The Response Characteristics Of Sugarcane Yield, ET and WUE To Meteorological Drought Based On DSSAT-Canegro Model In Lai-bin, China

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Abstract. Crop water use efficiency is an important indicator of the scientific and rational nature of agricultural water use. Studying the response characteristics of sugarcane yield accumulation and water use efficiency to meteorological drought scenarios is a key scientific issue to promote smart management and sustainable development of China's sugarcane industry. In this paper, based on SPEI index, different meteorological drought scenarios were set and the DSSAT-Canegro model was used to simulate the response mechanisms of sugarcane yield accumulation and canopy evapotranspiration to irrigation regime scenarios under different meteorological drought scenarios. Furtherly, in this study, the total on-farm water use efficiency (WUE_g), field water use efficiency (*WP*), true irrigation water use efficiency (WUE_{ti}), and irrigation water use efficiency (WUE_i) of sugarcane in the study area were evaluated quantitatively to screen the optimal irrigation regime. Specific studies have shown that the stem extension stage is the most sensitive growth stage for sugarcane response to irrigation. Soil evapotranspiration and crop transpiration in sugarcane fields in Laibin varied with irrigation quotas, and that reducing soil evapotranspiration could improve sugarcane water use efficiency. In meteorological drought scenarios with longer and more intense droughts, irrigation has a stronger stimulating effect on sugarcane growth and is more favourable to its yield accumulation.The correlations between WUE_g index and *WP*, WUE_i) and WUE_{ti} indicators of sugarcane in the study area were all significant, which can be used as key analytical indicators for the optimization of sugarcane irrigation regimes in Laibin. The results of this study can provide important scientific support for the accurate quantification of water demand and consumption of sugarcane in southern China and their coupled and coordinated intelligent management.

Keywords: Sugarcane; Meteorological drought; DSSAT-Canegro model; Cane yield; Canopy evapotranspiration; Water use efficiency.

1. Introduction

Crop water use efficiency is an indicator of the relationship between crop yield and water consumption, and is one of the main indicators of agricultural water conservation research at present. It comprehensively reflects the level of water management, irrigation technology and the condition of irrigation projects at different scales, etc. It is also an important indicator of the scientific and rational nature of agricultural water use. A large number of domestic and foreign scholars have proposed different evaluation indicators for irrigation water use, in different physical meanings and irrigation contexts. In this paper, the differences and applicability of total on-farm water use efficiency (WUE_g), field water use efficiency (WP), true irrigation water use efficiency (WUE_{ti}) and irrigation water use efficiency (WUE_i), which are more frequently used at home and abroad, are selected for study. At present, there are more studies on crop water use efficiency of maize, wheat, cotton and other crops in China, but there are few studies on water use efficiency of sugarcane.

Sugarcane is an important raw material for sugar production in China, not only as a major food source for human beings, but also as the most promising high-yielding bioenergy crop. Guangxi is located in the subtropical monsoon climate zone, with sufficient heat and rainfall, and its sugarcane cultivation area and sugar production account for more than 60% of the country, making it the most important sugarcane economic production area and sugar security area in China. Sugarcane cultivation area and production in Laibin City ranked second in Guangxi, but it is also a high meteorological drought-prone area with serious drought losses in sugarcane in previous years, coupled with insufficient regional irrigation engineering conditions, sugarcane cultivation is still rain-fed, and soil moisture deficit caused by meteorological drought has been a major factor affecting sugarcane growth and its yield in the region.

There are more international advances in water stress simulation of crops, such as Kelly et al[1] described how to use AquaCrop-OSPy for basic simulation and optimization of irrigation regime; Wang Hangdong et al[2] used AquaCrop and DSSAT-SUBSTOR-Potato models to simulate growth, yield and water productivity of potato under different drip irrigation fertilization conditions ; Omotayo et al[3] used AquaCrop to simulate soybean growth and yield under different water stress scenarios; Wenzhuo et al[4] used the crop model data assimilation (CMDA) approach to combine remotely sensed water stress factors (MOD16 ET PET-1) with the WOFOST model , using the ensemble Kalman filter (EnKF) for winter wheat yield estimation in the North China Plain region under drought stress and partial irrigation conditions, and the results showed the superiority of combining remotely sensed water stress factors with crop models for estimating winter wheat yield at the regional scale under drought stress conditions; Ahmed et al[5] studied the response of winter wheat to water stress scenarios using the CERES-Wheat model, and the results showed that with The results showed that the yield of irrigated 100 mm at pulling stage and 120 mm at flowering stage were similar compared to the fully irrigated scenario with higher WUE. Song Libing et al[6] incorporated water stress factors into the CERES-Maize model for phenological calculations, corrected soil water conductivity coefficients, and used linear regression of radiation use efficiency applied to optimal radiation use efficiency, and the results showed that the improved CERES-Maize model could better simulate maize growth and yield under water stress conditions; Panda et al[7] conducted a study on maize field trials with five different water stress treatments were conducted in combination with the CERES-Maize model, and the results identified effective strategies for managing irrigated maize under water deficit conditions in the subtropics, demonstrating that the CERES-Maize model can effectively simulate yield, aboveground dry biomass maximum leaf area, and soil moisture changes in the profile of maize in the subtropics; Yang Yanmin et al[8] used the DSSAT model to calculate water requirements of maize and wheat in the Hebei Plain; Morales Santos et al[9] used the Aqucrop model to assess the effects of different water stress scenarios on soybean yield and water productivity, and the results showed that moderate irrigation with reduced water stress during the growth period is suitable for soybean in semi-humid areas, especially when using drip irrigation systems; Araya et al[10] used the DSSAT model to simulate major cereal crops grown in the Ethiopian highlands and the results analyzed the effect of cropping system and water stress on crop yield. Singels et al [11] tested eight different models of water balance algorithms by simulating sugarcane water uptake, carbon assimilation rate, plant expansion rate and sucrose accumulation rate under water stress and the results showed that in implementation of a simple method in multilayer profiles using the soil layer water supply rate algorithm employed in the SWAMP model can improve the DSSAT-Canegro model.

The above studies show that water stress simulations for other crops have been widely applied internationally. However, the characteristics of sugarcane growth and water use efficiency in response to meteorological drought have been relatively poorly studied, especially in terms of day-by-day scale variation and differences in response at different reproductive stages. Therefore, based on the localized DSSAT-Canegro model, this paper simulates sugarcane yield and sugarcane canopy evapotranspiration under different irrigation system schemes under different meteorological drought scenarios. The response patterns of different sugarcane water use efficiency indicators were analyzed and the optimal irrigation system was screened. This study aims to provide important scientific support for the accurate quantification of sugarcane water demand and water consumption and their coupled coordination, and smart management of sugarcane fields in southern China.

2. Study area, data and methods

2.1 Study area

Laibin City is located between 108° 24′ -110° 28′ E and 23° 16′ -24° 29′ N. It is known as the "Hinterland in Gui" and belongs to the subtropical monsoonal humid climate zone, and the landform type is mainly mountainous and hilly (Figure 1(a)); it has a mild climate, sufficient sunshine, abundant rainfall and long frost-free period throughout the year, with an average annual sunshine hours of 1300-1700h and annual precipitation of 1200-1900mm, which is very compatible with the demand for heat and light for sugarcane growth[12], and is one of the three major sugarcane growing urban areas in Guangxi. Sugarcane in Laibin is mainly planted in low elevation depressions and slope areas developed by karst, with an overall non-uniform continuous dense and scattered extensive distribution (e.g. Figure 1(b)); for many years, due to insufficient regional irrigation conditions, sugarcane planting is still mainly rain-fed.

