DOI:10.13476/j.cnki.nsbdqk.2021.0100
NIE T Z, LIANG Q Z, WANG T Y, et al. Water requirement and supply and irrigation schedule formulation for maize in western Heilongjiang Province[J]. South-to-North Water Transfers and Water Science & Technology, 2021, 19(5): 960-971. (in Chinese)

# Water requirement and supply and irrigation schedule formulation for maize in western Heilongjiang Province

NIE Tangzhe[1], LIANG Qizong[1,2], WANG Tianyi[1],
CHU Lili[1], CHEN Xuan[3], LI Fengrui[4]

(1. *School of Water Conservancy and Electric Power, Heilongjiang University, Harbin* 150080, *China*; 2. *Center of Water Resources and Environment, School of Civil Engineering, Sun Yat-Sen University, Guangzhou* 510275, *China*; 3. *Water Affairs Bureau of Ninghai County, Ningbo* 315600, *China*; 4. *Xingtai Hydrographic Survey and Research Center of Hebei Province, Xingtai* 054000, *China*)

**Abstract**: Frequent drought events threaten the agricultural water cycle and food security in western Heilongjiang Province. Understanding the water supply-requirement relationship is vital to the exploration of drought mechanisms. The reference crop evapotranspiration ($ET_0$), crop water requirement ($ET_c$) and irrigation water requirement ($I_r$) during the maize growth period were calculated and irrigation schedules were formulated by the FAO-56 single crop coefficient method. The water requirement deficit or surplus of maize was analyzed with the crop water surplus deficit index ($C_W$). The results showed that $ET_0$ and $ET_c$ decreased, while effective precipitation ($P_e$), $I_r$, and $C_W$ displayed an increasing trend in the maize growth period in western Heilongjiang Province from 1960 to 2015. The average $ET_0$, $ET_c$, $P_e$, and $I_r$ were 639.64, 438.13, 224.40, and 273.87 mm, respectively. Drought conditions varied in different hydrological years, and it was challenging for $P_e$ to meet maize $ET_c$. Therefore, irrigation schedules were formulated for different hydrological years. The average net irrigation quotas of rainy year, normal year, dry year and extremely dry year were 152.43, 236.33, 276.53, and 353.47 mm, respectively. Analyzing the water requirement deficit or surplus of maize helps better understand the effect of drought on agricultural development.

**Key words**: maize; reference crop evapotranspiration ($ET_0$); crop water requirement ($ET_c$); crop water surplus deficit index ($C_W$); effective precipitation ($P_e$); irrigation water requirement ($I_r$); irrigation schedule

**Chinese Library Classification No.**: TV213　**Document Code**: A　OSID:

---

**Received**: 2020-10-18　**Revised**: 2021-06-12　**Online publishing**: 2021-06-28
**Online publishing address**: https://kns.cnki.net/kcms/detail/13.1430.TV.20210628.1130.002.html
**Funds**: Basic Scientific Research Fund of Heilongjiang Provincial Universities (RCCXYJ201912 & 2018-KYYWF-1570); National Natural Science Foundation of China (51779046)

**Author's brief**: NIE Tangzhe (1991-), male, Dandong Liaoning, mainly engaged in agricultural water-saving technology. E-mail: nietangzhe527@163.com
**Corresponding author**: LIANG Qizong (1996-), male, Huizhou Guangdong, mainly engaged in agricultural water-saving technology. E-mail: 20175390@s.hlju.edu.cn

## 1 Introduction

Climate change, characterized by rising temperatures, is a public concern worldwide [1]. The Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC) showed the annual temperatures in the northern Hemisphere from 1983 to 2013 were the warmest period during the past 800 years [2-3]. Nowadays, extremely high temperatures occur more frequently, and different degrees of drought are happening in different regions all over the world [4]. As one of China′s most critical meteorological disasters, drought has caused enormous wastage to China′s agriculture.

