

Application of the Revised Shuttleworth-Wallace Model to Evapotranspiration of Film-Mulched Maize in Semi-Arid Regions: A Postprint

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Abstract

Evapotranspiration (ET), comprising plant transpiration (T) and soil evaporation (E), plays a critical role in maintaining global energy balance and climate regulation. Quantifying evapotranspiration and its components is essential for accurately predicting ecosystem responses of carbon, water, and energy fluxes to climate variability. Based on observations from an eddy covariance system during the 2014 maize growing season at the Lanzhou University Semi-arid Agroecosystem Experimental Station, the revised Shuttleworth-Wallace model (S-W model) was employed to simulate evapotranspiration in mulched maize fields, with simulation results validated against measured values, and the influencing factors and sensitivity of evapotranspiration and its components were analyzed. The results demonstrated that the S-W model performed satisfactorily in simulating evapotranspiration for mulched maize cropland on sunny days and partly cloudy days with daily evapotranspiration exceeding $2 \text{ mm} \cdot \text{d}^{-1}$, whereas simulation performance was poor on rainy days, and model outputs were generally higher than eddy covariance measurements. The diurnal variation of E/ET exhibited a unimodal curve; at the growing season scale, it displayed a decreasing trend during the rapid growth phase of maize and remained essentially stable thereafter. The diurnal variation of E/ET in mulched maize cropland was primarily influenced by stomatal conductance, while at the growing season scale it was jointly controlled by leaf area index and soil water content. Sensitivity analysis revealed that evapotranspiration and its components were highly sensitive to aerodynamic resistance between crop canopy height and reference height (r_{aa}) and canopy boundary layer resistance (r_{ac}), moderately sensitive to crop canopy resistance (r_{sc}), and insensitive to aerodynamic resistance between ground and canopy (r_{as}) and underlying bare soil surface resistance (r_{ss}). Therefore, when applying the S-W model to simulate evapotranspiration in mulched maize cropland, particular attention must be paid to the proper determination of resistance parameters r_{aa} , r_{ac} , and r_{sc} .

Full Text

Estimation of Evapotranspiration in Maize Fields with Ground Mulching with Plastic Film in Semi-Arid Areas Using Revised Shuttleworth-Wallace Model

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Abstract

Evapotranspiration (ET), which comprises evaporation from the soil surface (E) and transpiration from vegetation (T), plays a critical role in maintaining global energy balance and regulating climate. Quantifying ET and its components is essential for accurately predicting ecosystem responses in terms of carbon, water, and energy fluxes. Based on eddy covariance measurements from the 2014 maize growing season at the Experiment Station of Agro-ecosystem in Semi-arid Area (ESASA) of Lanzhou University, we applied the revised Shuttleworth-Wallace (S-W) model to simulate ET in plastic film-mulched maize fields. The simulation results were validated against measured values, and the driving factors and parameter sensitivity of ET and its components were analyzed. The results indicated that the S-W model performed well in simulating ET on sunny and partly cloudy days when daily ET exceeded $2 \text{ mm} \cdot \text{d}^{-1}$, but performed poorly on rainy days, with simulated values generally higher than eddy covariance measurements. The E/ET ratio exhibited a unimodal diurnal pattern and decreased during the rapid growth period at the seasonal scale, remaining relatively stable thereafter. At the diurnal scale, E/ET variation was primarily controlled by stomatal conductance, while at the seasonal scale, it was jointly influenced by leaf area index (LAI) and soil moisture content. Sensitivity analysis revealed that ET and its components were most sensitive to aerodynamic resistance between canopy height and reference height (r_a), moderately sensitive to canopy resistance (r_s) and boundary layer resistance (r_a), and least sensitive to aerodynamic resistance between ground and canopy (r_a) and soil surface resistance (r_s). These findings suggest that careful determination of resistance parameters, particularly r_a and r_s , is crucial when applying the S-W model to simulate ET in plastic film-mulched maize fields.

