LATENT HEAT FLUXES OF A SOYBEAN FIELD MEASURED AND MODELED BY ENERGY BALANCE-COMBINATION MODELS

by

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A two-source model based on the energy balance equation and the Penman-Monteith combination equation was used to describe energy exchanges of a soybean canopy and the soil surface. Combination equations which eliminated soil surface resistance to soil latent heat flux were developed, but the equations contained a new variable, the soil surface vapor pressure deficit. Objectives were to quantify soil surface vapor pressure deficit and determine if the modified model improved estimates of soil and total latent heat flux compared with the original model.

Research was conducted in 1994 at North Platte, Nebraska. Total latent heat flux from an irrigated soybean field was estimated with the Bowen ratio-energy balance method. Latent heat flux from the soil was measured with microlysimetry. Soil surface vapor pressure deficit was quantified with a device which sampled air near the soil surface.

Soil surface vapor pressure was generally underestimated. Drier air from above the soil surface was mixed with near-surface air and reduced its humidity. Soil surface vapor pressure deficit was also underestimated, with the most likely error the underestimation of soil surface temperature.

There were no significant differences between the original soil surface resistance

model and the modified soil deficit model in the estimation of total or soil latent heat fluxes. Two-source models estimated total latent heat flux much better than a single-source model when the canopy was sparse, but there was no difference when the canopy was full. The models predicted soil latent heat flux best when there was no canopy. Their accuracy decreased when the canopy was sparse and was poorest when the canopy was full. Overestimation of soil latent heat flux by the surface deficit model was attributed to underestimation of soil surface temperature. However, overestimation when the canopy was full was attributed to canopy-dependent factors such as available energy at the soil surface, within-canopy aerodynamic resistance or canopy surface resistance.

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Seeker, there is no path;
the path is forged by walking.

--Antonio Machado

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Symbol	Units	Definition
a	W m^{-2}	Y-axis intercept of linear regression line
A_{ML}	m^2	Surface area of a microlysimeter
b	-	Slope of linear regression line
C_c	-	Resistance coefficient for Shuttleworth combination equation describing latent heat flux from canopy
C_m	J kg^{-1} K^{-1}	Mass specific heat of soil minerals
C_p	J kg^{-1} K^{-1}	Mass specific heat of air
C_r	-	Low level drag coefficient
C_s	-	Resistance coefficient for Shuttleworth combination equation describing latent heat flux from soil
C_v	J m^{-3} K^{-1}	Volumetric specific heat of soil
C_w	J kg^{-1} K^{-1}	Mass specific heat of soil water
d	m	zero plane displacement height
d_a	-	index of agreement
e_a	kPa	water vapor pressure of air
e_o	kPa	water vapor pressure at height of mean canopy flow
e_r	kPa	water vapor pressure at reference height
e_s, e_{surf}	kPa	water vapor pressure at soil surface
e_{spider}	kPa	water vapor pressure in sampling chamber of manifold air collector
$e^*(T)$	kPa	saturated water vapor pressure at temperature T
E	kg m^{-2} s^{-1}	Evapotranspiration from canopy and soil
E_c	kg m^{-2} s^{-1}	Transpiration from canopy
E_s	kg m^{-2} s^{-1}	Evaporation from soil
g	m s^{-2}	acceleration due to gravity
G	W m^{-2}	Soil heat flux corrected for heat storage

Symbol	Units	Definition
G_{trans}	W m^{-2}	Heat flux through soil heat flux transducers
h	m	canopy height
h_r	kPa	relative humidity at reference height
h_s	kPa	relative humidity at the soil surface
h_{spider}	kPa	relative humidity measured by manifold air collector
H	W m^{-2}	Total sensible heat flux from canopy and soil
H_s	W m^{-2}	Sensible heat flux from soil
k	-	Von Karmen's constant
K	m^2 s^{-1}	Eddy diffusivity
K_{chmbr}	m^2 s^{-1}	Exchange coefficient for water vapor of closed chamber
K_h	m^2 s^{-1}	Turbulent exchange coefficient for heat
K_w	m^2 s^{-1}	Turbulent exchange coefficient for water vapor
m	g	mass
M_a	kg mol^{-1}	Molecular weight of air
M_w	kg mol^{-1}	Molecular weight of water
n	-	Number of observations
P	kPa	Atmospheric pressure
PM_c	W m^{-2}	Shuttleworth combination equation describing latent heat flux from canopy
PM_s	W m^{-2}	Shuttleworth combination equation describing latent heat flux from soil
r^2		Coefficient of determination from least squares regression
r_{aa}, r_a	s m^{-1}	Aerodynamic resistance above the canopy
r_{ca}	s m^{-1}	Canopy boundary layer resistance
r_{cs}, r_c	s m^{-1}	Canopy surface resistance
r_{sa}	s m^{-1}	Aerodynamic resistance within the canopy
r_{ss}	s m^{-1}	Soil surface resistance

