Environmental Response and Simulation of Maize Canopy Resistance in the Oasis Area of the Middle Reaches of Heihe River (Postprint)

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Abstract

Evapotranspiration (ET) constitutes a critical link in regional energy and water balance. Accurate estimation of evapotranspiration is of great significance for enhancing water use efficiency and optimizing regional water use structure, with canopy resistance serving as a crucial variable for precise evapotranspiration calculation. To ascertain the regional applicability of canopy resistance models and address their parameterization challenges, this study leveraged existing flux observation data from the Heihe Major Research Program. Building upon the Irmak model and considering the relationship between micrometeorological factors and canopy resistance, we incorporated the influence of atmospheric CO2 concentration on canopy resistance, constructing two variants of the Irmak model (with and without CO2 consideration), and coupled them with the Penman-Monteith (P-M) model. Utilizing available eddy covariance data, we analyzed and evaluated the simulation responses of both canopy resistance models to environmental variables and atmospheric CO2 concentration, and conducted sensitivity analyses of model parameters. Results demonstrated that coupling the CO2-enhanced Irmak model with the Penman-Monteith model better simulated maize canopy resistance and evapotranspiration responses to external environmental variables. During the parameter calibration period, the model achieved R^2 values of 0.76 and 0.95 between simulated and observed canopy resistance and evapotranspiration, respectively, with corresponding RMSE values of 33.1 $s \cdot m^{-1}$ and 34.5 $W \cdot m^{-2}$. During the validation period, R^2 values reached 0.68 and 0.90, with RMSE values of 63.2 $s \cdot m^{-1}$ and 49.0 $W \cdot m^{-2}$, respectively. Results from two independent validation sites indicated that the CO2-enhanced Irmak model exhibits favorable spatial transferability and adaptability, capable of accurately simulating farmland water consumption processes in maize at half-hourly temporal resolution throughout the growing season. Sensitivity analysis revealed that maize canopy resistance and evapotranspiration are most sensitive to net radiation and relative humidity variations, followed by air temperature, leaf area index, and atmospheric CO2 concentration. The CO2-enhanced Irmak model developed in this study can reliably estimate crop evapotranspiration, providing a research foundation for investigations into farmland water consumption under scenarios of crop structure adjustment, land use change, and varying atmospheric CO2 concentrations.

Full Text

Preamble

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Response of Maize Canopy Resistance to Environmental Factors and Its Simulation in the Middle Reach Oasis of Heihe River Basin

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Abstract: Evapotranspiration (ET) is a critical component of regional energy and water balance. Accurate estimation of ET is essential for improving water use efficiency and optimizing regional water allocation, and canopy resistance serves as a key variable in this estimation. To determine the regional applicability of canopy resistance models and resolve their parameterization issues, this study utilized existing flux observation data from the Heihe River Basin Major Research Program. Building upon the Irmak model and considering the relationship between micrometeorological factors and canopy resistance, we incorporated the effect of atmospheric CO_2 concentration on canopy resistance and constructed two versions of the Irmak model—one without CO_2 consideration and one with CO_2 effects. These were coupled with the Penman-Monteith (P-M) model. Using available eddy covariance data, we analyzed and tested the simulation results of both canopy resistance models in response to environmental variables and atmospheric CO_2 concentration, and conducted sensitivity analysis of model parameters. The results demonstrated that coupling the CO_2-enhanced Irmak model with the Penman-Monteith model better simulated the response processes of maize canopy resistance and evapotranspiration to external environmental variables. During the parameter calibration period, the coefficients of determination (R^2) between simulated and observed values for canopy resistance and ET reached 0.76 and 0.95, respectively, with root mean square errors (RMSE) of 33.1 $s \cdot m^{-1}$ and 34.5 $W \cdot m^{-2}$. During the validation period, R^2 values were 0.68 and 0.90, with RMSE of 63.2 $s \cdot m^{-1}$ and 49.0 $W \cdot m^{-2}$, respectively. Results from two independent validation sites indicated that the CO_2-enhanced Irmak model exhibited good spatial transferability and adaptability, accurately simulating farmland water consumption processes at half-hourly time scales throughout the entire maize growing season. Sensitivity analysis revealed that maize canopy resistance and evapotranspiration were most sensitive to changes in net radiation and relative humidity, followed by air temperature, leaf area index, and atmospheric CO_2 concentration. The improved Irmak model developed in this study, which accounts for atmospheric CO_2 concentration effects on maize canopy resistance, can estimate crop evapotranspiration with reasonable accuracy and provides a scientific basis for research on farmland water consumption under scenarios of planting structure adjustment, land use change, and rising atmospheric CO_2 concentrations.

