soil conditions, plants have a large chance of water and heat stress. Soil hydraulic properties influence the availability of soil water to plant roots. Different soil types with various soil textures and structures have different hydraulic properties, and therefore, have different water availability. Soils with high hydraulic conductivity have small resistance to root water uptake.

Plant properties also influence plant water transport. Root density and root resistivity determine the potential for root water uptake. Leaf resistance is a biological control of transpiration. Leaf area index and canopy structure influence energy distribution, and hence affect potential water transport. Plant water capacitance affects the diurnal pattern of plant water transport and leaf water status.
In general, in the soil-plant-atmosphere system atmospheric conditions determine the maximum possible evapotranspiration rate, soil moisture content and soil hydraulic properties control actual root extraction and root density, root resistance and leaf resistance limit water transport from root to leaf and into atmosphere.

3. Model Studies

Simulation of water transport in the soil-plant-atmosphere system involves the processes of soil water and heat transport, root extraction, transpiration, and energy partitioning at the soil surface and in the canopy, as well as some functions related to stomatal resistance and root resistance. Soil water and heat transport have been well studied and many coupled heat and water transport models have been developed (Philip and De Vries, 1957; Klute, 1973; Van Bavel and Hillel, 1976; Chung and Horton, 1987; Nassar and Horton, 1989; Hanks, 1991). Root extraction and transpiration have also been extensively investigated as reviewed by Hillel (1980), Molz (1981) and Campbell (1991), but the stomatal mechanism and the root extraction function remain less than fully understood. Energy balance for a single layer canopy is well studied as presented by Deardorff (1978) and Dickinson et al. (1986). Besides the modeling of individual process, some studies have attempted to simulate the whole soil-plant-atmosphere system (Cowan, 1965; Ehleringer and Miller, 1975; Van Bavel and Ahmed, 1976; Federer, 1979; Zur and Jones, 1981; Johnson et al., 1991). However, most simplified some of the processes involved, especially energy balance, root extraction, stomatal resistance, and root resistance. With better understanding the system, it is possible to integrate the system of water transport in the soil-plant-atmosphere continuum to systematically describe crop water response to environmental stress.
Transpiration has long been studied and early simple empirical methods have generally been replaced by detailed models which more closely represent the physical and biological processes involved. The physical aspect of transpiration has been intensively studied (Penman, 1948; Monteith, 1965; Thom, 1975; Sharma, 1985), but the physiological aspect of transpiration is still not well understood, especially canopy resistance. Some authors have related canopy resistance to radiation, vapor pressure deficit, leaf water potential, and soil water potential (Jarvis, 1976; Deardorff, 1978; Hansen, 1979; Choudhury and Monteith, 1986; Bakker, 1991; Kim and Verma, 1991). Scaling canopy stomatal resistance from single leaf resistance was addressed in some studies (Jarvis and Mcnaughton, 1986; Baldocchi et al., 1991). The mechanism of stomatal resistance change is still unclear. At present, simulation of leaf resistances is at an empirical level. An empirical model based on plant characteristics is proposed in this study and the effect of environmental factors on leaf resistance is presented.

Root extraction is another less understood process. Many conceptual models have been developed to describe root water uptake. These models (Taylor and Klepper, 1978) assume either explicitly or implicitly, that uptake rate is a function of (a) water potential gradient between soil and roots, (b) plant root length density, (c) root resistance per unit of root length, and (d) transpiration rate. The models often differ only in assumptions incorporated to simplify calculations. A model describing root uptake was proposed by van den Hornert (1948); he stated that under steady state conditions the rate of water flow through a plant part was directly proportional to the water potential difference across that part and inversely proportional to the water flow resistance. One of the earliest detailed quantitative studies of water extraction by plant roots was that of Gardner (1964). The model developed by Gardner considers a root to be an infinitely long cylinder of uniform radius and water absorbing properties; this approach is called the microscopic approach. Following the lead of
Whisler et al. (1968), Molz and Remson (1970) suggested a macroscopic approach that combines the Darcy-Richards equation with a sink term representing water extraction by plant roots. The general form of this root extraction expression was proposed as a function of water potential difference between soil and root, and the resistance of soil and root (Whisler et al., 1968; Nimah and Hanks, 1973; Feddes et al., 1974; Hillel et al., 1976; Herkelrath et al., 1977; Molz, 1981; Reid and Huck, 1990; Campbell, 1991). Differences between the functions used by various authors are mainly in the determination of the resistance of the roots and of the soil. Some authors assumed that the dominant resistance to water flow in the soil-root system resides in the soil surrounding the root rather than in root tissue (Gardner, 1964; Whisler et al., 1968; Molz and Remson, 1970; Nimah and Hanks, 1973; Feddes et al., 1974). However, Newman (1969) and others (Taylor and Klepper, 1975; Molz, 1975; Rowse et al., 1978; Meyer et al., 1978) have presented both experimental and theoretical evidence that the hydraulic resistance of root usually exceeds the resistance of the soil immediately surrounding the roots. Several studies (Reicosky and Richie, 1976) suggest that either term can be important, the root resistance usually being more significant at high soil water potential and soil resistance at low water potentials. Determination of soil resistance and root resistance is still primarily at the empirical level.

Plant water storage effects are usually neglected by models. Under this situation, the amount of water extracted by roots from the soil is equal to the transpiration flux. However, Nobel (1986) and others (Waring and Running, 1978; Running, 1980; Nobel, 1986; Calkin and Nobel, 1986) noted that plant water capacitance, when water is removed from storage, does contribute to water flow in the plant. Large plant capacitances lead to large time lags between changes in transpiration and changes in water potential as well as a damping of oscillations in water potential. Nobel (1986) indicated that water relation models should incorporate plant capacitance representative of water
storage. However, quantitative determination of plant water capacitance is still not available, and the sensitivity of plant water status to plant water capacitance is not fully tested. In this study, potential effects of plant water capacitance are considered.

The purpose of this dissertation is to develop a mechanistic model of water transport in the soil-plant-atmosphere system with the best available data, and to use the model to study systematically water transport process and plant water response to environmental stress.

4. Explanation of Dissertation Format

The first part of this dissertation is a general introduction in which the soil-plant-atmosphere system has been described along with a brief literature review of models related to plant water transport. The following three parts are in the form of papers to be submitted for publication. The first paper describes the development of the model and some model features. The second paper presents the model validation and sensitivity studies. The third paper describes and validates a model simulating stomatal resistance related to leaf water potential and irradiance. A summary of the results from the three papers is presented after the last paper. The references following the General Summary are those cited in the General Introduction. Appendix A is the source code of the model used in papers one and two. The data set and format are in Appendix B, and sample output and format are in Appendix C. The first author of the three papers played the major role in the research and writing of the papers.
PAPER 1

SIMULATION OF WATER TRANSPORT IN THE SOIL-PLANT-ATMOSPHERE SYSTEM

I. MODEL DEVELOPMENT
Simulation of water transport in the soil-plant-atmosphere system

I. Model development

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(to be submitted to Agricultural and Forest Meteorology)
Understanding of water transport in the soil-plant-atmosphere system is important for crop production and soil water management. A dynamic model of water transport in the soil-plant-atmosphere system was developed as a research tool to study soil water availability and crop water response. The model mechanistically describes root extraction, transpiration, leaf water flux, soil water and heat transport, and energy partitioning in the canopy and at the soil surface. Leaf water potential and leaf resistance are also determined. The model inputs are: weather data (air temperature, dew point temperature, wind speed and solar radiation); initial soil moisture and soil temperature profiles; plant characteristics (leaf area index, shading factor, albedo and emissivity); root density; and soil hydraulic parameters. Principal outputs include: leaf resistance, leaf temperature, soil moisture profile and evapotranspiration rate. Diurnal patterns of system energy, temperature, and vapor pressure, and a feedback process of leaf water response to atmospheric stress are described. The model simulates basic system features and a complicated feedback process. The model may be useful as a research tool for studying plant water response to environmental factors and plant characteristics.
INTRODUCTION

Water transport from soil through plants and into the atmosphere is one of the major processes influencing plant growth and survival. The increasing importance of water use in crop production demands integrated studies of water transport in the soil-plant-atmosphere system. A better understanding of the processes can lead to better management techniques for efficient water use, crop management, water quality and production risk assessment.

Water transport in the soil-plant-atmosphere system includes the following processes: soil water and heat transport, root extraction, plant water flux, transpiration, energy partitioning at the soil surface and at the canopy. These processes are influenced by many factors, including atmospheric demand, soil water availability, plant hydraulic characteristics, and canopy structure. Atmospheric conditions limit the maximum rate of water transfer from the soil into the atmosphere. Soil water supply influences the actual water transport. Above-ground plant characteristics and rooting systems determine the capability of the plant to absorb and transfer water. No simple relationship can be used to describe this complicated process. Several numerical models have been developed to simulate different aspects of the system. Some models simulate root water extraction processes (Molz and Remson, 1970; Nimah and Hanks, 1973; Hillel et al., 1976; Feddes et al., 1974; Herkelrath et al., 1977; Rowse et al., 1983; Prasad, 1988; Campbell, 1991; Lafolie et al., 1991). Some simulate soil heat and water transport (Chung and Horton, 1987; Hanks, 1991); others focus on stomatal resistance or on plant capacitance (Calkin and Nobel, 1986; Lynn and Carlson, 1990). A few include osmotic adjustment, plant capacitance and plant responses to water stress (Fernandez and McCree, 1991). Some models use a simplified energy budget over a canopy to simulate the whole system of water transport (Cowan, 1965; Nimah and Hanks, 1973; Jones, 1978;
Federer, 1979; Hansen, 1979; Zur and Jones, 1981). A layered canopy model was proposed by van Bavel and Ahmed (1976), and later modified by adding energy balance (Lascano et al., 1987). Most models omit at least one important aspect of the soil-plant-atmosphere system. To study further the whole system and the interaction between each component, a comprehensive model is desired. As a better understanding of the overall system is obtained, it is possible to develop more comprehensive and mechanistic models to study systematically water transport processes.

Water transport in the soil-plant-atmosphere system is usually considered as a steady state flow driven by a water potential gradient (van den Honert, 1948; Cowan, 1965). At steady state, the amount of water extracted by roots from the soil is equal to the transpiration. As a result, leaf water content is kept constant. Leaf water storage or capacitance, however, can contribute to water flow in the plant (Nobel, 1986; Calkin and Nobel, 1986). Evidence for the importance of capacitance in water transfer within plants comes mostly from reports of time lags between changes in transpiration rate and in leaf water potential for trees (Waring et al., 1979; Running 1980). Large plant capacitances lead to large time lags between changes in transpiration and changes in water potential as well as a damping of oscillations in water potential (Calkin and Nobel 1986). As indicated by Nobel (1986), water relation models should incorporate plant capacitance to represent water storage. Under this situation, plant water content changes with time, and is equal to the flux difference between root extraction and transpiration. In this study, the effect of plant water capacitance will be included.

The driving force for the movement of liquid water into the plant is defined to be the water potential gradient of leaf and soil. Leaf water potential influences root water extraction and leaf
transpiration. Changes in leaf water potential may reflect a change in atmospheric demand or in soil water supply. Leaf water potential is profoundly influenced by plant hydraulic properties and by environmental factors, and has a direct effect on stomatal closure which affects water vapor diffusion from the leaf into the atmosphere. The determination of leaf water potential is, therefore, essential to the simulation of water movement in the soil-plant-atmosphere system. Some regression relationships between leaf water potential and several environmental factors have been proposed (Jarvis, 1976; Jones, 1978; Stanley et al., 1981). However, leaf water potential has a diurnal change (Klepper 1968; Reicosky et al., 1975) that can introduce appreciable variation into a simple regression model (Jarvis 1976). Attempts to correlate leaf water potential with particular environmental variables are generally of only limited success. A systematic modeling study of the effect of leaf water potential on water transport is desirable.

Recent studies suggest that root water potential, instead of leaf water potential, triggers stomatal opening (Zhang et al., 1987; Gollan et al., 1986) and, thus, controls water transport. This function, however, is not yet well defined, because of the difficulty in observing actual leaf water potential, root water potential, soil water potential, and stomatal resistance concurrently in the field. In this study, we still consider leaf water potential, instead of root water potential, as the driving force of plant water transport.

Plant resistance and soil resistance are important for water transport from soil, into root, through xylem, and to the transpiring surface. Some studies assume that the dominant resistance to water flow in the soil-root system resides in the soil surrounding the root rather than in root tissue (Gardner, 1964; Whisler et al., 1968; Molz and Remson, 1970; Nimah and Hanks, 1973; Feddes et al., 1974). However, Newman (1969), and others (Taylor and Klepper, 1975; Molz, 1975; Rowse et al., 1978; Meyer et al., 1978) have presented both experimental and theoretical evidence that the
hydraulic resistance of the root usually dominates the resistance of the soil immediately surrounding the roots. Several studies (Reicosky and Richie, 1976; Hillel et al., 1976; Reid and Huck, 1990) suggest that either term can be important, the root resistance usually being significant at high soil water potential while soil resistance dominates at low water potentials. The behavior of the resistances in the system is important to understanding of the system.

Stomatal resistance controls water vapor diffusion from the leaf into the atmosphere. Many factors influence stomatal aperture, including irradiance, leaf water potential, vapor pressure difference between leaf and atmosphere, leaf temperature, etc. This process is complex and simulation of it is essential for plant water transport modeling.

Plant water stress is influenced by atmospheric and soil water stress, and by the ability of the plant to accommodate stress. By studying the effects of soil moisture, atmospheric demand, and plant hydraulic properties on leaf water potential, the process of plant response to water stress can be better understood.

The objectives of this paper are: (1) to describe a dynamic model of water transport in the soil-plant-atmosphere system; and (2) to delineate system features and feedback processes. A subsequent paper, model validation and sensitivity to environmental factors and plant characteristics, will be presented.
MODEL DESCRIPTION

The soil-plant-atmosphere system (Figure 1) is considered here as n layers of soil profile with a rooting depth of d, a single layer of canopy with a leaf area index of L and a shading factor of σ, and the free atmosphere. The lower boundary of the soil profile is set to the depth of z, at which water flux is considered equal to zero and temperature is constant.

The model describes the processes of energy and mass transport of the system. The processes include the energy partitioning between the canopy and the soil surface, sensible heat and latent heat transfer from the canopy and soil surfaces, soil heat and water transport, root water extraction and plant water content changes. Mass and energy fluxes in the system are assumed to follow Ohm's law in that flux is proportional to the potential difference and inversely proportional to the resistance of the pathway. The electrical analogue used in the model is shown as Figure 2. Water transport from the soil through the plant and into the atmosphere is divided into three sub-processes: root extraction, plant water flux, and transpiration. The pathways for the three sub-processes are: (1) from soil to root xylem; (2) from roots to leaves; and (3) from leaves into the atmosphere. The driving force for root extraction is the water potential gradient between the soil (ψ) and root (ψr); for plant water flux, the potential gradient between root (ψr) and leaf (ψl); and for transpiration, the vapor pressure gradient between leaf (eL) and the atmosphere (eA). The resistances along the total pathway are: (1) soil resistance (rS) and root radial resistance (rR); (2) root axial resistance (rA) (above ground xylem resistance is ignored); and (3) leaf stomatal resistance (rS) and canopy bulk air resistance (rB). For leaf water flux change, leaf water capacitance C is considered. Evaporation from the soil surface is driven by the vapor pressure difference between the soil surface and the atmosphere. The
resistances along the evaporation pathway are soil surface resistance ($r_s$) and air resistance underneath the canopy ($r_a$). Vapor transfer from canopy air into the free atmosphere is driven by the vapor pressure difference between the canopy air ($e_a$) and the free atmosphere ($e_f$), and the associated resistance is the free air resistance ($r_f$).

The driving force for heat transfer from the leaves to the canopy air is the temperature gradient between the leaves ($T_l$) and the canopy air ($T_c$), and the resistance is the canopy air resistance ($r_c$) (air resistances to heat transfer is assumed the same as to vapor transfer). Similarly, heat transfer from the soil surface to the canopy air and from the canopy air to the free atmosphere corresponds to the temperature gradients and the resistances of the sub-canopy air ($r_k$) and the free atmosphere ($r_f$).

The basic model assumptions are: (1) one representative leaf water potential value is used for the canopy (Hillel et al., 1976; Reid and Huck, 1990; Campbell, 1991); (2) stomatal resistance is a function of environmental factors (Jarvis, 1976; Lynn and Carlson, 1990); (3) above ground xylem resistance is assumed negligible compared to root radial resistance and leaf resistance (xylem resistance is a factor of 10 smaller for potato (Campbell, 1985)); and (4) all roots are equally permeable to water uptake (Arya et al., 1975).

1. Plant Water Transport

Plant water content change per unit volume is described by mass balance of the form:

\[
\text{Water content change} = \text{in-flux} - \text{out-flux}
\]

Leaf water content $W_l$ (m) change per unit area is described as the difference of in-flux $q_{r-l}$ (m s$^{-1}$) (from root to leaf) and out-flux $q_{l-a}$ (m s$^{-1}$) (from leaf to atmosphere):
\[
\frac{dW_l}{dt} = q_{r,l} - q_{l,a}
\]  \hspace{1cm} (1)

where subscript \( l \) stands for leaf, \( r \) for root, and \( a \) for atmosphere.

By assuming that root and xylem water storage is negligible, water flux from soil to root, root to leaf, and soil to leaf, are equal to each other:

\[
q_{x,r} = q_{r,l} = q_{s,l}
\]  \hspace{1cm} (2)

so (1) becomes:

\[
\frac{dW_l}{dt} = q_{s,l} - q_{l,a}
\]  \hspace{1cm} (3)

where the subscript \( s \) stands for soil.

According to Ohm's law, water flux is determined by the driving force and resistance along the pathway:

\[
\text{flux} = \frac{\text{driving force}}{\text{resistance}}
\]

therefore, flux from soil to leaf \( q_{s,l} \) is then described as:

\[
q_{s,l} = \frac{\psi_s - \psi_l}{r_s + r_r + r_x}
\]  \hspace{1cm} (4)

where \( \psi_s \) is soil water potential (m), \( \psi_l \) leaf water potential (m) (in meter, 1 m = 9.8 kPa), \( r_s \) soil resistance (s), \( r_r \) root radial resistance (s), and \( r_x \) root axial resistance (s) (above ground xylem resistance is neglected). The dimensional notation used for water potential and root resistance in these equations follows that of Reid and Huck (1990). Flux \( q_{l,a} \) is the transpiration rate, \( E_T \) (m s\(^{-1}\)), which will be described later.
Leaf water content $W$ (m) can be related to leaf water potential $\psi$ (m) by water capacitance $C$ (m m$^{-1}$):

$$W = C\psi$$  \hspace{1cm} (5)

Substituting (4) and (5) into (3), we obtain:

$$C_T \frac{d\psi_t}{dt} = \frac{\psi_s - \psi_t}{r_s + r_r + r_x} - E_T$$  \hspace{1cm} (6)

Equation (6) describes leaf water potential change as a function of root water uptake rate and transpiration rate. The first term on the right hand side of equation is called root extraction term ($S$).

We can rewrite (6) to:

$$C_T \frac{d\psi_t}{dt} = S - E_T$$  \hspace{1cm} (7)

Equation (6) or (7) is used to solve for leaf water potential, $\psi_t$, iteratively as $\psi_t$ also appears in the ET expression, as will be shown later.

This study treats $C_I$ as a constant although Cowan (1972) pointed out some potentially significant differences between plant water capacitance and the electrical analogue used in his model. A constant value is a reasonable approximation over the range of leaf water potentials commonly encountered (Jones, 1978; Calkin and Nobel, 1986).

Each component in equation (7) is determined as follows.

1.1 Root extraction

Root water uptake rate is defined in (7) as the $S$ term. Because of variability of soil structure, root distribution and soil water potential, the soil profile is considered as n horizontal
layers. Root water uptake rate $S_i$ (m s$^{-1}$) from the cross sectional area of the soil layer $i$ with depth of $\Delta z_i$ is adapted from Reid and Huck (1990):

$$S_i = \frac{\psi_{si} - \psi_i}{r_{si} + r_{ri} + r_{xi}}$$

(8)

where $\psi_{si}$ is soil water potential in the $i$th layer (m), $r_{si}$ is soil hydraulic resistance (s), $r_{ri}$ is resistance (s) to water flow radially across the roots, and $r_{xi}$ is crop axial resistance (s) to flow from the $i$th layer to the leaves. The total root extraction $S = \Sigma S_i$.

Soil water potential is described as a function of soil volumetric water content by (Van Genuchten, 1980):

$$\psi_{si} = \left(\frac{\theta_i - \theta_{ri}}{\theta_{si} - \theta_{ri}}\right)^{1/n}$$

(9)

where $\psi_{si}$ is soil matric potential, $\theta_{si}$ and $\theta_{ri}$ are soil moisture content (m$^3$ m$^{-3}$), saturated soil moisture (m$^3$ m$^{-3}$) and residual soil moisture (m$^3$ m$^{-3}$), respectively. Empirical constants $a$ and $n$ are dependent upon soil type.

Soil resistance to water uptake is inversely related to the root density $L_{ri}$ (m m$^{-3}$) and hydraulic conductivity of soil $K$ (m s$^{-1}$) (Gardner, 1964; Cowan, 1965). Following Reid and Huck (1990):

$$r_{si} = \frac{1}{B K L_{ri} \Delta z_i}$$

(10)

where $B$ is the root length activity factor defined as:

$$B = \frac{2\pi}{\ln((\pi L_{ri})^{-1/2}/r)}$$

(11)

where $r$ is root radius.
There is limited understanding of the physical expression of plant resistance. Generally, it is calculated indirectly (Reicosky and Richie, 1976). Here root radial resistance $r_r$ is estimated following Reid and Huck (1990):

$$r_r = \frac{P_r(\theta_{oi} - \theta_i)}{L_{vi} \Delta z_i}$$

(12)

where $P_r$ is root radial resistivity (s m$^{-1}$), $\Delta z_i$ is thickness of the $i$th soil layer (m). Use of $(\theta_{oi}/\theta_i)$ accounts for the fraction of the root surface not in contact with water filled soil pores and hence unable to directly absorb water.

As pointed out by Reid and Huck (1990), it is difficult to estimate root axial resistance accurately unless the precise rooting pattern of the crop is known. However, it can be approximated by assuming that its principal component is associated with water transfer from the center of a soil layer to the base of the plant stem. According to Klepper et al. (1983), axial resistance ($r_a$) can be described as:

$$r_a = \frac{P_a \Delta z_i}{0.5/L_{vi}}$$

(13)

where $P_a$ is root axial resistivity (s m$^{-1}$), and $z_i$ depth of the midpoint of the $i$th soil layer. At a given depth, the number of roots which connect directly to the stem base is a fraction ($f$) of the total number of roots crossing a horizontal plane at that depth. After Klepper et al. (1983), $f=0.22$.