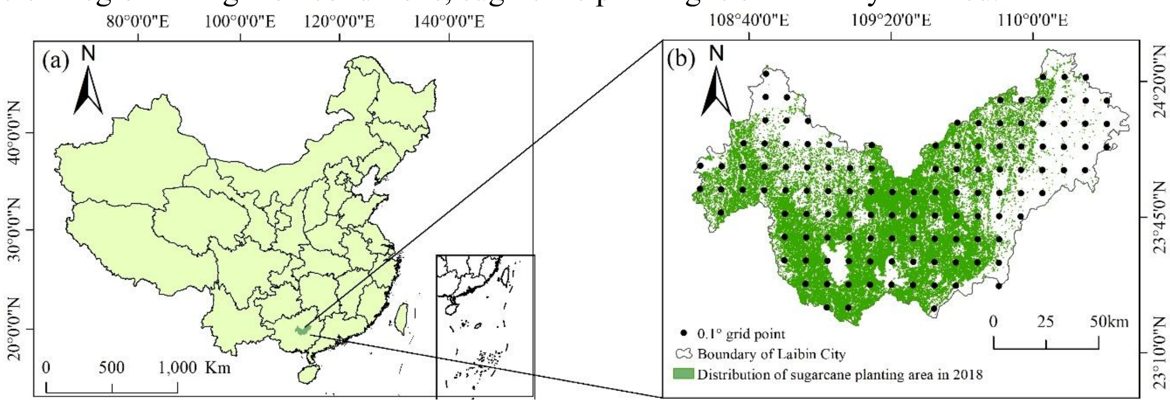


Fig.1 The geographical location and sugarcane planting distribution in Laibin city

2.2 Data sources

This paper deals with 3 types of datasets, including meteorology, soil, and field trials. Among them, meteorological data use the day-by-day scale Chinese meteorological forcing dataset(CMFD), which is a 0.1° spatial resolution gridded data developed by He et al [13], including day-by-day rainfall, maximum temperature, minimum temperature, average temperature, relative humidity, wind speed, and solar radiation for 40 consecutive years from 1979-2018; its fusion by remote sensing products, reanalysis datasets and in situ station data, it has continuous time coverage and consistent quality, and is one of the most widely used climatic meteorological datasets today （http://data.tpdc.ac.cn/en/data/8028b944-daaa-4511-8769-965612652c49/）.

Soil data were mainly obtained from the China Soil Database (http://vdb3.soil.csdb.cn/), and the Chinese Soil Dataset based on the World Soil Database (WSDB) of the Cold and Dry Zone Science and Data Center was used as a reference. Among them, the DSSAT-Canegro model requires input of soil information including soil type and soil profile characteristics, i.e. soil name, color, soil capacity, field water holding capacity, wilting coefficient, saturation water content, pH value, etc.

In this paper, data from two full-growth period monitoring trials of sugarcane grown in the field in Laibin City were used for DSSAT-Canegro model parameter rate determination and validation. Among them, parameter rate determination data were used from field trials conducted by the Academy of Agricultural Sciences of Xingbin District, Laibin City, from January 22, 2011 to January 17, 2012[14]; simulation validation data were used from field trials conducted from January 16, 2015 to December 31, 2015 in the sugarcane field of Longpan Village, Qianjiang Town, Laibin City[15].

2.3 Research Methods

2.3.1 SPEI daily drought index

To finely reflect the spatial and temporal characteristics of meteorological drought in the study area and the day-by-day response mechanism of sugarcane growth during the whole growth period, the daily scale SPEI index proposed by Wang et al [16] was used in the paper for meteorological drought characterization in the study area from 1979-2018; the daily SPEI calculation was implemented by Matlab programming, and the specific calculation steps are detailed in the literature [17, 18], and its drought class classification is shown in Table 1.

Table 1 Classification of drought grade based on daily SPEI

Grade	1	2	3	4	5
SPEI	SPEI≥-0.5	-1<SPEI<-0.5	-1.5<SPEI≤-1	-2<SPEI≤-1.5	SPEI≤-2
Type	No drought	Light drought	Moderate drought	Severe drought	Extreme drought

In the paper, based on the day-by-day SPEI of 119 0.1° grid points from 1979-2018 in Laibin City, the meteorological drought events in the study area were counted and the sliding model described by Yevjevich[19] was used to identify the onset and end times of a drought event, which in turn determined the integrated intensity and duration of this drought event. In the specific statistics, considering the coexistence of seasonal drought and sudden drought in Laibin, China [20], each grid point with daily SPEI less than -0.5 for 5 consecutive days or more is considered as a drought event, and the first day of the period is considered as the drought occurrence time and the last day is considered as the drought end time, and the drought duration of the grid point is the number of days from the occurrence to the end of a drought event (excluding the end day); drought intensity is the sum of the values of daily SPEI less than -0.5 during the drought event period, and the smaller the value, the greater the intensity; drought frequency is the number of drought events occurring in a given period. The final statistical annual drought intensity is the sum of the sub-drought intensity values within the year, the annual drought duration is the sum of the duration of the sub-drought events within the year, and the annual drought frequency is the sum of the number of drought events within the year[17].

2.3.2 Sensitivity analysis of sugarcane variety parameters and rate determination methods

Sensitivity analysis and localization of model parameters are the keys to ensure the reliability of simulation results and improve simulation accuracy. There are 20 varietal parameters controlling sugarcane in the DSSAT-Canegro model. In this paper, sensitivity analysis and localization rate determination of model parameters were performed for the main sugarcane variety Xintai Sugar 16 in Laibin based on the standard sugarcane variety NCo376 in the model database.

In this paper, the Morris method, a global sensitivity analysis method, was used to perform sensitivity analysis on 20 sugarcane variety parameters in the DSSAT-Canegro model. Morris method is improved for the shortcomings of the local sensitivity analysis method, it calculates the sensitivity of each parameter by differentiation method, which requires less calculation[21], and its specific calculation method can be referred to the related literature[22]. A larger average value μ for each parameter indicates a stronger sensitivity of the parameter, while a higher standard deviation σ indicates a stronger parameter interaction. The global sensitivity analysis was implemented with the help of the sensitivity and uncertainty analysis software SimLab (Version 2.2). In the localization rate determination of model parameters, yield, stalk height, aboveground dry weight and leaf area index of sugarcane in Laibin were used as the objective functions, and debugging validation was conducted based on field trial data[14, 15] to realize the localization of parameters; the validation accuracy is evaluated quantitatively by the normalized root mean square error NRMSE and the consistency index D. Its specific calculation procedure can be found in the related literature[23].

2.3.3 Crop water use efficiency index

Crop water use efficiency is usually defined as the ratio of crop yield to the corresponding water consumption. In this study, four currently used crop water use efficiency evaluation indicators were selected for analysis and evaluation, namely, total on-farm water use efficiency ($WUEg$), field water use efficiency (WP), true irrigation water use efficiency ($WUEti$), and irrigation water use efficiency ($WUEi$) [24, 25].

(1) Total on-farm water use efficiency $WUEg$.

$$WUE_g = Y/(P + I) \#(1)$$

(2) Field water use efficiency WP.

$$WP = Y/ET \#(2)$$

(3) True irrigation water use efficiency $WUEti$.

$$WUE_{ti} = \Delta Y/I \#(3)$$

(4) Irrigation water use efficiency $WUEi$.

$$WUE_i = Y/I \#(4)$$

Where: Crop water use efficiency, kg/m^3; Y is crop yield per unit area, kg/hm^2; P is precipitation, m^3/ hm^2; I is irrigation amount, m^3/ hm^2; ET is field evapotranspiration, m^3/ hm^2; ΔY is the difference between crop yield per unit area under irrigated and non-irrigated (rainfed) conditions, kg/hm^2.

2.4 Simulation scenario setting for meteorological drought and sugarcane irrigation

2.4.1 Meteorological drought simulation scenario setting in the study area

Sugarcane growth period is often divided into four stages such as seedling stage, tillering stage, stem extension stage and mature harvest stage, etc. According to Chen Yanli et al[26], the specific dates of each growth period of sugarcane in Laibin City were determined as shown in Table 2.

Based on our team's research[27], it is known that in Laibin, China, during the sugarcane seedling stage (3.10-5.10, 62d in total), meteorological drought is mainly light and moderate, with drought episodes mainly in the range of 10-30 d,30-60 d and daily accumulation intensity mainly in the range of -10 to -50. During the tillering stage (5.11-6.11, 32d in total), meteorological drought was basically absent due to the short period and the calendar rainy season. During the stem extension stage (6.12-11.12, 154d in total) and maturity stage (11.13-12.31, 49d in total), the frequency of meteorological droughts was high, mostly light droughts with a drought duration of 30-60d and a cumulative daily intensity range of -10~-100, while the frequency of moderate, severe and exceptional droughts was relatively low, but they still occurred occasionally in the last 40 years. Combining the above results, the actual possible scenarios for the occurrence of meteorological drought in Laibin at various sugarcane growth period are set out in Table 2. In particular, considering the occurrence of sudden droughts in Laibin, the starting drought duration and variation step was set at 5 days, increasing to 30 days in succession; thereafter, the variation step was set at 10 days, increasing to 60 d. The maximum drought duration was also set at 40 days, considering the maturation period of sugarcane. The baseline meteorological data are the average values of 119 meteorological elements in Laibin City.