Keywords: Canopy resistance; Evapotranspiration; Penman-Monteith model; Irmak model; Atmospheric CO_2 concentration

Stomata on plant leaves serve as channels for gas exchange between the plant and atmosphere, and their opening and closing behavior affects both transpiration and photosynthesis. Water in plant tissues enters the atmosphere through transpiration, enabling energy exchange between vegetation and its surroundings [1], a process jointly controlled and regulated by external environmental factors and plant physiology [2]. Canopy resistance represents the resistance that water must overcome when cycling between the crop canopy and atmosphere. Accurately simulating canopy resistance is crucial for precise evapotranspiration (ET) estimation and consequently for improving water use efficiency and optimizing regional water allocation [3-6].

Numerous empirical and semi-empirical models have been used to estimate canopy resistance responses to environmental variables, including the Jarvis model, two-source coupled model, Irmak model, S-W model, and K-P model [1,7-12]. The Jarvis model, the most typical among these, treats canopy resistance as the result of external environmental variable stress and establishes a simple, flexible canopy resistance model [11], but it lacks clear physiological meaning, does not consider interactions among factors, and its complexity increases with more environmental variables while its accuracy decreases over longer simulation periods—particularly in determining minimum canopy resistance [13]. Li et al. [6,14-15] developed a coupled model integrating soil evaporation and vegetation transpiration based on extensive experiments in the Shiyang River Basin, which showed good simulation results for both maize (*Zea mays*) and wine grapes (*Vitis vinifera*), but the model has many parameters, some of which are difficult to obtain [6], and some require further correction with experimental data; model accuracy remains limited when leaf area index

(LAI) is low. Irmak et al. [10] used multi-year observation data to consider relationships between micrometeorological factors and canopy resistance, designing seven models using generalized nonlinear regression methods, with model complexity increasing as more micrometeorological factors were included. Although this model is empirical with unclear physiological meaning, it has a simple form, straightforward calculations, and is convenient to use. Irmak et al. [5] used their constructed resistance model to simulate maize canopy resistance and evapotranspiration, and later applied it to soybean (*Glycine max*) canopy resistance and evapotranspiration simulation [10] with high accuracy, though the model’s adaptability and transferability require further investigation.

Numerous studies [2,5,11-17] have demonstrated that these models achieve good simulation results and high applicability, with many new models being revised and improved based on them, incorporating more comprehensive factors. However, these models have overlooked the effect of atmospheric CO_2 concentration on canopy resistance [5]. Under current climate change conditions, the diurnal variation of atmospheric CO_2 concentration is small, exerting minor effects on canopy resistance. However, from a long-term model prediction perspective, especially in simulations of future climate and ecosystem water-carbon balance changes, considering the impact of atmospheric CO_2 concentration changes on evapotranspiration becomes more important. Existing experiments show that changes in atmospheric CO_2 concentration affect water vapor flux exchange between plants and the atmosphere. Increased atmospheric CO_2 concentration leads to decreased stomatal conductance in many plants [18-21], increased canopy resistance, and weakened transpiration, particularly as high CO_2 concentrations can induce stomatal closure [22-26]. Wand et al. [27] found that when CO_2 concentration doubled, stomatal conductance in C4 and C3 crops decreased by 29% and 24%, respectively. Against the backdrop of global change, rising atmospheric CO_2 concentration and water resource shortages have significantly impacted regional agricultural sustainable development [28]. Therefore, considering CO_2 concentration effects on canopy resistance is crucial for revealing plant photosynthesis and water consumption patterns and improving water use efficiency [22].

