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Modeling evapotranspiration in maize/soybean strip intercropping system with the evaporation and radiation interception by neighboring species model

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ABSTRACT

An experiment was carried out at Shangqiu Agro-Ecosystem experimental station in 2008–2009 to determine the partitioning of evapotranspiration in a maize/soybean intercropping. Sap flow gauges and micro-lysimeters, were used to determine plant transpiration and soil evaporation. Average daily soil evaporation in the intercropping system during the observation period (from June 1 to June 30) in 2008 and 2009 seasons were 2.07 and 2.41 $\mathrm{mm\,d^{-1}}$, respectively. During the observation period, the mean transpiration rates of maize and soybeans in the intercropping arrangement were 1.47 and 0.78 $\mathrm{mm\,d^{-1}}$, respectively. A multi-source model – the ERIN (evaporation and radiation interception by neighboring species), was used to simulate soil evaporation and plant transpiration in the maize/soybean intercropping. Results showed that the ERIN model overestimated plant transpiration of maize and soybean, while the mean bias error (MBE), the root mean square error (RMSE) and the index of agreement (d) were 0.06 $\mathrm{mm\,d^{-1}}$, 0.23 $\mathrm{mm\,d^{-1}}$ and 0.93, respectively. However, the ERIN model underestimated soil evaporation; MBE, RMSE and d were −0.02 $\mathrm{mm\,d^{-1}}$, 0.44 $\mathrm{mm\,d^{-1}}$ and 0.97, respectively. Sources of error were attributed to the uncertainties in characterizing the micrometeorological conditions and specifying the empirical parameters of the resistance terms. The multi-source model was extremely sensitive to the water vapor deficit at canopy source height and the radiation captured by crop and stomatal resistance. Overall, the ERIN model is useful in simulating the partitioning of evapotranspiration in intercropping systems.

1. Introduction

Intercropping involves growing several plant species simultaneously in the same field, and is often a means to better use of land and other resources (Willey, 1990; Tournebize et al., 1996; Rodrigo et al., 2001). The management of viable plant combinations suitable for different environmental conditions requires knowledge of mechanisms that control partitioning of factors such as light, water and nutrients between the intercrop components (Ozier-Lafontaine et al., 1997). Water is essential for plant growth and yield formation, especially in the arid and semi-arid regions. Therefore, a fundamental understanding of how the intercrop system captures and uses water would provide the scientific basis for recommending this practice in the arid and semi-arid regions. However, few experiments were carried out to investigate water partitioning in intercropping in the arid and semi-arid regions, even in the humid and semi-humid zones (Ozier-Lafontaine et al., 1997).

Water partitioning between intercrop components is determined by dynamic interactions between shoot and root system above and below ground, as well as by the interactions between environmental conditions and plant growth (Ozier-Lafontaine et al., 1998). Hence, water partitioning in intercropping is a complex process as it simultaneously involves above-ground and below-ground spaces (Tournebize et al., 1996). Under the ground, water partitioning depends on available soil moisture, root growth and development, and root water uptake capacity (Ozier-Lafontaine et al., 1995); while meteorological conditions and spatial distribution of foliage determine the water demand of intercrop components in the above-ground space (Tournebize et al., 1996).

Above the ground, measurements of transpiration and partitioning between intercrop components are rare and mainly concern tree-grass canopies due to instrument limitations (Kelliher et al., 1990; Tournebize et al., 1996). But the development of the sap flow method makes it possible to measure plant transpiration directly