The above root extraction model assumes that all parts of the root system are equally permeable to water. This is clearly an over simplification (Taylor and Klepper, 1973; Arya et al., 1975). According to Taylor and Klepper (1973), root water uptake per centimeter of root was greater at lower root densities than at higher root densities. This was because the roots were younger and more permeable at low root densities than at high root densities. Because of the limited
understanding of root activity, and to avoid excessive complexity, all roots are considered equally permeable for this study.

1.2 Transpiration

Transpiration is influenced by atmospheric water demand, soil water supply, leaf resistance and root resistances. Transpiration of water (\(E_r\)) in m s\(^{-1}\) is described by the method of bulk vapor transfer as (Deardorff, 1978):

\[
E_r = \frac{\rho_a (q_l - q_a)}{\rho_w \, r_c + r_b}
\]  

where \(q_l\) and \(q_a\) are specific humidity (kg kg\(^{-1}\)) of leaf and the atmosphere, \(\rho_a\) and \(\rho_w\) are density (kg m\(^{-3}\)) of dry air and water vapor, respectively. Canopy resistance is \(r_c\) (s m\(^{-1}\)) and \(r_b\) is canopy air resistance (s m\(^{-1}\)). Latent heat flux (W m\(^{-2}\)) is then defined as: \(\lambda E = \rho_w L_a E\), where \(L_a\) is the specific latent heat (J kg\(^{-1}\)).

Specific humidity (\(q\)) is related to vapor pressure \(e\) (kPa) by (Rosenberg et al. 1983):

\[
q = \frac{0.622 e}{p}
\]  

where \(p\) is standard atmospheric pressure (kPa).

Substituting (15) into (14):

\[
E_r = \frac{0.622 \, \rho_a \, e_l - e_a}{p \, \rho_w \, r_c + r_b}
\]  

where \(e_l\) and \(e_a\) are leaf vapor pressure and air vapor pressure.

Leaf vapor pressure can be related to leaf water potential at the equilibrium condition by (Philip, 1957):
where $e_{sat}$ is saturated leaf vapor pressure (kPa), $\psi_i$ is leaf water potential (m), $T_i$ is leaf temperature ($^\circ$C), $g$ is gravitational acceleration (m s$^{-2}$), and $R$ is ideal gas constant (461 J kg$^{-1}$ C$^{-1}$).

Saturated leaf vapor pressure is assumed to be a function of leaf temperature (Rosenberg et al., 1983):

$$e_{sat} = 0.61078 \exp \left( \frac{17.269T_i}{237.3+T_i} \right)$$  \hspace{1cm} (18)

Substituting $e_i$ in equation (16) with (17), we can see that transpiration is a function of leaf water potential, leaf resistance, leaf temperature, air vapor pressure and air resistance. Both canopy and atmospheric conditions affect transpiration. However, from equation (18) we observe that leaf water potential has little effect on leaf vapor pressure for a large range of $\psi_i$ (e.g., at $T_i = 30^\circ$C, $\psi_i = -150$ m, $e_i$ is 98.9% of $e_{sat}$; at $\psi_i = -300$ m, $e_i$ is 97.9% of $e_{sat}$). This implies that leaf water potential has little direct contribution to vapor pressure deficit since the leaf is nearly saturated most of the time. Nevertheless, leaf water potential has significant effect on leaf resistance, and thus influences transpiration as will be discussed later.

1.3 Leaf resistance

Leaf resistance depends on many environmental factors, including irradiation, leaf temperature, leaf water potential, soil water potential, vapor pressure difference, CO$_2$ concentration, etc. When the water supply in the root zone is adequate to meet a plant’s needs, stomatal aperture is determined primarily by irradiance and temperature.

Stomatal resistance is almost independent of leaf water potential until leaf water potential
falls below a critical value after which leaf resistance increases rapidly (Kanemasu and Tanner, 1969; Turner, 1974; West and Gaff, 1976; Brown et al., 1976; Hand et al., 1982).

A direct effect of soil moisture on leaf resistance has been described recently (Turner et al., 1985; Gallon et al., 1985). Some have suggested that roots sense the drying of soil and send a message to leaves which induces stomatal closure (Gollan et al., 1986; Zhang et al., 1987; Munn and King, 1988; Tardieu et al., 1991). Soil water deficit may induce stomatal closure even when leaf water potential does not change.

Vapor pressure deficit can also have a direct effect on stomatal resistance in addition to effects induced by decreasing leaf water potential (Lange et al., 1971; Turner et al., 1985; Gollan et al., 1985; Bakker, 1991; Turner, 1991; Alphalo and Jarvis, 1991).

Since the data of direct effects of vapor pressure deficit, soil moisture, and leaf temperature on leaf resistance are not sufficient to develop a function, only their indirect effects related to transpiration and leaf water potential are included. Only direct effects of irradiance and leaf water potential on leaf resistance are considered in this study.

The relationship of leaf water resistance (r$_{1}$ s cm$^{-1}$) to irradiance (IR w m$^{-2}$) and to leaf water potential ($\psi_{l}$ m) is determined as (Guo and Taylor, 1992b):

$$r_{1}=r_{min} \times \left( \frac{\alpha \text{IR}_{\text{max}}}{\text{IR}+\beta \text{IR}_{\text{max}}} \right) e^{-\gamma (\psi_{l}-\psi_{c})} \ (\psi_{\text{lim}}<\psi_{l}<\psi_{c}) \ (19)$$

where $r_{\text{min}}$ is minimum leaf resistance when there is no stress of water or light, $\text{IR}_{\text{max}}$ is saturated IR, $\psi_{c}$ is critical value of leaf water potential $\psi_{l}$ at which leaf resistance starts to increase markedly. When $\psi_{l} > \psi_{c}$, $r_{1} = r_{\text{min}}$, when $\psi_{l} < \psi_{\text{lim}}$, $r = r_{\text{max}}$, $r_{\text{max}}$ is maximum leaf resistance under water stress.
\( \alpha, \beta \) and \( \gamma \) are defined as:

\[
\alpha = \frac{r_{\text{max}}}{r_{\text{max}} - r_{\text{min}}} \tag{20}
\]

\[
\beta = \frac{r_{\text{min}}}{r_{\text{max}} - r_{\text{min}}} \tag{21}
\]

\[
\gamma = \frac{\ln(r_{\text{wmax}}/r_{\text{min}})}{\psi_{\text{im}} - \psi_{\text{c}}} \tag{22}
\]

where \( r_{\text{max}} \) is cuticular resistance, and \( \psi_{\text{im}} \) is the leaf water potential at which \( r_{l} \) reaches \( r_{\text{wmax}} \).

Equation (19) indicates that leaf resistance is only a function of radiation when leaf water potential is above a critical leaf water potential. As leaf water potential decreases to below the critical value \( \psi_{c} \), \( \psi_{t} \) has a significant effect on \( r_{l} \). As mentioned above, in equation (18) \( \psi_{t} \) has little effect on vapor pressure deficit; thus, the effect of \( \psi_{t} \) on transpiration is through its influence on leaf resistance \( r_{l} \). Low \( \psi_{t} \) is a major control on transpiration because severe water stress can result in stomatal closure and, thus, prevent transpiration. However, when leaf water potential is above the critical value, leaf water status does not have any influence on transpiration through either vapor pressure deficit or stomatal opening; therefore, the only factor controlling transpiration is atmospheric demand.

Equation (19) is applied for a single leaf only. For a canopy, irradiance at different levels of canopy should be considered. Following Choudhury and Idso (1985), canopy resistance is described for varied radiation regimes and leaf area indices as (Roberts et al., 1980):
where $i = 1$ to $n$ represents a canopy strata having a leaf area index of $L_i$ and leaf resistance $r_i$. $L'$ is the downward cumulative leaf area index, and $L$ is total canopy leaf area index.

Radiation in the canopy may be expressed as $IR = rIR_o$, where $IR_o$ is radiation at the top of canopy, $r$ is attenuation coefficient of radiation within a canopy, which may be determined by an exponential function (Ross, 1975) as:

$$
\tau = \exp\left(-\frac{\kappa L'}{\sin \delta}\right) \quad (24)
$$

where $\kappa$ is an empirical constant whose values range from 0.21 to 0.6 for maize, depending on solar elevation ($\delta$) and crop structure, 0.7 for sugar beet and 0.32 to 0.5 for winter wheat.

From (19), (23) and (24), we obtain canopy resistance as:

$$
r_c = r_{\text{min}} e^{\gamma (\varphi - \varphi^*)} \left(\frac{\alpha IR_{\text{max}}}{IR\tau' + \beta IR_{\text{max}} L}\right) \quad (25)
$$

where

$$
\tau' = (1 - \exp(-\frac{\kappa L'}{\sin \delta})) \frac{\sin \delta}{\kappa} \quad (26)
$$

1.4 Leaf water potential

Leaf water potential change is a result of water flux differences between root extraction and transpiration as shown in equation (7). Substituting transpiration rate defined in (16) into (7), and
using (8) for root extraction at each soil layer, we can obtain an equation for determining leaf water potential:

\[
C \frac{d\psi_i}{dt} = \sum_{i=1}^{n} \left( \frac{\psi_m(\theta) - \psi_i}{r_m(K_n L_n) + r_n(L_n) + r_m(L_n)} \right) - \frac{0.622 \rho_a}{\rho_w} \left( \frac{e_f(\psi_i, T) - e_a}{r_e(\psi_i, IR, L) + r_b} \right) \tag{27}
\]

In equation (27), all the variables, except \( \psi_h \), can be determined; thus, \( \psi_i \) could be obtained by an iteration method. Transpiration rate and root water uptake from each soil layer can be obtained accordingly. From (27) we can see that leaf water potential change is a function of soil water potential \( \psi_m \), soil hydraulic conductivity \( K_n \), vapor pressure deficit \( (e_f - e_a) \), irradiance \( IR \), aerodynamic resistance and plant characteristics in terms of root resistances, leaf resistance, leaf capacitance, root density and leaf area index. So plant water stress is not only caused by soil water shortage, it also is influenced by atmospheric conditions, as well as plant hydraulic conductivity.

2. Soil Water and Heat Flow

2.1 Soil water flow

The water transfer in the soil may be described as:

\[
\frac{\partial \theta}{\partial t} = \nabla \cdot (D \nabla \theta) - \frac{\partial K}{\partial z} - S_v \tag{28}
\]

where \( K \) is hydraulic conductivity (m s\(^{-1}\)), \( D \) is diffusivity (m\(^2\) s\(^{-1}\)), \( S_v \) is the volume of water extracted by roots from a unit volume of soil per unit time (s\(^{-1}\)), which may be derived from equation (8) at node \( i \) by \( S_v = S_i / \Delta z_i \), where \( S_i \) is defined as the root extraction rate from unit of cross surface (m s\(^{-1}\)).
According to Van Genuchten (1980), K and D may be determined by:

\[
K(\psi_s) = K_s \frac{(1-(a\psi_s)^{(n-1)})(1+(a\psi_s)^n)^{(1-n)/2n}}{(1+(a\psi_s)^n)^{(n-1)/2n}}
\]  

(29)

\[
D = K(\psi_s) \frac{\partial \theta}{\partial \psi_s}
\]

(30)

\[
\frac{\partial \theta}{\partial \psi_s} = \left(\frac{1}{\psi_s}\right)(n-1)(\theta_s - \theta_r)\left(1 - \frac{\theta_s - \theta_r}{\theta_s - \theta_r}ight)
\]

(31)

where \( \psi_s \) is soil matric potential (m), \( \theta_s \) and \( \theta_r \) are saturated and residual water content, \( K_s \) is saturated hydraulic conductivity, and \( a \) and \( n \) are empirical coefficients.

Under natural drying conditions, the upper boundary condition for an evaporating surface is determined by:

\[-D(\theta) \frac{\partial \theta}{\partial z} = -E_g\]

(32)

Where \( E_g \) is the surface evaporation rate (m s\(^{-1}\)). The lower boundary is assumed to be zero flux:

\[
\frac{\partial \theta}{\partial z} \bigg|_{z = z_*} = 0
\]

(33)

2.2 Soil heat flow

Heat transport in the soil is described as:

\[
c_i \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right)
\]

(34)

where \( T \) is the soil temperature (°C), \( c_i \) (J m\(^{-3}\)°C\(^{-1}\)) is soil heat capacity, and \( \lambda \) (W m\(^{-1}\) °C\(^{-1}\)) is soil
thermal conductivity. Chung and Horton (1987) described $c_i$ as dependent on soil moisture:

$$c_i = (1 - \theta) 1.92 \times 10^6 + 4.18 \times 10^6 \theta$$

(35)

$\lambda$ is determined following Campbell (1985):

$$\lambda = A + B\theta - (A - D) \exp(-(C\theta)^E)$$

(36)

where $A$, $B$, $C$, $D$ and $E$ are determined as follows:

$$A = 0.65 - 0.78 p_c + 0.60 p_b^2$$

$$B = 1.06 p_b$$

$$C = 1 + 2.6 m_c^{1/2}$$

$$D = 0.03 + 0.1 p_b^2$$

$$E = 4$$

(37)

where $\rho_b$ is bulk density (g cm$^{-3}$), and $m_c$ is the clay fraction.

The upper boundary for solving (34) is set by the energy budget at the soil surface as described later, and the lower boundary is that of constant temperature.

3. Energy Budgets

A gross energy budget for the canopy must be established in order to estimate leaf temperature $T_l$ ($^\circ$C) which is used for leaf transpiration calculation. A soil surface energy budget is needed for estimating soil surface temperature $T_s$ ($^\circ$C), which is the upper boundary condition for soil heat flow. A single layer of vegetation, with negligible heat capacity, is assumed represent the canopy.
Following Deardorff (1978), the energy budget for the canopy may be determined as:

\[ S_h + R_{h\downarrow} - S_h - R_{h\uparrow} - (S_g + R_{g\downarrow} - S_g - R_{g\uparrow}) = H_f + \lambda E_T \]  

(38)

where the values at the top of the canopy are denoted by subscript \( h \), those at the ground by subscript \( g \), and the direction of radiative fluxes by arrows. \( S \) is the shortwave (W m\(^{-2}\)) and \( R \) the longwave flux (W m\(^{-2}\)), \( H_f \) the sensible heat (W m\(^{-2}\)) from canopy, and \( \psi E_T = L_h \rho_w E_T \) is latent heat (W m\(^{-2}\)). \( E_T \) is the canopy transpiration rate (m s\(^{-1}\)), \( L_h \) is specific latent heat (J kg\(^{-1}\)), and \( \rho_w \) is water density (kg m\(^{-3}\)).

3.1 Radiation components

\( R_{h\downarrow} \) can be determined following Van Bavel and Hillel (1976):

\[ R_{h\downarrow} = \sigma (T_a + 273.16)^4 (0.605 + 0.048 (1370 h_a)^{-2}) \]  

(39)

where \( \sigma \) the is the Stefan-Boltzmann constant, \( T_a \) is atmospheric temperature (°C) and \( h_a \) is the atmospheric humidity (kg m\(^{-3}\)) which can be calculated as (Chung and Horton, 1987):

\[ h_a = \frac{1.323 \exp(17.27 T_d / (T_d + 237.3))}{(T_d + 273.16)} \]  

(40)

where \( T_d \) is dew point temperature (°C).

\( S_g \downarrow, S_g \uparrow \) are described as following:

\[ S_g \downarrow = (1 - \alpha) S_h \downarrow \]  

(41)

\[ S_g \uparrow = \alpha_s (1 - \alpha) S_h \downarrow \]  

(42)

where \( \alpha \) is the canopy shading factor, \( \alpha_s \) is the ground surface albedo. \( S_h \downarrow \) is measured solar radiation.
The upward longwave flux just above the ground, $R_{\text{tg}}$, is obtained by interpolating with $\sigma_t$ between the expression applicable above bare soil and that applicable just above soil overlain with a dense canopy:

$$R_{\text{tg}} = (1 - \sigma)[e_s \sigma(T_s+273)^4 + (1 - e_s)R_{\text{th}}] + \sigma\{e_s \sigma(T_s+273)^4 + (1 - e_s)e_f \sigma(T_f+273)^4\}[(1 + e) - e_f]$$  (43)

The three remaining radiative fluxes are similarly obtained:

$$S_{\text{h}} = (1 - \sigma_s \epsilon_s S_{\text{h}} + \sigma_s \epsilon_s S_{\text{h}})$$  (44)

$$R_{\text{h}} = (1 - \sigma)[e_s \sigma(T_s+273)^4 + (1 - e_s)R_{\text{th}}] + \sigma\{e_s \sigma(T_s+273)^4 + (1 - e_s)e_f \sigma(T_f+273)^4\}[(1 + e) - e_f]$$  (45)

$$R_{\text{g}} = (1 - \sigma)R_{\text{th}} + \sigma\{e_f \sigma(T_f+273)^4 + (1 - e_f)e_s \sigma(T_s+273)^4\}[(1 + e) - e_f]$$  (46)

where $\epsilon_s$ and $\epsilon_f$ are emissivity of the ground and of the canopy, and $\alpha_t$ is the foliage albedo.

Soil surface albedo $\alpha_s$ and emissivity $\epsilon_s$ are assumed to be a function of soil moisture, following Chung and Horton (1987):

$$\alpha_s = \begin{cases} 0.1 & 0.25 \leq \theta \\ 0.35 - \theta & 0.1 < \theta < 0.25 \\ 0.25 & 0.1 \leq \theta \end{cases}$$

$$\epsilon_s = 0.9 + 0.180 \theta$$  (47)

Foliage albedo and emissivity are assumed as constants, $\alpha_t = 0.2$, $\epsilon_f = 0.95$

With these substitutions of (39)-(46), (38) becomes:

$$\sigma(1 - \alpha_s)S_{\text{h}} + e_f R_{\text{h}} + \frac{e_f \epsilon_s}{e_f + e_s - e_f} - e_s \sigma(T_s+273)^4 - e_s \sigma(T_f+273)^4 = H_f + \lambda E_f$$  (48)

which may be solved for $T_f$. 

3.2 Sensible heat flux

If canopy heat capacity is negligible, the heat flux from the canopy $H_f$ and from the ground $H_g$ must be balanced by heat flux to the atmosphere $H_a$ (Dickinson et al., 1986). From following heat balance equations adapted from Dickinson et al. (1986); canopy air temperature $T_{af}$ can be determined:

$$H_a = H_f + H_g \quad (49)$$

where the heat flux from canopy air into free atmosphere is determined by:

$$H_a = \rho_a c_p \frac{T_{af} - T_a}{r_a} \quad (50)$$

where $\rho_a$ is air density ($\text{kg m}^{-3}$), $c_p$ is specific heat capacity ($\text{J kg}^{-1} \text{ °C}^{-1}$), $r_a$ is air resistance ($\text{s m}^{-1}$).

Flux from the canopy is:

$$H_f = L \rho_a c_p \frac{T_f - T_{af}}{r_b} \quad (51)$$

where $L$ is leaf area index, and $r_b$ is air resistance ($\text{s m}^{-1}$) in the canopy.

Sensible heat flux from the ground is expressed as:

$$H_g = \rho_a c_p \frac{T_g - T_{af}}{r_g} \quad (52)$$

where $r_g$ is air resistance ($\text{s m}^{-1}$) underneath canopy.

Substituting (50), (51) and (52) into (49), we obtain canopy air temperature:

$$T_{af} = \frac{c_s T_s + c_f T_f + c_g T_g}{c_s + c_f + c_g} \quad (53)$$
3.3 Vapor flux

Similarly, canopy air vapor pressure may be determined by assuming that canopy atmospheric water capacity is negligible. The flux of vapor from the canopy air $E_a$ balances the flux from the canopy $E_T$ and from the ground $E_g$:

$$E_a = E_T + E_g$$  \hspace{1cm} (55)

Vapor flux from canopy into canopy air is described in equation (16) as transpiration rate:

$$E_T = \left(\frac{0.622 \rho_a e_a}{\rho_w} \right) \left( e_i - e_a \right)$$ \hspace{1cm} (56)

Similarly, vapor flux from canopy air to the atmosphere is determined as:

$$E_a = \left(\frac{0.622 \rho_a e_a}{\rho_w} \right) \left( e_a - e_g \right)$$ \hspace{1cm} (57)

and, vapor flux from the soil surface is determined by:

$$E_g = \left(\frac{0.622 \rho_a e_a}{\rho_w} \right) \left( e_s - e_g \right)$$ \hspace{1cm} (58)

where $e_g$ can be related to $T_g$ and $\psi_g$ in the same way as shown in (17). Soil surface resistance, $r_{sfc}$, is estimated by an empirical expression given by Shu Fen Sun (1982):

$$r_{sfc} = d_1 + d_2 (\theta_s)^{-d_3}$$ \hspace{1cm} (59)

where $d_1$, $d_2$ and $d_3$ are empirical constants.

Substituting (56), (57) and (58) into (55), we obtain canopy air vapor pressure:

$$e_a = \frac{c_a e_a + c_f e_f + c_g e_g}{c_a + c_f + c_g}$$ \hspace{1cm} (60)
3.4 Soil surface energy balance

A soil surface energy balance is used to determine soil surface temperature $T_s$ (Chung and Horton, 1987):

$$-\lambda \frac{\partial T_s}{\partial z} = R_n - H_s - \lambda E_g$$

(62)

where $R_n$ is net radiation, $H_s$ is sensible heat flux at the soil surface and $\lambda E_g = L_{re} \rho \omega E_g$ is latent heat flux. The left hand side is the soil heat flux.

The net radiation is determined by:

$$R_n = (1 - \alpha_g) S_g + R_{ig} - R_{ir}$$

(63)

The determination of components in (64) and (65) were described in previous sections.

3.5 Aerodynamic resistance

For the air above the canopy, aerodynamic resistance is defined as (Dickinson et al., 1986):

$$r_a = 1/c_H \Phi u_a$$

(64)

where $c_H$ is a non-dimensional heat or moisture transfer coefficient, $\Phi$ is correction factor for atmospheric stability, and $u_a$ is wind speed (m s$^{-1}$).

The heat or moisture transfer coefficient $c_H$ is determined under neutral conditions as (Dickinson et al., 1986):
where \(d\) is distance of displacement (m), \(z_a\) is degree of roughness (m), \(z\) is the height at which wind speed is measured, and \(k\) is a constant which is equal to 0.4.

\[ c_H = k^2 l \left( \ln \left( \frac{z}{d} \right) \right)^2 \]  

(65)

\(\Phi\) is determined under unstable conditions \((R_i < 0)\) (Dickinson et al., 1986) as:

\[ \Phi = 1 + 24.5 \left( -c_H R_i \right)^{0.5} \]  

(66)

and for the stable case \((R_i > 0)\) as:

\[ \phi = \frac{1}{1 + 11.5 R_i} \]  

(67)

where \(R_i\) is the Richardson number of the form:

\[ R_i = \frac{g \left( T_a - T_p \right)}{T_a u_a^2} \]  

(68)

where \(g\) is the acceleration of gravity and \(z\) is observation height.