Based on the Irmak model and drawing upon Morison et al. [29] and Easterling et al. [30] regarding crop responses under elevated CO_2 scenarios, this study assumed a linear relationship between atmospheric CO_2 concentration and maize leaf stomatal conductance. Considering relationships between leaf area index (LAI), net radiation (R), relative humidity (RH), air temperature (T), effective soil water content ( ), aerodynamic resistance (r), wind speed at 3 m height (U_3), atmospheric CO_2 concentration, and canopy resistance, we constructed two canopy resistance models—one without CO_2 effects and one with CO_2 effects—and coupled them with the Penman-Monteith model to determine regional applicability and parameterization issues. Using existing flux observation data from the “Heihe River Basin Eco-Hydrological Process Integration Study” major research program, we established relationships between canopy resistance and environmental factors, with particular emphasis on atmospheric

CO_2 concentration effects, to screen canopy resistance models that can reflect changing CO_2 concentration environments. This work provides a scientific basis for revealing crop water consumption patterns, accurately estimating crop evapotranspiration, improving water use efficiency, and understanding the response mechanisms of crop evapotranspiration under future elevated atmospheric CO_2 concentration scenarios.

1.1 Study Area Overview

The Heihe River Basin [Figure 1: see original paper] is located in the central Hexi Corridor, situated in the transitional zone between the Tibetan Plateau and Inner Mongolia Plateau, and represents the second largest inland river basin in China' s arid and semi-arid northwest region, with a drainage area of approximately 14.3$×10^{4}$ km^2. The basin has a dry climate with scarce precipitation and uneven water resource distribution. It is divided into three geomorphic regions: the upper Qilian Mountains, the middle corridor oasis plain, and the lower Alxa Plateau. The middle reaches of the Heihe River refer to the flat terrain area between Yingluoxia (the mountain outlet) and Zhengyixia along the main stream, characterized by a typical temperate continental climate with annual precipitation of 116.8 mm, annual evaporation intensity of 2,365.6 mm, and mean annual temperature of 7.6 °C. Precipitation from July to September accounts for about 60% of annual precipitation, while winter precipitation comprises only 3%; annual precipitation gradually decreases with increasing altitude and distance from the river. Annual sunshine duration is 3,085 hours, and the frost-free period is 165 days. In the middle reach oasis area, cultivated land accounts for 95% of the total cultivated land in the entire basin, and water resource consumption represents 68% of the basin total, with farmland evapotranspiration being the main water consumption item. Maize is one of the main local crops [4].

1.2 Data Sources and Processing

The automatic weather station, flux, and crop height data used in this study were all obtained from the Heihe Plan Data Management Center (http://heihedata.org/). Site 8 in the flux observation matrix (100°22 35 E, 38°52 21 N; 1,550.06 m) was used for model parameter calibration, while data from Site 11 (100°20 31 E, 38°52 12 N; 1,575.65 m) and Daman Station (100°22 20 E, 38°51 20 N; 1,556.06 m) were used for model validation (FIGURE:1).

Each flux observation system primarily consisted of a three-dimensional ultrasonic anemometer thermometer (CSAT3, Campbell Scientific, USA) and an open-path CO_2/H_2O infrared gas analyzer (Li-7500A, Li-Cor Inc., USA). The original data sampling frequency was 10 Hz, with 30-minute average flux values and 10 Hz raw data output [31]. The underlying surface crops at all three flux observation sites were maize, with row spacing of 50.8 cm, plant spacing of 43.3

cm, and intra-plant spacing of 22 cm. Maize plant height was interpolated to every half hour using cubic spline interpolation based on measured data. Leaf area index (LAI) was obtained from the MCD15A3H LAI product released by NASA (https://search.earthdata.nasa.gov/), which provides 4-day composite, 500 m resolution Level 4 LAI data. Cubic spline interpolation was used to interpolate uniformly to daily values, assuming LAI remained unchanged at different times on the same day.