Cereal crops are highly important in ensuring global food security. According to the Food and Agriculture Organization (FAO), maize is one of the world's three most widely cultivated crops and accounted for almost 38% of the cereal production in the globe in 2007 [5]. The planting area of maize in western Heilongjiang Province reached 17.43% of the whole province, with its yield accounting for 17.41% accordingly [6]. With the population density increasing, ensuring global agriculture development and food security has gradually become a key challenge [7].

The semi-arid region in western Heilongjiang Province is a typical dry agricultural area in China. The climate there features strong wind in spring, less rain, extensive evaporation, a sharp air temperature increase in summer, and small snowfall in winter[8]. Drought has always been one of the most common natural disasters in the region. Maize production in Heilongjiang Province mainly depends on precipitation. Zhang et al.[9] found that the spring drought occurred in Heilongjiang Province, which inevitably reduced agricultural production. Yao et al.[10] indicated that the western region of Heilongjiang Province was a severe drought area in northeast China. Wang et al.[7] pointed out even though the maize water deficit in the west region was alleviated during maize growth periods from 1960 to 2015, the drought situation in western Heilongjiang Province should still be taken seriously. Therefore, the drought in western Heilongjiang Province highly impacts regional food and water security.

For better understanding the irrigation schedule and water requirement of maize in semi-arid areas, it is urgent to explicate knowledge about the variations in reference crop evapotranspiration ($ET_0$), crop water requirement ($ET_c$), effective precipitation ($P_e$), and irrigation water requirement ($I_r$) under climate change, which can guide future agricultural policy-making, development, research, and investment [11]. In recent years, many studies used the Penman-Monteith equation recommended by the FAO to calculate $ET_0$[12-15]. $ET_0$ and maize $ET_c$ were found increasing in many regions of the world [16-17]. Arshad et al. pointed out that the air temperature and wind speed would increase, while precipitation and relative humidity may decrease from 1961 to 2099 [18]. However, many studies revealed that precipitation was increasing and $ET_0$ was decreasing. Wang et al.[7] reported that soybean $ET_0$ in Heilongjiang Province decreased by 5.17 mm every decade. Nie et al.[19] found that precipitation and $ET_0$ showed decreasing trends of −12.04 and −2.98 mm every decade, respectively, and pointed out that the $I_r$ of maize in the western region was larger than that in other areas of Heilongjiang Province. Carolina et al.[20] discovered that the irrigated fields would remain stable under climate change in the future compared with rainfed fields. Wang et al.[7] found the deficit in water requirement of maize in most regions of Heilongjiang Province, especially in the western region. Nevertheless, previous studies have not formulated a more detailed irrigation schedule concerning the drought situation in western Heilongjiang Province.

This study aimed to (1) quantify $ET_0$, $ET_c$, $P_e$, and $I_r$ of maize in western Heilongjiang Province, (2) quantify the crop water surplus deficit index ($C_W$) using the ratio of $ET_c$ to $P_e$ during the maize growth period and (3) formulate irrigation schedule for western Heilongjiang Province by selecting representative stations (Tailai, Qiqihar, and Fuyu).

## 2 Materials and methods

### 2.1 Study area

Daily meteorological data of 1960-2015 were collected from agricultural meteorological stations in Fuyu (123°29′, 47°48′), Tailai (123°25′, 46°27′), and Qiqihar (123°58′, 47°19′), including the maximum temperature, minimum temperature, average relative humidity, sunshine hours, wind speed, precipitation, longitude, and latitude of each station (Fig. 1). Observed data of maize in different growth stages in the study area from 1991 to 2008 were also obtained from these agricultural observation stations. The quality of the above data was carefully assessed, and the missing data were estimated with the methods suggested in FAO-56[21]. The meteorological, geographical, and phenological data were collected from the China Meteorological Data Sharing Service System [22]. The soil in these three areas is chernozem, which is mainly distributed in the western Songnen Plain. This kind of soil is suitable for cultivation and conducive to the coordination of water, gas, and heat, thus becoming an ideal medium for planting many types of crops, such as maize, wheat, sorghum, and millet. The soil data were collected from Soil Science Database [23].