Underneath the canopy, the transfer coefficient is defined:

\[ c_{H_e} = c_H \left( 1 - \sigma \right) u_a + \sigma \mu_a d \]  

(69)

where \(\sigma\) is a canopy shading factor and \(u_a\) is wind speed in the canopy.

Air resistance underneath the canopy can be determined as:

\[ r_s = \frac{1}{c_{H_e} \Phi u_a \mu_a} \]  

(70)
Within the canopy, the heat and moisture transfer coefficient was defined by Deardorff (1978) as:

\[ c_f = 0.01(1 + 0.3/u_{df}) \]  

(71)

\( u_{df} \) was defined as:

\[ u_{df} = 0.83 \sigma \int_{H}^{0.5} u_a + (1 - \sigma) u_a \]  

(72)

and aerodynamic resistance in the canopy was:

\[ r_b = 1/(c \mu_{qg}) \]  

(73)
NUMERICAL SOLUTION

The model was coded in FORTRAN 77 and can be run either on an IBM PC or a software compatible Work Station. The time interval is variable (we used 200 seconds in simulation runs). Soil depth spaces could be defined by users, and the soil profile may be inhomogeneous. The governing equations are solved by an implicit finite difference scheme. Leaf water potential and leaf temperature are obtained by iteratively solving the leaf water balance equation (27) and the canopy energy balance equation (48), respectively.

The inputs for the model include weather data, plant parameters, soil parameters and initial soil moisture and temperature profiles. Weather data are: daily global radiation, maximum and minimum air temperature, maximum and minimum dew point temperature, and average wind speed at the reference level. Plant parameters are: LAI, canopy shading factor, critical leaf water potential, leaf resistance parameters, root resistivity, and root density. Soil parameters include: saturated soil moisture, residual soil moisture, and saturated hydraulic conductivity. The outputs are: soil moisture and soil temperature profiles, evaporation, transpiration, root extraction, leaf temperature, leaf water potential, soil water potential, leaf resistance, root resistance and soil resistance, and the energy budget partition over the canopy and the soil surface.
RESULTS AND DISCUSSION

A 9-day simulation run was made to show the basic functions and features of the model. The soil type is silt loam. The initial profiles of soil moisture and temperature are shown in Figures 3 and 5, and the root length density profile is shown in Figure 4.

Figure 3 shows the initial soil moisture profile and simulated moisture profiles on the 4th and 9th days. Initially, the soil was wet at the top and in the deeper soil layers, and was relatively dry in the .25-1.0 m root zone. On the 4th day, top soil moisture was somewhat reduced due to evaporation, root extraction and moisture redistribution. The slight gain of moisture in the 1-1.5 meter zone was associated with moisture transmission from the wetter subsoil layer and with drainage from the top soil. The deep soil moisture depletion is a result of root extraction and of water transport to the dry zone by capillary rise. By the 9th day, soil moisture was depleted for the whole profile. Similar results were obtained in the simulation by Hillel et al. (1976).

The corresponding root length density profile and accumulated root extraction of water on the 4th and 9th days are shown in Figure 4. Root density was higher in the top soil, and decreased as soil depth increased. Below 1.5 meters, root density decreased to zero. The maximum root extraction zone was around 1.2 meters where soil was moist and roots were plentiful. For the top soil, although root density was higher, low soil moisture content limited root extraction. Below 1.5 meters, soil moisture was high; however, root density was low so root extraction was small. Therefore, root extraction is dependent on both soil water availability and root length density distribution. The results agree with the field observation by Allmaras et al. (1975) and with simulation results by Hillel et al. (1976).
Simulation results for the soil temperature profile are shown in Figure 5. The initial temperature profile was assumed to be uniformly 20°C. Surface temperature heated up to 28°C during the day and decreased to 15°C during the night. Soil temperature is determined by surface heat flux, which is influenced by canopy shading and surface moisture. If the canopy is dense, little radiation arrives at the soil surface; consequently, soil heat flux is small and soil temperature is low. For moist soil, more energy is used for evaporation, keeping soil heat flux low. With a sparse canopy and dry soil, soil heat flux is large and results in high soil temperature.

Figure 6 shows the diurnal pattern of energy partitioning in the canopy and soil surface under a moist soil condition. Most solar energy in canopy was used for canopy transpiration during the day, a small amount of energy was used in sensible heat transfer. During the night, the canopy cooled due to longwave radiation emission, transpiration was small, and sensible heat was transferred from air to canopy. Net radiation at the soil surface was much less than that at the canopy because of the canopy shading. Since the soil surface was wet, soil surface temperature was lower than the canopy air temperature (as shown in Figure 7); thus, sensible heat was negative during the day. Therefore, most of the energy on the soil surface was used for surface evaporation. The rest of the energy went into the soil.

Figure 7 shows the diurnal pattern of the temperatures. During the daytime, leaf temperature was higher than the air temperature, and canopy air temperature was in between. Soil surface temperature was higher than free air temperature, but below canopy air temperature. This results in the negative soil surface heat flux as shown in Figure 6. Similar observations were reported by Gates (1980).
Figure 8 shows the diurnal variation of vapor pressures in the system. During the day, leaf vapor pressure was higher than the surrounding air because of higher leaf temperature. Similarly, soil surface vapor pressure was higher than that of the surrounding air.

Figure 9 shows the diurnal variation of leaf water potential, soil water potential, transpiration and evaporation for a 9-day period. Leaf water potential fluctuates with transpiration. While integrated soil water potential varied little with time, high transpiration rates induced low leaf water potential. Many field observations have reported the diurnal variation of leaf water potential and its relationship to transpiration (Klepper, 1968; Reicosky et al., 1982). Evaporation rate varied diurnally and decreased as soil surface became drier. Although total soil moisture decreased due to transpiration, the integrated soil moisture, defined as a function of soil water potential, hydraulic conductivity and root density, didn't decrease substantially. This is because roots were able to extract deeper soil moisture for transpiration.

Figure 10 presents the daily leaf water flux (Figure 10a), transpiration and root extraction (Figure 10b) for a plant with large leaf water storage ($C_p = 10^{-3}$ m$^{-1}$). In the morning and early afternoon, leaves lost water into the atmosphere, and in the late afternoon and evening, leaves recharged with water from the soil (Figure 10a). Correspondingly, transpiration was larger than root extraction in the morning and early afternoon, and root extraction was larger than transpiration in the late afternoon and evening (Figure 10b). Plant water storage has the effect of shifting the diurnal pattern of water transport. The results agree with actual measurements (Waring et al., 1979; Running, 1980) and simulation results by Fernandez and McCree (1991).

The above results illustrate the basic model functions. Some complicated processes can also be illustrated by the model results. Figure 11 presents a mechanism of the feedback process of leaf
water response to atmospheric demand. In the model, leaf water potential is a function of transpiration, and transpiration is a function of leaf resistance. Leaf resistance, in turn, is a function of leaf water potential. This negative feedback process is demonstrated in Figure 11. As atmospheric demand, or potential transpiration $E_p$ increases, leaf water potential $\psi_l$ decreases; as a result, leaf resistance $r_l$ increases. This leaf resistance increase reduces the rate of actual transpiration; consequently, leaf water potential is prevented from decreasing further.

In conclusion, the dynamic model mechanistically describes the water transport process in the soil-plant-atmosphere system. Simulation results show that the model can simulate not only the basic system features, but also complicated feedback processes. Therefore, the model may be used as a research tool to study soil water availability and crop water response. Model validation and sensitivity testing is presented in a subsequent paper (Guo and Taylor, 1992a).
REFERENCES


K.G. Wilson (Editors), Models in plant physiology/biochemistry/technology, CRC Press,
Boca-Raton, Florida.


Reicosky, D.C., Campbell, R.B. and Doty, C.W., 1975. Diurnal fluctuation of leaf-water potential

Reicosky, D.C. and Richie, J.T., 1976. Relative resistance of soil resistance and plant resistance in


stomatal and canopy conductances and transpiration from bracken below a forest canopy. J.
Appl. Ecol., 17:409-422.


Ross, J, 1975. Radiative transfer in plant communities. In: J.L. Monteith (Editor), Vegetation and


Running, S.W., 1980. Relating plant capacitance to the water relations of Pinus contorta. For.

Shu Fen Sun, 1982. Moisture and heat transport in a soil layer forced by atmospheric conditions.
M.S. Thesis, Dept. of Civil Engineering, University of Connecticut, pp. 72.


Figure 1. Scheme of the soil-plant-atmosphere system
Figure 2. Analogue of water and heat transfer in the soil-plant-atmosphere system
Figure 3. Initial and simulated soil moisture profiles
Figure 4. Root density and simulated root extraction accumulation on the 4th and 9th day.
Figure 5. Initial and simulated soil temperature profiles
Figure 6. Simulated energy partition of the canopy and the soil surface
- \( R_{nc} \), \( R_{ng} \), net radiation for the canopy and the soil surface
- \( \lambda E_T \), \( \lambda E_g \), latent heat from the canopy and the soil surface
- \( H_f \), \( H_g \), sensible heat from the canopy and the soil surface

Figure 7. Simulated diurnal pattern of the temperatures
- \( T_a \), \( T_{af} \), \( T_f \), \( T_g \), are temperature of the atmosphere, the canopy air, the leaf, and the soil surface
Figure 8. Simulated diurnal variation of the vapor pressures

\( e_a, e_{af}, e_f, e_g \) are vapor pressure of the atmosphere, the canopy air, the leaf, and the soil surface.

Figure 9. Variation of leaf water potential, soil water potential, transpiration and evaporation over a 9-day simulation

\( \psi_l, \psi_s \), leaf and soil water potential

\( E_T, E_g \), transpiration and evaporation rate
Figure 10. Simulated effect of plant water capacitance ($C_p = 10^{-5}$ m m$^{-1}$)

a. Daily variation of leaf water flux

b. Daily variation of transpiration and root extraction
Figure 11. Description of a feedback process of leaf water response to atmospheric stress
\( \psi_i, \psi_r \), leaf and soil water potential
\( E_p, E_T \), potential and actual transpiration
\( r_l \), leaf resistance
PAPER 2

SIMULATION OF WATER TRANSPORT IN THE SOIL-PLANT-ATMOSPHERE SYSTEM

II. MODEL VALIDATION AND SENSITIVITY STUDIES
Simulation of water transport in the soil-plant-atmosphere system

II. Model validation and sensitivity studies

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(to be submitted to Agricultural and Forest Meteorology)
A mechanistic model of water transport in the soil-plant-atmosphere system was tested by comparing simulation results with the field measurements. The sensitivity of the model to some environmental factors and plant properties was studied.

Comparisons of the simulated and measured soil moisture profiles, leaf water potentials and evapotranspiration rates show that model performs reasonably well under natural conditions. Accurate input data, rather than estimated values, are essential for model validation.

The sensitivity studies indicate that soil moisture has a significant effect on leaf water potential, stomatal aperture, root extraction and transpiration. Besides soil moisture, atmospheric conditions and root radial resistance also significantly influence plant water transport. Soil resistance is relatively small compared with root resistance except when soil is very dry. Plant water capacitance has the effect of delaying stress and reducing stress under some conditions. However, for most crops, plant water capacitance is relatively small; therefore, its effect is negligible.

The model allows plant water transport to be influenced not only by soil water supply and atmospheric demand, but also by plant resistance and capacitance. The model could be used to study plant water stress response to various environmental factors and to investigate the water stress responses of various crops.
INTRODUCTION

A mechanistic model of water transport in the soil-plant-atmosphere system was presented in Guo and Taylor (1992). The model includes water and heat transfer processes: root extraction, transpiration, soil water and heat transfer, vapor and heat transfer from the soil surface, and energy budgets for the soil surface and the canopy. The model may be used to study plant water responses to soil water stress, atmospheric conditions, and to other environmental factors. Crop behavior under various environmental conditions can also be investigated using the model.

The basic model assumptions are: (1) representative leaf water potential is used for the entire canopy; (2) stomatal resistance is a function of environmental factors; (3) above-ground xylem resistance is assumed negligible compared with root radial resistance and leaf resistance; (4) all roots are equally permeable to water uptake.

The major model features are: (1) a comprehensive model; (2) description of a feedback mechanism of leaf water potential response to transpiration and leaf resistance; (3) inclusion of root resistances; (4) inclusion of plant water capacitance.

Analytical application of the model requires that the model results and model assumptions be validated, and the general model behavior be studied. The objectives of this study were: (1) to test the model by comparing the simulated results with the field observations collected by Mason et al. (1980); and (2) to study the sensitivity of the model to environmental factors and plant properties.
MATERIALS AND METHODS

The model has been field tested using data gathered at the Western Iowa Experimental Farm, Castana, Iowa in 1979 (Mason et al., 1980). The test crop was soybean planted at 1.0 and 0.25 m row spacings. The soil was an Ida Silt Loam. The soil physical properties included soil texture and soil bulk density (Table 1). The soil profile was 2.7 m deep; the clay fraction is higher at the top, and the sand fraction is higher at the bottom.

The soil water retention curve and hydraulic conductivity were calculated by the Van Genuchten (1980) method. The measured soil water retention curves for various soil layers were fitted (Figure 1). The fitting parameters and saturated hydraulic conductivity are shown in Table 2. Figure 1 shows that soil hydraulic properties were different with depth, although the soil type was the same.

A period without rainfall (July 31 to August 8) was chosen for the comparison. During this period, the soybean leaf area index was about 5.6 and 5.0 for 1.0 m rows and .25 m rows, respectively. The root length density distributions are shown in Table 3. Most roots were in the top 1.5 m of soil and over 50% of the roots were in the top 0.5 m.

Climate data are shown in Table 4. Mean wind speed was used in the model. Since there was no dew point temperature record for Castana, data for Des Moines were used. Diurnal air temperature \( T_d \) was fitted by a sine function as follows:
where $T_{\text{max}}$ and $T_{\text{min}}$ are maximum and minimum air temperature, $t$ is time of day beginning from midnight. The maximum temperature was assumed to occur at 2 pm. Diurnal dew point temperature was determined similarly. Instantaneous solar radiation ($S_g$) was estimated from daily total radiation following Chung and Horton (1987):

$$S_g = \frac{(\pi/2)DR}{DL} \sin\left(\pi - \frac{SN+DL}{2}\right)$$

where $S_g$ is W m$^{-2}$, DR daily global radiation (J m$^{-2}$), SN solar noon (s), and DL daylength (s).

Initial soil moisture profiles (July 31), and the soil moisture profiles of Aug. 3 and 8, 1979 for both .25 m rows and 1.0 m rows are presented in Figure 2. On July 31, the top 0.25 m of soil was moist, 0.25 to 1.0 m was relatively dry, and the deeper soil was moist. After 9 days (Aug. 8), the top one meter of soil was dry, and the deeper soil was still moist. Since the initial soil temperature profile was not available, an initially uniform profile of 20°C was assumed referring to the temperature profile at 5 pm at the weather observation site.

Evapotranspiration was measured using the portable chamber technique of Reicosky and Peters (1977) with some modifications (Mason et al., 1980). Leaf water potential was measured using a pressure chamber. Soil moisture data were determined gravimetrically. Soil water retention was determined by in situ measurements of soil water content and pore water pressure. Root length density was obtained from field soil sampling. Weather measurements were recorded at a site about 300 m from the plot area.
Integrated soil water potential ($\psi_s$) was estimated following Gardner (1964):

$$\psi_s = \sum_{i=1}^{n} \frac{(K_i L_{ri} \Delta z_i \psi_{si})}{\sum_{i=1}^{n} (K_i L_{ri} \Delta z_i)}$$

(3)

where $K_i$ (m s$^{-1}$) is hydraulic conductivity at each soil depth, $L_{ri}$ (m m$^{-3}$) is root length density, $\psi_{si}$ (m) is soil water potential at depth $i$, and $\Delta_i$ (m) is thickness of each soil layer.

The model parameters used for the validation are shown in Table 5. Maximum and minimum soybean leaf resistances were generalized from the data of Li (1989) and unpublished data of Jiang and Shibles$^{(1)}$ as $r_{\text{max}} = 2000$ s m$^{-1}$ and $r_{\text{min}} = 50$ s m$^{-1}$; critical leaf water potential $\psi_c = -120$ m, $\psi_{\text{im}} = -220$ m were obtained from Carlson et al. (1979). Root radial resistivity $P_r = 8 \times 10^{11}$ s m$^{-1}$ was generalized from Blizzard and Boyer (1980), and root axial resistivity for soybean was not available, so a value of $P_a = 5 \times 10^{10}$ s m$^3$ for wheat from Reid and Huck (1990) was used. Leaf water capacitance was considered small enough to be negligible for soybean.

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MODEL VALIDATION

The model was run for 9 days for soybean in both .25 and 1.0 m row spacing, with the initial soil moisture profiles (July 31) as shown in Figure 2, the climate data as in Table 4, and the model parameters are given in Table 5.

Simulated diurnal variations of leaf water potential, transpiration and soil water potential for the period are shown in Figure 3. Integrated soil water potential decreased slightly during the 9-day period. Leaf water potential and transpiration rate fluctuated diurnally. Simulated leaf water potential and evapotranspiration rate (sum of transpiration and evaporation) were compared with available field measurements of July 31 and August 1, 1979, for both .25 and 1.0 m row spacings (Figures 4 and 5). Soil moisture profiles were compared for August 3 and August 8, 1979 (Figure 6).

Figure 4a shows that simulated leaf water potential fits the observation data very well. Since July 31 was a cloudy day, leaf water potential was higher than that of August 1. During the daytime, leaf water potential dropped to about -100 m and -120 m for July 31 and August 1, and recovered to about -40 m during the night. Similarly, comparisons for 1.0 rows soybean of July 31 and August 1 (Figure 4b) showed reasonable agreement between the simulated and measured diurnal pattern of leaf water potentials. For both .25 m row and 1.0 m row soybean, the model overestimated leaf water potentials during the late evening. The reason could be inaccurate estimated weather data input, the neglect of osmotic regulation, root resistance or soil resistance to water uptake.

Comparisons of evapotranspiration for .25 m rows on July 31 and August 1 are shown in Figure 5a. Simulated results closely agreed with the observations most of the time. In the morning, the model underestimated evapotranspiration. The variation of the observation data might be due to
clouds, canopy difference or instrument operation. The model did not consider hourly cloud effects since only daily total global radiation data were available. Hourly or even a smaller time interval data would allow better model response. Figure 5b presents similar results for the comparison using 1.0 m row soybean.

Measured soil moisture profiles of August 3 and 8 (Figure 2) for both .25 and 1.0 m rows were compared with simulations (Figure 6). Since actual measurements were the average for the day, simulation results at 1500 hour were selected for comparison. Figure 6a shows the comparisons of measured and simulated soil moisture profiles of the .25 rows on August 3 and 8. Simulated results were very close to the measured ones. Similarly, the comparisons of 1.0 m rows on August 3 and 8 are shown in Figure 6b. The deviation of simulations from measurements may be due to the assumption of equal root permeability in the profile, or properties of the soil in the surface layer.

The model is able to describe the major features of the system being studied. To validate the model with the actual field measurements, accurate and complete observations are essential. For example, as shown in Figure 7, August 8 was a cloudy day; solar radiation fluctuated with cloud cover, and resulted in leaf water potential fluctuation. Since only daily total radiation data were available, the model couldn't track the hourly cloud effect, and only simulated the average hourly case.
SENSITIVITY STUDIES

To study the model behavior, model sensitivities to environmental factors and plant characteristics were studied with the basic model parameters shown in Table 5.

1. Soil Moisture Condition

Leaf water potential is modeled as dependent upon soil water potential and transpiration rate (Guo and Taylor, 1992). Soil moisture was shown to directly affect root radial resistance (Reid and Huck, 1990). Also the soil resistance to water transport is influenced by soil water content (Gardner, 1964; Van Genuchten, 1980). These resistance factors also contribute to leaf water potential. The computations of leaf water potential as influenced by soil water potential are shown in Figure 8. At \( \psi_s = -12 \) m, minimum \( \psi_l = -100 \) m; and at \( \psi_s = -55 \) m, minimum \( \psi_l = -160 \) m. This indicates that soil water potential has a significant effect on leaf water potential. Since leaf water potential affects leaf stomatal aperture and soil moisture influences leaf water potential, soil water potential has an effect on leaf resistance as shown in Figure 9. Lower soil water potential causes higher leaf resistance. For the moist soil \( (\psi_s = -12 \) m), leaf resistance is only a function of radiation, it is not influenced by soil water potential since leaf water potential is above the critical value of -12 bars. When soil is dry \( (\psi_s = -55 \) m), leaf water potential could be as low as -160 m at the middle of the day (Figure 8), and leaf resistance increases from 60 s m\(^{-1}\) in the morning to 200 s m\(^{-1}\) in the late afternoon. Note that although the soil water potential term is not directly presented in the leaf resistance model (equation (27)), its indirect effect on stomatal aperture by changing leaf water potential is reflected by the model. Since soil moisture influences stomatal aperture, it therefore,
affects transpiration as shown in Figure 10. At higher soil water potential, transpiration rate is high, and at lower level of soil water potential, transpiration rate is low. Therefore, soil water potentials are indirectly related to transpiration by stomatal resistance because of the effect on leaf water potential.

2. Atmospheric Condition

Atmospheric demand is the driving force of leaf transpiration. The modeled effect of atmospheric demand on leaf water potential (\(\psi_l = -27\) m) is shown in Figure 11. High atmospheric demand results in low leaf water potential. When \(E_p = 9.7\) mm day\(^{-1}\), minimum \(\psi_l = -120\) m. When atmospheric demand is low, \(E_p = 2.4\) mm day\(^{-1}\), minimum leaf water potential is higher (\(\psi_l = -110\) m). High atmospheric demand increases transpiration and thereby causes low leaf water potential, thus leaf stomatal closure.

3. Root Resistances

Root resistances have a direct influence on plant water transport. Figure 12 shows different levels of root radial resistivity (\(P_r\)) and leaf water potential. The larger the root radial resistivity, the lower the leaf water potential. In this case, the smaller value of \(P_r\) represents the root tip, the median value represents the whole root system of wheat, and the largest value is close to the root system of barley (Reid and Huck, 1990). Actual measurements reported by Boyer (1971) showed that soybean, bean and sunflower have different root resistances. Therefore, for plants with various root radial resistances, transpiration rates and leaf water potentials may be different at the same soil and atmospheric conditions.
Root axial resistance $P_a$ doesn't have remarkable effects on transpiration rate and leaf water potential. The two extreme values of $P_a$ estimated by Reid and Huck (1990) are $1.7 \times 10^9$ and $7.0 \times 10^{11}$ (s m$^{-2}$). $P_a$ is often relatively small compared with $P_r$. Axial resistance ($P_a$) may become significant in the upper range.

The above results show that transpiration and leaf water potential are highly sensitive to root radial resistivity. Root axial resistance is often insignificant compared to radial resistance.