The study time series covered the entire crop growing season (early May to late September 2012), with the time period from 9:00 to 18:30. Details on the original eddy covariance instrument information and data processing can be found in reference [31]. The original eddy covariance data had undergone outlier removal, time delay correction, coordinate rotation, frequency response correction, and strict quality control, but required further reprocessing [32] according to the following rules: (1) Energy balance closure checks were performed on the original eddy covariance data, with data having energy closure outside the 0.5–1.5 range being removed, and the remaining non-closed data were forced to close using the method described in [33]; (2) Data with missing values were removed; (3) Abnormal data were eliminated, such as measured latent heat flux (LE) < 0, r_c_{ob} > 2,000, or r_c_{ob} < 0 (where r_c_{ob} is the canopy resistance value derived from the Penman-Monteith equation and defined here as the observed value).

1.3.1 Irmak Model

Based on the models constructed by Irmak [5,10] and considering the effects of external environmental variables including leaf area index (LAI), net radiation (R), relative humidity (RH), air temperature (T), effective soil water content ( ), aerodynamic resistance (r), wind speed at 3 m height (U_3), and atmospheric CO_2 concentration (CO_2) on canopy resistance, we constructed two canopy resistance models—one without CO_2 effects and one with CO_2 effects—as follows:

Where: r_c-I1 and r_c-I2 represent the canopy resistance models based on the Irmak model without and with atmospheric CO_2 concentration effects, respectively; f_{CO}$_2$ is the CO_2 concentration stress function. In equation (4), the parameter represents the multiple by which leaf stomatal conductance decreases when CO_2 concentration doubles [30], taken as 0.3 in this study; f_ is the soil water content function; _w is the wilting coefficient, taken as 0.1 $cm^3 \cdot cm^{-3}$; _f is field capacity, taken as 0.34 $cm^3 \cdot cm^{-3}$; and a, b, c, d, e, g, h, i are empirical coefficients to be calibrated.

1.3.2 Penman-Monteith Model

The Penman-Monteith model was developed by Monteith based on the Penman model, expressed as:

From equation (5), we can derive:

Where: r_c_{ob} is the canopy resistance derived from the Penman-Monteith equation; λ is the latent heat of vaporization, $\mathrm{J \cdot kg^{-1}}$; ET is actual evapotranspiration, $\mathrm{W \cdot m^{-2}}$; Δ is the slope of the saturation vapor pressure versus temperature curve, $\mathrm{kPa \cdot °C^{-1}}$; R is net radiation, $\mathrm{W \cdot m^{-2}}$; G is soil heat flux, $\mathrm{W \cdot m^{-2}}$; C_p is specific heat of air at constant pressure, $\mathrm{J \cdot kg^{-1} \cdot °C^{-1}}$; _a is air density, $\mathrm{kg \cdot m^{-3}}$; VPD is vapor pressure deficit, kPa; r_c is canopy resistance, $\mathrm{s \cdot m^{-1}}$; r is aerodynamic resistance, $\mathrm{s \cdot m^{-1}}$; and γ is the psychrometric constant, $\mathrm{kPa \cdot °C^{-1}}$. Aerodynamic resistance is calculated as follows [1]:

Where: r is aerodynamic resistance, $\mathrm{s \cdot m^{-1}}$; Z_m is wind speed measurement height, m; Z_h is humidity measurement height, m; d is zero-plane displacement, m, d = 2/3 h; h is crop height, m; Z_{om} is roughness length controlling momentum transfer, m, Z_{om} = 0.123 h; Z_{oh} is roughness length controlling heat and water vapor transfer, m, Z_{oh} = 0.1 Z_{om}; K is the von Kármán constant, 0.41; U_z is wind speed at height Z, $\mathrm{m \cdot s^{-1}}$; in this study, Z_m = 3 m and Z_h = 5 m.