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List of symbols

A	total available energy (MJ m^{-2} d^{-1})
$A_{c,i}$	available energy for crop species i (MJ m^{-2} d^{-1})
A_S	available energy for soil (MJ m^{-2} d^{-1})
$C_{c,i}$	canopy resistance coefficient
c_d	mean drag coefficient for the individual vegetative elements making up the canopy
C_i	resistance coefficient
c_p	specific heat of air (J kg^{-1} K^{-1})
C_s	soil surface resistance coefficient
D	vapor pressure deficit at the reference height (kPa)
d	zero plane displacement of crop (m)
D_0	vapor pressure deficit in canopy source height (kPa)
d_p	'preferred value' of zero plane displacement (m)
E	evapotranspiration (mm d^{-1})
e_a	actual vapor pressure (kPa)
e_r	vapor pressure at the reference height (kPa)
$e_s(T_0)$	saturated vapor pressure at the canopy source height (kPa)
$e_s(T_r)$	saturated vapor pressure at the reference height (kPa)
F_i	fraction of radiation intercepted by crop species i
G	soil heat flux (MJ m^{-2} d^{-1})
h	crop height (m)
k	extinction coefficient
K	eddy diffusion coefficient (m^2 s^{-1})
K_h	eddy diffusion coefficient at top of canopy (m^2 s^{-1})
LAI	leaf area index (m^2 m^{-2})
LAI_e	effective leaf area index (m^2 m^{-2})
n_e	eddy diffusivity decay constant in the canopy
$PM_{c,i}$	canopy transpiration (mm d^{-1})
PM_i	total evapotranspiration (mm d^{-1})
PM_s	soil evaporation (mm d^{-1})
$r^a{}_a$	aerodynamic resistance between the canopy and the reference height (s m^{-1})
$r^{c,i}{}_a$	bulk boundary layer resistance of the canopy for crop species i (s m^{-1})
$r^{c,i}{}_s$	bulk stomatal resistance of the canopy for crop species i (s m^{-1})
$r^i{}_b$	mean boundary layer resistance per unit surface area of crop i (s m^{-1})
R_n	daily net radiation (MJ m^{-2} d^{-1})
$r^s{}_a$	aerodynamic resistance between the soil and mean canopy flow (s m^{-1})
$r^s{}_s$	soil surface resistance (s m^{-1})
r_{STmin}	minimal stomatal resistance of individual leaves under optimal conditions (s m^{-1})
S	solar radiation (W m^{-2})
T_0	temperatures at the canopy source height (°C)
T	air temperature(K)
T_r	temperatures at the reference height (°C)
u	wind speed at the reference height (m s^{-1})
$u(h)_i$	wind speed at the top of canopy i (m s^{-1})
$u(z)_i$	wind speed at height z within canopy (m s^{-1})
u^*	friction velocity (m s^{-1})
w_i	leaf width of crop i (m)
z	height variable (m)
Z_0	'preferred value' of roughness length (m)
z_0	crop roughness length (m)
z_{0c}	roughness length of the closed canopy (m)
Z_{0g}	roughness length of the soil surface (m, the default value is 0.01)
z_r	reference height (m)
α'	attenuation coefficient for wind speed
γ	psychrometric constant (kPa °C^{-1})
Δ	slope of the saturating vapor pressure versus temperature (kPa °C^{-1})
θ	soil water content (cm^3 cm^{-3})
θ_F	field capacity (cm^3 cm^{-3})
θ_S	water content of an upper soil surface layer (cm^3 cm^{-3})
θ_W	wilting moisture content (cm^3 cm^{-3})
κ	Von Kármán's constant
λ	latent heat of vaporization (MJ kg^{-1})
ρ	air density (kg m^{-3})
X_i	environmental factors

(Swanson, 1994; Grime et al., 1995; Sellami and Sifaoui, 2003). Transpiration partitioning between each species in intercropping system of maize and sorghum (Ozier-Lafontaine et al., 1997, 1998), maize and sunflower (Teh et al., 2001), and maize and cowpea (Adiku et al., 2001) were respectively studied using sap flow with reasonable accuracy. Soil evaporation in intercropping system is often measured using microlysimeters (Wallace et al., 1999). Soil evaporation in the agro-forestry system was observed by means of microlysimeters (Jackson and Wallace, 1999; Wallace et al., 1999) and in maize/sunflower intercropping (Teh et al., 2001).

Crop water consumption is often calculated using the water balance method (Hillel, 1998), while the water balance studies rarely separate water loss through the crop and the soil surface. Nevertheless, this information is critical for yield estimates (Walker and Ogindo, 2003). The Penman–Monteith (PM) equation (Allen et al., 1998) is often used to assess reference and crop evapotranspiration. The Shuttleworth–Wallace (SW) model was developed based on the PM model to separately account for vegetation and substrate (soil) contributions (Shuttleworth and Wallace, 1985). The basic idea in the SW model is that the two sources of water vapor and heat can be superimposed, and hence coupled (Lhomme and Chehbouni, 1999). Thus, the SW model explicitly specifies the energy exchanges between substrate and vegetation. Therefore, it can be used to estimate the fraction of water vapor that transpired from leaves and evaporated from soil, respectively. Soil evaporation and plant transpiration in maize/sunflower intercropping was simulated using the SW model with reasonable accuracy, and the SW model was sensitive to the partitioning of captured solar radiation, canopy resistance and bulk boundary layer resistance (Teh et al., 2001). The SW model was extended for intercropping systems to include the transpiration from 'n' crop species (with soil interaction) and evaporation from the soil, and a new model, ERIN (evaporation and radiation interception by neighboring species, ERIN) was developed (Wallace, 1997).

Interaction among crops in strip intercropping occurs primarily at the edge rows of the strips (Iragavarapu and Randall, 1996). Narrow strips allow for relatively more interaction among intercrop components. The interaction has a significant influence on the microclimate of the intercropping system and finally, on the process of soil evaporation and crop transpiration in the intercropping system. However, few researchers measured and simulated soil evaporation and plant transpiration in the narrow strip intercropping. Therefore, the objectives of this research were to (i) measure sap flow of intercrop components and investigate transpiration partitioning between plant species in maize/soybean strip intercropping, (ii) predict crop transpiration and soil evaporation in maize/soybean strip intercropping using the ERIN model, and compare predictions with measurements, and (iii) discuss the reasons