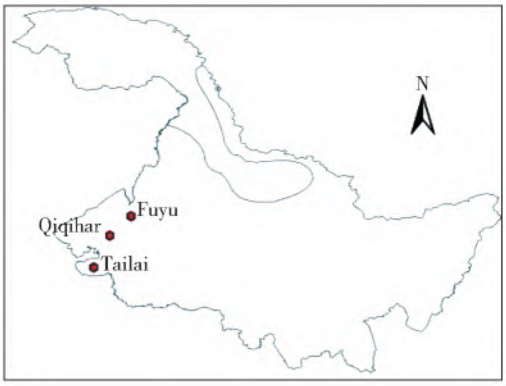


Fig. 1 Study area

### 2.2 Effective precipitation

We used the method recommended by the Soil Conservation Agency of the U S Department of Agriculture to calculate $P_e$[23]:

$$P_e=\begin{cases} P(4.17-0.2P)/4.17 & (P\leqslant 8.3\ \text{mm}) \\ 4.17+0.1P & (P>8.3\ \text{mm}) \end{cases} \tag{1}$$

where: $P_e$ is effective precipitation, mm; and $P$ is precipitation, mm.

### 2.3 Water requirement of maize

$ET_0$ was calculated by the Penman-Monteith method recommended by the FAO, as shown in Equation (2).

$$ET_0=\frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273T}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2} \tag{2}$$

where: $ET_0$ is the reference crop evapotranspiration, mm·day$^{-1}$; $R_n$ is the net radiation at the crop surface, MJ·(m$^2$·d)$^{-1}$; $G$ is the soil heat flux, MJ·(m$^2$·d)$^{-1}$; $T$ is the average air temperature, ℃; $u_2$ is the wind speed measured at 2 m height, m·s$^{-1}$; $e_s-e_a$ is the vapor pressure deficit, kPa; $\Delta$ is the slope of the vapor pressure curve, kPa·℃$^{-1}$; $\gamma$ is a psychrometric constant, kPa·℃$^{-1}$; 900 is a conversion factor.

Maize water requirement was calculated with the CROPWAT 8.0 computer program for Windows, which was designed to calculate $ET_c$ with the existing crop, climate, and soil data. The altitude, latitude, longitude, and daily maximum temperature, daily minimum temperature, average relative humidity, wind speed, sunshine hours of each station were imported into the Climate/$ET_0$ module to calculate $ET_0$. The planting date, harvest date, $K_c$ values, and duration of each growth stage were loaded to the crop module to calculate $ET_c$. The water requirement of maize was clarified by the single crop coefficient method [9]. The total water requirement of maize was accumulated by the daily water requirement during the growth period, taking into account the crop coefficient in different months as well (Equation (3)). Crop evapotranspiration under standard conditions is denoted as $ET_c$, namely the evapotranspiration from disease-free, well-fertilized crops grown in large fields under optimum soil water conditions which achieve full production under the given climatic conditions[24].

$$ET_c=K_c\times ET_0 \tag{3}$$

where: $ET_c$ is the crop water requirement, mm; $ET_0$ is the reference crop evapotranspiration, mm; $K_c$ is the crop coefficient.

FAO-56 divides the crop growth period into four stages, i. e., initial stage ($L_{ini}$), crop development stage ($L_{dev}$), mid-season stage ($L_{mid}$), and late-season stage ($L_{late}$), which were respectively from the planting date to the time when the ground cover reached approximately 10%, from 10% of ground cover to effective full cover, from effective full cover to maturity, and from maturity to harvest or full senescence[24]. The whole growth period of maize was divided into four stages: sowing-seven-leaf stage ($L_{ini}$), seven-leaf stage-tasseling stage ($L_{dev}$), tasseling stage-milk-ripening stage ($L_{mid}$), and milk-ripening stage-mature stage ($L_{late}$). The FAO-56 method reports generalized $K_c$ values for different growing stages of maize under standard conditions. The single crop coefficient $K_c$ is described by $K_{mc\text{-}ini}$, $K_{c\text{-}mid}$, and $K_{c\text{-}end}$ for the initial, middle, and late growth stages, whose recommended values are 0.30, 1.20, and 0.35 for maize, respectively. However, to improve the estimation of the $K_c$ curve for a specific site, the recommended values need to be adjusted to yield a local $K_c$ value. The recommended values of $K_{c\text{-}ini}$, $K_{c\text{-}mid}$, and $K_{c\text{-}end}$ in the FAO-56 and were adopted and underwent automatic correction by CROPWAT model with average infiltration depth, wind speed, humidity, and crop height at different growing stages. The correction formula of $K_c$ has been embedded into the CROPWAT model[25].