Table 2 Simulation meteorological drought scenarios setup in sugarcane growth period

Growth period		Light drought	Moderate drought	Severe drought	Extreme drought
Seeding stage	3.10-5.10（62）	5-60	5-60	——	——
Tillering stage	5.11-6.11（32）	——	——	——	——

Stem extension stage	6.12-11.12（154）	5-60	5-60	5-60	5-60
Maturity stage	11.13-12.31（49）	5-40	5-40	5-40	5-40

2.4.2 Simulation scenario setting for sugarcane irrigation in the study area

According to the actual situation in the cane area of Laibin, China, its irrigation amount is stable at 200-400mm. In order to guarantee the production of sugar cane, this paper sets the maximum total irrigation quotas at 400mm and the single irrigation quota at 80mm. Sugarcane was irrigated at various stages of growth, such as seedling stage (3.10-5.10), tillering stage (5.11-6.11), stem extension stage (6.12-11.12) and maturity stage (11.13-12.31). Due to the long duration of the stem extension stage, it was divided into the early stem extension stage and the late stem extension stage, with a total of 5 irrigation dates. Six irrigation patterns were set, i.e. non-irrigated, irrigated once, irrigated twice, irrigated three times, irrigated four times and irrigated five times, so 32 irrigation system scenarios were obtained (Table 3). Among them, T_1 is the seedling stage, T_2 is the tillering stage, T_3 is the early stem extension stage, T_4 is the late stem extension stage and T_5 is the maturity stage.

Table 3 Irrigation system scenario combination setup

Number of irrigations	Single irrigation quota /mm	Total irrigation quotas /mm	Irrigation combinations
0	0	0	zero
1	80	80	T_1, T_2, T_3, T_4, T_5
2	80	160	T_1T_2, T_1T_3, T_1T_4, T_1T_5, T_2T_3, T_2T_4, T_2T_5, T_3T_4, T_3T_5, T_4T_5
3	80	240	$T_1T_2T_3$, $T_1T_2T_4$, $T_1T_2T_5$, $T_1T_3T_4$, $T_1T_3T_5$, $T_1T_4T_5$, $T_2T_3T_4$, $T_2T_3T_5$, $T_2T_4T_5$,$T_3T_4T_5$
4	80	320	$T_1T_2T_3T_4$, $T_1T_2T_3T_5$, $T_1T_2T_4T_5$, $T_1T_3T_4T_5$, $T_2T_3T_4T_5$
5	80	400	$T_1T_2T_3T_4T_5$

3. Results and analysis

3.1 Parameter sensitivity analysis, localisation and simulation validation of the DSSAT model for sugarcane varieties

According to the parameter sensitivity method described in section 2.3.2, this section focuses on the sensitivity analysis of varietal parameters of the DSSAT-Canegro model for sugarcane Xintai Sugar 16 in Laibin City; after comparing the simulation results with field data[14, 15], it was found that 12 of the 20 sugarcane varietal parameters had different effects on the yield, stalk height, aboveground dry weight and leaf area index of objective functions, and its quantitative sensitivity is shown in Figure 2 (a) (b) (c) (d). As can be seen from Figure 2, among them, the parameters with greater influence on the cane yield of sugarcane are Parcemax, Lfmax, Chupibase; the parameters with greater influence on the stalk height of sugarcane are Ttplntem; the parameters with greater influence on the aboveground dry biomass of sugarcane are Parcemax, Lfmax; the parameters with greater influence on the leaf area index of sugarcane are Mxlfarea. The results of the localization parameters of the DSSAT-Canegro model for sugarcane varieties in Laibin were finally obtained by combining the effects of sensitive parameters and several debugging experiments, as detailed in Table 4.

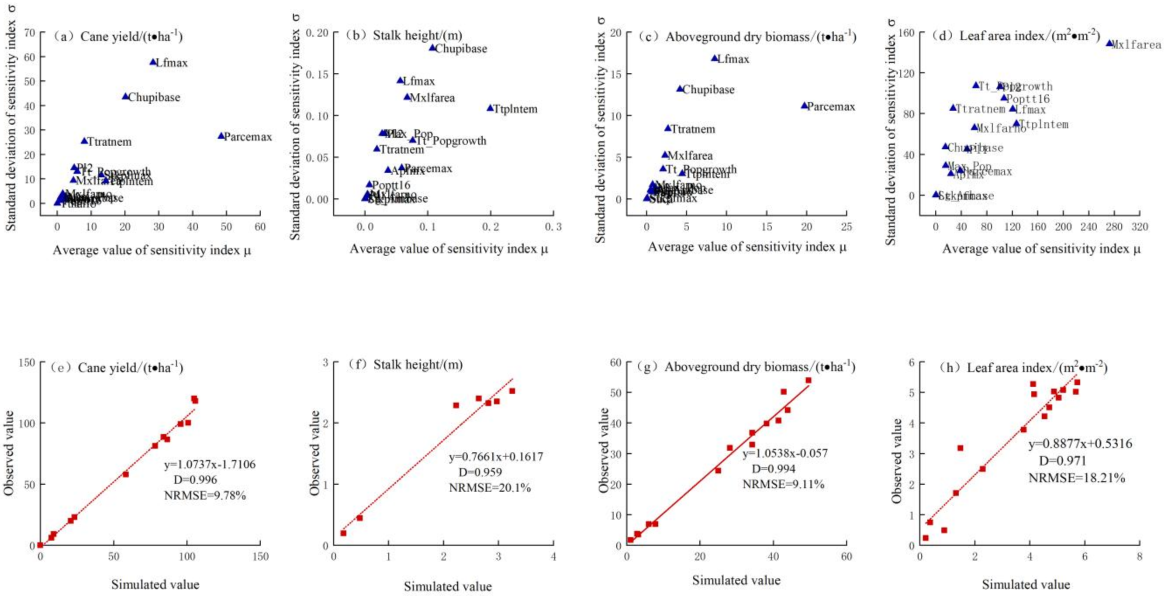


Fig.2 Sensitivity of sugarcane variety parameters in DSSAT model and Comparison of simulated and observed values of DSSAT model

Table 4 Parameter description and debugging results of model varieties

Parameter	Description	Unit	Optimal fitting	Parameter	Description	Unit	Optimal fitting
Parcemax	Maximum radiation conversion efficiency in the absence of stress	$g.MJ^{-1}$	12.50	PI1	Phyllocron interval 1 for leaf numbers below Pswitch	°Cd	89
Apfmx	Maximum fraction of dry mass increments that can be allocated to aerial dry mass	$t.\ t^{-1}$	0.92	PI2	Phyllocron interval 2 for leaf numbers above Pswitch	°Cd	179
Stkpfmax	Fraction of daily aerial dry mass increments partitioned to stalk at high temperatures in a mature crop	$t.\ t^{-1}$	0.78	Pswitch	Leaf number at which the phyllocron changes.	leaf	18
Suca	Maximum sucrose contents in the base of stalk	$t.\ t^{-1}$	0.58	Ttplntem	Thermal time to emergence for a plant crop	°Cd	488

Continued from table 4 above

Parameter	Description	Unit	Optimal fitting	Parameter	Description	Unit	Optimal fitting
Tbft	Temperature at which partitioning of unstressed stalk mass increments to sucrose is 50% of the maximum value	°C	25	Ttratnem	Thermal time to emergence for a ratoon crop	°Cd	203
Tthalfo	Thermal time to half canopy	°Cd	250	Chupibase	Thermal time from emergence to start of stalk growth	°Cd	1050
Tbase	Base temperature for canopy development	°C	16	Tt_Popgrowth	Thermal time to peak tiller population	°Cd	400
Lfmax	Maximum number of green leaves a healthy, adequately-watered plant will have after it is old enough to lose some leaves	leaves	12	Max_Pop	Maximum tiller population	stalks . m^{-2}	10
Mxlfarea	Maximum leaf area assigned to all leaves above leaf number MXLFARNO	cm^2	640	Poptt16	Stalk population at/after 1600°Cd–1	stalks. m^{-2}	13.3
Mxlfarno	Leaf number above which leaf area is limited to MXLFAREA	leaf	15	Lg_Ambase	Aerial mass (fresh mass of stalks, leaves, and moisture) at which lodging starts	$t.ha^{-1}$	220

Based on the localization parameters of the above DSSAT-Canegro model, combined with the field trial data[14, 15], sugarcane yield, stem height, aboveground dry biomass, and leaf area index were simulated and fitted for validation in Laibin City, and the statistical results are shown in Figure 2(e)(f)(g)(h).