Symbol	Units	Definition
R	$J\ kg^{-1}\ mol^{-1}\ K^{-1}$	Universal gas constant
R_n	$W\ m^{-2}$	Total net radiation flux to canopy and soil
R_{ns}	$W\ m^{-2}$	Net radiation flux to soil
s_{Ts}	-	Sensitivity of latent heat flux to soil surface temperature
s_{hs}	-	Sensitivity of latent heat flux to soil surface relative humidity
S	$W\ m^{-2}$	Heat storage in soil above heat flux transducer
t	s	Time
T_a	°C	Air temperature
T_o	°C	Air temperature at height of mean canopy flow
T_r	°C	Air temperature at reference height
T_s	°C	Soil temperature
T_{soil}	°C	Soil temperature just below soil surface
T_{surf}	°C	Soil temperature at soil surface
T_{spider}	°C	Air temperature in manifold air collector sampling chamber
T_{sip}	°C	Air temperature where air enters manifold air collector
T_{sv}	K	Mean temperature of soil volume above soil heat flux transducers
u	$m\ s^{-1}$	Wind velocity
u_*	$m\ s^{-1}$	Friction velocity
U	$m\ s^{-1}$	Wind velocity averaged over height
x	m	Distance in x direction
z	m	Height
z_o	m	Roughness height of plant canopy
z_o'	m	Roughness height of soil surface
z_r	m	Reference height
α	-	Coefficient for surface evaporation model

Symbol	Units	Definition
β	-	Bowen ratio
β_{DF}	-	Coefficient for drying front evaporation model
γ	kPa °C^{-1}	Psychrometric constant
Δ	kPa °C^{-1}	Mean rate of change of saturated vapor pressure with temperature
ϵ	-	ratio of molecular weights of water vapor and air
η	-	Extinction coefficient for net radiation and wind through a canopy
θ, θ_v	m^3 m^{-3}	Volumetric soil water content
θ_m	m^3 m^{-3}	Volume fraction of soil mineral component
λ	J kg^{-1}	Latent heat of vaporization
ρ, ρ_a	kg m^{-3}	Density of air
ρ_m	kg m^{-3}	Density of soil minerals
ρ_w	kg m^{-3}	Density of liquid water
ϕ	-	Atmospheric thermal stability correction factor
ψ_s	kPa	Soil water potential
e	-	Error or deviation of model estimate from measured value

LIST OF ABBREVIATIONS

Abbreviation	Description
AEM	Automatic exchange mechanism
BR, BREB	Bowen ratio-energy balance method
CC	Closed chamber
CM88	Choudhury and Monteith (1988) model
CSH	Canopy source height
DOY	Day of year
DS	Soil surface deficit model
EBC	Energy balance-combination model
FC	Flux certainty
ID	Inside diameter
LAI	Leaf area index
MAC	Manifold air collector
MAE	Mean average error
ML	Microlysimeter
OD	Outside diameter
PM	Penman-Monteith combination equation
PRTD	Platinum resistance temperature device
PVC	Polyvinyl chloride
RMSE	Root mean square error
RS	Soil surface resistance model
STDEV	Standard deviation of a mean
SG90	Shuttleworth and Gurney (1990) model
SW85	Shuttleworth and Wallace (1985) model
TC	Thermocouple

Chapter 1. Introduction

Approach of dissertation

This dissertation adopts the structural approach of a scientific paper. Chapter One serves as introduction, literature review, theory and model development and statement of hypotheses and objectives. Chapter Two contains general methods and materials; a description of the field layout, instrumentation and sensors used, and sampling techniques. Chapters Three, Four, and Five are analogous to results and discussion. Each chapter contains a discreet paper which treats a detailed aspect of the research. Format of each chapter follows that of a scientific paper with introduction and focused literature review, methods and materials specific to the chapter's facet of research, results and discussion, and summary and conclusions. Chapter Three addresses the first major objective, quantification of the near-soil surface environment. Chapter Four analyzes the sensitivity of the model to soil surface temperature and humidity. Chapter Five addresses the second major objective; model performance, contrasts, and comparisons. Chapter Six summarizes and offers conclusions and suggestions for further research and Chapter Seven contains cited references. Refer to the Table of Contents to see the overview of this approach.

Introduction

Evaporation is a key process in surface hydrology (Hatfield et al. 1992). Evaporation from soil and plants (evapotranspiration) returns water from land surfaces to the atmosphere and influences soil water storage, water available to plants and recharge of

groundwater. The ability to quantify and predict evaporation is important to understanding links between agricultural practices and water quantity and quality, the hydrology of natural ecosystems and global climate.