4. Soil Resistance

Ida silt loam, as described in Table 1, was used to study the soil resistance at two levels of soil water potential ($\psi_s = -6$ m and $\psi_s = -71$ m). Root resistivities, $P_r = 7 \times 10^{11}$ s m$^{-1}$ and $P_a = 5 \times 10^{10}$ s m$^{-3}$ are used. When soil is moist ($\psi_s = -6$ m), soil resistance is insignificant compared with the root radial and axial resistances as shown in Table 6. Root radial resistance is 3-4 orders larger than soil resistance. This agrees with the experimental results of Reicosky and Ritchie (1976), indicating that plant resistance to water transport was much larger than soil resistance, until the soil matric potential was low ($-10$ and $-80$ m for the sandy and clay soils). When soil is dry ($\psi_s = -71$ m), soil resistance is as important as root radial resistance (Table 6). Soil resistance varies with depth because of root length density and soil properties. So the relative importance of root resistance and soil resistance is dependent upon root characteristics and soil properties. As indicated by Newman (1969) soil resistance may become appreciable when the soil matric potential decreases to a few bars below zero. Generally, soil resistance is considered significant only when soil is dry.
5. Soil Types

Various soil types have different hydraulic properties. Diurnal variations of leaf and soil water potential for several soils are shown in Figure 13. For the same soil moisture profile ($\theta=0.15$), sandy soil has higher soil water potential than loam, and clay is lower. Correspondingly, leaf water potential is higher for sand than for loam. Clay has the lowest value. Consequently, transpiration rates varies with soil types, sand has higher transpiration, clay has the lower value, and loam is in the middle (Figure 14). The results suggest that soil type has a large effect on plant water response. It must be considered, however, that the total water capacity for sands is relatively low.

6. Plant Capacitance

Sensitivity of plant water transport to plant capacitance was tested by running the model with different levels of plant capacitance. Figure 15 shows the diurnal variation of leaf water flux at different levels of leaf water capacitance. In the morning and early afternoon, the leaf has a net loss of water into the atmosphere, and in the late afternoon and evening, the leaf absorbs water from the soil in excess of transpiration. Note that, for the smaller value of $C_p$, corresponding to wheat (Jones, 1978), the leaf water flux variation is very small. This suggests that the effects of leaf water capacitance for crops is not highly significant.

The diurnal variation of transpiration rate, root extraction rate and leaf water potential at $c_p=10^{-5}$ (m m$^{-1}$) is shown in Figure 16. There is a time lag between transpiration ($E_r$) and root extraction ($S$). The maximum root extraction occurs at about the same time as minimum leaf water potential occurs. Such a time lag phenomenon agrees with the field observations for trees (Kaufmann, 1977; Waring et al., 1979; Running, 1980). By comparison, when leaf water capacitance is negligible, $C_p=0$ (Figure 17), there is no time lag between transpiration and leaf water.
potential. This is because the leaf directly extracts soil water for transpiration without changing plant water storage.

Figure 18 shows the effect of leaf water capacitance on diurnal variation of leaf water potential. There is a time lag between the diurnal patterns of $\psi_l$ for different levels of $C_p$. Plants with smaller $C_p$ dehydrate earlier and also recharge earlier than those with larger $C_p$. Also, larger $C_p$ may prevent low leaf water potential. The results indicate that leaf water potential variation is influenced not only by atmospheric and soil water conditions, but plant water storage may be significant.
DISCUSSION AND CONCLUSIONS

The model simulates a mechanistic process of water transport in the soil-plant-atmosphere system, and the interactions between system components. The system is complicated and is influenced by atmospheric conditions, soil moisture supply and plant characteristics.

The model results compared reasonably well with the field observations. For model validation, model input data are crucial. To simulate crop response in actual field conditions, accurate inputs of crop parameters, soil parameters and weather data are essential. Sensitive parameters are: LAI, root density, soil water retention, initial soil moisture profile, and solar radiation. Root density distribution and soil water retention have substantial effects on soil water movement and root water uptake, and thus influences the soil moisture profile. Weather, especially cloud cover, controls the diurnal pattern of the plant water transport process. To simulate diurnal variations, weather data, at least hourly, are required.

Many factors influence plant water transport. Soil moisture directly affects soil hydraulic conductivity and root resistances. As a result, soil water content indirectly influences leaf water potential, stomatal aperture, and transpiration rate (as shown in Figures 8-10). Soil type has a significant effect on soil water availability.

Leaf water potential is significantly influenced by soil water potential; as soil water potential decreases, leaf water potential decreases accordingly. However, the variation of leaf water potential reflects not only soil moisture condition, but also atmospheric demand, root resistance, and plant water storage. Under high soil moisture conditions, leaf water potential could decrease to below critical value $\psi_c$ because of high atmospheric demand or large root resistance. As leaf water
potential drops below the critical value, stomata begin closing and transpiration decreases. When soil is dry, roots may send a message to leaves so that stomata close (Zhang et al., 1987). However, when soil is moist, stomata could also close due to the high atmospheric demand or high root resistances.

In the model, leaf resistance is assumed to be directly influenced by irradiance and leaf water potential, and indirectly affected by soil moisture, leaf temperature and vapor pressure difference. The model illustrates that such indirect factors affect leaf resistance by changing the leaf water potential.

Plant water storage capacitance is likely important for most plants with larger $C_p$ (trees and succulents) and is probably insignificant for most crops (smaller $C_p$).

In conclusion, a mechanistic model of water transport in the soil-plant-atmosphere was developed and validated with field observations. The sensitivity of plant water transport to environmental factors and plant properties was studied. The results showed the plant water response to soil water supply, atmospheric conditions, and plant characteristics. The results suggest that the model could be incorporated into existing crop models for simulation of crop water relations, and that the model may also be used to study the effects of environmental factors and plant properties on plant water transport.
REFERENCES


Table 1. Soil physical properties of Ida silt loam, Castana, Iowa\textsuperscript{a}

<table>
<thead>
<tr>
<th>Soil depth 2-05mm</th>
<th>Sand percent</th>
<th>Co silt 50-20(\mu)</th>
<th>Fi silt 20-2(\mu)</th>
<th>Clay &lt;2(\mu)</th>
<th>bulk density g cm(^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-0.3</td>
<td>9.9</td>
<td>51.9</td>
<td>24.1</td>
<td>14.1</td>
<td>1.29</td>
</tr>
<tr>
<td>0.3-0.6</td>
<td>9.8</td>
<td>53.3</td>
<td>25.4</td>
<td>11.5</td>
<td>1.19</td>
</tr>
<tr>
<td>0.6-0.9</td>
<td>9.6</td>
<td>57.7</td>
<td>22.5</td>
<td>10.2</td>
<td>1.24</td>
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<tr>
<td>0.9-1.2</td>
<td>7.8</td>
<td>50.9</td>
<td>27.8</td>
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<td>1.22</td>
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<tr>
<td>1.2-1.5</td>
<td>12.0</td>
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<td>1.23</td>
</tr>
<tr>
<td>1.5-1.8</td>
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<td>28.4</td>
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<td>1.24</td>
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<td>1.8-2.1</td>
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<tr>
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<td>1.24</td>
</tr>
<tr>
<td>2.4-2.7</td>
<td>13.1</td>
<td>54.7</td>
<td>24.1</td>
<td>8.1</td>
<td>1.24</td>
</tr>
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</table>

\textsuperscript{a} data adapted from Mason et al. (1980)

Table 2. Parameters for calculating the soil water retention and hydraulic conductivity

<table>
<thead>
<tr>
<th>Depth m</th>
<th>(\theta_s) m(^3) m(^{-3})</th>
<th>(\theta_r) m(^3) m(^{-3})</th>
<th>a m(^3) m(^{-3})</th>
<th>n m(^3) m(^{-3})</th>
<th>(K_s) m s(^{-1})</th>
</tr>
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<tbody>
<tr>
<td>0.0-0.3</td>
<td>.348 .05</td>
<td>.4377 1.3786</td>
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<td>0.3-0.6</td>
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<td>.7394 1.7859</td>
<td>.334x10(^{-5})</td>
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</tr>
<tr>
<td>0.6-0.9</td>
<td>.375 .10</td>
<td>.5569 1.8540</td>
<td>.334x10(^{-5})</td>
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</tr>
<tr>
<td>0.9-1.2</td>
<td>.385 .05</td>
<td>.7512 1.3777</td>
<td>.838x10(^{-5})</td>
<td></td>
<td></td>
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<tr>
<td>1.2-1.5</td>
<td>.395 .08</td>
<td>.4989 1.7366</td>
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<td>.4495 1.9432</td>
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<td>1.8-2.1</td>
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<td>2.1-2.4</td>
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<td>.4245 1.7318</td>
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<td></td>
</tr>
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<td>.405 .09</td>
<td>.4590 1.7306</td>
<td>.334x10(^{-5})</td>
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\textsuperscript{a} \(\theta_s\), \(\theta_r\) are saturated and residual soil moisture contents, a and n are empirical coefficients, \(K_s\) is hydraulic conductivity.
Table 3. Root length density distribution (10^4 m/m^3)*

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>7/31-8/4</th>
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<th>8/5-8/8</th>
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<td>0.075-0.150</td>
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<td>.45</td>
<td>.40</td>
<td>.39</td>
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<tr>
<td>0.150-0.225</td>
<td>.20</td>
<td>.17</td>
<td>.23</td>
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<tr>
<td>0.225-0.300</td>
<td>.17</td>
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<td>.17</td>
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<td>0.375-0.450</td>
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<td>0.525-0.600</td>
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<td>.17</td>
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<td>.16</td>
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<td>0.600-0.750</td>
<td>.22</td>
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<td>.17</td>
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* data were extracted from Mason et al. (1980).
Table 4. Climate data for Castana, Iowa*

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<th>Date</th>
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<td>8/2</td>
<td>30.0</td>
<td>16.1</td>
<td>86</td>
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<td>8/3</td>
<td>32.2</td>
<td>17.8</td>
<td>59</td>
<td>598</td>
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<td>8/4</td>
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<td>573</td>
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<tr>
<td>8/6</td>
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<td>20.6</td>
<td>101</td>
<td>608</td>
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<tr>
<td>8/7</td>
<td>36.1</td>
<td>23.3</td>
<td>150</td>
<td>600</td>
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<tr>
<td>8/8</td>
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<td>106</td>
<td>284</td>
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</table>

* data adapted from Mason et al. (1980).
Table 5. Parameters used for model validation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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<td>$C_p'$</td>
<td>plant water capacitance (m m$^{-1}$) 0.0</td>
</tr>
<tr>
<td>$d_1$</td>
<td>distance of displacement (m) 0.6</td>
</tr>
<tr>
<td>$D_L$</td>
<td>day length (s) 14x3600</td>
</tr>
<tr>
<td>LAI</td>
<td>leaf area index 5.6</td>
</tr>
<tr>
<td>$P_a$</td>
<td>root axial resistivity (s m$^{-3}$) 5x10$^{10}$</td>
</tr>
<tr>
<td>$P_r$</td>
<td>root radial resistivity (s m$^{-1}$) 8x10$^{11}$</td>
</tr>
<tr>
<td>$r_{max}$</td>
<td>maximum leaf resistance (s m$^{-1}$) 2000</td>
</tr>
<tr>
<td>$r_{min}$</td>
<td>minimum leaf resistance (s m$^{-1}$) 50</td>
</tr>
<tr>
<td>$S_N$</td>
<td>solar noon (s) 14x3600</td>
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<tr>
<td>$z_o$</td>
<td>degree of roughness (m) 0.05</td>
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<tr>
<td>$\alpha_f$</td>
<td>canopy albedo 0.2</td>
</tr>
<tr>
<td>$\epsilon_f$</td>
<td>canopy emissivity 0.95</td>
</tr>
<tr>
<td>$\psi_c$</td>
<td>critical leaf water potential (m) 120</td>
</tr>
<tr>
<td>$\psi_{lm}$</td>
<td>leaf water potential at which stomatal totally closed (m) 220</td>
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Table 6. Comparison between soil and root resistances

<table>
<thead>
<tr>
<th>Wet Soil ($\psi_s = -6$ m)</th>
<th>Dry Soil ($\psi_s = -71$ m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>$r_s$</td>
</tr>
<tr>
<td>0.15</td>
<td>.47x10$^7$</td>
</tr>
<tr>
<td>0.60</td>
<td>.38x10$^6$</td>
</tr>
<tr>
<td>0.90</td>
<td>.31x10$^7$</td>
</tr>
<tr>
<td>1.50</td>
<td>.57x10$^7$</td>
</tr>
</tbody>
</table>

$^a$ $r_s$, $r_r$, $r_x$ are resistance of soil, root radial and root axial, respectively
Figure 1. Fitted soil water retention curves using measurements from Mason et al. (1980) and parameters in Table 2
Figure 2. Soil moisture profiles of July 31, August 3 and 8 for .25 and 1.0 m rows
Figure 3. Diurnal variation of soil water potential ($\psi_s$), leaf water potential ($\psi_l$), transpiration ($E_T$) and evaporation ($E_P$) for the 9-day simulation.
Figure 4. Comparison of measured and simulated leaf water potential
a. 0.25 m rows; b. 1.0 m rows
Figure 5. Comparision of measured and simulated evapotranspiration
a. 0.25 m rows; b. 1.0 m rows
Figure 6. Comparison of measured and simulated soil moisture profiles
a. 0.25 m rows; b. 1.0 m rows
Figure 7. Simulated and measured leaf water potential on a cloudy day
Figure 8. Effect of soil moisture on leaf water potential (soil water potential $\psi_s = -12$, -27 and -55 m)

Figure 9. Effect of soil moisture on canopy resistance (soil water potential $\psi_s = -12$, -27, and -55 m)
Figure 10. Effect of soil moisture on transpiration
(soil water potential $\psi_s = -12$, -27, and -55 m)

Figure 11. Effect of atmospheric demand on leaf water potential
(potential transpiration $E_p = 2.4$, 4.6, and 9.7 mm day$^{-1}$)
Figure 12. Effect of root radial resistivity on leaf water potential (root radial resistivity $P_r=1\times10^{11}$, $5\times10^{11}$, and $1\times10^{12}$ m s$^{-1}$)

Figure 13. Effect of soil type on leaf water potential (sand, loam and clay)
Figure 14. Effect of soil type on transpiration (sand, loam, and clay)

Figure 15. Effect of plant water capacitance on leaf water flux
(plant water capacitance $C_p = 1 \times 10^{-6}$, $5 \times 10^{-6}$, and $1 \times 10^{-5}$ m$^{-1}$)
Figure 16. Diurnal variation of leaf water potential ($\psi$), root extraction $S$, and transpiration ($E_T$) for a large leaf water capacitance ($C_p = 10^{-5} \text{ m m}^{-1}$).

Figure 17. Diurnal variation of leaf water potential ($\psi$) and transpiration ($E_T$) for zero leaf water capacitance.
Figure 18. Effect of leaf water capacitance on leaf water potential (plant water capacitance $C_p=1 \times 10^{-6}$, $5 \times 10^{-6}$, and $1 \times 10^{-5}$ m m$^{-1}$, soil water potential $\psi_s=-26$ m)
PAPER 3

MODELING LEAF STOMATAL RESISTANCE IN RELATION TO IRRADIANCE AND LEAF WATER POTENTIAL
Modeling leaf stomatal resistance in relation to
  irradiance and leaf water potential

Yimei Guo and S. E. Taylor

From the Department of Agronomy, Iowa State University, Ames, IA 50011

(to be submitted to Agricultural and Forest Meteorology)
Leaf resistance has been recognized as an important factor in plant water transport. Many empirical models of leaf resistance related to environmental factors were developed in recent years to study water transport in the soil-plant-atmosphere system. Most of these models require many empirical parameters which are obtained by curve fitting of data. The objective of this paper is to develop and verify a simple model that includes the direct effect of irradiance and leaf water potential, and relates the model parameters to plant properties. The simultaneous effects of light and leaf water potential are functionally described. The functional response is evaluated by comparing simulated results with experimental data. The application of the response function in water transport simulation is described. Results indicate that the model is capable of simulating the effects of irradiance and leaf water potential on leaf resistance. In addition, the model has the ability to simulate diurnal variation of leaf resistance under natural conditions. The results suggest that irradiance and leaf water potential determine the basic diurnal variation of leaf resistance; the other factors only influence the magnitude of leaf resistance.
INTRODUCTION

Canopy transpiration is an important component of surface energy balance. Stomatal resistance is a primary biological control of water loss and it is, therefore, essential to simulate stomatal function in relation to environmental factors in order to simulate transpiration.

Stomatal aperture adjustment is a complex process which is influenced by environmental factors, including irradiance, leaf water potential, soil water potential, vapor pressure deficit, air temperature, CO₂ concentration, etc. The effects of these factors on stomatal resistance are different and some are not clearly defined.

Stomatal opening is determined primarily by irradiance when water supply in the root zone is adequate to meet plant needs and temperature, wind speed and humidity conditions are favorable. At high leaf water potential, stomatal resistance is high in low light and rapidly decreases as irradiance increases (Turner and Begg, 1973; West and Gaff, 1976). A simple hyperbolic relationship between irradiance and leaf resistance has been used to describe the stomatal response (Turner and Begg, 1973; Deardorff, 1976; Gates, 1980).

Stomatal resistance is reported to be almost independent of leaf water potential until leaf water potential falls below a critical value after which leaf resistance increases rapidly (Kanemasu and Tanner, 1969; Turner, 1974; Brown et al., 1976; West and Gaff, 1976; Hand et al., 1982). Low leaf water potential has a predominant effect on the diurnal pattern of leaf resistance (Van Bavel et al., 1965). Severe leaf water deficit influences the normal effect of light on the opening of the stomatal and may cause partial or full stomatal closure during the day.

Direct effects of soil moisture on leaf resistance have been described (Gallon et al., 1985; Turner et al., 1985). It has been suggested that roots can sense the drying of soil and send a message to
leaves which induces stomatal closure (Gollan et al., 1986; Zhang et al., 1987; Munn and King, 1988; Tardieu et al., 1991). They found that soil water deficit can induce stomatal closure even when leaf water potential does not change. In this study, soil water potential is assumed to be directly related to leaf water potential. The effect of soil moisture on leaf resistance is discussed later.

Stomatal resistance was found to be little influenced by vapor pressure deficit at high soil water potential and very sensitive at low soil water levels (Taylor and Gates, 1970). Vapor pressure deficit has been shown to have a direct effect on stomatal resistance in addition to any effect induced by a lowering of the leaf water potential (Lange, 1971; Turner et al., 1985; Gollan et al., 1985; Bakker, 1990; Aphalo and Jarvis, 1991; Turner, 1991). Some empirical models consider vapor pressure deficit as a principal factor controlling leaf resistance (Jarvis, 1976; Avissar et al., 1985; Choudhury and Monteith, 1986; Bakker, 1991; Kim and Verma, 1991; Lynn and Carlson, 1990). However, this direct effect has not yet been fully investigated (Choudhury and Idso, 1985; Lynn and Carlson, 1990). Thus, effect of vapor pressure deficit is considered, in our study, to contribute to transpiration rate, and, thereby influence leaf water potential.

Stomatal resistance shows a response to air temperature (Turner, 1991). However, there are relatively few data on which to base a function (Lynn and Carlson, 1990). Furthermore, the effect of temperature on stomatal functioning might be coupled with other effects, such as vapor pressure deficit, photosynthetic rate and leaf water potential. Also, it is widely accepted that in the optimum range, temperature has little effect on stomatal resistance. Direct effects of temperature on leaf resistance are not considered in this study.

Turner (1991) reported that increasing carbon dioxide concentration above ambient decreases stomatal conductance, whereas decreasing the concentration below ambient increases stomatal
conductance. Data presented in Avissar et al. (1985) indicate that the effect is not likely to be significant during the course of a day. Concentration of CO$_2$ was not included in this model.

Stomatal action is related to transpiration. A high transpiration rate induces low leaf water potential if root or stem resistances are significant. This results in high stomatal resistance and, in turn, may reduce transpiration rate. Observed cycling of stomatal resistance (Barrs and Klepper, 1968; Taylor and Gates, 1970) may be induced by this effect. Many environmental factors influence transpiration directly, thus, they have either direct or indirect effects on leaf resistance. Stomatal opening is a very complicated process resulting from the simultaneous effects and interactions of many factors. Cycling is not included in this functional model although the effects are implicit.

Gates (1964) and Lange (1959) noted a tendency for clustering of observed leaf temperatures near the photosynthetic ($P_*$) optimum temperature. The effect was apparently due to stomatal control of transpiration and the associated evaporational cooling. At cool temperatures, stomata may have been relatively restricted because of direct temperature effects or as a result of internal CO$_2$ concentration resulting in higher resistance and elevation of leaf temperature above air temperature. At higher air temperatures, the leaf temperature may have been in the range to sustain high assimilation rates and lowest resistance.

It is difficult to develop precise relationships between leaf resistance and environmental factors. Many factors, such as local turgor in response to temperature distribution within the leaf, have not been investigated. Physiological knowledge of stomatal functioning is not adequate to provide a comprehensive mechanistic model of stomatal resistance and environmental factors. However, reliable prediction of stomatal resistance is essential for functional simulation of water transport in the soil-plant-atmosphere system. Empirical relationships between stomatal resistance and environmental factors have been proposed (Szeicz et al., 1973; Jarvis, 1976; Deardorff, 1978;
Pallardy and Kozlowski, 1979; Federer, 1979; Avissar et al., 1985; Choudhury and Idso, 1985; Lynn and Carlson, 1990; Bakker, 1991; Kim and Verma, 1991). Most of the models require many empirical parameters that must be determined by curve fitting. This is very difficult in practice. It is, therefore, necessary to develop a simple model which uses only a few meaningful plant characteristics and environmental factors as model parameters.

Developing a mechanistic model of leaf resistance considering all possible influencing factors is an ultimate physiological goal. Operational models of water use may, however, be sufficiently precise if only primary functions are considered. Including too many potential factors in the model might not improve the model accuracy, but instead, merely introduce more parameters into the model. Thus, the goal of this paper is to develop a simple model with parameters related to plant properties. Light and leaf water potential were chosen as the model parameters because there are considerable data available for model verification. The other environmental factors, such as vapor pressure deficit, leaf temperature, and soil moisture, are assumed to be related to leaf water potential, thus affecting stomatal aperture implicitly.

The objectives of this paper are: (1) to develop a functional model of leaf resistance in relation to irradiance and leaf water potential; (2) to evaluate the model using published experimental data; and (3) to evaluate the combined effect of irradiance and leaf water potential.
MODEL DEVELOPMENT

It is assumed that leaf resistance ($r_l$) is a function of irradiance (IR) and leaf water potential ($\psi$):

$$r_l = f(IR, \psi)$$

$r_l$ is only a function of IR while $\psi$ is high, $r_l = f(IR)$. $r_l$ is only a function of $\psi$ while IR is above saturation, $r_l = f(\psi)$. Assuming $r_l$ is the result of complete expression of the influence of $\psi$ and IR without any synergistic interactions (Jarvis, 1976), the relationship is expressed as:

$$r_l = f_1(IR) \cdot f_2(\psi)$$

The functional relationship between leaf resistance and irradiance for a single leaf has been suggested to approximately be a hyperbolic function (Turner and Begg, 1973) as presented in Figure 1. When other environmental factors are not limiting, leaf resistance increases slightly as irradiance decreases when light intensity is relatively high. When light intensity is low, leaf resistance increases rapidly as irradiance decreases. Dependence of leaf resistance $r_l$ on irradiance IR can be approximately represented by:

$$r_l = r_{\text{min}} \frac{a}{IR + b}$$

where $r_{\text{min}}$ is the minimum value of $r_l$ under full sun light and without water stress, a and b are empirical coefficients.