From Fig. 2(e)(f)(g)(h), it can be seen that the consistency indices D of the simulated sugarcane yield, stalk height, aboveground dry biomass, and leaf area index of the DSSAT-Canegro model in Laibin reached 0.996, 0.959, 0.994, and 0.971, and their corresponding fitted normalized root mean square error NRMSEs were 9.78%, 20.1%, 9.11%, and 18.21%. This shows that the DSSAT-Canegro model and its localization parameters used in the paper have a high accuracy for the simulation of sugarcane growth in Laibin City.

3.2 Simulation of cane yield response under meteorological drought scenarios

Section 3.1 has confirmed that the model after localization can simulate the growth of sugarcane in Laibin well. In this section, simulations of the response mechanism of cane yield to various ephemeral and intensity meteorological drought scenarios occurring in the same growth stage are carried out, and the results of cane yield changes are statistically presented in Figure 7. The rate of yield change is used in the paper to express the yield differences affected by different meteorological drought scenarios with the following equation:

$$Y_{Wi} = (Y_{Ti} - Y_{CK})/Y_{CK} \times 100\% \#(5)$$

Where: Y_{Wi} is the rate of change of drought stress yield or yield components for the first treatment. Y_{Ti} and Y_{CK} is the yield or yield components for the i-th treatment and the control group. The control group is the simulation result under the baseline meteorological data in Section 2.4.1.

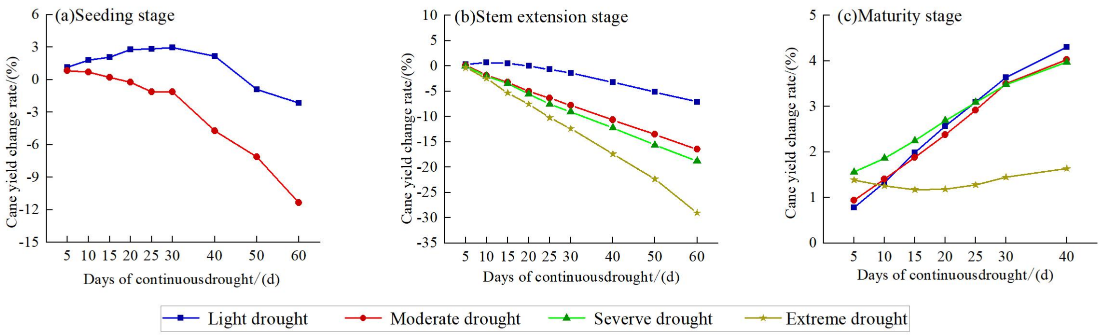


Fig.3 Cane yield change rate of sugarcane under different drought intensities in the same growth stage

From Fig. 3(a), it can be seen that the duration of light drought in seedling stage was within 5d~30d, which showed the effect of yield increase with the highest rate of yield increase of 2.96%, while when the duration of light drought reached 30d~60d, it showed the effect of yield reduction with the lowest rate of yield reduction of -2.17%; a significant yield reduction effect was observed when a moderate drought occurred in the seedling stage with a duration greater than 10 d, The minimum yield reduction rate of -11.35% was reached at a moderate drought duration of 60 d. Among them, 30 d is the drought duration threshold for the effect of light drought in seedling stage to increase yield to decrease yield, and it is also the turning point threshold for medium drought in seedling stage to have slow yield decrease to fast yield decrease; while 10 d of medium drought in seedling stage also reflects the sudden drought in the monthly scale of Laibin City also has suppressive effect on cane yield.

Figure 3(b) shows that sugarcane in Laibin City showed significant yield reduction effect when light, moderate, severe and extreme drought occurred during the stem extensiom stage, and the rate of yield reduction change increased with the increase of drought duration, among which, the trend size of yield reduction rate and its minimum value were: extreme drought (-29.05%) > severe drought (-18.80%) > moderate drought (-16.48%) > light drought (-7.12%). On the contrary, Figure 3(c) shows that when light, moderate and severe drought occurred at maturity, sugarcane showed a more significant yield increase effect with the increase of drought duration, and the change trends and quantitative values were similar, and the maximum yield increase change rate was 4.30%; while when special drought occurred at maturity, there was no significant yield increase or decrease effect.

To investigate the response of cane yield of Laibin sugarcane to different irrigation system schemes under different meteorological drought scenarios, the meteorological drought scenarios with a change rate of -10% (compared with the control group) were selected for irrigation simulation, i.e., moderate drought at seedling stage for 60 days, moderate drought at stem extension stage for 40-60 days, severe drought at stem extension stage for 30-60 days, and extreme drought at stem extension stage for 25-60 days. For the convenience of later discussion, the above 13 drought scenarios are corresponded by letters and numbers, as shown in Figure 4.

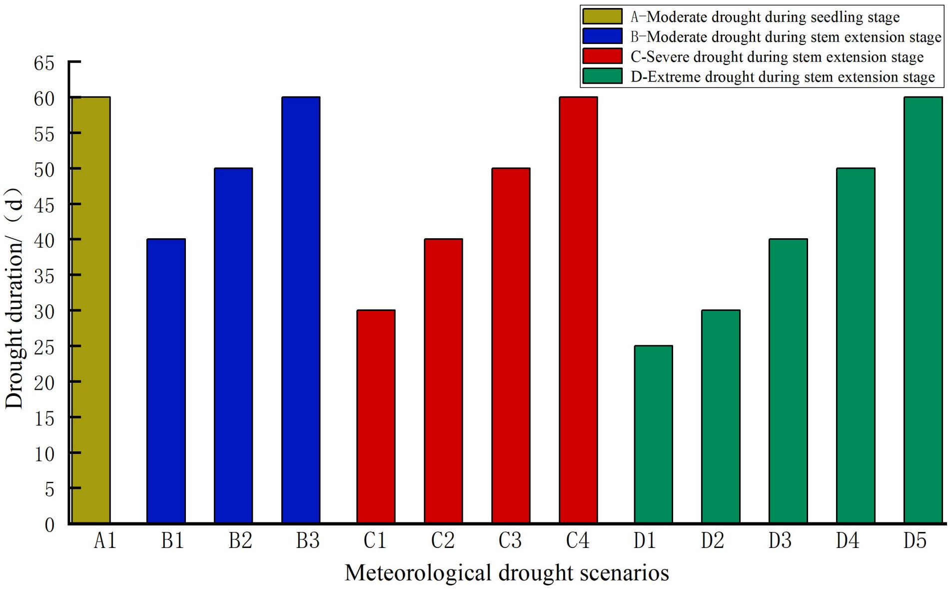


Fig.4 Meteorological drought scenarios description

Note: A1 - moderate drought at seedling stage 60d, B1, B2, B3 - moderate drought at stem extension stage 40d, 50d, 60d, C1, C2, C3, C4, C5 - Severve drought at stem extension stage 30d, 40d, 50d, 60d, D1, D2, D3, D4, D5 - Extreme drought at stem extension stage 25d, 30d, 40d, 50d, 60d.

3.3 Characteristics of canopy evapotranspiration response under meteorological drought and irrigation regime scenarios

Evapotranspiration is the main process of water circulation in the soil-crop-atmosphere system. Canopy evapotranspiration includes soil evaporation and crop transpiration, which is the basis for determining crop irrigation systems and is of great importance for the rational development and efficient use of regional water resources.

3.3.1 Characteristics of canopy evapotranspiration response of sugarcane under meteorological drought and single irrigation quota scenarios

This section was set up under 13 meteorological drought scenarios in Figure 4, using the irrigation regimes of T1-T5 in Table 3, and irrigating sugarcane at the seedling, tillering, early stem extension, late stem extension, and maturity stages, respectively, in order to investigate the effect of a single irrigation quota of 80 mm on canopy evapotranspiration (i.e., soil evaporation and sugarcane transpiration) during the whole sugarcane growth period under 13 meteorological drought scenarios.