Evapotranspiration is commonly simulated by mathematical models which partition energy available to evaporate water. These models have wide applicability. They evaluated management practices in agriculture (Ritchie 1972, Williams et al. 1984, Jones and Kiniry 1986, DeCoursey 1992), investigated hydrology of natural ecosystems (Kelliher et al. 1986, Lafleur and Rouse 1990, Massman 1992, Stannard 1993), and generated surface inputs to global climate models (Sellers et al. 1986, Wilson et al. 1987, Dolman 1993). These physically-based models sought to be applicable to a variety of environments, to use a limited number of readily available input data and parameters and to have low sensitivities to errors in characterizing generalized parameters.

Researchers have studied evaporation from soil only (Fuchs and Tanner 1967, van Bavel and Hillel 1976, Hammel et al. 1981, Bristow et al. 1986, Lascano and van Bavel 1986, ten Berge 1990) or considered soil and plant evaporation together in a single-layer "big leaf" approach (Blad and Rosenberg 1976, Verma et al. 1976, Heilman and Kanemasu 1976; see Raupach and Finnigan 1988 for a general discussion). However, the big leaf model assumes that sources of sensible and latent heat are at the same height and temperature (Stannard 1993) and that resistances to fluxes are 'bulk' extensions of individual leaf stomatal and boundary layer resistances. The assumption of a single source is reasonable for extremes of no canopy and full canopy, but for a sparse canopy there are multiple sources of sensible and latent heat at different temperatures. A more detailed

model is needed which accounts for at least two sources.

Ritchie (1972) was among the first to partition evaporation between plant and soil. This semi-empirical approach was subsequently incorporated in crop growth and water use models (e.g. EPIC, Williams et al. 1984; CERES-Maize, Jones and Kiniry 1986). Shuttleworth and Wallace (1985) partitioned energy between soil and plant evaporation with a physically based model based on the energy balance equation (Rosenberg et al. 1983), Penman-Monteith combination equations (Monteith 1965) and fluxes modeled with an Ohm's Law analog (Hillel 1991). This two layer energy balance-combination (EBC) approach was theoretically extended (Choudhury and Monteith 1988, Shuttleworth and Gurney 1990) and also incorporated into a water quality model (RZWQM, DeCoursey 1992). Only a few field studies have explored different limited aspects of the EBC approach (Kelliher et al. 1986, Lafleur and Rouse 1990, Ham and Heilman 1991, Massman 1992, Stannard 1993, Dolman 1993, Farahani and Bausch 1995), although interest and research has increased.

One area of uncertainty in EBC theory is the soil-atmosphere interface (Shuttleworth and Wallace 1985, Shuttleworth and Gurney 1990, Ham and Heilman 1991, Massman 1992). Shuttleworth and colleagues assumed that water evaporates from moist soil beneath a dry layer of increasing thickness. They defined soil resistance to evaporation as the diffusive resistance to vapor movement through this dry layer. Some have defined soil resistance as a function of soil physical properties (Fuchs and Tanner 1967, Novak and Black 1985, Choudhury and Monteith 1988, Brisson and Perrier 1991). Others have parameterized soil resistance as a function of soil surface wetness (Camillo

and Gurney 1986, Sellers et al. 1986, Kondo et al. 1990, Mahfouf and Noilhan 1991). This 'drying front' model is conceptually attractive because it incorporates both diffusion and turbulent transfer processes of evaporation from soil. However, drying front models which rely on soil physical properties such as porosity, tortuosity or depth of dry layer may be at a scale of detail inappropriate to EBC models. Parameterization of soil resistance as an empirical function of soil wetness is not generally applicable. Moreover, the concept of a uniform dry layer is uncertain when considering a highly variable evaporation rate or a drying and rewetting soil.

Another way to describe evaporation from soil is to assume that water evaporates from the soil surface (van Bavel and Hillel 1976, Hammel et al. 1981, ten Berge 1990, Ham and Heilman 1991). The gradient driving evaporation is the difference between vapor pressure at the soil surface and vapor pressure of the atmosphere. Flux is limited by a single aerodynamic resistance. Though the soil surface model simplifies the evaporative path it has the advantage of integrating the below-surface path into a single potentially measurable term, soil surface vapor pressure.

Whether considering a single source model like the Penman-Monteith combination equation, or a multi-source model, estimation of surface and aerodynamic resistances is critical; or as Raupach and Finnigan (1988) observed, estimation of resistances "may be fairly said to constitute the whole art of using [the combination equation]". The soil-atmosphere interface and how best to describe it in the context of energy balance-combination models clearly demands detailed study to improve the ability of these models to simulate energy fluxes.