Empirical coefficients are usually obtained by curve fitting. It would be helpful if these coefficients could be related to plant properties. When stomata are closed in the dark, leaf resistance is equal to cuticular resistance ($r_{\text{max}}$), IR = 0, $r_l = r_{\text{max}}$, so we obtain from (3):
When irradiance reaches saturation, $\text{IR} = \text{IR}_{\text{max}}$, leaf resistance reaches its minimum, $r_i = r_{\text{min}}$, so

$$r_{\text{min}} = r_{\text{min}} \frac{a}{\text{IR}_{\text{max}} + b}$$

From (4) and (5), we get

$$a = \frac{r_{\text{max}} - \text{IR}_{\text{max}}}{r_{\text{max}} - r_{\text{min}}}$$

$$b = \frac{r_{\text{min}} \cdot \text{IR}_{\text{max}}}{r_{\text{max}} - r_{\text{min}}}$$

let

$$\alpha = \frac{r_{\text{max}}}{r_{\text{max}} - r_{\text{min}}}$$

$$\beta = \frac{r_{\text{min}}}{r_{\text{max}} - r_{\text{min}}}$$

then we may express the relationship between $r_i$ and IR as:

$$r_i = r_{\text{min}} \times \left( \frac{\alpha \text{IR}_{\text{max}}}{\text{IR} + \beta \text{IR}_{\text{max}}} \right)$$

where parameters $\alpha$ and $\beta$ are obtained from maximum and minimum leaf resistance under dark and full sun light conditions.

Equation (8) shows that as irradiance reduces to zero, $r_i$ increases to the maximum. As $\text{IR}$ increases to $\text{IR}_{\text{max}}$, $r_i$ decreases to minimum $r_{\text{min}}$. When $\text{IR} < \text{IR}_{\text{max}}$, $r_i$ increases hyperbolically as $\text{IR}$ decreases.
The relationship between leaf resistance and leaf water potential is presented in Figure 2 (Turner 1974). Leaf resistance does not change as \( \psi_i \) decreases until a critical value \( \psi_c \) of \( \psi_i \) is reached, at which \( r_i \) increases abruptly.

The relationship between leaf resistance \( (r_i) \) and leaf water potential \( (\psi_i) \) when \( \psi_i < \psi_c \) is treated as an exponential function when other environmental factors are not limited:

\[
\begin{align*}
    r_i &= r_{\text{min}} e^{-\gamma(\psi_i - \psi_c)} \quad (\psi_{\text{im}} < \psi_i < \psi_c) \\
    r_i &= r_{\text{min}} \quad (\psi_i \geq \psi_c) \\
    r_i &= r_{\text{wmax}} \quad (\psi_i \leq \psi_{\text{im}})
\end{align*}
\]

where \( \psi_c \) is critical value of \( \psi_i \) above which \( r_i \) is constant, \( \gamma \) is a parameter.

\( r_i \) is equal to \( r_{\text{min}} \) when \( \psi_i \) is above \( \psi_c \). When \( \psi_i \) reduces to a value \( \psi_{\text{im}} \) where stomata fully close under water stress, \( r_i \) increases to the maximum value \( r_{\text{wmax}} \). So \( \gamma \) can be determined by substituting \( \psi_{\text{im}} \) and \( r_{\text{wmax}} \) into (9):

\[
\gamma = \frac{-\ln(r_{\text{wmax}}/r_{\text{min}})}{\psi_{\text{im}} - \psi_c}
\]

where \( r_{\text{wmax}} \) is the cuticular resistance of the leaves when stomata close in response to water stress. \( \psi_{\text{im}} \) is the leaf water potential at which \( r_i \) reaches \( r_{\text{wmax}} \).

Equation (9) shows that as leaf water potential \( \psi_i \) increases above \( \psi_c \), leaf resistance \( r_i \) keeps at constant \( r_{\text{min}} \). When \( \psi_i \) reduces to \( \psi_{\text{mim}} \), \( r_i \) increases to \( r_{\text{wmax}} \) exponentially.

According to (2), we can obtain the relationship of leaf resistance to both irradiance and leaf water potential as (when \( \psi_i < \psi_c \)):

\[
\begin{align*}
    r_i &= r_{\text{min}} \times \left( \frac{\alpha I R_{\text{max}}}{{IR} + \beta I R_{\text{max}}} e^{-\gamma(\psi_i - \psi_c)} \right) \quad (\psi_i < \psi_c)
\end{align*}
\]
Equation (11) shows that \( r_1 \) is approximately a hyperbolic function of \( IR \) and an exponential function of \( \psi_i \). When \( \psi_i \geq \psi_e \), \( r_1 \) is determined only by irradiance \( IR \). When \( \psi_i < \psi_e \), leaf water potential has an exponential contribution to leaf resistance.
MODEL VERIFICATION

The model is evaluated by comparing the simulated results with the experimental data (Turner and Begg, 1973; Turner, 1974); the results are presented in Figures 1 and 2. The parameters used for fitting data in Figures 1 and 2 are shown in Table 1.

Figure 1 shows the comparison between simulated and measured leaf resistance response to irradiance. The simulated $r_i$ from irradiance fits measured data very well. Good agreement between the simulated $r_{iw}$ from leaf water potential and measured $r_i$ is shown in Figure 2. As shown in Figures 1 and 2, the shapes of the curves of three different plants are similar, while the critical values corresponding to irradiance and leaf water potential are different. As presented in Table 1, the critical value of leaf water potential for maize is larger than that of sorghum. With the same values of IR and $\psi_{iw}$, maize has the larger leaf resistance. Hence, to fit equation (11), different plants need different parameters. At present only limited data are available to determine these parameters; more experimental data are needed to obtain reliable parameters for different plants. Critical levels vary between species but once exceeded, diffusion resistance usually increases rapidly with a further small increases in stress (West and Gaff, 1976). While water potential and light intensity have the potential to exert major control over leaf resistance, they generally do so only after certain limits are exceeded.

Results shown in Figures 1 and 2 indicate that equations (8) and (9) are capable of simulating leaf resistance, separately, i.e., under well-watered condition, a hyperbolic function can reasonably estimate leaf resistance from light intensity, and an exponential function under high light intensity expresses the effect of leaf water potential.
In order to know whether equation (11) is capable of simulating the combined effect of IR and $\psi_l$, a diurnal variation of leaf water potential under natural conditions is simulated; the results were compared with experimental data from Choudhury and Idso (1985) for wheat at both well-watered and stressed conditions. Diurnal variation of radiation and leaf water potential are shown in Figures 3 and 4. The comparisons between simulated and measured leaf resistances are shown in Figure 5. The critical value $\psi_c = -180 \text{ m}$, $r_{\text{min}} = 0.5 \text{ s cm}^{-1}$, $r_{\text{max}} = 20.0 \text{ s cm}^{-1}$, $r_{\text{wmax}} = 20.0 \text{ s cm}^{-1}$ at $\psi_{\text{ln}} = -300 \text{ m}$, and $\text{IR}_{\text{max}} = 920 \text{ W m}^{-2}$ was used.

As presented in Figure 5, the simulated resistance closely follows the diurnal pattern of the measured one under well-watered and stressed conditions. For the well-watered condition, leaf water potential was above $-180 \text{ m}$ (Figure 4), and variation of leaf resistance followed radiation closely (Figure 3). $r_i$ decreases as irradiance increases and change little when radiation increases above saturation; after that, $r_i$ starts increasing as irradiance decreases. Under a stressed condition, the situation is different due to the effect of leaf water potential. In the morning, when leaf water potentials are high (above the critical value of $-185 \text{ m}$ as in Figure 4) the stomatal resistance is a function of irradiance only; thus, the leaf resistances are close under both conditions. As irradiance increases, leaf water potential decreases in response to transpiration. Both simulated and measured leaf resistance reached a peak at 1500 hours and then decreased with increasing water potential. After the sun sets, although leaf water potential is recovering, resistance increases as irradiance decreases.

The simultaneous effects of irradiance and leaf water potential described by simulation at different levels of $\psi_l$, and effect of water potential at different levels of IR, are shown in Figure 6 and 7. The parameters for maize are used (Table 1).
Figure 6 shows that at high leaf water potential ($\psi_l > -100 \text{ m}$), leaf resistance does not increase markedly until a very low irradiance of $143 \text{ W m}^{-2}$. As water potential decreases, leaf resistance demonstrates a marked increase at a higher level of irradiance. That is, the marked increase of leaf resistance at a high water potential occurs at a higher level of light intensity than that at low water potential. Figure 6 also indicates that the leaf stomata close at higher irradiance when the leaf is under high water stress and at lower irradiance when the leaf under low water stress. This demonstrates that even at high irradiance, very low leaf water potential can cause stomatal closure. Figure 7 shows the relationship between leaf resistance and leaf water potential at different levels of irradiance. Under all levels of irradiance, leaf resistance remains small until $\psi_l$ falls to the critical value $\psi_c$, then increases. The rate of leaf resistance increase is smaller for high levels of irradiance than for lower levels of irradiance. However, the critical values for $\psi_l$ are about the same for the three levels of irradiance, i.e., the critical value of leaf water potential at which leaf resistance begins to increase is determined mainly by leaf water potential. Irradiance level affects the rate of leaf resistance change. At lower irradiance, $\tau_l$ increases more rapidly than that at higher irradiance. Figure 7 also shows stomatal close at lower $\psi_l$ when IR is high, and at a higher $\psi_l$ when IR is low. Photosynthetic production may tend to hold stomata open even as $\psi_l$ decreases; i.e., photosynthetic effect is not directly on $\psi_l$, but influences guard cell potential and keeps $\tau_l$ lower.
DISCUSSION AND CONCLUSIONS

As shown in Figure 5, in the early morning and late afternoon, leaf water potentials were above critical value of -180 m under both well-watered and stressed conditions, so \( \varphi \) did not have significant influence on \( r_c \). However, the measured leaf resistance under the well-watered condition was lower than that under the stressed condition. The soil moisture difference was assumed to directly cause this, since the other factors, such as irradiance, vapor pressure deficit and air temperature, were essentially the same for all plants.

Leaf resistance reflects the leaf water status, especially guard cell turgor pressure, which is influenced not only by atmospheric conditions, but also soil moisture and plant properties. This complex process is hard to study under experimental conditions. A numerical model is useful to investigate the sensitivity of \( r_c \) to environmental factors. The leaf resistance relationship presented in this paper is proposed to be used in such models.

These models are based on the steady state flow assumption that transpiration from leaf \( (E_T) \) is equal to the total roots extraction from soil \( (RET) \) (van den Honert, 1948):

\[
\sum_{i=1}^{n} RET(i) = E_T
\]

where root extraction from each soil layer \( i \) is described as (Reid and Huck, 1990):

\[
RET(i) = \frac{\psi_i - \psi_{r_i}(\theta)}{r_{ni}(K_n L_o) + r_{ri}(L_o) + r_{ai}(L_o)}
\]

where \( \psi_i \) is soil water potential, \( r_{ni}, r_{ri} \) and \( r_{ai} \) are soil resistance, root radial and root axial resistance, respectively.
Transpiration may be determined by (Guo and Taylor, 1992):

\[
E_T = \left( \frac{0.622 \rho_a}{P} \right) \left( \frac{r_c (\psi_T - e_a)}{\rho_w P (r_c (\psi_T) + r_b)} \right)
\]  

(14)

where \(e_l\) and \(e_a\) are leaf vapor pressure which related to \(\psi_l\), and air vapor pressure, \(r_c\) and \(r_b\) are canopy resistance and canopy air resistance, respectively. \(\rho_a\) and \(\rho_w\) are density of dry air and water. \(P\) is air pressure.

Substituting (13) and (14) into (12); we obtain:

\[
\sum_{i=1}^{n} \frac{\psi_l - \psi_a(\theta)}{r_a (K_v L_v) + r_n (L_v) + r_m (L_v)} = \left( \frac{0.622 \rho_a}{P} \right) \left( \frac{e_l (\psi_T - e_a)}{r_c (\psi_T) + r_b} \right)
\]  

(15)

Leaf water potential \(\psi_l\) can be obtained by solving equation (15) iteratively. Effects of vapor pressure deficit, leaf temperature, soil moisture, root resistance, and soil resistance on leaf resistance can also be described by combining (15) with (11). It is clear that leaf water potential is related to soil moisture, vapor pressure, leaf temperature and leaf resistance. Therefore, the assumption that the effects of vapor pressure, leaf temperature and soil moisture on leaf resistance are related to leaf water potential is valid. Coupling the leaf resistance model (11) with the plant water transport model allows simulation of the effects of environmental factors on leaf resistance. Figures 8, an example from the plant water transport model of Guo and Taylor (1992), shows the effect of soil water potential on canopy resistance (integration of the leaves in the whole canopy). Low soil water potential induces high canopy resistance. Similar results are obtained for the vapor pressure deficit (graph is not shown).

To use (11), determination of critical leaf water potential \(\psi_c\) is essential. There are only limited data at present, and more experiments are needed to determine \(\psi_c\) and to investigate whether \(\psi_c\) is a constant or not.
In conclusion, irradiance and leaf water potential dominate the diurnal pattern of leaf resistance; the other factors influence only the magnitude of \( r \). The proposed simple model with two variables can describe diurnal variation of leaf resistance under natural conditions reasonably well, and it has potential utility in a simulation model of plant water transport. More research is needed to determine the direct effects of vapor pressure deficit, leaf temperature and soil moisture on leaf water potential and leaf resistance. Direct application of this model requires that the leaf water potential be functionally related to soil water potential and that the soil water potential as a function of soil water balance be known. These relationships are treated by authors elsewhere (Guo and Taylor, 1992).
REFERENCES


<table>
<thead>
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<th></th>
<th>$IR_{\text{max}}$</th>
<th>$\psi_e$</th>
<th>$\psi_{\text{lm}}$</th>
<th>$r_{\text{min}}$</th>
<th>$r_{\text{max}}$</th>
<th>$r_{\text{wmax}}$</th>
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<tr>
<td>Maize</td>
<td>572</td>
<td>-140</td>
<td>-180</td>
<td>2.42</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>Sorghum</td>
<td>572</td>
<td>-160</td>
<td>-220</td>
<td>2.18</td>
<td>30</td>
<td>24</td>
</tr>
</tbody>
</table>
Figure 1. Comparison of simulated and measured leaf resistance related to irradiance under high water potential (measured data adapted from Turner and Begg (1973))
Figure 2. Comparison of simulated and measured leaf resistance related to leaf water potential under high irradiance (measured data adapted from Turner (1974))
Figure 3. Diurnal variation of radiation (adapted from Choudhury and Idso (1985))
Figure 4. Diurnal variation of leaf water potential (adapted from Choudhury and Idso (1985))
Figure 5. Comparison of simulated and measured diurnal variation of leaf resistance (measured data adapted from Choudhury and Idso (1985))
Figure 6. Effect of irradiance on leaf resistance for different levels of leaf water potential.
Figure 7. Effect of leaf water potential on leaf resistance for different levels of irradiance
Figure 8. Effect of soil water potential on canopy resistance
(soil water potential $\psi_s = 12, 27,$ and $55$ m)
GENERAL SUMMARY

This dissertation presents a one-dimensional comprehensive model of water transport in the soil-plant-atmosphere system based on mass and energy balance principles. The model integrates the whole system with the best available understanding of each process in the system. The processes considered in the model are: soil moisture and heat transport, root extraction, transpiration, latent and sensible heat transfer at the soil surface, and energy partitioning in the canopy and at the soil surface.

The model was validated by comparing the simulated results with the field measurements. Comparison of leaf water potential, evapotranspiration and soil moisture profile indicated that the model is capable of simulating plant water transport under natural conditions reasonably well. Accurate model inputs and model parameters are essential for model validation.

The proposed model for simulating leaf resistance as related to leaf water potential and irradiance successfully simulated leaf resistance under natural conditions. The leaf resistance model is capable of simulating the effects of soil moisture, transpiration, leaf temperature and vapor pressure deficit on leaf water potential, and thus leaf resistance while coupling with the comprehensive plant water transport model.

The experimental run of the water transport model presents reasonable results of energy partitioning, leaf water potential, soil water potential and leaf resistance variation. The relationship of root extraction to the soil moisture profile and to root length density distribution was also described.

The sensitivity studies showed that soil moisture has a significant effect on leaf water potential and transpiration. Atmospheric conditions also influence plant water status substantially. Under the
same soil moisture and atmosphere conditions, root resistance has a large effect on water uptake. Therefore, both environmental factors and plant properties influence on plant water transport.
ADDITIONAL WORK

The one dimensional model of water transport in the soil-plant-atmosphere system presented in this dissertation could be expanded and improved in the following areas:

1. expansion of the one layer canopy energy budget model into a multiple layer model;
2. development a mechanistic model for leaf resistance, including osmotic adjustment;
3. detailed study of the effects of plant water capacitance;
4. additional field investigations of root resistance, soil resistance and xylem resistance;
5. inclusion of a root growth model in the simulation;
6. coupling the model with soil solute transport and water vapor transport models;
7. expanding the one dimensional soil model to a two dimensional model.
BIBLIOGRAPHY


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APPENDIX A

Simulation of Water Transport in the Soil-Plant-Atmosphere System

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DIMENSION DX(30),X(30)
COMMON/ATM/IDAY,HR,TA,TF,TG,EA,EAF,ESF,UA,RFR,SG
COMMON/SOIL/B(30),KS(30),PSI(30),B1(30),B2(30),B3(30),EN(30),
* AAPHA(30),THETAS(30),THETAR(30),CI(30)
COMMON/CANOPY/SIGMAF,RMIN,RMAX,RWMAX,PSIC,PSILM,CPT
COMMON/GEO/AL
COMMON/SOLARPARM/DR,DL
COMMON/ENERGY/HG,HP,EG,TR,RN,RG,RU,PETR,RNC
COMMON/ROOTParm/PR,PA,BO,FP,RJ,TRL,PRTL(30),IRT
COMMON/TIME/IM
COMMON/SOILFT/CLAY(30)
REAL KS
CHARACTER*64 WNAME,DNAME,ONAME,VNAME,ENAME,RNAME

C MAIN PROGRAM WHICH CALLS THE PARAMETER AND SOLUTE SUBROUTINE

10 FORMAT(IOA)
WRITE(*,*) 'Please enter weather dataset name: '
READ(*,10) WNAME
OPEN(1,FILE=WNAME, STATUS ='OLD')
WRITE(*,*) 'Please enter your initial dataset name: '
READ(*,10) DNAME
OPEN(4,FILE = DNAME, STATUS = 'OLD')
WRITE(*,*) 'Please enter your output file names: '
WRITE(*,*) 'ENTER soil moisture profile output: '
READ(*,10) ONAME
OPEN(8,FILE = ONAME, STATUS = 'UNKNOWN')
WRITE(*,*) 'ENTER variable output name: '
READ(*,10) VNAME
OPEN(10,FILE = VNAME, STATUS = 'UNKNOWN')
WRITE(*,*) 'ENTER energy budget output name: '
READ(*,10) ENAME
OPEN(11,FILE = ENAME, STATUS = 'UNKNOWN')
WRITE(*,*) 'ENTER resistant output name: '
READ(*,10) RNAME
OPEN(13,FILE = RNAME, STATUS = 'UNKNOWN')
OPEN (3,FILE = 'spacc.dat',ACCESS = 'SEQUENTIAL',STATUS = 'OLD')
OPEN (9,FILE = 'depth.dat',ACCESS = 'SEQUENTIAL',STATUS = 'OLD')
OPEN (12,FILE = 'canopy.dat',ACCESS = 'SEQUENTIAL',STATUS = 'OLD')
OPEN (15,FILE = 'clayft.dat',STATUS = 'old')

C
READ IN SOIL GEOGRAPHIC PROFILE, AND TIME SCALE, A, B are upper and lower boundary, DT is time step, N is space grid point
READ(3,*) BL,BR,DT,N,IMESH
NTMAX=24*60*60/DT

CALL SPACE(IMESH,X,DX,BL,BR,N)

CALL PARAMETER SUBROUTINE
WRITE(6,*) 'Input soil type, 1 for loam, 2 for sand, 3 for clay
* 4 for sandy clay loam, 5 for silt loam'
READ(5,*) SOIL
CALL PARAMET(SOIL,N,X)

CALL THE SUBROUTINE FOR SOLVING THE PROBLEM
CALL SOLUTE(NTMAX,N,DX,DT,X)

CLOSE(1)
CLOSE(3)
CLOSE(4)
CLOSE(8)
CLOSE(9)
CLOSE(10)
CLOSE(11)
CLOSE(12)
CLOSE(13)
CLOSE(15)
STOP
END

SUBROUTINE SOLUTE(NTMAX,N,DX,DT,X)
COMMON/ATM/IDAY,HR,TA,TAF,EA,EF,ESF,UA,RFR,SG
COMMON/SOIL/B(30),KS(30),PSIS(30),B1(30),B2(30),B3(30),EN(30),
AAPHA(30),THETAS(30),THETAR(30),CL(30)
COMMON/CANOPY/SIGMAF,RMIN,RMAX,RWMAX,PSIC,PSILM,CPT
COMMON/GEO/AL
COMMON/SOLARPARM/DR,DL
COMMON/ENERGY/HG,HE,TR,RN,ET,PE,TR,FR,PE,TR
COMMON/ROOTPARM/PR,PA,B0,FP,RJ,TRL,PRTL,30,IRT
COMMON/TIME/IM
COMMON/SOILFT/CLAY(30)
DIMENSION U0(3,2),C(2,30),G(2,30),F(2,30),U(30),DX(30),
AA(30),BB(30),DD(30),CC(30),UX(30),TX(30),FX(30),FLUX(30),
* CU(30), GU(30), FT(30), RET(30), THETA(30), 
  PSI(30), RS(30), RA(30), RK(30), SR(30), VAP(30), SS(30), X(30)
REAL KS, LAI

C
C ****************************************
IL = 1
IU = N

C INPUT PARAMETERS FROM USER

WRITE(6, *) 'Please input day length in hours:'
READ(5, *) DL
DL = DL * 3600.
WRITE(6, *) 'Is canopy considered here? 0 for none, 1 for YES'
READ(5, *) CANP
IF (CANP.EQ.1) THEN
  WRITE(6, *) 'If the canopy exist, input shading coeff:'
  READ(5, *) SIGMAF
  WRITE(6, *) 'If root density file exist, enter 1, otherwise 0:'
  READ(5, *) IRT
ENDIF
WRITE(6, *) 'If vapor trans considered, input I, otherwise 0'
READ(5, *) VPR
WRITE(6, *) 'Please input low boundary, 1 for const, 2 for zero
  flux'
READ(5, *) IBD
WRITE(6, *) 'Please input albedo status, 1 for nature, 0 for const'
READ(5, *) alp
ALP = 1.
WRITE(6, *) 'If water transport in plant is equilibrium, input 1,
  otherwise input 0'
READ(5, *) IEQP
wind = 1.