As can be seen from Figure 5, in the 13 meteorological drought scenarios, crop transpiration accounted for 60%-70% and soil evaporation accounted for 30%-40% of canopy evapotranspiration at different stages of sugarcane growth period, respectively, and crop transpiration was always greater than soil evaporation for the entire sugarcane growth period; for the same meteorological drought scenario, soil evapotranspiration and its share in canopy evapotranspiration is greatest when irrigating 80 mm at the seedling stage compared to irrigation at other stages of sugarcane growth period, because this is the weakest stage of the sugarcane growth period, with more physiological water demand and less ecological water demand, mainly based on soil evaporation, which is further increased by irrigation at this time; tillering stage as the leaves start to develop, physiological water demand gradually increases, crop transpiration gradually increases, irrigation at this stage 80 mm, still dominated by soil evaporation; stem extension stage is the stage when sugarcane requires the most water throughout its growth period , requiring a large amount of water to be absorbed from the soil, and water consumption is dominated by physiological water requirements. The leaf area index, an important index influencing crop transpiration, grows rapidly at this stage, with more leaves on, an increase in canopy area of sugarcane, higher canopy cover and cane field closure, so that soil evapotranspiration is further reduced and crop transpiration increases significantly when irrigation is applied at 80 mm in the early and late stages of stem extension; compared to irrigation at other stages of fertility, sugarcane has the highest percentage of crop transpiration and canopy evapotranspiration. At maturity stage, sugarcane is converted from a predominantly elongated growth to a predominantly sucrose-accumulating one, and cane growth begins to slow, with a gradual reduction in physiological water requirements, so crop evapotranspiration also starts to decrease gradually, and the proportion of soil evaporation increases at this stage of irrigation at 80 mm compared to irrigation at tillering stage and stem extension stage.

In summary, the canopy evapotranspiration of sugarcane at different stages of growth period was ranked as follows: early stem extension stage > late stem extension stage > seedling stage > maturity stage > tillering stage. From the above analysis, it can be seen that the most sensitive stage of sugarcane growth period to irrigation is the stem extension stage.

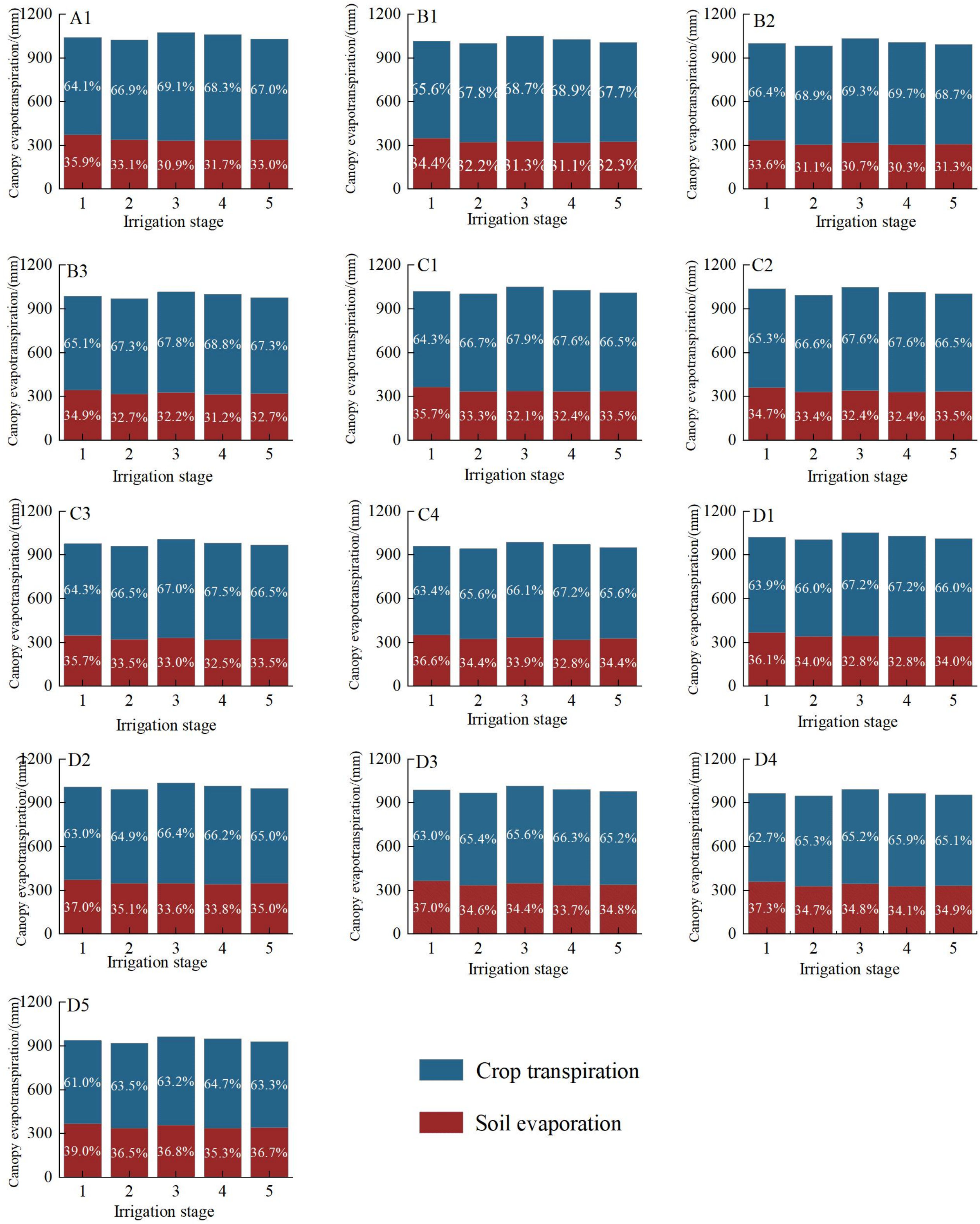


Fig. 5 Effects of single irrigation quota of canopy evapotranspiration under different meteorological droughts and growth stages

3.3.2 Characteristics of canopy evapotranspiration response under meteorological drought and total irrigation quotas scenarios

This section was set up to irrigate sugarcane at different irrigation quotas under each of the 13 meteorological drought scenarios in Figure 4, using the 32 irrigation regimes in Table 3, in order to investigate the response of canopy evapotranspiration to different irrigation rates throughout sugarcane growth period under the 13 meteorological drought scenarios, as shown in Figure 6.

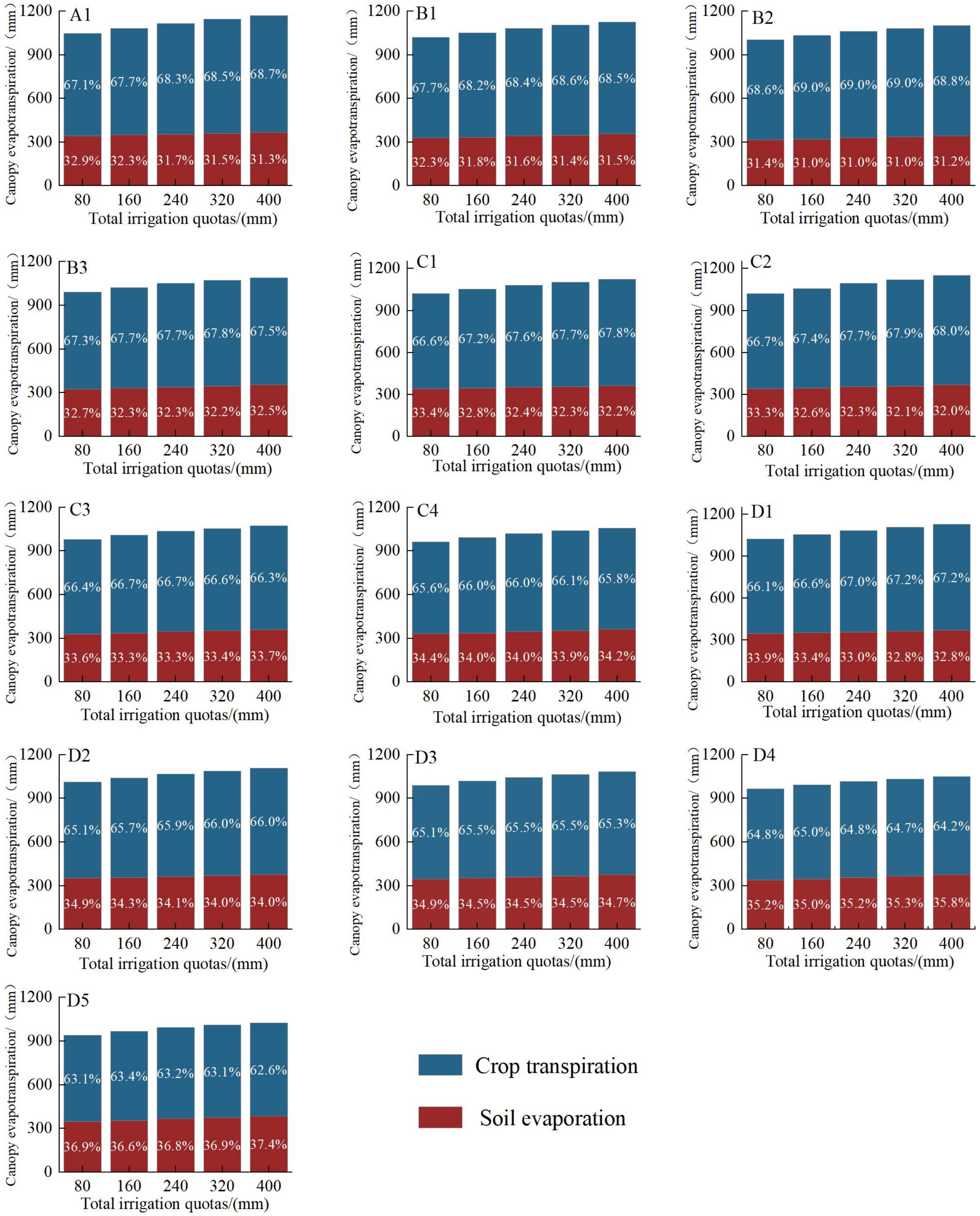


Fig. 6 Effects of different total irrigation quotas on canopy evapotranspiration under different meteorological droughts