## 2.4 Crop water surplus deficit index

$C_W$ is defined as water surplus/deficit for maize during the maize growth period[26], which can be calculated as follows:

$$C_W=\frac{P_e-ET_c}{ET_c} \tag{4}$$

## 2.5 Irrigation water requirement

$I_r$ is defined as the difference between $ET_c$ and $P_e$ in each growth stage (Equation (5)):

$$I_r=\max\left(\sum_{i=1}^{n}ET_c-\sum_{i=1}^{n}P_e,0\right) \tag{5}$$

where: $I_r$ is the irrigation water requirement of a crop, mm.

## 2.6 Precipitation data processing

For the programming of irrigation water supply and management, we utilized the annual precipitation data for extremely dry year ($P=95\%$), dry year ($P=75\%$), normal year ($P=50\%$), and rainy year ($P=25\%$). The respective precipitation data can be estimated by the computation and plotting of probabilities with precipitation records. Specifically, the steps included (i) tabulating the annual precipitation from 1960 to 2015, (ii) arranging data in a descending order of magnitude, and (iii) tabulating the plotting position according to Equation (6).

$$F_a=\frac{100m}{N+1} \tag{6}$$

where: $F_a$ is the plotting position, $N$ the number of the records, and $m$ the rank number.

The precipitation in Tailai, Qiqihar, and Fuyu is 111.8, 202.9, and 143.1 mm, respectively, in an extremely dry year; 167.3, 222.2, and 175.2 mm, respectively, in a dry year; 195.4, 290.5, and 227.3 mm, respectively, in a normal year; 236.4, 350.4, and 315.0 mm, respectively, in a rainy year.

## 2.7 Climate tendency rate

The climate tendency of factors is expressed by a linear equation using the least-squares method, as present in Equation (7).

$$\hat{Y}=b_0t+b \tag{7}$$

where: $\hat{Y}$ represents the fitted values of the studied elements; $t$ is the corresponding year; $b_0$ and $b$ are regression coefficients.

$10b_0$ is the climate tendency rate, which means the change of a meteorological element in every 10 years (10 a). A positive value indicates an increasing trend of the meteorological element, while a negative value suggests a decreasing trend.

## 2.8 Data processing

We used the CROPWAT model to formulate irrigation schedule for western Heilongjiang Province. According to the daily soil water balance, maize rooting depth, and crop coefficient recorded by the agricultural meteorological stations, the daily irrigation water demand of maize was calculated. The planting date recorded by each agricultural meteorological station was taken as the sowing date, and the irrigation schedule was developed with the CROPWAT model. Finally, the irrigation schedule was encompassed in the "irrigation schedule" module of CROPWAT model. Considering the actual situation, the data were processed into irrigation systems understandable to farmers.

We employed MATLAB 2004b to calculate the climate tendency rates of $ET_c$, $I_r$, $P_e$, and $C_W$ for maize in western Heilongjiang Province and conduct the Mann-Kendall trend test. As a non-parametric statistical test method, the Mann-Kendall trend test well reveals the changing trend in time series and has more prominent adaptability for meteorological data in non-normal distribution, with the positive and negative signs of the statistical variable $Z$ indicating the trend of data change. The test can analyze the changing trend and mutation point of the data series by calculating $UF_K$ and $UB_K$ statistics and plotting their curves. The absolute value of $Z$ greater than 1. 64, 2. 32, and 2. 56 stated that it had passed the significance test with the confidence of 95%, 99%, and 99. 9%, respectively[19].