Keywords: Plastic film mulch; Maize; Shuttleworth-Wallace model; Evapotranspiration; Semi-arid area

Introduction

Farmland evapotranspiration, which includes crop transpiration and soil evaporation, constitutes a critical component of water conversion and energy transfer in the soil-plant-atmosphere continuum (SPAC) and has long been a focal research topic across multiple disciplines including meteorology, botany, hydrology, ecology, geography, and soil science. Crop evapotranspiration interacts with various meteorological factors, soil moisture conditions, crop species, and physiological characteristics, thereby constraining microclimatic conditions at small scales and climate change at larger scales. In the arid and semi-arid regions of northwest China, characterized by dry climate, scarce precipitation, and strong evaporation, water resources are particularly precious. Understanding crop evapotranspiration and water transport patterns in this region not only provides a theoretical basis for studying energy balance and water cycles but also plays a key role in determining water use efficiency and water resource allocation.

Among numerous ET models, the Penman-Monteith (P-M) model serves as a benchmark formula and was recommended by the Food and Agriculture Organization (FAO) in 1998 as the standard method for calculating reference crop evapotranspiration. In 1985, Shuttleworth and Wallace refined the P-M approach by dividing the system into crop canopy and underlying surface components, establishing the Shuttleworth-Wallace (S-W) dual-source evapotranspiration model primarily for sparsely vegetated surfaces. Compared with the P-M model, the S-W model separately calculates crop transpiration and soil evaporation, accounting for resistance differences between vegetation and bare soil, thereby improving ET calculation accuracy. Previous comparative studies have demonstrated the superiority of the S-W model under sparse vegetation conditions. Stannard compared P-M, S-W, and modified Priestley-Taylor models in semi-arid rangeland vegetation, finding that the S-W model outperformed the P-M model in sparse vegetation scenarios. Kato et al. reported that the S-W model produced significantly lower root mean square errors than the P-M model for sparse vegetation. Fisher et al. reached similar conclusions in their comparative analysis.

However, the S-W model contains numerous parameters, with several resistance parameters exerting substantial influence on simulation results. Leuning et al., Sellers et al., and Zhu et al. optimized stomatal conductance by introducing vapor pressure deficit and soil moisture. Anadranistakis et al. optimized soil surface resistance parameters using soil moisture content. Zhu et al. improved model accuracy by incorporating Bayesian methods into resistance parameter calculation. Li et al. optimized the S-W model by considering the effects of plastic film mulch on evapotranspiration, finding that the revised model outperformed the traditional S-W model and produced soil evaporation estimates closer to measured values.

Maize (*Zea mays* L.) ranks as the third most widely cultivated grain crop world-

wide, following wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.), and serves as a major crop and primary income source for farmers in the arid and semi-arid regions of northwest China. Plastic film mulching, an effective yield-increasing practice that substantially reduces soil evaporation, has been widely adopted in agricultural production across northern China in recent years. Previous studies on farmland ecosystem evapotranspiration rarely considered the effects of plastic film mulching. Applying the revised S-W model to study ET in plastic film-mulched maize fields on the Loess Plateau not only tests the model's applicability but also provides a foundation for developing reasonable cultivation and management practices, offering significant implications for improving water use efficiency and local economic benefits. Based on observations from the 2014 growing season, this study applied the revised S-W model to simulate ET in plastic film-mulched maize fields, aiming to comprehensively investigate ET patterns, explore influencing factors and parameter sensitivity of ET and its components, and provide theoretical guidance for determining appropriate irrigation regimes for mulched maize.

1. Materials and Methods

1.1 Study Area Description

The experimental field was located at the Experiment Station of Agro-ecosystem in Semi-arid Area (ESASA) of Lanzhou University (35.42°N, 105.24°E, elevation 1,951 m) in the loess hilly and gully region of the Loess Plateau. The study area features a typical warm temperate semi-arid monsoon climate with an average annual temperature of 7.9°C, mean annual precipitation of 340 mm concentrated in July-September, potential annual evaporation of 1,800 mm, and a frost-free period of approximately 136-186 days. The region experiences large diurnal temperature variations and abundant sunlight. Winters are dry and windy, summers are hot, surface water is scarce, and groundwater is deep. The area comprises mainly hillside dryland, plateau dryland, and valley dryland, with severe water shortage in cultivated land and maize as the primary grain crop. Drought represents the main meteorological disaster.