Firstly, it is known that for the same meteorological drought scenario, crop evapotranspiration increases to varying degrees with increasing irrigation quotas, while soil evaporation tends to increase, but the overall change is small; in each meteorological drought scenario, when the total irrigation quotas is the same, for the same sugarcane growth stage, the same drought intensity occurs in different drought calendars, the longer the drought calendars, the canopy evapotranspiration decreases, and the percentage of sugarcane evapotranspiration is a decreasing trend showing a certain regularity, for example, D1, D2, D3, D4, D5 scenarios are 25, 30, 40, 50, 60 days of extreme drought in sugarcane stem extension stage, respectively. In the D1, D2, D3, D4 and D5 scenarios, when the total irrigation quotas are 400 mm, the canopy evapotranspiration is D1 (1127.59 mm) > D2 (1107.78 mm) > D3 (1082.86 mm) > D4 (1048.72 mm) > D5 (1023.74 mm), and the percentage of sugarcane evapotranspiration is D1 (67.2%) > D2 (66%) > D3 (65.3%) > D4 (64.2%) > D5 (62.6%). When the duration of drought increases and the degree of drought enhances, the water obtained by sugarcane from the outside is insufficient or lower than the water required by sugarcane, soil evaporation and crop transpiration will be reduced, resulting in reduced canopy evapotranspiration; similarly, it can be seen from the graph that changes in irrigation quotas can change soil evaporation and crop transpiration and their percentages, soil evaporation does not participate in the growth and development process of sugarcane, which is non-productive water consumption, and efficient water use is to reduce this part of water consumption[28]. Therefore, when irrigating sugar cane, the water retention capacity of the soil should be improved to reduce soil evaporation, which is more conducive to ensuring sugarcane production and sugar quality.

3.4 Characteristics of cane yield response under meteorological drought and irrigation regime scenarios

Figure 7 shows the mean cane yield response under 13 different meteorological drought scenarios at different total irrigation quotas levels. It is evident from Figure 7 that for the same meteorological drought scenario, the variability in the maximum, minimum and mean values of simulated cane yields at different total irrigation quotas levels is significant. The maximum, minimum and mean values of simulated cane yield for the different meteorological drought scenarios increased to different degrees with increasing total irrigation quotas, with the lowest cane yield under no irrigation condition and the highest simulated value at 400 mm (maximum total irrigation quota). There is also a significant horizontal difference between the maximum and minimum values of the simulated cane yield under different irrigation quotas, indicating that there is scope for optimising irrigation.

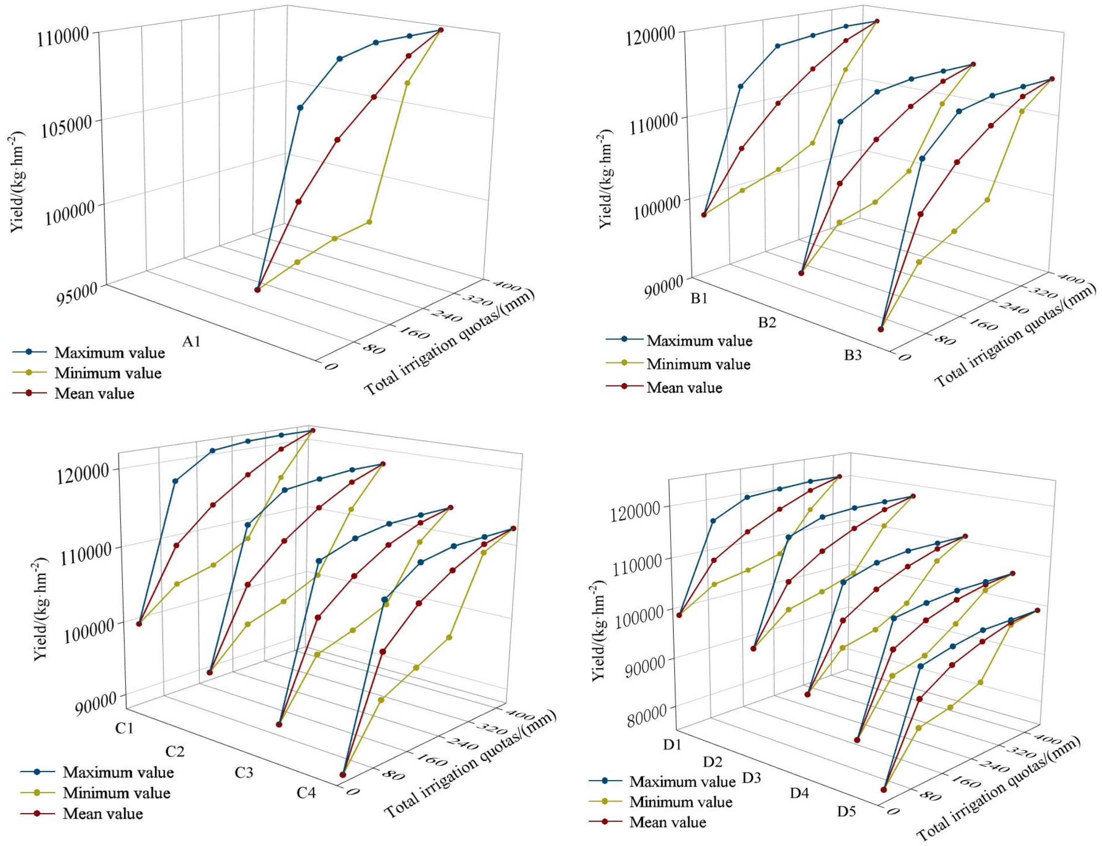
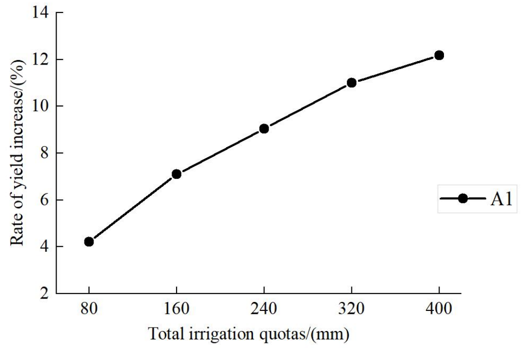
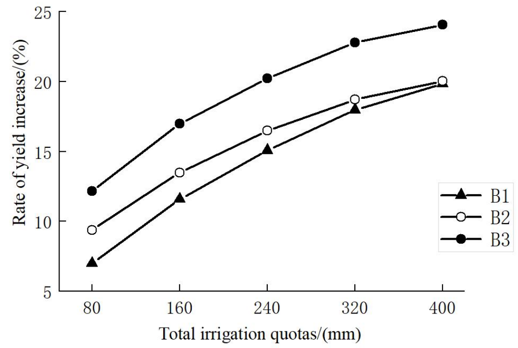


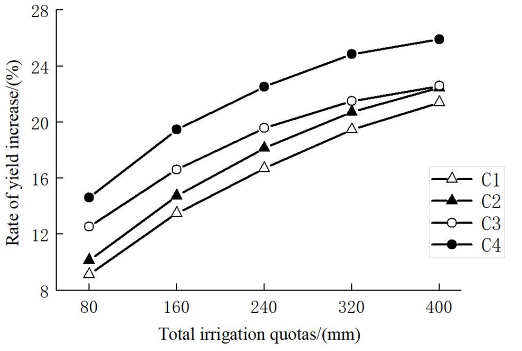
Fig. 7 Cane yield distribution under different total irrigation quotas under different meteorological droughts