1.4 Model Evaluation

This study used the coefficient of determination (R^2), mean bias error (MBE), and root mean square error (RMSE) to evaluate differences between model-simulated values (E_m) and observed values (O_{ob}) and to test model simulation accuracy.

Where: E_m is the simulated value, O_{ob} is the observed value, is the mean of observed values, and n is the sample size. In this study, canopy resistance derived from eddy covariance-measured latent heat flux combined with the Penman-Monteith equation was defined as the observed value of maize canopy resistance (r_c_{ob}), canopy resistance fitted by the model was the simulated value (r_{c_m}), eddy covariance-measured latent heat flux was the observed ET value (ET_{ob}), and ET simulated by the model was the simulated value (ET_m).

2.1 Model Parameter Calibration and Validation

This study divided the data from Site 8 (data period: June 6–September 20, 2012) into two parts: the first part (June 6–August 5) was used for model parameter calibration, and the second part (August 6–September 20) for model validation. The calibration period data were substituted into the two constructed Irmak models, and nonlinear regression using the least squares method was employed to calibrate model parameters and establish empirical formulas relating canopy resistance (r_c) to external environmental factors. Validation period data were then used to validate the established models, yielding the optimal parameter values shown in Table 1 . To further test model simulation accuracy throughout the entire crop growing season, Site 11 and Daman Station were used as additional validation sites.

2.1.1 Simulation Performance of Irmak Model and Its Improved Version

Using the two constructed models—without CO_2 concentration (r_c_{I1}) and with CO_2 concentration (r_c_{I2})—we simulated maize canopy resistance and evapotranspiration at Site 8. Model parameters are shown in Table 1, and comparison results are presented in Figure 2 [Figure 2: see original paper] and Figure 3 [Figure 3: see original paper].

Table 1 Optimum values of parameters in the Irmak models without CO_2 concentration (r_c_{I1}) and with CO_2 concentration (r_c_{I2})

Parameter	r_c_{I1} model (without CO_2)	r_c_{I2} model (with CO_2)
a	-0.003	-0.003
b	-0.027	-0.028
c	-0.036	-0.035
d	-0.004	-0.004
e	-0.083	-0.044
g	-0.468	-0.742

As shown in Figures 2 and 3, both models (with and without atmospheric CO_2 concentration) could accurately reflect the variation patterns of maize canopy resistance and evapotranspiration, with high consistency between simulated and observed values. The r_c_{I2} model, which incorporated atmospheric CO_2 concentration effects in addition to LAI, R , RH, T , r , U_3, and , achieved higher simulation accuracy. During the calibration period, the r_c_{I2} model yielded R^2 values of 0.76 and 0.95 for canopy resistance and evapotranspiration, respectively, with RMSE of 33.1 $s \cdot m^{-1}$ and 34.5 $W \cdot m^{-2}$. During the validation period, R^2 values were 0.68 and 0.90, with RMSE of 63.2 $s \cdot m^{-1}$ and 49.0 $W \cdot m^{-2}$, respectively. Model accuracy was also slightly improved compared to the r_c_{I1} model. Due to relatively small vapor pressure deficits and available energy in the morning and afternoon, canopy resistance showed greater variation and some abnormal values [34], which reduced simulation accuracy for canopy resistance, but errors remained within acceptable ranges.

In summary, the r_c_{I2} model considering atmospheric CO_2 concentration effects could accurately simulate the response process of maize canopy resistance to environmental variables with high simulation accuracy. The model has a simple form with easily obtainable parameters. While models such as Jarvis contain many empirical parameters that change with plant physiological structure and meteorological elements, the Irmak model can comprehensively reflect canopy resistance responses to environmental variables through major farmland micrometeorological factors, thereby achieving scaling from leaf to canopy level [5,10,15]. The r_c_{I2} model, particularly after incorporating atmospheric CO_2 concentration effects, can more realistically and comprehensively reflect canopy resistance responses to environmental variables and achieve this scale transformation.