The experimental field was a conventionally cultivated farmland with maize row spacing of 0.5 m and plant spacing of 0.4 m. Maize was sown at the end of April (with plastic film laid during planting) and harvested in early October. During July-August, maize underwent rapid growth stages including jointing, tasseling, and filling, with intense transpiration. The field remained under natural conditions without artificial irrigation during this period. Plastic film covered 65% of the farmland area at planting, decreasing to approximately 60% as the crop emerged, grew, and was affected by weather conditions.

1.2 Data Collection

1.2.1 Evapotranspiration Measurements Farmland evapotranspiration was measured using an eddy covariance system deployed from June 29 to

September 10, 2014. A flux observation tower was erected in the center of a well-growing maize field, with the eddy covariance instrument installed at 3 m height, consisting of a three-dimensional ultrasonic anemometer (CAST3, Campbell, USA) and a CO₂/H₂O infrared gas analyzer (Li-7500, LiCor Inc., USA). The sampling frequency was 10 Hz, with data collected by a data logger (CR5000, Campbell, USA) and stored as 30-minute averages, including sensible heat flux, latent heat flux, CO₂, and water vapor flux. Additionally, a net radiometer CNR1 (Kipp&Zonen, Netherlands) was installed at 3 m height, and soil heat flux plates were buried at 5 cm depth in four orientations (east, south, west, north) below the net radiometer, with soil heat flux calculated as the average of the four plates.

Eddy covariance data require correction and processing. This study used Eddypro 5.3.0 software for data processing and applied the following criteria for data rejection: (1) data during precipitation and 1 hour before/after; (2) data with abnormal sensor status; (3) data with values beyond physical meaning. Missing and rejected data were gap-filled using interpolation methods based on diurnal variation analysis of turbulent fluxes. The FSAM model calculated that 90% of the flux originated from 0-150 m upwind and -45 to 45 m perpendicular to the wind direction during the maize growing season, an area fully planted with maize. The energy balance ratio (EBR) method yielded an energy closure of 0.905 for July-August, indicating good data quality. Processed latent heat data were converted to farmland evapotranspiration (ET) values.

1.2.2 Soil Moisture and Meteorological Data ECH2O sensor probes were installed at 10 cm depth for continuous monitoring of soil volumetric water content from June 12 to September 10, 2014, with a recording interval of 0.5 h. Conventional meteorological data, including solar radiation, atmospheric pressure, temperature, humidity, wind direction, wind speed, and precipitation, were measured by a Watchdog 2700 automatic weather station near the flux tower. Saturated vapor pressure was calculated from air temperature and relative humidity.

1.2.3 Leaf Area Index Measurement Approximately every week during the observation period, eight maize plants were randomly selected to measure plant height, leaf number, and length and width of each leaf. Leaf area index (LAI) was calculated using:

$$LAI = (\sum(L_{ij} \times B_{ij}) \times n \times \rho) / m$$

where L_{ij} is leaf length, B_{ij} is maximum leaf width, n is total leaf number per plant, m is number of measured plants, and ρ is planting density. Additionally, stomatal conductance was observed weekly during the measurement period. On typical sunny days, stomatal conductance and photosynthetic rate were measured hourly from 7:00 to 19:00 on three leaves (upper, middle, lower) of each plant using a Li-6400 portable photosynthesis system.

1.3 Revised Shuttleworth-Wallace Model

The revised S-W model by Li et al. is illustrated in [Figure 1: see original paper]. Total latent heat flux comprises contributions from the canopy (λT), bare soil (λE_s), and soil under plastic film (λE_m). Under mulched conditions, latent heat flux is expressed as:

$$\begin{aligned}\lambda T &= C_c \times PM_c \\ \lambda E_s &= C_s \times PM_s \\ \lambda E_m &= C_m \times PM_m\end{aligned}$$

where PM_c , PM_s , and PM_m are Penman-Monteith calculations for vegetation transpiration, bare soil evaporation, and mulched soil evaporation ($W \cdot m^{-2}$), respectively; C_c , C_s , and C_m are canopy resistance coefficient, soil surface resistance coefficient, and mulch resistance coefficient (dimensionless); λ is latent heat of vaporization ($MJ \cdot kg^{-1}$); Δ is slope of saturation vapor pressure-temperature curve ($kPa \cdot K^{-1}$); ρ_a is air density ($kg \cdot m^{-3}$); e_s and e_a are saturated and actual vapor pressure at reference height (3 m) (kPa); γ is psychrometric constant; f_m is ratio of mulched area to farmland area; r_a is aerodynamic resistance between canopy height and reference height ($s \cdot m^{-1}$); $r_{a,c}$ is canopy boundary layer resistance ($s \cdot m^{-1}$); $r_{a,g}$ is aerodynamic resistance between ground and canopy ($s \cdot m^{-1}$); $r_{s,b}$ and $r_{s,m}$ are surface resistance of bare soil and mulched soil ($s \cdot m^{-1}$); A is total available energy ($W \cdot m^{-2}$), with components calculated as:

$$\begin{aligned}A_c &= A \times [1 - \exp(-KA \times LAI)] \\ A_s &= A \times \exp(-KA \times LAI) \times (1 - f_m) \\ A_m &= A \times \exp(-KA \times LAI) \times f_m\end{aligned}$$

where G_s and G_m are soil heat flux for bare and mulched soil ($W \cdot m^{-2}$), KA is light extinction coefficient, and LAI is leaf area index ($m^2 \cdot m^{-2}$).

Following Li et al., $G_s = G_m = G$, and plastic film prevents water evaporation through the mulch ($\lambda E_m = 0$). The equations simplify to:

$$\begin{aligned}\lambda T &= C_c \times PM_c \\ \lambda E_s &= C_s \times PM_s \\ \lambda E_m &= 0\end{aligned}$$

1.4 Model Resistance Parameter Calculation

Different calculation methods were selected for various resistance parameters. Soil surface resistance coefficient (r_s) was calculated using the formula proposed by Anadranistakis et al.:

$$r_s = r_{s_{\min}} \times [1 + a_1 \times (F - F_c) / F_c]^{a_2}$$

where F_c is field capacity ($cm^3 \cdot cm^{-3}$); $r_{s_{\min}}$ is soil surface resistance at F_c ($100 s \cdot m^{-1}$); F is surface soil moisture content ($cm^3 \cdot cm^{-3}$); and a_1 and a_2 are parameters determined as 2.5 and 1.5 based on Zhang et al.

Canopy resistance parameter (r_s) was calculated following Zhu et al., where r_s is the reciprocal of stomatal conductance (g_s). The calculation formula is:

$$g_s = g_{\max} \times [Q_h / (Q_h + Q_{50})] \times \exp(-D_a / D_{50}) \times [1 - \exp(-(a - b) / (a - b))]$$

where g_{\max} is maximum stomatal conductance at canopy height ($\text{m} \cdot \text{s}^{-1}$); KQ is extinction coefficient for shortwave radiation; Q_h is visible light flux density at canopy top ($\text{W} \cdot \text{m}^{-2}$); Q_{50} is visible light at half-maximum stomatal conductance ($\text{W} \cdot \text{m}^{-2}$); D_a is vapor pressure deficit at reference height (kPa); D_{50} is vapor pressure deficit at half-maximum stomatal conductance (kPa); b is soil moisture at wilting point; a is critical soil moisture when crop stress begins (taken as 3/4 of saturated moisture s).

Boundary layer resistance parameters (r_a and r_a) and aerodynamic parameters (r_a) were calculated using formulas proposed by Shuttleworth and Gurney (1990).

2. Results and Analysis

2.1 Analysis of Maize Growth Environment

Environmental factors during the maize growth period significantly influenced ET and its components. Variations in net radiation, air temperature, vapor pressure, wind speed, LAI, and soil moisture content from June 29 to September 10, 2014, are shown in [Figure 2: see original paper]. Maize entered the rapid growth phase starting June 29, with rapid increases in plant height and LAI. After July 20, changes in leaf width and plant height slowed. From August 12, maize entered the filling stage, with plant height stabilizing and LAI gradually decreasing. Daily mean temperature ranged from 13-22°C, with greater variability ($>9^\circ\text{C}$) before August 2 and relatively lower, stable temperatures (13-18°C) afterward. Overall temperature showed an initial increase followed by a decrease. Net radiation followed a similar trend, ranging from 0.3-18 $\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ and maintaining high levels during the rapid growth period in July. Vapor pressure deficit fluctuated substantially in July, with a maximum of 1.35 kPa, decreasing from early August. Wind speed showed an initial increase followed by decrease, with daily averages of 0.5-2.5 $\text{m} \cdot \text{s}^{-1}$. Soil volumetric water content at 10 cm depth varied significantly with precipitation, ranging from 0.17 $\text{cm}^3 \cdot \text{cm}^{-3}$ to saturation (0.3 $\text{cm}^3 \cdot \text{cm}^{-3}$).