## 3 Results

### 3. 1 Temporal variation of $ET_0$

The temporal distribution of $ET_0$ in Tailai, Qiqihar, and Fuyu from 1960 to 2015 is shown in Fig. 2. The $ET_0$ values in the three places ranged from 588. 59 to 821. 38 mm, 543. 18 to 771. 06 mm, and 516. 42 to 739. 04 mm, with the average being 679. 97, 626. 27, and 612. 69 mm, respectively. The average annual $ET_0$ was 639. 64 mm in the study area. The highest annual $ET_0$ was found mainly distributed in Tailai (Fig. 2) with the maximum of 821. 38 mm. The climate tendency rates of $ET_0$ in Tailai, Qiqihar, and Fuyu were −8. 19, −2. 27, and −5. 96 mm/(10 a), respectively, and the $ET_0$ generally presented a decreasing trend in the study area.

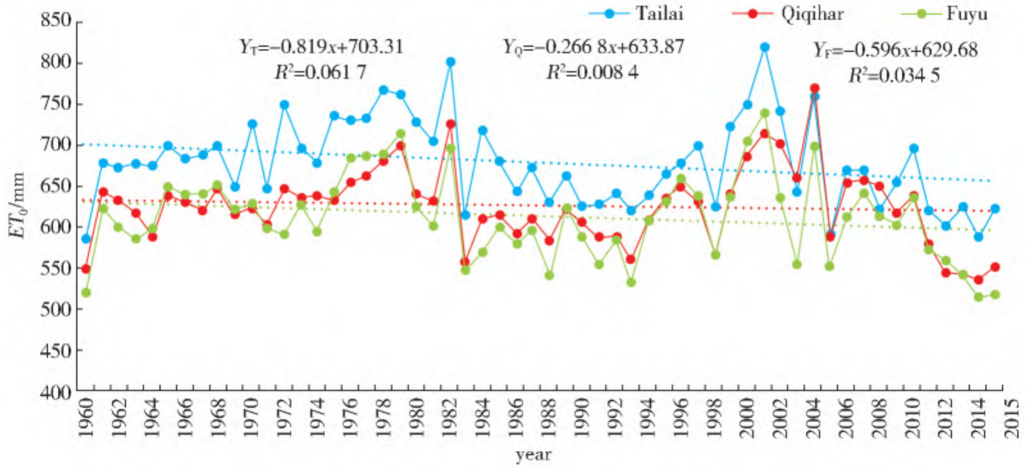


Fig. 2 Distribution of average reference crop evapotranspiration ($ET_0$) and its trends from 1960 to 2015 in the study area

### 3. 2 Temporal variation of $ET_c$

The temporal distribution of maize $ET_c$ in Tailai, Qiqihar, and Fuyu from 1960 to 2015 is listed in Tab. 1. The $ET_c$ values in the three regions were in ranges of 577. 20 - 377. 20, 551. 6 - 361. 5, and 517. 80 - 343. 60 mm, with the average being 679. 97, 626. 27, and 612. 69 mm, respectively. The average $ET_c$ was 438. 13 mm in the study area. The highest value (821. 38 mm) was observed in Tailai. The climate tendency rates of $ET_c$ in Tailai, Qiqihar, and Fuyu were − 9. 079, − 2. 092, and −5. 514 mm/(10 a), respectively. Regarding the whole study area, the climate tendency rate showed a downward trend. Fig. 3 demonstrates the variations of tested and analyzed water requirement of maize. The UF value was positive from 1960 to 1991 in Tailai and from 1960 to 1987 and most years from 2000 to 2010 in Fuyu, which manifested the increasing water requirements of maize during these periods in the two places; while it was negative from 1963 to 1967, 1992 to 2001, and 2014 to 2015 in Qiqihar, which means the decreasing maize $ET_c$ in these periods. UF and UB intersected in 1994 and 2010 in Tailai, 1965 and 2013 in Qiqihar, and 2014 in Fuyu. This indicated that maize $ET_c$ had turn points at these years.