C INITIAL TIME, FROM MIDNIGHT
C Initialize soil profile

TS = 0.0
CALL INDIY(N, U0, UX, TX)
CALL DEFINE LOWER BOUNDARY.
BW, BT ARE WATER CONTENT AND TEMP.
BW = UX(N)
BT = TX(N)
TG = U0(2, 1)

WRITE(8, *)'***********This is the initial data***********
WRITE(8, *)' MOISTURE  TEMPERATURE'
WRITE(8, 300) (U0(1, I), U0(2, I), I = 1, N)

DO 12 JJ = 1, N

C CHECK IF INITIAL SOIL MOISTURE IS BELOW WILTING, IF SO, CORRECT
C IT TO WILTING POINTER
}
IF(U0(1,JJ).LE.THETAR(JJ)) UO(1,JJ)=THETAR(JJ)+0.001

CONTINUE

read in canopy parameters, if root file exist, read PRTL
IF(CANP.EQ.1) THEN
READ(12,*) RMIN,RMAX,RWMAX,PSIC,PSILM,CPT
READ(12,*) PR,PA,B0,FP,RJ,TRL
WRITE(10,*) RMIN,RMAX,RWMAX,PSIC,PSILM,CPT
WRITE(10,100) RMIN,RMAX,RWMAX,PSIC,PSILM,CPT
100 FORMAT(1X,3F8.1,2F8.1,E10.2)
WRITE(10,*) PR,PA,B0,FP,RJ,TRL
WRITE(10,200) PR,PA,B0,FP,RJ,TRL
200 FORMAT(1X,2E10.2,4F8.2)
IF(IRT.EQ.1) THEN
READ(12,*) (PRTL(I),I=1,N)
DO 2 I = 1,N
PRTL(I) = PRTL(I)*1.E4
2 CONTINUE
ENDIF
ENDIF

read soil clay fraction data
READ(15,*) (CLAY(I),I=1,N)
WRITE(10,*) 'DEPTH, ROOT DENSITY, CLAY FRACTION'
WRITE(10,400) (X(I),PRTL(I),CLAY(I),I=1,N)
400 FORMAT(1X,F5.2,2F10.2)

set initial plant water potential to -10m
PSIP=-10.0

Initialize accumulated root extraction
DO 80 I = 1,N
SS(I)=0.0
80 CONTINUE

START DAILY SIMULATION

INPUT BEGINNING DATE AND ENDING DATE IN CALENDAR DAY
READ(1,* ) IBDAY, Ieday
DO 10 IDAY = IBDAY, Ieday
WRITE(*,*) 'THIS IS ',IDAY,' DAY'
10 CONTINUE

READ IN DAILY TEMP, AND DEW POINT TEMP DATA

READ(1,* ) TAMAX,TAMIN,TDMIN,TDMAX,UAM,DR,ER,RF
convert T from F to C, UA from M.P.H. to m/s
TAMAX=(TAMAX-32.0)*5./9.
TAMIN=(TAMIN-32.0)*5./9.
TDMIN=(TDMIN-32.0)*5./9.
TDMAX=(TDMAX-32.0)*5./9.
UAM=UAM*0.5144
DR=DR*4.1855E4
SIMULATION IN A DAY FOR THE TIME INTERVAL OF 240 S
WRITE(8,*) '***THE CALENDAR DAY IS: ',IDAY
WRITE(10,*) '***THE CALENDAR DAY IS: ',IDAY
WRITE(13,*) '***THE CALENDAR DAY IS: ',IDAY
WRITE(10,*) 'TIME EA ESF EF EAF TA TF TG TAF
+ THETA PSIP PSI SIM RL'
WRITE(11,*) '***THE CALENDAR DAY IS: ',IDAY
WRITE(11,*) 'TIME RN RNC HG HF LEG LEF EG
+ TR SUMR PETR'
TEG=0.0
TEF=0.0
TPETR=0.0
TRET=0.0
TQ=0.0
initialize leaf temperature to minimum air temperature
TL=TAMIN
C Calculate water balance at the beginning of the day
WBEG=0.0
DO 4 1 = 1,N-1
   WBEG=WBEG+(U0(1,1)+U0(1,1+1))/2.*DX(I)
4 CONTINUE
C Set initial time at midnight, and time in second
TI=TS+FLOAT(IM)*DT
T=TI/3600.0
WRITE(*,*) '************* IM = ',IM,'**************'
C Calculate hour angle
HR=3.14*(FLOAT(IM)*DT/3600.0-2.0)/12.0
CALL WEATHER(TAMAX,TAMIN,TDMAX,TDMIN,RF,BR,ER,TI,IM,UAM)
C Set up equation
ITER=0
11 ITER=ITER+1
CALL PDEF(C,G,F,U0,N,CANP,THETA,RER,DX,VAP,VPR,
+ PSIP,PSI,RR,RS,RA,RL,RK,S,TL,DT,TI,IEQP,SUMR,PSIM)
DO 30 J = 1,N
   C(J)=C(I,J)
   G(J)=G(I,J)
   F(J)=F(I,J)
   T(J)=T(J)
   G(J)=G(J)
   F(J)=F(J)
30 CONTINUE
C Set up coefficient for linear equation
PM = 1.0 IS FOR CALLING SOIL MOISTURE, PM = 0.0 FOR TEMP

CALL COEFF(N,DX,U,U0,UX,TX,AA,BB,CC,DD,CU,GU,FU,
DT,PM,CANP,BW,BT,IBD,VAP)

Solve the linear equation by Thomas method
CALL THOMAS(IL,IU,BB,DD,AA,CC)

Store the solution into UX(N)

DO 40 L=I,N
 IF (CC(L).LE.THETAR(L)) CC(L) = THETAR(L)+0.001
 IF (CC(L).GT.THETAS(L)) CC(L) = THETAS(L)
 UX(L) = CC(L)
40 CONTINUE

CALL FOR TEMPERATURE
CALL TEMP(N,DX,U,U0,TX,UX,AA,BB,CC,DD,CT,GT,FT,
IL,IU,DT,CANP,BW,BT,IBD,VAP)

TG = TX(1)

CALL CONVTEST(N,TX,UX,U0,IERR)

WRITE(*,*) '********** Iteration = ',ITER,'**********'
IF(ITER.GT.1000) THEN
 WRITE(*,*) 'Not convergence, iteration = ',ITER
 STOP
ENDIF
IF(IERR.EQ.0) GO TO 51
GO TO 11

PRINT OUT THE FINAL RESULTS
CALCULATE DAILY EVAPORATION AND TRANSPIRATION
AND CONVERT IT TO M/S

DO 50 I=1,N
 U0(I,1) = UX(I)
 U0(I,2) = TX(I)
50 CONTINUE

WRITE(*,*) 'calculus water flux
FLUX(1) = EG
DO 70 I=2,N
 CALL SOILPARM(UX(I),RK(I),PSI(I),DF,I)
 FLUX(I) = -RK(I)*(PSI(I)-PSI(I-1))/DX(I-1)
70 CONTINUE
sum up root extraction and transpiration
DO 90 I = 1, N
SS(I) = SS(I) + SR(I) * DT
90 CONTINUE
write(*,*) 'iteration = ', ITER
TEG = TEG + EG * DT
TEF = TEF + TR * DT
TPETR = TPETR + PETR * DT
TRET = TRET + SUMR * DT
TQ = TQ + RK(N) * DT
CALL OUTPUT(DT, IM, N, UO, RET, ITER, PSI, PSI, RK, SR, SUMR, PSI, RL, 
RR, RA, RS, FLUX, X)
20 CONTINUE
C CALCULATE DAILY EVAPORATION TEG, TEF FROM M TO MM UNIT
TEG = TEG * 1000.0
TEF = TEF * 1000.0
TPETR = TPETR * 1000.0
TRET = TRET * 1000.0
TQ = TQ * 1000.0
WEND = 0.0
DO 3 I = 1, N - 1
   WEND = WEND + (UO(1, I) + UO(1, I + 1)) / 2. * DX(I)
3 CONTINUE
WBEG = WBEG * 1000.
WEND = WEND * 1000.
WBAL = WBEG - WEND
WRITE(11, *) 'TOTAL EVAP ROOTEXT TRANSP POTENTTR'
WRITE(11, 600) TEG, TRET, TEF, TPETR
WRITE(11, *) ' PR PA CPT'
WRITE(11, 700) PR, PA, CPT
WRITE(11, *) ' WBEG WEND WBAL EVTR TQ '
WRITE(11, 900) WBEG, WEND, WBAL, TEG + TEF + TQ, TQ
WRITE(11, *) 'This is accumulated root extraction'
WRITE(11, 800) (I, SS(I), I = 1, N)
C END OF DAILY SIMULATION
10 CONTINUE
300 FORMAT(X, 2(1X, E10.2))
500 FORMAT(X, 6(F5.2, 2X))
600 FORMAT(5X, 4(E12.3))
700 FORMAT(X, 3(E10.2))
800 FORMAT(X, 2(E12.3))
900 FORMAT(X, 5(F10.3, 1X))
RETURN
END
C******************************************************************************
c Subroutine for determining boundary conditions
******************************************************************************
SUBROUTINE BNDY(N, DX, DT, P, Q, R, IBND, THETA, CANP, BW, BT, IBD, VAP)
COMMON/ATM/IDAY, HR, TA, TF, TAF, TG, EA, EF, EAF, ESF, UA, RFR, SG
COMMON/SOIL/B(30), KS(30), PSIS(30), B1(30), B2(30), B3(30), B4(30),
COMMON/ENERGY/HG, HF, EG, TR, RN, RG, RU, PETR, RNC
DIMENSION P(2), Q(2), R(2), DX(N), VAP(N)
REAL L, KS, IMAX
DATA L, PW/2.5E6, 1000.0/
C***************************************************************
C L IS LATENT HEAT
C EG evaporation M/S, PW*EG in KG/M²/S, PW*EG*L, in W/M²
C PW is water density
C equation: PU + Q(DU/DX) = R
C P IS THE COEFFICIENT AHEAD OF VARIABLE U IN THE BOUNDARY EQ
C Q IS THE COEFFICIENT AHEAD OF DU/DX
C R IS THE COEFFICIENT AT THE RIGHT SIDE OF EQUATION
C***************************************************************
C IBND = 0, for upper boundary
C IBND = 1, for lower boundary
C CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C C Define upper boundary
C C CCCCCCCCCCCCCCCCCCCCCCCCCCCC
IF (IBND.EQ.0) THEN
C Heat condition
P(2) = 0.0
CALL THERMAL(Q(2), Theta, 1)
R(2) = -(RN - L*PW*EG - HG)
C CALL SOILPARM(THETA.COND.PSI.DIFF, 1)
C Moisture condition
C If it is raining, R(1) = rainfall rate, else R(1) = EG
IF (RFR.EQ.0.0) THEN
P(1) = 0.0
Q(1) = DIFF
R(1) = EG
ELSE
P(1) = 0.0
CALL VAPD(DTV, DWV, Theta)
Q(1) = DWV
R(1) = EG
ENDIF
ENDIF
IF (RFR.GT.0.0) THEN
DSAT = B(1)*KS(1)*PSI(1)/Theta
IMAX = DSAT*(THETAS(1) - Theta)/DX(1) + KS(1)
IF (RFR.GE.IMAX) THEN
P(1) = 0.0
Q(1) = DIFF
R(1) = -IMAX
ELSE
P(1) = 0.0
Q(1) = DIFF
R(1) = -RFR
ENDIF
C  Here EG is in KG/M^2 S, we need M/S, so dividing it by
C  Water density 1000 KG/M^3
ELSE
C
C set up lower boundary, ibd = 1 for constant boundary,
C  ibn = 2 for zero flux boundary
C
CALL SOILPARM(THETA,COND,PSI,DIFF,N)
IF(IBD.EQ.1) THEN
  P(2) = 1.0
  Q(2) = 0.0
  R(2) = BT
  IF(THETA.GT.THETAS(N)) THEN
    P(1) = 0.0
    Q(1) = DIFF
    R(1) = -Q(1)
  ELSE
    P(1) = 1.0
    Q(1) = 0.0
    R(1) = BW
  ENDIF
ELSE
  P(2) = 0.0
  CALL THERMAL(Q(2),THETA,N)
  R(2) = 0.0
  P(1) = 0.0
  Q(1) = DIFF
ENDIF
ENDIF
RETURN
END

C Subroutine for setting initial soil moisture and temperature profile
C******************************************************************************
SUBROUTINE INDY(N,U0,UX,TX)
DIMENSION U0(2,N),UX(N),TX(N)
C U0(N) stores initial data
DO 10 I = 1,N
  READ(4,*) UX(I),TX(I)
  U0(1,I) = UX(I)
  U0(2,I) = TX(I)
10 CONTINUE
RETURN
END

C Subroutine for determining coefficient of governing equations
C******************************************************************************
SUBROUTINE PDEF(C,G,F,U0,N,CANP,THETA,RET,DX,VAP,VPR,
  + PSIP,PSI,RR,RS,RA,RL,RK,SL,DT,TIME,IEQP,SUMR,PSIM)
COMMON/ATM/IDAY,HR,TA,TF,TAF,TG,EA,EF,EAF,ESF,UA,RFR,SG
COMMON/SOIL/B(30),KS(30),PSIS(30),B1(30),B2(30),B3(30),EN(30),
REAL KS
DO 10 I = 1,N
CALL SOILPARM(UO(1,I),RK(I),PSI(I),DIFF,I)
C(1,I) = 1.0
C(2,I) = (1.0-THETAS(I))*CI(I)+4.18E6*U0(1,I)
G(1,I) = DIFF
CK(I) = RK(I)
CALL THERMAL(G(2,I),U0(1,I),I)
F(2,I) = 0.0
THETA(I) = U0(1,I)
10 CONTINUE
C IF NO CANOPY, CANP=0, F is vapor term, OTHERWISE, CANP=1
CALL VAPOR(N,VAP,U0,DX,QVAP)
IF(CANP.EQ.0) THEN
   DO 30 J = 2,N-1
   IF(VPR.EQ.1) THEN
      F(1,J) = -(VAP(J)-RK(J+1)+RK(J-1))/(DX(J)+DX(J+1))
   ELSE
      F(1,J) = -(RK(J+1)-RK(J-1))/(DX(J+1)+DX(J))
   ENDIF
30 CONTINUE
F(1,1) = 0.0
F(1,N) = 0.0
ELSE
   CALL PLANTPT(PSIP,RET,N,PSI,THETA,RR,RS,RA,RL,RK,DX,S,CANP,TL,
   + DT,TIME,IEQP,SUMR,PSIM)
   DO 20 J = 2,N-1
   IF(VPR.EQ.1) THEN
      F(1,J) = -(RET(J)-VAP(J)-(RK(J+1)-RK(J-1))/(DX(J)+DX(J+1))
   ELSE
      F(1,J) = -(RET(J)-(RK(J+1)-RK(J-1))/(DX(J+1)+DX(J))
   ENDIF
20 CONTINUE
F(1,1) = 0.0
F(1,N) = 0.0
ENDIF
IF(VPR.EQ.1) F(1,1) = VAP(1)
RETURN
END
CALL BNDY(N, DX, DT, P, Q, R, IBND, U0(1, N), CANP, BW, BT, IBD, VAP)
IF (PM.EQ.1.0) GO TO 40
  P0 = P(2)
  Q0 = Q(2)
  R0 = R(2)
  U(J) = U0(2, J)
  Q1 = Q0
  GO TO 50
40  P0 = P(1)
  Q0 = Q(1)
  R0 = R(1)
  U(J) = U0(1, J)
C Calculate coefficient for the linear eq.
Q1 = SQRT(Q0*G0(J + 1))
50  DD(J) = P0*DX(J)-Q1*(1.0 + DX(J)**2*C0(J)/(2.0*G0(J)*DT))
  AA(J) = Q1
  CC(J) = R0*DX(J) + Q1*(DX(J)**2*C0(J)*U(J)/(2.0*G0(J)*DT) +
            F0(J)*DX(J)**2/(2.0*G0(J)))
  GO TO 20
ENDIF

C Set coefficient for lower boundary
IF (J.EQ.N) THEN
  IBND = 1
  CALL BNDY(N, DX, DT, P, Q, R, IBND, U0(1, N), CANP, BW, BT, IBD, VAP)
  IF (PM.EQ.1.0) GO TO 60
  P0 = P(2)
  Q0 = Q(2)
  R0 = R(2)
  U(J) = U0(2, J)
  GO TO 70
60  P0 = P(1)
  Q0 = Q(1)
  R0 = R(1)
  U(J) = U0(1, J)
  BB(J) = -Q0
70  DD(J) = P0*DX(J-1) + Q0*(1.0 + DX(J-1)**2*C0(J)/(2.0*G0(J)*DT))
  CC(J) = R0*DX(J-1) + Q0*(DX(J-1)**2*C0(J)*U(J)/(2.0*G0(J)*DT) +
            F0(J)*DX(J-1)**2/(2.0*G0(J)))
  GO TO 20
ENDIF

C Set up coefficients for interior points
IF (PM.EQ.1.0) THEN
  U(J) = U0(1, J)
ELSE
  U(J) = U0(2, J)
ENDIF

DDM = DX(J)*DX(J-1)*(DX(J) + DX(J-1))/2.0
BB(J) = -(SQRT(G0(J)*G0(J-1)))*DT*DX(J)/C0(J)
  * /DDM
AA(J) = -(SQRT(G0(J + 1)*G0(J)))*DT*DX(J)/C0(J)
  * /C0(J)/DDM
DD(J) = 1.0 - AA(J) - BB(J)
CC(J) = U(J) + F0(J)*DT/C0(J)
C Subroutine for soil temperature calculation

SUBROUTINE TEMP(N, DX, U, UO, TX, UX, AA, BB, CC, DD, CT, FT, IL, IU, DT, PM, CANP, BW, BT, IBD, VAP)

DIMENSION TX(N), UX(N), CT(N), GT(N), FT(N), U0(2, N),

AA(N), BB(N), CC(N), DD(N), U(N), DX(N), VAP(N)

COMMON/ATM/IDAY, HR, TA, TF, TAF, TG, EA, EF, EAF, ESF, UA, RFR, SG

C

PM = 0.0
CALL COEFF(N, DX, U, UO, UX, AA, BB, CC, DD, CT, FT, IL, IU, DT, PM, CANP, BW, BT, IBD, VAP)

CALL THOMAS(IL, IU, BB, DD, AA, CC)

DO 10 I = 1, N

TX(I) = CC(I)

10 CONTINUE

RETURN

END

C

This is subroutine for calculating transpiration rate, evaporation, sensible heat, energy balance and leaf temp in canopy, by a iteration method.

C CPd SPECIFIC HEAT CONTENT OF DRY AIR AT PRESSURE P, J/kg C
C CP SPECIFIC HEAT CONTENT OFF MOIST AIR, J/KG C
C P0 PRESSURE, KPA
C EA VAPOR PRESSURE, KPA
C FN THE FUNCTION USED TO CALCULATE LEAF TEMP. TF
C CH0, CHH AND CHG ARE HEAT TRANSFER COEFF. AT BARE GROUND, TOP OF CANOPY AND GROUND UNDER CANOPY
C RA, RESISTANCE OF AIR
C TF, TLEAF ARE LEAF TEMPERATURE AT t=t1 and t=t2
C UAF, TAF, QAF ARE WIND, TEMP, AND SPECIFIC HUMIDITY IN THE AIR OF THE CANOPY
C SAl, stem area index = 0.5 for cropland

SUBROUTINE ENERGYBL(PSIP, EG, TR, HG, HF, RN, RG, RU, THETA, CANP, FN, TL, RL, PETR, RNC)

REAL LAI, L, KS, K

COMMON/ATM/IDAY, HR, TA, TF, TAF, TG, EA, EF, EAF, ESF, UA, RFR, SG
COMMON/CANOPY/SIGMAF, RMIN, RMAX, RWMAX, PSIC, PSILM, CPT
COMMON/TIME/IM

DATA L, SIGMA, Z, Z0, D, K, PA, CPD, R, CP, ALPHAF, EPSF, SAI, PW/2.427E6, 5.67E-8, 2.0, .05, .7, .4, 1.27, 1004.0, 8.314E3, 1015.0, .2, 95, 5, 1000.0/

C Define parameters
C

CH0 = K**2/(LOG(Z/Z0))**2
CHH = K**2/(LOG((Z-D)/Z0))**2
LAI = 7. * SIGMAF
\[ C = (75. * K^2 * ((Z + Z0)/Z0)^2)/((Z + Z0)/Z0)^2 \]
\[ R1 = 9.81 * (Z - Z0) * (TA - TG)/((TA + 273.16) * UA)^2 \]
IF (R1 LT 0.) THEN
  CQ = 1. + 24.5 * (-CHH * RI)^0.5
ELSE-
  CQ = 1. / (1. + 11.5 * RI)
ENDIF

C calculate drag coefficients

C

CD = CHH * CQ
UAF = 0.83 * SIGMAF * CD + 0.5 * UA + (1. - SIGMAF) * UA
CG = CD * ((1 - SIGMAF) * UA + SIGMAF * UAF)
RAE = 1. / CG
CF = 0.01 * (1.0 + 0.3 / UAF)
RLA = 1 / (CF * UA)
RAA = RLA / LAI / SIGMAF
CA = CD * UA
RAR = 1. / CA
CF = (LAI + SAI) * SIGMAF / RLA

C calculate sensible heat

C

TAF = (CA * TA + CG * TG + CF * TL)/(CA + CF + CG)
HG = PA * CP * CG * (TG - TAF)
HF = PA * CP * CF * (TL - TAF)

C calculate evaporation and transpiration

C

CF = LAI * SIGMAF / RLA
CALL EVAPTRAN(PSIP, TR, EG, RL, RLA, THETA, TL, PETR, CG, CA, CF)

C call subroutine for calculating radiation balance

C

CALL RADIAT(RN, RD, THETA, RG, RU, CANP, EPSG, ALPHA)
AA = EPSF * EPSG / (EPSF + EPSG * EPSF * EPSG)
BB = EPSF * EPSG + 2.0 * EPSG * EPSF * EPSG
  * /(EPSF + EPSG * EPSF * EPSG)