2.2 Comparison of Simulated and Measured Evapotranspiration

To evaluate maize ET under different weather conditions and time scales, we selected three typical weather types (sunny, partly cloudy, and rainy) for validation at half-hourly intervals, with results shown in [FIGURE:3a-c]. Weather classification followed the method of Chu et al. Sunny days showed maximum ET rates of 0.5 $\text{mm} \cdot \text{h}^{-1}$ and daily averages of 3.5 $\text{mm} \cdot \text{d}^{-1}$, with good correlation between S-W model simulations and eddy covariance measurements ($R^2 = 0.917$). On partly cloudy days, maximum ET rates were similar to sunny days

during strong solar radiation but decreased to 0.2-0.3 mm · h⁻¹ under cloudy conditions, with daily ET of 1.5-2.5 mm · d⁻¹ and good correlation ($R^2 = 0.869$). On rainy days, ET rates decreased significantly to maximum values of approximately 0.2 mm · h⁻¹ and daily ET of 0.3-1.0 mm · d⁻¹, with relatively poor model performance ($R^2 = 0.733$). The S-W model performed better on sunny and partly cloudy days than on rainy days with low solar radiation.

At the daily time scale, comparison between S-W model simulations and measured ET is shown in [Figure 3d: see original paper]. Correlation analysis indicated a coefficient of 0.909 between simulated and observed ET. Scatter points were mostly distributed above the 1:1 line, indicating overestimation by the S-W model compared to eddy covariance measurements. For daily ET > 2 mm · d⁻¹, simulated and measured values clustered near the 1:1 line with good agreement. For daily ET < 2 mm · d⁻¹, points deviated more from the 1:1 line, showing poorer fit.

2.3 Temporal Variation of Simulated E/ET Ratio

Diurnal and seasonal variations of the soil evaporation to evapotranspiration ratio (E/ET) in plastic film-mulched maize fields are shown in [Figure 4: see original paper]. The diurnal variation of E/ET followed a unimodal curve similar to net radiation, remaining low and fluctuating at night due to weak soil evaporation, with a peak at 14:00. At the seasonal scale, E/ET decreased rapidly from 18% to approximately 8% during the jointing stage, then remained relatively stable around 8% during tasseling and filling stages. Ferretti et al. reported an average E/ET of 7% for shortgrass prairie in northeastern Colorado. Sauer et al. found E/ET < 8% for soybean crops with high vegetation cover (LAI > 5 m² · m⁻²). Zhu et al. simulated E/ET of 13% for maize fields in the Heihe River basin of Gansu Province. Our lower E/ET values likely resulted from plastic film mulch effectively reducing bare soil evaporation. Similarities with Ferretti et al. and Sauer et al. may also reflect effects of vegetation cover density beyond mulching.

To investigate environmental influences on E/ET, we analyzed correlations with LAI, soil moisture content, and stomatal conductance during the growing season (). E/ET was negatively correlated with LAI and stomatal conductance and positively correlated with soil moisture content. LAI and stomatal conductance affected E/ET by increasing the proportion of leaf transpiration, while soil moisture influenced E/ET by increasing water availability for soil evaporation.

2.4 Model Parameter Sensitivity Analysis

To examine sensitivity of ET and its components to five resistance parameters, we analyzed changes in response to ±10% variation in each parameter (). For total ET, r_a was the most influential parameter, causing 3.30-3.55% change in ET with 10% variation. r_{soil} and r_{stom} were the second most important, causing 1.34-1.74% and 1.40-2.35% changes, respectively. r_{veg} had minimal impact, causing

only ~0.7% change. Transpiration (T) was sensitive to r_a and r_s (1.32-1.60% change), moderately sensitive to r_s , and insensitive to r_a and r_s (<0.2% change). Evaporation (E) was highly sensitive to r_a (4.65-5.39% change) and r_s (2-3% change), but only 0.31-0.36% sensitive to r_a changes. Overall, ET, transpiration, and evaporation were all sensitive to r_a , while r_s and r_a showed moderate sensitivity, and r_a was insensitive. These results indicate that canopy resistance parameters exert greater influence on ET components. Li et al. similarly found that both S-W and P-M models were most sensitive to canopy resistance when estimating ET in wheat fields, consistent with our findings. Therefore, careful parameterization of r_a and r_s is essential when applying the S-W model.