2.1.2 Further Model Validation

Both models developed in this study divided the entire maize growing season data into parameter calibration and model validation periods. However, plant physiological structure and meteorological elements change throughout the growing season, raising questions about whether models established based on early growth data are applicable to later growth stages or the entire season, how model adaptability performs under different locations and meteorological conditions, and whether model parameters are transferable—these remain key limitations for model scaling and transferability. To test the adaptability and parameter transferability of the two Irmak models, we used effective measured data from the entire 2012 maize growing season at two additional flux observation matrix sites (Site 11 and Daman Station) for further validation. Comparison results between simulated and observed values are shown in Figures 4 [Figure 4: see original paper], 5 [Figure 5: see original paper], 6 [Figure 6: see original paper], and 7 [Figure 7: see original paper].

Figures 4 and 5 show that both models could satisfactorily simulate the response processes of canopy resistance and evapotranspiration to environmental variables during the maize growing season at Site 11, with good agreement between simulated and observed values. The r_c_{I2} model considering atmospheric CO_2 concentration achieved R^2 values of 0.62 and 0.93 for canopy resistance and evapotranspiration, respectively, with RMSE of 94.1 $s \cdot m^{-1}$ and 67.4 $W \cdot m^{-2}$. Comparing Figures 4c and 5c reveals that the r_c_{I2} model showed smaller errors and fluctuations throughout the growing season, with less underestimation than the r_c_{I1} model. The r_c_{I1} model slightly underestimated ET values from mid-June to late August and failed to simulate ET peaks well, whereas the r_c_{I2} model successfully simulated ET peaks throughout the entire growing season. Therefore, the r_c_{I2} model can more comprehensively simulate actual maize evapotranspiration and reflect farmland water consumption processes.

Figures 6 and 7 indicate that both Irmak models (with and without atmospheric CO_2 concentration) could accurately simulate maize canopy resistance and evapotranspiration throughout the growing season at Daman Station. The r_c_{I1} model without atmospheric CO_2 concentration achieved R^2 values of 0.57 and 0.97 for canopy resistance and evapotranspiration, respectively, with RMSE of 45.6 $s \cdot m^{-1}$ and 36.8 $W \cdot m^{-2}$. The r_c_{I2} model with atmospheric CO_2 concentration effects achieved R^2 values of 0.58 and 0.97, with RMSE of 41.5 $s \cdot m^{-1}$ and 28.4 $W \cdot m^{-2}$, respectively. Figures 6c and 7c demonstrate that the r_c_{I2} model could more realistically reflect actual maize evapotranspiration throughout the growing season, with minimal underestimation and higher simulation accuracy. From June 6 to harvest, simulated and observed values were nearly identical.

Maize canopy transitions from sparse to dense during the growing season, with significant changes in physiological structure and external meteorological elements, leading to large variations in evapotranspiration. Under future climate change scenarios, farmland evapotranspiration becomes even more complex. Therefore, considering atmospheric CO_2 concentration effects on canopy resistance and evapotranspiration is extremely important in ecosystem water-carbon balance simulations. Figures 4-7 show that the r_c_{I2} model considering atmospheric CO_2 concentration effects could more accurately simulate changes in canopy resistance and evapotranspiration under changing physiological structures and meteorological elements, demonstrating good spatial transferability. This provides a basis for research on maize farmland water consumption processes under scenarios of planting structure adjustment, land use change, and atmospheric CO_2 concentration variation.

2.2 Sensitivity Analysis

Due to changes in crop characteristics and external environmental variables, canopy resistance and evapotranspiration show substantial differences in their responses to environmental variables. Therefore, we conducted further sensitivity analysis of the improved r_c_{I2} model by introducing sensitivity coefficients of model results to environmental variables as follows:

Where S_i is the sensitivity coefficient of model results to environmental variable x_i, which is dimensionless and allows comparison of sensitivity to different environmental variables. When S_i > 0, model results increase with environmental variable x_i; when S_i < 0, model results decrease with increasing x_i. The magnitude of S_i reflects the degree of sensitivity of model results to environmental variable x_i, with larger absolute values indicating greater influence.