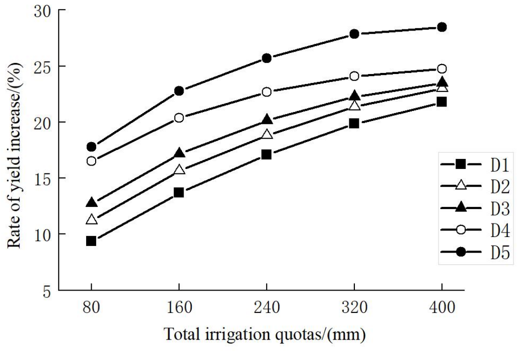
a. Yield increase rate for moderate drought at seedling stage



b. Yield increase rate for moderate drought at stem extension stage



c. Yield increase rate for severe drought at stem extension stage



d. Yield increase rate for extreme drought at stem extension stage

Fig. 8 Yield increase rate of different meteorological droughts under different total irrigation quotas

The simulated cane yield under the no irrigation scenario was used as a control, and the yield increase rate was calculated for different meteorological drought scenarios at each irrigation level. Figure 8 shows the rate of increase in average cane yield for the 13 meteorological drought scenarios at different irrigation quotas, from which it can be seen that the rate of increase tends to increase with increasing irrigation quotas corresponding to the 13 meteorological drought scenarios. When the degree of drought is the same during the sugarcane growth period but the duration of drought is different, the longer the duration of drought, the higher the average yield increase at the same irrigation quotas, e.g. when the stem extension stage is extreme drought, the yield increase at an total irrigation quotas of 400 mm is D1 (21.8%) <D2 (23.0%) <D3 (23.5%) <D4 (24.7%) <D5 (28.5%); when the duration of drought is the same, but the degree of drought is not consistent during the sugarcane growth period, the more severe the drought, the higher the yield increase rate of the average yield under the same irrigation quotas, for example, the drought duration is 60 days and the yield increase rate of A1 (12.2%) < B3 (23.0%) < C4 (23.5%) < D5 (28.5%) for an total irrigation quotas of 400 mm. The meteorological drought scenarios with longer drought durations and stronger droughts had the greatest rise in the irrigation yield increase curve, indicating that irrigation contributed the most to their cane yield increase.

3.5 Correlation analysis and selection of different crop water use efficiency indicators

Based on the simulated results of canopy evapotranspiration and cane yield of sugarcane under different meteorological drought scenarios and different irrigation quotas, the mean values of the four indicators for different meteorological drought scenarios were calculated according to the equations listed in section 2.3.3, as shown in Figure 9. The values of WP, WUE_{ti} and WUE_{g} are relatively close, and WUE_i is larger because only irrigation is considered from the expression. According to the detailed analysis of the meteorological drought characteristics of sugarcane in Laibin at each growth stage in section 2.4.1, and the actual possible meteorological drought scenarios which showed a certain regularity were set, so from Figure 9, the magnitude of the four indicators of the 13 meteorological drought scenarios showed an obvious consistent regularity, i.e. $WUE_{ti} < WUE_{g} < WP < WUE_i$.

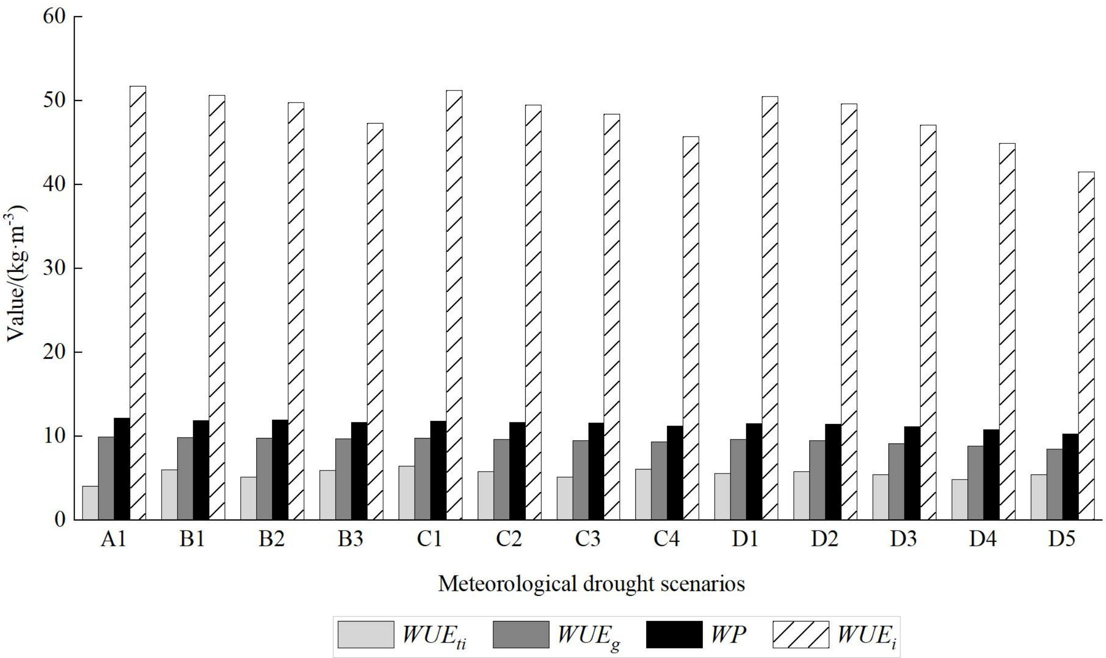


Fig. 9 Comparison of average values of indicators in different meteorological drought scenarios

Pearson correlation analysis was performed on the calculated results to produce correlation coefficients between the four indicators under 13 different meteorological drought scenarios. As shown in Figure 10, firstly, we can see that the correlation between WUE_g and the other three indicators for different meteorological drought scenarios are all high, especially *WP* and WUE_{ti}, the correlation coefficients basically reach above 0.7, and they all pass the significance test level of α=0.01; the correlation between WUE_{ti} and *WP* is also relatively strong, the correlation coefficients are all around 0.8; however, the WUE_{ti} and WUE_i.for the 13 meteorological drought scenarios are mostly not significantly correlated; the WUE_i and *WP* for the 13 meteorological drought scenarios are not significantly correlated.

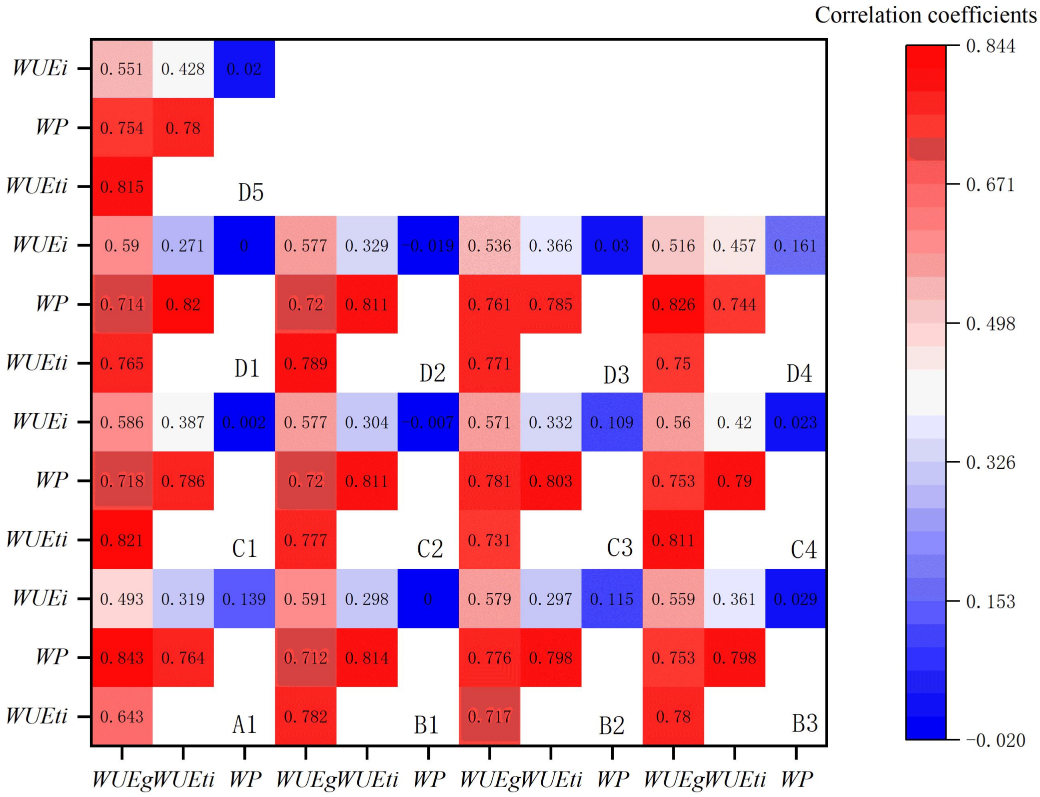


Fig.10 Correlation coefficients of various indicators for different meteorological drought scenarios