3. Discussion

3.1 Factors Influencing Evapotranspiration in Mulched Fields

Plastic film primarily functions to increase temperature and conserve soil moisture by converting ineffective soil evaporation into effective crop transpiration. The film barrier forces most water to be released to the atmosphere through crop root uptake and transpiration, with only minimal evaporation through film openings. Additionally, plastic film increases soil temperature, promoting root water absorption. To investigate meteorological influences on mulched field ET, we analyzed correlations between ET and meteorological factors (). The correlation order was net radiation > wind speed > air temperature > relative humidity, with net radiation showing the best correlation ($R^2 = 0.991$), followed by wind speed ($R^2 = 0.814$) and air temperature ($R^2 = 0.789$). Relative humidity showed poor correlation with ET. Gao et al. studied ET in grasslands of the upper Heihe River basin, finding that solar radiation, relative humidity, and temperature were the main factors affecting ET simulation. Zhang et al. reported good correlations between reed wetland ET and solar radiation, temperature, and relative humidity in the Liaohe Estuary. Consistent with these studies, our results show good correlations between solar radiation, temperature and ET, suggesting these relationships are not substantially affected by plastic film. However, unlike previous studies showing good correlations between relative humidity and ET, our mulched field showed poor correlation, likely because relative humidity remains relatively stable under the film. The weak correlation between soil moisture content and ET may also be related to mulching effects. Therefore, the primary meteorological factors affecting mulched field ET are solar radiation and temperature.

3.2 Factors Influencing the E/ET Ratio

The E/ET ratio reflects farmland water use efficiency, with lower values indicating more water is transpired through plant stomata and effectively utilized. In practice, minimizing E/ET is desirable. Besides mulching, E/ET is influenced by maize growth conditions. Previous studies indicate that E/ET variation is primarily controlled by LAI, stomatal conductance, and soil moisture content, with different dominant factors at different time scales. At the diurnal scale,

where LAI and soil moisture remain relatively constant, E/ET is mainly controlled by stomatal conductance changes induced by solar radiation variation. At the seasonal scale, E/ET is jointly influenced by LAI, stomatal conductance, and soil moisture content. Our results show that at the seasonal scale, E/ET was strongly affected by canopy energy absorption and stomatal conductance changes induced by LAI, solar radiation, and vapor pressure deficit, while soil moisture became a limiting factor under drought stress, consistent with previous findings.

LAI influences E/ET through three primary pathways: (1) increasing canopy energy absorption while reducing bare soil energy absorption; (2) increasing leaf stomatal conductance; and (3) increasing aerodynamic resistance from bare soil to canopy. These combined effects make LAI the dominant factor controlling seasonal E/ET variation. Therefore, stomatal conductance is the most important factor at the diurnal scale, while LAI is most influential at the seasonal scale.

4. Conclusion

Based on 2014 observational data from the Lanzhou University agro-ecosystem experimental station, this study applied the revised S-W dual-source model to simulate ET in semi-arid maize fields, validated the results against eddy covariance measurements, analyzed E/ET variation and influencing factors, and conducted parameter sensitivity analysis. The main conclusions are:

1. The S-W model performed well in simulating ET on sunny and partly cloudy days when daily ET exceeded $2 \text{ mm} \cdot \text{d}^{-1}$, but performed poorly on rainy days, with simulated values generally higher than measured values. The primary meteorological factors influencing mulched field ET were net radiation and air temperature.
2. The E/ET ratio in plastic film-mulched maize fields showed unimodal diurnal variation and decreased initially then stabilized during the growing season. At the diurnal scale, E/ET was primarily controlled by stomatal conductance, while at the seasonal scale, it was jointly influenced by LAI and soil moisture content.
3. Sensitivity analysis revealed that ET and its components were most sensitive to r_a , moderately sensitive to r_s and r_{sh} , and insensitive to r_{so} . Careful parameterization is essential when applying the S-W model to simulate farmland ET.

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