C Define the function for calculating leaf temperature

C from energy balance by iteration method
C
canopy net radiation
\[ RNC = ((1.0 - \text{ALPHAF}) \times \text{SG} + \text{EPSF} \times \text{RD} + \text{AA} \times \text{SIGMA} \times (\text{TG} + 273.)^4. \times -\text{BB} \times \text{SIGMA} \times (\text{TL} + 273.)^4.) \times \text{SIGMAF} \]

\[ FN = RNC - (\text{HF} + L \times \text{TR} \times \text{PW}) \]

RETURN
END

Subroutine for root searching by bisection method
to calculate leaf temperature TF

**SUBROUTINE BISECT(PSIP,THETA,CANP,TL,RL)**

COMMON/ATM/IDAY,HR,TA,TF,TG,EA,EF,EAF,ESF,UA,RFR,SG
COMMON/ENERGY/HG,HF,EG,TR,RN,RG,RU,PETR,RNC
DATA XMAX,DELTX,FMAX/70.0,0.01,1000.0/

N=200
X=TL
!TER=0
3 CALL ENERGYBL(PSIP,EG,TR,HG,HF,RN,RG,RU,THETA,CANP,FX,X,RL,
* PETR,RNC)
IF(ABS(FX).LT.1.E-4) THEN
XROOT=X
GO TO 15
ENDIF
4 X1=X+DELTX
CALL ENERGYBL(PSIP,EG,TR,HG,HF,RN,RG,RU,THETA,CANP,FX1,X1,RL,
+ PETR,RNC)
IF(ABS(FX1).LT.1.E-4) THEN
XROOT=X1
GO TO 15
ENDIF
IF(ABS(FX1).GT.ABS(FX)) THEN
INDEX=0
ELSE
INDEX=1
ENDIF
20 ITER=ITER+1
IF(ITER.GT.1000) THEN
WRITE(*,*) 'Initial Ti is not fit'
STOP
ENDIF
CALL ENERGYBL(PSIP,EG,TR,HG,HF,RN,RG,RU,THETA,CANP,FX1,X1,RL, + PETR,RNC)

IF(ABS(FX1).LT.1.E-4) THEN
  XROOT=X1
  GO TO 15
ENDIF

IF(FX*FX1.EQ.0.0) THEN
  5 XROOT=X1
  X=X1+DELTX
  GO TO 15
ENDIF

IF(FX*FX1.GT.0.0) THEN
  7 IF(X1.GE.XMAX) THEN
      WRITE(*,*) 'X is out of maximum range, stop'
      STOP
  ELSE
      X=X1
      FX=FX1
      IF(INDEX.EQ.0) THEN
          X1=X-DELTX
      ELSE
          X1=X+DELTX
      ENDIF
      GO TO 20
  ENDIF
ENDIF

IF(FX*FX1.LT.0.0) THEN
  8 DO 11 1=1,N
      XAVG=(X+X1)/2.0
      CALL ENERGYBL(PSIP,EG,TR,HG,HF,RN,RG,RU,THETA,CANP,FAVG, + XAVG,RL,PETR,RNC)
      IF(ABS(FAVG).LT.1.E-4) GOTO 12
      IF(ABS(FAVG).GT.FMAX) THEN
          14 WRITE(*,*) 'FUNCTION APPROACHING INFINITY FOR X = ',XAVG
          GO TO 13
      ENDIF
      IF (FX*FAVG.LT.0.0) THEN
          10 X1=XAVG
          FX1=FAVG
      ENDIF
      IF(FX*FAVG.GT.0.0) THEN
          9 X=XAVG
          FX=FAVG
      ENDIF
      IF(FX*FAVG.EQ.0.0) THEN
          GO TO 12
      ENDIF
  11 CONTINUE
ENDIF

12 XROOT=XAVG
  GO TO 15

13 FX=FX1
  X=X1
  GO TO 4

15 X=XROOT
  TL=X
This is the subroutine for calculating plant water potential by assuming transpiration rate is equal to root extraction. Also, root extraction, transpiration rate can be obtained.

SUBROUTINE PLANTPT(PSIP, RET, N, PSI, THETA, RR, RS, RA, RL, RK, DX, SR, CANP, TL, DT, TIME, IEQP, SUMR, SIM)
DIMENSION SR(N), PSI(N), THETA(N), RR(N), RS(N), RA(N), RK(N), DX(N), RET(N)
COMMON/ATM/IDAY, HR, TA, TF, TG, EA, EF, EAF, UA, RFR, SG
COMMON/ENERGY/HG, HF, EG, TR, RR, RG, RU, PETR, RNC
COMMON/CANOPY/SIGMAF, RMIN, RMAX, RWMAX, PSIPC, PSILM, CPT
COMMON/ROOTPARM/PR, PA, BO, FJ, R, TL, PRTL(30), IRT
COMMON/TIME/IM
DATA EPSI.XMIN, DELTX, FMAX/0.001, -500, -0.1, 1000/
IF(TIME.EQ.DT) THEN
   PSIP1 = PSIP
ELSE
   PSIP1 = PSIP + 0.001*PSIP
ENDIF
M = 2000
ITER = 0
X = PSIP1
THETA1 = THETA(1)
IF(IM.GE.228) THEN 31
   CALL EQRETR(X, THETA1, CANP, TL, RL, PSI, SR, RR, RS, RA, RK, SUMR, N,
          THETA, DX, FX, TIME, DT, PSIP, IEQP)
   IF((FX.GE.0.0).AND.(FX.LT.EPSI)) THEN
      XROOT = X
      GO TO 15
   ENDIF
   X1 = X + DELTX
   CALL EQRETR(X1, THETA1, CANP, TL, RL, PSI, SR, RR, RS, RA, RK, SUMR, N,
          THETA, DX, FX1, TIME, DT, PSIP, IEQP)
   IF((FX1.GE.0.0).AND.(FX1.LT.EPSI)) THEN
      XROOT = X1
      GO TO 15
   ENDIF
IF(ABS(X1).GT.ABS(FX)) THEN
   INDEX = 0
ELSE
   INDEX = 1
ENDIF
ITER = ITER + 1  
IF (ITER.GT.5000) THEN  
  WRITE(*,*) 'Loop is over 1000'  
  STOP  
ENDIF  
CALL EQRETR(X1,THETA1,CANP,TL,RL,PSI,SR,RR,RS,RA,RK,SUMR,N,  
  THETA,DX,FX1,TIME,DT,PSIP,IEQP)  
IF((FX1.GE.0.0).AND.(FX1.LT.EPSI)) THEN  
  XROOT = X1  
  GO TO 15  
ENDIF  
IF(FX*FX1.EQ.0.0) THEN  
  XROOT = X1  
  X = X1 + DELTX  
  GO TO 15  
ENDIF  
IF(FX*FX1.GT.0.0) THEN  
  IF(X1.LE.XMIN) THEN  
    WRITE(*,*) 'X is oui of maximum range, stop'  
    STOP  
  ELSE  
    X = X1  
    FX = FX1  
    IF(INDEX.EQ.0) THEN  
      X1 = X - DELTX  
    ELSE  
      X1 = X + DELTX  
    ENDIF  
    GO TO 20  
  ENDIF  
ENDIF  
IF(FX*FX1.LT.0.0) THEN  
  DO 11 K=1,M  
    XAVG = (X + X1)/2.0  
    CALL EQRETR(XAVG,THETA1,CANP,TL,RL,PSI,SR,RR,RS,RA,RK,SUMR,  
      N,THETA,DX,FX1,TIME,DT,PSIP,IEQP)  
    IF((F1AVG.GE.0.0).AND.(F1AVG.LT.EPSI)) GO TO 12  
    IF(ABS(F1AVG).GT.FMAX) THEN  
      WRITE(*,*) 'x,favg,rl,tr,sumr',XAVG,F1AVG,RL,TR,SUMR  
      WRITE(*,*) 'Function approaching infinite for x = ',XAVG  
      GO TO 13  
    ENDIF  
    IF(FX*F1AVG.GT.0.0) THEN  
      X = XAVG  
      FX = F1AVG  
    ENDIF  
    IF(FX*F1AVG.EQ.0.0) THEN  
      GO TO 12  
    ENDIF  
  CONTINUE  
ENDIF  
IF(FX*F1AVG.LT.0.0) THEN  
  X1 = XAVG  
  FX1 = F1AVG  
ENDIF  
IF(FX*F1AVG.GT.0.0) THEN  
  X = XAVG  
  FX = F1AVG  
ENDIF  
IF(FX*F1AVG.EQ.0.0) THEN  
  GO TO 12  
ENDIF  
CONTINUE  
ENDIF  
XROOT = XAVG
GO TO 15
13 FX = FX1
    X = X1
GO TO 4
15 X = XROOT
PSIP1 = X

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C C Set final leaf water potential, leaf temperature,
C and root extraction.
C Components of energy balance are also set at the same time
C
CCCCCCCCCCCCCCCCCCCCCCCCCCC
    PSIP = PSIP1
    TF = TL
C calculate root extraction from unit volume of soil.
    DO 30 J = 2, N - 1
        RET(J) = SR(J) / ((DX(J - 1) + DX(J)) / 2.0)
    30 CONTINUE
C assume no root in the layer underneath soil surface and the layer
C above bottom of the soil profile
    RET(1) = 0.0
    RET(N) = 0.0
C calculate integrated soil water potential
    TOP = 0.0
    BOT = 0.0
    DO 60 I = 1, N
        IF (PRTL(I) .GT. 0.0) THEN
            TOP = TOP + RK(I) * PRTL(I) * PSI(I) * (DX(I - 1) + DX(I)) / 2.0
        ENDIF
    60 CONTINUE
    PSIM = TOP / BOT
RETURN
END

SUBROUTINE EQRETR(X, THETA1, CANP, TL, RL, PSI, SR, RR, RS, RA, RK, SUMR, N,
    THETA, DX, FX, TIME, DT, PSIP, IEQP)
    DIMENSION SR(N), PSI(N), THETA(N), RR(N), RS(N), RA(N), RK(N), DX(N)
    COMMON/ATM/IDAY, HR, TA, TF, TAF, TG, EA, EF, EAF, ESF, UA, RFR, SG
    COMMON/ENERGY/HG, HF, EG, TR, RN, RG, RU, PETR, RNC
    COMMON/CANOPY/SIGMAF, RMIN, RMAX, RWMAX, PSIPC, PSILM, CPT
    COMMON/ROOFTERM/RN, PA, BO, FP, RJ, TRL, PRTL(20), IRT
    COMMON/TIME/IM
    CALL BISECT(X, THETA1, CANP, TL, RL)
    CALL ROOT(X, PSI, SR, RR, RS, RA, RK, SUMR, N, THETA, DX)
    IF (TIME .EQ. DT) THEN
        FX = (SUMR - TR) / TR
        GO TO 10
    ENDIF
    IF (IEQP .EQ. 1) THEN
        FX = (SUMR - TR) / TR
    ELSE
        FX = (SUMR - CPT * (X - PSIP) / DT - TR) / TR
    ENDIF
CONTINUE
RETURN
END

This is subroutine to calculate transpiration rate.

SUBROUTINE EVAPTRAN(PSIP, TR, EG, RL, RLA, THETA, TL, PETR, CG, CA, CF)
COMMON/ATM/IDAY.HR, TA, TF, TAF, TH, EA, EF, EAF, ESF, UA, RFR, SG
COMMON/CANOPY/SIGMAF, RMIN, RMAX, RMAX, PSIC, PSILM, CPT
COMMON/SOIL/B(30), KS(30), PSIS(30), B1(30), B2(30), B3(30), EN(30),
AAPHA(30), THETAS(30), THETAR(30), CI(30)
COMMON/SOLARPARM/DR, DL
COMMON/TIME/IM
REAL LAI, IR, IRMAX, KS
DATA R, G, RHOA, RHOW, PRES, CKP
/ /461.5, 9.8, 1.27, 1000., 100., 0.5/

calculate leaf resistance

IRMAX = 700.0
LAI = 7.0 * SIGMAF
IF (SG.EQ.0.0) THEN
RL = RMAX/LAI/SIGMAF
RLMIN = RL
ENDIF
IRMAX = (3.14/2.)*DR/DL
BETA = RMAX/(RMAX-RMIN)
GAMA = RMIN/(RMAX-RMIN)
IF (SINPHI.LE.0.0) THEN
RL = RMAX/LAI/SIGMAF
RLMIN = RL
ENDIF
IF (SG.GT.0.0) THEN
CALL SOLAR(HR, IDAY, SINPHI)
IR = SG
RMM = RWMAX
ELSE
TAU = (1.-EXP(-CKP*LAI/SINPHI))*SINPHI/CKP
RLMIN = RMIN*(BETA*IRMAX/(IR*TAU + GAMA*IRMAX*LAI))
ENDIF
IF (PSIP.GE.PSIC) THEN
\[ RL = R_{MIN} \times (\beta \times IR_{MAX} / (IR \times TAU + \gamma \times IR_{MAX} \times LAI)) \]

\[ ALP = \frac{-\log(RW_{MAX}/R_{MIN})}{PSIL_{M}-PSIC} \]

\[ IF(PSIP \leq PSIL_{M}) THEN \]
\[ RL = R_{MIN} \times (\beta \times IR_{MAX} / (IR \times TAU + \gamma \times IR_{MAX} \times LAI)) \]
\[ * \exp(-ALP \times (PSIL_{M}-PSIC)) \]
\[ ELSE \]
\[ RL = R_{MIN} \times (\beta \times IR_{MAX} / (IR \times TAU + \gamma \times IR_{MAX} \times LAI)) \]
\[ / \exp(-ALP \times (PSIP-PSIC)) \]
\[ ENDIF \]
\[ ENDIF \]
\[ IF(RL \geq RMM) RL = RMM \]
\[ ENDIF \]

\[ c \]
\[ c \text{ Scaling up from leaf to canopy.} \]
\[ c RL = RL/LAI \]
\[ c \]
\[ c \]
\[ c \text{ calculate soil surface resistance to evaporation} \]
\[ c \]
\[ ALP_{1} = 3.5 \]
\[ ALP_{2} = 2.3 \]
\[ ALP_{3} = 33.0 \]
\[ RS = ALP_{1} \times (\theta_{S(I)}/\theta)^{ALP_{2}}+ALP_{3} \]

\[ c \]
\[ c \text{ calculate total conductance for transpiration} \]
\[ C \]
\[ RG = 1./CG \]
\[ RLA = 1./CF \]
\[ CV = 1. /(RL + RLA) \]
\[ CG = 1. /(RG + RS) \]

\[ c \]
\[ c \text{ calculate transpiration and evaporation} \]
\[ C \]
\[ ELSAT = 0.61078 \times \exp(17.269 \times TL/(237.3 + TL)) \]
\[ EF = ELSAT \times \exp(G \times PSIP/(R \times (TL + 273.))) \]
\[ EGSAT = 0.61078 \times \exp(17.269 \times TG/(237.3 + TG)) \]
\[ PSIG = (((\theta_{S(I)}-\theta_{S(I)})/(\theta_{S(I)}-\theta_{S(I)})))^{**} + (-EN(1)/(EN(1)-1.0)-1.0)**(1.0/EN(1))) / AAPHA(1) \]
\[ ESF = EGSAT \times \exp(G \times PSIG/(R \times (TG + 273.))) \]
\[ EAF = (CA \times EA + CG \times ESF + CV \times EF)/(CA + CG + CV) \]
\[ PETR = 0.622 \times RHOA \times RHOW \times (EF-EAF)/(R_{MIN}+RLA)/PRES \]
\[ TR = 0.622 \times RHOA \times RHOW \times (EF-EAF)/(RL+RLA)/PRES \]
\[ RAE = 1./CG \]
\[ EG = 0.622 \times RHOA \times RHOW \times (ESF-EAF)/(RAE+RS)/PRES \]
\[ IF(TR.LT.1.E-10) TR = 1.E-10 \]
\[ IF(TR.LT.0.0) TR = 1.E-10 \]
\[ IF(EG.LT.0.0) EG = 0. \]
RETURN
END

c This is the subroutine for root extraction at each layer
c PSIP, plant water potential m
PS, soil water potential m
RS, soil resistance s
RR, radial resistance s
RA, axial resistance s
TR, transpiration rate m/s

Subroutine Root(PSIP, PS, RS, RR, RA, SUM, N, THETA, DX)
DIMENSION PSI(N), RS(N), RR(N), RA(N), S(N), RK(N),
DX(N), THETA(N)
COMMON/SOIL/B(30), KS(30), PSI(S), B1(30), B2(30), B3(30), EN(30),
AAPHA(30), THETAS(30), THETAR(30), CI(30)
COMMON/ROOTPARM/PR, PA, B0, FP, RJ, TRL, PRTL(30), IRT
REAL KS
c define root radius (RAD) and plant height (H)
RAD = 1. E-4
H = 0.6
c call subroutine for calculation of hydraulic conductivity
c and soil water potential
c DO 11 J = 1, N
c CALL SOILPARM(THETA(J), RK(J), PSI(J), DF, J)
11 CONTINUE
c calculation of root extraction
SUM = 0.0
Z = DX(I)/2.0
PRTL = 0.0
MM = 0
DO 44 I = 1, N
IF(PRTL(I).NE.0.0) THEN
MM = MM + 1
PRTL = PRTL + PRTL(I)
ENDIF
44 CONTINUE
PRTL = PRTL/FLOAT(MM)
DO 22 I = 2, N-1
c call subroutine for roots distribution
c soil layer i is the layer centered by node i
Z = Z + (DX(I) + DX(I-1))/2.
DD = (DX(I-1) + DX(I))/2.0
IF(IRT.EQ.0) THEN
CALL ROOTDIST(PRTL(I), Z, DD)
ENDIF
PRTL = 8000.0
IF(PRTL(I).NE.0.0) THEN
B0 = 2.*3.14/(LOG(((PRTL(I)*3.14)**(-0.5))/RAD))
RS(I) = 1.0/(B0*RS(I)*PRTL(I)*DD)
RR(I) = PR*(THETAS(I)/THETA(I))/(PRTL(I)*DD)
RA(I) = PA*Z/(0.5*FP*PRTL(I))
S(I) = (PSI(I) - PSIP - H)/(RS(I) + RR(I) + RA(I))
IF(PSI(I) .LE. -150.0) S(I) = 0.0
ELSE
  S(I)=0.0
ENDIF
IF(S(I).LT.0.0) S(I)=0.0
SUM=SUM+S(I)
22 CONTINUE
RETURN
END

This is a function to define root distribution

SUBROUTINE R00TDIST(PRTL1,Z,DELTZ)
  COMMON/ROOTPARM/PR,PA,B0,F0,RJ,TRL,PRTL(30),IRT
  P=1.-EXP(-RJ*Z)
  P1 = 1.-EXP(-RJ*(Z-DELTZ))
  PRTL1 = TRL*(P-P1)
  RETURN
END

This is a subroutine for calculating soil hydraulic conductivity,
diffusivity and water potential by van Genuchten method

SUBROUTINE SOILPARM(THETA,COND,PSI,DIFF,I)
  COMMON/SOIL/B(30),KS(30),PSIS(30),B1(30),B2(30),B3(30),EN(30),AAPHA(30),THETAS(30),THETAR(30),CI(30)
  REAL KS
  PSI = ((((THETA-THETAR(I))/(THETAS(I)-THETAR(I)))**(-EN(I)+1))**((EN(I)-1.)/(EN(I)-1.)))/AAPHA(I)
  COND = (KS(I)*(1-((AAPHA(I)*PSI)**(EN(I)-1.))))**((1.-((AAPHA(I)*PSI)**(EN(I)-1.))))**2
  FN = (EN(I)-1.)*(THETA-THETAR(I))**(1.-((AAPHA(I)*PSI)**(EN(I)-1.))))**2
  DIFF = COND/FN
  PSI = -PSI
  RETURN
END
c Subroutine for radiation balance, including short and long
wave radiation, and net radiation
SUBROUTINE RADIAT(RN,RD,THETA,RG,RU,CANP,EPSG,ALPHA)
COMMON/ATM/IDAY,HR,TA,TF,TAF,TG,EA,EF,EAF,ESF,UA,RFR,SG
COMMON/GEO/AL
COMMON/CANOPY/SIGMAF,RMIN,RMAX,RWMAX,PSIC,PSILM
C S IS THE SHORT WAVE RADIATION
C SG IS THE SHORT WAVE RADIATION THAT ARRIVE THE GROUND
C RD IS THE LONG WAVE RADIATION
C RG IS THE LONG WAVE RADIATION THAT ARRIVE THE GROUND
C RU IS THE LONG WAVE RADIATION THAT GOES OUT OF GROUND
C RN IS NET RADIATION
C ALPHA IS ALBEDO
C EPS IS EMISSIVITY
C THETA IS SOIL MOISTURE CONTENT
C SIGMA IS STEFAN-BOLZMAN CONSTANT
C SC IS CLOUD COVER FRACTION
C
PR = 100.0
SIGMA = 5.6699E-8
EPSF = 0.95
C HERE IS THE CALCULATION FOR ALBEDO AND EMISSIVITY
C
ALPHA = 0.1
IF (THETA.LT.0.1) ALPHA = 0.25
IF (THETA.LT.0.25) ALPHA = 0.35-THETA
EPSG = 0.9 + 0.18*THETA
C Radiation balance calculation
QA = 0.622*EA/PR
HA = 2.166*EA/(TA + 273.16)
IF (CANP.EQ.0.) THEN
  C ground radiation balance
  C without canopy
  RG = (0.605 + 0.048*SQR1370*HA))
  * SIGMA*(TA + 273.0)**4
  RU = EPSG*SIGMA*(TG + 273.0)**4
  S = SG
  ELSE
    C with canopy
    S = (1.0-SIGMAF)*SG
    RD = (0.605 + 0.048*SQR1370*HA))
    * SIGMA*(TA + 273.0)**4
    RG = (1.0-SIGMAF)*RD + SIGMAF*(EPSF*SIGMA*(TF + 273.)**4. +
    * (1.0-EPSF)*EPSG*SIGMA*(TG + 273.)**4.)/
    * (EPSF + EPSG-EPSF*EPSG)
RU = (1.0 - SIGMAF) * (EPSG * SIGMA * (TG + 273.)**4 + (1.0 - EPSG) * RD) 
+ SIGMAF * (EPSG * SIGMA * (TG + 273.)**4 + (1.0 - EPSG) * EPSF) 
+ SIGMAF * (EPSG * SIGMA * (TG + 273.)**4 + (1.0 - EPSG) * EPSF) 
ENDIF

C NET RADIATION
RN = (1.0 - ALPHA) * S + RG - RU
C
RETURN
END

C**************************************************************
SUBROUTINE RADIAT(RN, RD, THETA, RG, RU, CANP, EPSG, ALPHA)
C Subroutine that calculates NET radiation
C
PR = 100.0
SIGMA = 5.6699E-8
EPSF = 0.95

C HERE IS THE CALCULATION FOR ALBEDO AND EMISSIVITY
C
ALPHA = 0.1
IF (THETA .LT. 0.1) ALPHA = 0.25
IF (THETA .LT. 0.25) ALPHA = 0.35 - THETA
EPSG = 0.9 + 0.18 * THETA