From the expression, WUE_g includes both precipitation and irrigation amount, and the sum of the two is used as the water input, fully reflecting that the water consumption of sugarcane originates from precipitation and irrigation replenishment, and more comprehensively reflecting the real relationship between simulated sugarcane yield and precipitation and irrigation water; WUE_{ti} is the ratio between the increase in yield under irrigation (compared to no irrigation) and the corresponding amount of irrigation, which directly reflects the contribution of the amount of irrigation input to the increase in sugarcane yield and gives a comprehensive picture of the level of irrigation in the cane area; WUE_i calculation only takes into account irrigation, not natural precipitation, and reflects the overall yield from irrigation, but in areas like Laibin, where precipitation is abundant, the WUEi calculation can be large, so it is not recommended; *WP* is the ratio of yield to field evapotranspiration (ET), which gives a good indication of the efficiency of water uptake and use by sugarcane, but in practice, data on field evapotranspiration are not easy to obtain and some elements are complicated to measure, limiting its application at large scales and over long periods of time[29], and Shen Rongkai and other[29] scholars believe that this indicator is the effect of a combination of various factors such as irrigation systems and natural meteorological conditions, and is not determined by a single water supply condition.

Based on the above analysis, this paper recommends WUE_g as the water use efficiency indicator for sugarcane in Laibin because of its high correlation with the other three indicators, which can more objectively and comprehensively reflect the water use efficiency of the crop.

According to Figure 9, the WUE_g of sugarcane for 13 meteorological drought scenarios was analyzed, the more severe the drought, the lower the WUEg value; when the degree of drought during sugarcane growth period was the same, but the drought duration was different, the longer the drought duration, the lower the WUEg value. For example, when the stem extension stage was extreme drought , the WUEg value D1 (9.64 kg/m^3) > D2 (9.47 kg/m^3) > D3 (9.17 kg/m^3) > D4 (8.82 kg/m^3) > D5 (8.49 kg/m^3); when the drought duration during sugarcane growth period was the same, but the degree of drought was not consistent, the more severe the drought, the lower the WUEg value, e.g. when the drought lasted 60 days, the WUEg value B3 (9.7 kg/m^3) > C4 (9.37 kg/m^3) > D5 (8.49 kg/m^3). Apparently, the *WUE* of sugarcane decreases in varying degrees with increasing drought levels. How to improve *WUE* while mitigating drought in sugarcane, scholars Zhang Zhengbin et al [30]suggested that improving *WUE* can be done in four ways, i.e. the crop absorbs more water in a dry soil, conserves more water under drought conditions, improves transpiration efficiency , then produces more biomass and transports more photosynthetic products into crop yield.

4. Discussion of optimal irrigation regimes

With the objective of simulating the highest cane yield, the optimal irrigation regime was selected among 32 different irrigation schemes for 13 meteorological drought scenarios, where the crop water use efficiency was the total on-farm water use efficiency, WUE_g, which correlated more significantly with all three other indicators, and the results are shown in Table 5.

According to Table 5, it was firstly found that when the irrigation regime was screened with the objective of simulating the highest cane yield, all of the meteorological drought scenarios were irrigated three times or more, except A1 which was irrigated twice; and the number of irrigations increased with increasing drought duration at the same degree of drought, for example, the number of irrigations gradually increased from three to five times in the meteorological scenarios C1-C4. Next, the irrigation periods for all 13 meteorological drought scenarios were found to be in the early and late stem extension stage. The 12 meteorological drought scenarios in B1-D5 were all irrigated twice during the stem extension stage. In addition to setting the drought to occur during the stem extension stage, it is also because the stem extension stage is the stage when sugarcane requires the most water during the entire growth period, and it is also the critical stage for the fastest growth and yield accumulation of sugarcane, when sugarcane must absorb large amounts of water from the external environment; while A1 represents a 60-day severe drought scenario at the seedling stage, the fact that both irrigations occurred during the stem extension stage reinforces the fact that the stem extension stage is the most favourable stage for sugarcane growth and a critical stage for determining sugarcane yield. It was also shown that the longer the drought duration or the more severe the drought, the lower the crop water use efficiency WUE_g and the simulated cane stem yield under the 13 meteorological drought scenarios. For example, when stem extension stage is exceptionally dry, crop water use efficiency WUE_g D1 (9.87 kg/m^3) > D2 (8.92 kg/m^3) > D3 (8.53 kg/m^3) > D4 (7.45 kg/m^3) > D5 (7.20 kg/m^3), simulated cane yield D1 (120.41 t/hm^2) > D2 (118.92 t/hm^2) > D3 (112.55 t/hm^2) >
D4 (106.87 t/hm^2) > D5 (100.59 t/hm^2).

Table 5 Results of screening for optimal irrigation systems with the objective of simulating maximum cane yield

Meteorological drought scenarios	Crop water use efficiency WUE_g(kg/m)	Simulated yield (t/hm^2)	Total Irrigation quotas (mm)	Number of irrigations	Seeding stage (mm)	Tillering stage(mm)	early stem extension stage (mm)	late stem extension stage (mm)	maturity stage (mm)
	Aiming for the highest yield of simulated sugarcane			Irrigation regime					
A1	10.85	109.24	160	2			80	80	
B1	10.11	117.68	240	3			80	80	80
B2	9.90	114.43	240	3			80	80	80
B3	9.03	114.30	320	4	80		80	80	80
C1	10.03	121.70	240	3	80		80	80	
C2	9.09	118.56	320	4	80		80	80	80
C3	8.81	114.12	320	4	80		80	80	80
C4	8.68	112.80	400	5	80	80	80	80	80
D1	9.87	120.41	240	3	80		80	80	
D2	8.92	118.92	320	4	80		80	80	80
D3	8.53	112.55	320	4	80		80	80	80
D4	7.45	106.87	400	5	80	80	80	80	80
D5	7.20	100.59	400	5	80	80	80	80	80

In summary, the more severe the drought, the lower the sugarcane *WUE* and yield under the same irrigation conditions. Sustainable agricultural production of sugarcane should also focus on improving WUE while pursuing high yields. How to use water scientifically for irrigation in drought-prone sugarcane production, how to increase sugarcane yields while improving its *WUE*, and how to balance the relationship between yield and *WUE* are issues that need to be considered.

5. Conclusion

Based on the parametric localised DSSAT-Canegro model, the paper simulates canopy evapotranspiration and yield of sugarcane in Laibin, China, under different meteorological drought scenarios and different irrigation regime schemes, and develops a quantitative analysis and assessment of different sugarcane water use efficiency indicators. The following main conclusions were drawn.

(1)At the seedling and tillering stages of sugarcane in the study area, its evapotranspiration is dominated by soil evaporation. At stem extension and maturity stages, crop evapotranspiration was dominant. Crop evapotranspiration was always greater than soil evaporation in all meteorological drought scenarios and at different growth periods when irrigation was 80 mm. The canopy evapotranspiration of sugarcane was ranked as follows: early stem extension stage > late stem extension stage > seedling stage > maturity stage > tillering stage. In particular, sugarcane was most sensitive to drought stress and irrigation during the stem extension stage.

(2)Under the same meteorological drought scenario, sugarcane transpiration increased to varying degrees with increasing irrigation quotas, while soil evaporation increased to a lesser extent. The longer the duration of meteorological drought occurring in the same growth stage, the lower the canopy evapotranspiration of sugarcane. Soil evapotranspiration and crop transpiration and their ratios can vary according to irrigation quotas, and sugarcane water use efficiency can be improved by reducing soil evapotranspiration.

(3) The longer the duration of meteorological drought and the stronger the degree of drought occurring in the same growth stage, the higher the stimulation and yield increase of irrigation on sugarcane growth in the study area. Among the four water use efficiency coefficients, WUE_g correlated strongly with WP, WUE_{ti} and WUE_i and was the best indicator for evaluating the water use efficiency of sugarcane in the study area.

(4) Various combinations of irrigation regimes screened for maximum cane yield existed, but the stem extension steage was the necessary irrigation period. The more severe the meteorological drought, the lower the WUEg and cane yield of sugarcane in the study area when irrigation conditions are the same.

Acknowledgements

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