Tables 2 and 3 show that canopy resistance (r_c) changes inversely with R , RH, U_3, LAI, , and r —decreasing as these variables increase—while r_c changes directly with T and atmospheric CO_2 concentration, increasing as these variables increase. The absolute values of sensitivity coefficients indicate that r_c is most sensitive to changes in R and RH, followed by , with sensitivity to T , LAI, and atmospheric CO_2 concentration being nearly equivalent, and sensitivity to U_3 and r being the smallest. This demonstrates that in the study area, R and RH are the main factors affecting r_c, because under natural conditions, net radiation, air temperature, humidity, soil water content, and CO_2 concentration are the primary factors influencing stomatal resistance [34-36].

Evapotranspiration (ET) changes in the same direction as R , RH, U_3, LAI, and —increasing as these variables increase—while ET changes inversely with T , r , and atmospheric CO_2 concentration, decreasing as these variables increase. The absolute values of sensitivity coefficients indicate that ET is most sensitive to R , followed by RH and , with lower sensitivity to T , LAI, and atmospheric CO_2 concentration, and the lowest sensitivity to U_3 and r . These results indicate that in this study area, R and RH are the main controlling factors for

ET, because the evapotranspiration process primarily depends on the energy required for water vaporization, which is mainly driven by radiation and air temperature, while the water vapor pressure difference between the evaporating surface and surrounding atmosphere determines water vapor movement, a process largely dependent on large-scale wind patterns and air flow above the evaporating surface.

3 Conclusions and Discussion

Based on the Irmak model, this study considered the effect of atmospheric CO_2 concentration changes on maize canopy resistance. Drawing upon previous research results and assuming a linear relationship between atmospheric CO_2 concentration and stomatal conductance, we considered relationships between micrometeorological factors and maize canopy resistance. Using available data, we constructed canopy resistance models both with and without CO_2 concentration effects, coupled them with the Penman-Monteith model, and analyzed and tested the simulation results of the established canopy resistance models in response to environmental variables and atmospheric CO_2 concentration.

The results demonstrated that using LAI, R , RH, T , r , U_3, and effective soil water content , combined with atmospheric CO_2 concentration, could more comprehensively reflect the response processes of canopy resistance and evapotranspiration to external environmental variables, accurately simulating farmland water consumption processes at half-hourly time scales throughout the entire maize growing season. Sensitivity analysis indicated that both r_c and ET were most sensitive to changes in R and RH, followed by T , LAI, and atmospheric CO_2 concentration. The improved model developed in this study, which accounts for atmospheric CO_2 concentration effects on maize stomata, has easily obtainable parameters and better simulation accuracy than the model without CO_2 effects. Therefore, this model can provide a basis for research on crop water consumption under scenarios of planting structure adjustment, land use change, and future CO_2 concentration changes.

Meanwhile, the model constructed in this study is based on a "single-source model" and achieves high accuracy in simulating evapotranspiration. However, due to relatively small vapor pressure deficits and available energy in the morning and afternoon, canopy resistance shows large fluctuations that the model cannot respond to quickly, resulting in lower simulation accuracy for some canopy resistance values, though errors remain within acceptable ranges. Second, this study only considered the effect of rising CO_2 concentration on maize stomatal conductance and assumed a linear relationship between CO_2 concentration and stomatal conductance, but did not consider the effect of CO_2 concentration changes on maize leaf area index. This limitation should be addressed in future work. Additionally, due to constraints of short-term observation data, the coefficient for atmospheric CO_2 concentration effects on canopy resistance (r_c) in the model requires further correction based on experimental data. Finally, although the study area is relatively large and the model has been independently validated, considering spatial complexity and heterogeneity, more comprehensive research on parameter transferability issues is needed based on the calibrated empirical model.

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