C Radiation balance calculation
C
QA = 0.622 * EA / PR
HA = 2.166 * EA / (TA + 273.16)
IF (CANP .EQ. 0.) THEN
C ground radiation balance
C without canopy
\[ \text{RG} = (0.605 + 0.048 \sqrt{1370 \cdot \text{HA}}) \times \text{SIGMA}^{(\text{TA} + 273.0)^4} \]

\[ \text{RU} = \text{EPSG} \times \text{SIGMA}^{(\text{TG} + 273.0)^4} \]

\[ S = \text{SG} \]

\[ \text{ELSE} \]

\[ S = (1.0 - \text{SIGMAF}) \times \text{SG} \]

\[ \text{RD} = (0.605 + 0.048 \sqrt{1370 \cdot \text{HA}}) \times \text{SIGMA}^{(\text{TA} + 273.0)^4} \]

\[ \text{RG} = (1.0 - \text{SIGMAF}) \times \text{RD} + \text{SIGMAF} \times (\text{EPSF} \times \text{SIGMA}^{(\text{TF} + 273.)^4} + (1.0 - \text{EPSF}) \times \text{EPSG}) / (\text{EPSF} + \text{EPSG} - \text{EPSF} \times \text{EPSG}) \]

\[ \text{RU} = (1.0 - \text{SIGMAF}) \times (\text{EPSG} \times \text{SIGMA}^{(\text{TG} + 273.)^4} + (1.0 - \text{EPSG}) \times \text{EPSF}) + \text{SIGMAF} \times (\text{EPSG} \times \text{SIGMA}^{(\text{TG} + 273.)^4} + (1.0 - \text{EPSG}) \times \text{EPSF}) / (\text{EPSF} + \text{EPSG} - \text{EPSF} \times \text{EPSG}) \]

\[ \text{ENDIF} \]

\[ C \]

\[ \text{NET RADIATION} \]

\[ \text{RN} = (1.0 - \text{ALPHA}) \times S + \text{RG} - \text{RU} \]

\[ C \]

\[ \text{RETURN} \]

\[ \text{END} \]

---

**Function for direct solar radiation**

**SUBROUTINE SOLAR(HR, IDAY, SINPHI)**

**COMMON/GEO/AL**

**COMMON/TIME/IM**

\[ A = 2.0 \times 3.14 \times \text{FLOAT(IDAY)} / 365.0 \]

\[ D = 0.006918 - 0.399912 \times \text{COS}(A) + 0.070257 \times \text{SIN}(A) - 0.006758 \times \text{COS}(2.0 \times A) + 0.000907 \times \text{SIN}(2.0 \times A) \]

\[ \text{SINPHI} = \text{COS}(A) \times \text{COS}(HR) \times \text{COS}(D) + \text{SIN}(A) \times \text{SIN}(D) \]

\[ \text{RETURN} \]

**END**

---

**This is the subroutine for calculating thermal conductivity using the procedure provided by Campbell.**

**RHOB**, bulk density kg/m-3

**Clay**, clay fraction

**LAMBDA**, thermal conductivity

**THETA**, soil moisture

**SUBROUTINE THERMAL(LAMBDA, THETA, I)**

**COMMON/SOILFT/CLAY(30)**

**REAL LAMBDA**

**RHOB** = 1.24

\[ E = 4.0 \]

\[ D = 0.03 + 0.1 \times \text{RHOB}^2 \]

\[ B = 1.06 \times \text{RHOB} \]

\[ A = 0.65 - 0.78 \times \text{RHOB} + 0.60 \times \text{RHOB}^2 \]

\[ C = 1.0 + 2.6 \times \sqrt{\text{CLAY}(I)} \]

\[ \text{LAMBDA} = A + B \times \text{THETA} \times (A - D) \times \exp((-C \times \text{THETA})^E) \]

**RETURN**
SUBROUTINE CONVTEST(N, TX, UX, U0, IERR)
DIMENSION TX(N), UX(N), U0(2,N)

C compute the maximum value for TX and UX
EPS1 = 0.01
EPS2 = 0.01
TMAX = TX(1)
UMAX = UX(1)
DO 20 I = 2,N
   IF(TX(I).GT.TMAX) TMAX = TX(I)
   IF(UX(I).GT.UMAX) UMAX = UX(I)
20 CONTINUE

C CALCULATE THE SQUARE ROOT
SUM = 0.0
SUM1 = 0.0
DO 10 I = 1,N
   SUM = SUM + (UX(I) - U0(I,I))**2
   SUM1 = SUM1 + (TX(I) - U0(2,I))**2
10 CONTINUE
SUM = SUM/FLOAT(N)
SUM1 = SUM1/FLOAT(N)
ERROR = SQRT(SUM)/UMAX
ERROR1 = SQRT(SUM1)/TMAX
IF(ERROR.GT.EPS1) GO TO 30
IF(ERROR1.GT.EPS2) GO TO 30
IERR = 0
GO TO 40
30 IERR = 1
40 CONTINUE
RETURN
END

C subroutine for dividing space
SUBROUTINE SPACE(IMESH, X, DX, A, B, N)
DIMENSION X(N), DX(N)

C DO 10 I = 1,N
IF(IMESH.EQ.5) GO TO 20
IF(IMESH.EQ.1) THEN
   DX(I) = (B-A)/FLOAT(N-1)
   X(I) = A + FLOAT(I-1)*DX(I)
   GO TO 10
ENDIF
C
IF(IMESH.EQ.2) THEN
   X(I) = 0.5*(A-B)*COS(3.14159*FLOAT(I-1)/FLOAT(N-1))
   * + .5*(B+A)
ENDIF
C
IF(IMESH.EQ.3) THEN
   X(I) = A + (B-A)*(1.-COS(.5*3.14159*FLOAT(I-1)/FLOAT(N-1)))
   * - .5*(B+A)
ENDIF
ENDIF

IF(IMESH.EQ.4) THEN
    X(I)=A+(B-A)*SIN(.5*3.14159*FLOAT(I-1)/FLOAT(N-1))
ENDIF

C
*c Read in the space defined by user
20  IF(I.EQ.1) GO TO 30
    DX(I-I)=X(I)-X(I-I)
    GO TO 10
30  READ(9,*) X
10  CONTINUE
C
RETURN
END

C subroutine for solving tridiagonal system by elimination
C**************************************************************
SUBROUTINE THOMAS(IL, IU, BB, DD, AA, CC)
    DIMENSION AA(1), BB(1), CC(1), DD(1)
C*-------------------------------------------------------------
C IL = subscript of first equation
C IU = subscript of last equation
C BB = coefficient behind diagonal
C DD = coefficient on diagonal
C AA = coefficient ahead of diagonal
C CC = element of constant vector
C*-------------------------------------------------------------
C establish upper triangular matrix
C
LP=IL + 1
DO 10 I=LP, IU
    R=BB(I)/DD(I-1)
    DD(I)=DD(I)-R*AA(I-1)
10    CC(I)=CC(I)-R*CC(I-1)
C
C back substitution
CC(IU)=CC(IU)/DD(IU)
DO 20 I=LP, IU
    J=IU-1 + I
    CC(J)=(CC(J)-AA(J)*CC(J+1))/DD(J)
20    CONTINUE
C
C solution stored in CC
RETURN
END
C
C subroutine for input of the daily weather data
C**************************************************************
SUBROUTINE WEATHER(TAMAX, TAMIN, TDMAX, TDMIN, RF, BR, ER, TI, IM , UAM)
    COMMON/ATM/IDAY, HR, TA, TF, TAF, TG, EA, EF, EAF, ESF, UA, RFR, SG
    COMMON/SOLARPARM/DR, DL
C
IMPLICIT DOUBLE PRECISION (A-H, O-Z)
DATA PR/100.0/
C**************************************************************
C TA AIR TEMPERATURE
*
155

C TD DEW POINT TEMPERATURE
C EA VAPOR PRESSURE
C QA SPECIFIC HUMIDITY
C RF RAINFALL
C RFR RAINFALL RATE
C BR BEGINNING OF THE RAIN
C ER ENDING OF THE RAIN
C DR DIRECT SOLAR RADIATION
C SN SOLAR NOON
C DL DAY LENGTH
C*****************************************

C set solar noon to 12 o'clock

C CALCULATE AIR TEMP (TA) AND DEW POINT TEMP (TD)
C FROM SIN FUNCTION, assume Tmax is at 14hr, Tmin at 2hr.
TAM = (TAMAX + TAMIN) / 2.0
TAA = (TAMAX - TAMIN) / 2.0
TA = TAM + TAA * SIN(2.0 * 3.14 * TI / 86400 - 8. * 3.14 / 12.0)

C TD = TDMAX
TDM = (TDMAX + TDMIN) / 2.0
TDA = (TDMAX - TDMIN) / 2.0
TD = TDM + TDA * SIN(2.0 * 3.14 * TI / 86400 - 8. * 3.14 / 12.0)

UAA = UAM / 3.
UA = UAM + UAA * SIN(2.0 * 3.14 * TI / 86400 - 8. * 3.14 / 12.0)
TIME = FLOAT(IM) / 10.

C FROM DEW POINT TEMPERATURE CALCULATE VAPOR PRESSURE
EA = 0.61078 * EXP((17.269 * TD) / (TD + 237.3))

C FROM VAPOR PRESSURE CALCULATE SPECIFIC HUMIDITY
QA = 0.622 * EA / (PR - 0.378 * EA)

C Calculate solar radiation from daily value
SG = 3.14 / 2. * DR / DL * SIN((TI - SN + DL / 2.) * 3.14 / DL)
IF (SG LT 0.0) SG = 0.0

C CALCULATE RAINFALL RATE M/S
IF (RF EQ 0.0) GO TO 3
IF (TI GT ER * 3600.0) GO TO 3
IF (TI LT BR * 3600.0) GO TO 3
RFR = RF / ((ER - BR) * 3600.0)
GO TO 4
3 RFR = 0.0
4 CONTINUE
RETURN
END

C**************************************************************

SUBROUTINE VAPD(DTV, DWV, THETA)
OPEN(12, FILE = 'vapor.dat', STATUS = 'OLD')

READ(12, *) THET, DTV, DWV
IF (THETA EQ THET) GO TO 12
IF (THETA LT THET) GO TO 10
THET1 = THET
DTV1 = DTV
DWV1 = DWV
GO TO 11
10 DTV2 = DTV
11 DTV2 = DTV
THET2 = THET
DWV2 = DWV
DTV = DTV1 + ((DTV2 - DTV1) / (THET2 - THET1)) * (THETA - THET1)
DWV = DWV1 + ((DWV2 - DWV1) / (THET2 - THET1)) * (THETA - THET1)

11 CONTINUE
12 CONTINUE
CLOSE(12)
RETURN
END

C **********************************************************
C Subroutine for vapor transport
C **********************************************************
SUBROUTINE VAPOR(N, VAP, U0, DX, QVAP)
COMMON/SOIL/B(30), KS(30), PSIS(30), B1(30), B2(30), B3(30), EN(30),
AAPHA(30), THETAS(30), THETAR(30), CI(30)
DIMENSION U0(2, N), DX(N), VAP(N)
REAL KS
THETA = U0(1, 1)
CALL VAPD(DTV, DWV, THETA)
VAP(1) = DTV*(U0(2,2) - U0(2,1))/DX(1)**2 + DWV*(U0(1,2) - U0(1,1))
* /DX(1)**2
VAP(N) = DTV*(U0(2,N) - U0(2,N-1))/DX(N-1)**2 + DWV*(U0(1,N) - U0(1,N-1))
* /DX(N-1)**2
D = KS(1)*PSIS(1)*B(1)*(THETA/THETAS(1))**(B(1)+3)
QVAP = DTV*(U0(2,2) - U0(2,1))/DX(1) + DWV*(U0(1,2) - U0(1,1))/DX(1)
* + D*(U0(1,2) - U0(1,1))/DX(1)
DO 22 I = 2, N-1
VAP(I) = DTV*((U0(2,I+1) - U0(2,I))/DX(I) - (U0(2,I) - U0(2,I-1))
* /DX(I-1))/DX(I-1))/DX(I-1)+DX(I-1))/2.0 + DWV*((U0(I,I+1) - U0(I,I))/DX(I)
* - (U0(I,I) - U0(I,I-1))/DX(I-1))/DX(I-1))/DX(I-1))/2.0.
22 CONTINUE
RETURN
END

C **********************************************************
C Subroutine of defining parameters in the system
C **********************************************************
SUBROUTINE PARAMET(SOIL, N, X)
COMMON/SOIL/B(30), KS(30), PSIS(30), B1(30), B2(30), B3(30), EN(30),
AAPHA(30), THETAS(30), THETAR(30), CI(30)
COMMON/ATM/IDAY.HR, TA, TF, TAF, TG, EA, EP, EAF, ESF, UA, RFR
COMMON/GEO/AL
COMMON/CANOPY/SIGMAF, RMIN, RMAX, RWMAX, PSIC, PSILM, CPT
DIMENSION X(N)
REAL KS
C AL IS ALTITUDE for Des Moines, 41 degree
C AAPHA, EN, NONLINEAR REGRESSION PARAMETERS
C B is a coefficient dependent on soil type
C B1, B2, B3 ARE COEFFICIENTS DEPENDENT ON SOIL TYPE
C KS saturated hydraulic conductivity
C PSIS saturation moisture potential
C THETAS saturated soil moisture content
C THETAR IS RESIDUAL SOIL MOISTURE
C EPSF, ALPHAF, EMISSIVITY AND ALBEDO OF THE CANOPY
C N space grid points
C ****************************************
AL = 41.0 * 3.14 / 180.0
PR = 100.0
DO 11 I = 1, N
C soil type is loam
IF (SOIL.EQ.1) THEN
  B(I) = 5.39
  KS(I) = 0.68E-5
  PSIS(I) = 0.47
  THETAS(I) = 0.451
  B1(I) = 0.243
  B2(I) = 0.393
  B3(I) = 1.536
  EN(I) = 1.5
  AAPHA(I) = 0.6
  THETAR(I) = 0.05
  CI(I) = 1.28E6
ENDIF
IF (SOIL.EQ.6) THEN
  B(I) = 5.3
  PSIS(I) = 0.786
  B1(I) = 0.243
  B2(I) = 0.393
  B3(I) = 1.536
  CI(I) = 1.28E6
  KS(I) = 0.54E-5
  EN(I) = 1.59
  AAPHA(I) = 0.8
  THETAR(I) = 0.08
  THETAS(I) = 0.4
ENDIF
C soil type is silt loam
IF (SOIL.EQ.5) THEN
  B(I) = 5.3
  PSIS(I) = 0.786
  B1(I) = 0.243
  B2(I) = 0.393
  B3(I) = 1.536
  CI(I) = 1.28E6
  IF (XI(I).LT.0.3) THEN
    KS(I) = .201E-5
    THETAS(I) = 0.348
    THETAR(I) = 0.05
    AAPHA(I) = 0.4377
    EN(I) = 1.3789
  ENDIF
  IF (XI(I).GE.0.3).AND.(XI(I).LE.0.6)) THEN
    KS(I) = .334E-5
    THETAS(I) = 0.365
    THETAR(I) = 0.10
    AAPHA(I) = 0.7394
    EN(I) = 1.7859
  ENDIF
  IF (XI(I).GT.0.6).AND.(XI(I).LE.0.9)) THEN
    KS(I) = .334E-5
  ENDIF
ENDIF
THETAS(I) = 0.357
THETAR(I) = 0.10
AAPHA(I) = 0.5569
EN(I) = 1.8540
ENDIF

IF((X(I).GT.0.9).AND.(X(I).LE.1.2)) THEN
KS(I) = .838E-5
THETAS(I) = 0.385
THETAR(I) = 0.05
AAPHA(I) = 0.7512
EN(I) = 1.3777
ENDIF

IF((X(I).GT.1.2).AND.(X(I).LE.1.5)) THEN
KS(I) = .838E-5
THETAS(I) = 0.395
THETAR(I) = 0.08
AAPHA(I) = 0.4989
EN(I) = 1.7366
ENDIF

IF((X(I).GT.1.5).AND.(X(I).LE.1.8)) THEN
KS(I) = .301E-5
THETAS(I) = 0.411
THETAR(I) = 0.10
AAPHA(I) = 0.4495
EN(I) = 1.9432
ENDIF

IF((X(I).GT.1.8).AND.(X(I).LE.2.1)) THEN
KS(I) = .334E-5
THETAS(I) = 0.404
THETAR(I) = 0.09
AAPHA(I) = 0.4335
EN(I) = 1.6788
ENDIF

IF((X(I).GT.2.1).AND.(X(I).LE.2.4)) THEN
KS(I) = .334E-5
THETAS(I) = 0.409
THETAR(I) = 0.09
AAPHA(I) = 0.4245
EN(I) = 1.7318
ENDIF

IF((X(I).GT.2.4).AND.(X(I).LE.2.8)) THEN
KS(I) = .334E-5
THETAS(I) = 0.405
THETAR(I) = 0.09
AAPHA(I) = 0.4590
EN(I) = 1.7306
ENDIF

ENDIF

C soil type is sandy clay loam
IF(SOIL.EQ.4) THEN
B(I) = 7.12
KS(I) = 0.63E-5
PSIS(I) = 0.29
THETAS(I) = 0.42
THETAR(I) = 0.02
B1(I) = .20
ENDIF
C soil type is sand
IF(SOIL.EQ.2) THEN
  B(l)=4.05
  KS(I)=1.8E-4
  PSIS(I)=0.2
  THETAS(I)=0.40
  THETAR(I)=0.005
  B1(l)=0.228
  B2(l)=-2.406
  B3(l)=4.909
  EN(I)=1.54
  AAPHA(I)=3.28
  CI(I)=1.46E6
ENDIF
C soil type is clay
IF(SOIL.EQ.3) THEN
  B(I)=11.
  KS(I)=0.20E-5
  PSIS(I)=0.40
  THETAS(I)=0.482
  THETAR(I)=0.03
  B1(I)=-0.197
  B2(I)=-0.962
  B3(I)=2.521
  EN(I)=1.36
  AAPHA(I)=0.43
  CI(I)=1.05E6
ENDIF
11 CONTINUE
RETURN
END
WRITE(8,*) '*****TIME IS ','NN','*****'
WRITE(13,*) '*****TIME IS ','NN','*****'
WRITE(*,*) '*****TIME IS ','NN','*****'

LEG=L*EG*PW

WRITE(10,600) NN,EA,ESF,EF,EA,EF,TA,TF,TAF,U0(I,1),PSIP,PSIM,RL
WRITE(11,800) NN,RN,RNC,HG,HF,L*PW*EG,L*PW*TR,EG,TR,SUMR,PETR
WRITE(13,*) 'DEPHT RADIAL RESIST AXIAL RESIST SOIL RESIST
+ RET L v '
WRITE(8,*)'DEPHT MOISTURE TEMPERATURE ROOT SEXT FLUX
+ PSI COND'

IF(N.LE.11) THEN
  WRITE(8,400) (X(I),U0(I,1),U0(2,I),SR(I),FLUX(I),PSI(I),RK(I),
+ I = 1,N)
  WRITE(13,500) (X(I),RR(I),RA(I),RS(I),SR(I),PRTL(I),I = 1,N)
ELSE
  WRITE(8,400) (X(I),U0(I,1),U0(2,I),SR(I),FLUX(I),PSI(I),RK(I),
+ I = 1,N,2)
  WRITE(13,500) (X(I),RR(I),RA(I),RS(I),SR(I),PRTL(I),I = 1,N,2)
ENDIF
ENDIF

50 CONTINUE

400 FORMAT(1x,(F5.3,6(E11.3,1x)))
500 FORMAT(1x,(F5.3,5(E12.2)))
600 FORMAT(1X,I2,1x,4F5.1,4F6.1,F6.2,3F8.1)
800 FORMAT(1X,I2,6F6.1,4E10.3)

RETURN
END
APPENDIX B

This is the weather data file
Heading is beginning and ending dates
Data are Tmax, Tmin, TDmin, TDmax, Wind, Radiat.,
Beginning and ending of the rainfall period, and rainfall

<table>
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<tr>
<th>Date</th>
<th>Tmax</th>
<th>Tmin</th>
<th>TDmin</th>
<th>TDmax</th>
<th>Wind</th>
<th>Radiat.</th>
<th>Rainfall</th>
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<td>16.1</td>
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</table>
This is the space.dat file to define the top and bottom of the profile, the time step, number of the layers, and method-to-grid

0. 2.74 300 23 5

This is the canopy.dat file to define canopy parameters and root density rmin, rmax, rmwmax, \( \Psi_c \), \( \Psi_{lm} \), and \( C_p \)
P0, Pn, B, f, root coeff., and total root length density Root length density in each layer

50.0 2000.0 2000. -120.0 -220. 1.0E-5
1.0E12 5.0E10 1.0 0.22 6.14 12000.
.42 .42 .42 .42 .32 .14 .16 .17 .17 .16 .12 .04 .02 .01
0 0 0 0 0 0

This is the clay.dat file to define clay fraction at each layer

14.1 14.1 14.1 14.1 14.1 14.1 14.1 14.1 11.5 11.5 10.2 10.2 13.5 13.5 8.4 8.4 10.6
10.6 10.3 10.3 8.9 8.9 8.1 8.1
**THE CALENDAR DAY IS: 212**

<table>
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<tr>
<th>TIME</th>
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<th>HG</th>
<th>HF</th>
<th>LEG</th>
<th>LEF</th>
<th>EG</th>
<th>ET</th>
<th>Root EXT</th>
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**TOTAL** EVAP  ROOTEXT  TRANSP  POTENTTR

0.499E+00  0.239E+01  0.239E+01  0.236E+01

PR  PA  CPT

0.10E+13  0.50E+11  0.10E-04

WBEN  WEND  WBAL  EVTR  TQ

470.037  466.381  3.657  3.582  0.692

This is accumulated root extraction

|   | 0.00E+00 | 0.84E-04 | 0.96E-04 | 0.21E-03 | 0.22E-03 | 0.16E-03 | 0.16E-03 | 0.20E-03 | 0.20E-03 | 0.19E-03 | 0.52E-04 | 0.13E-03 | 0.28E-03 | 0.24E-03 | 0.91E-04 | 0.51E-04 | 0.21E-04 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
This is the output for temperature, vapor pressure and potential variables

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<th>RMAX</th>
<th>RWMAX</th>
<th>PSIC</th>
<th>PSILM</th>
<th>CPT</th>
<th>PR</th>
<th>PA</th>
<th>B0</th>
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**DETH, ROOT DENSITY, CLAY FRACTION**

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<th>CLAY FRACTION</th>
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***THE CALENDAR DAY IS: 212***

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<th>EF</th>
<th>EAF</th>
<th>TA</th>
<th>TF</th>
<th>TG</th>
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DP ***THE CALENDAR DAY IS: 212

*****TIME IS 1*****

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**THE CALENDER DAY IS: 212**

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