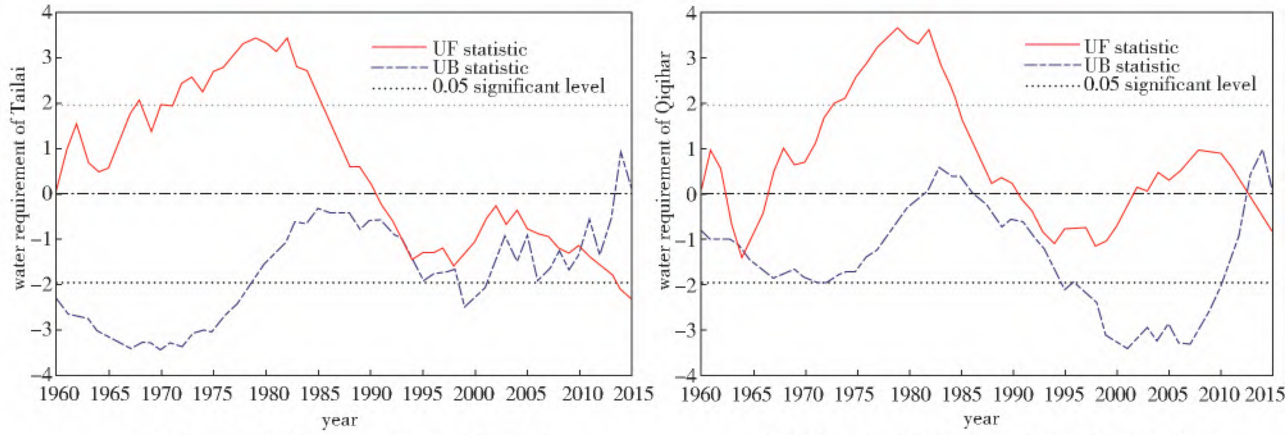
Tab. 1 Changes of maize $ET_c$ during the maize growing seasons from 1960 to 2015

| $ET_c$ | Tailai | Qiqihar | Fuyu |
|---|---|---|---|
| Average/mm | 459.37* | 432.69 | 422.33 |
| $Z$ | −2.275 70* | −0.833 97 | −1.732 00 |
| Range/mm | 577.20—377.20 | 551.60—361.50 | 517.80—343.60 |
| Climate tendency rate/[mm·(10 a)$^{-1}$] | −9.079 | −2.092 | −5.514 |

Note: " * "means a significant changing trend at the 0.05 level.

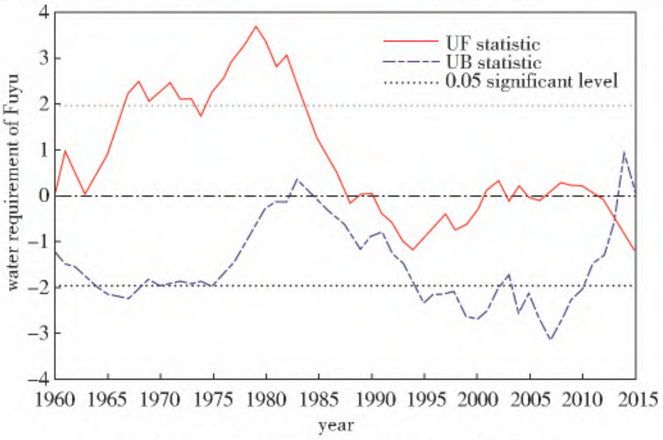
## 3.3 Temporal variation of $P_e$ and $C_W$

$P_e$ values in Tailai, Qiqihar, and Fuyu ranged from 61.9 to 394.4, 103.4 to 386.5, and 442.6 to 89.9 mm, with the average calculated as 196.84, 252.51, and 223.87 mm, respectively. The average annual $P_e$ was 224.40 mm in the study area. The $C_W$ was − 1.84% to −89.07%, 6.68% to 79.61%, and 19.62% to −80.89% in Tailai, Qiqihar, and Fuyu, which was averaged as −55.38%, −40.23%, and −45.07%, respectively.



(a) Mann-Kendall test curve of maize $ET_c$ in Tailai

(b) Mann-Kendall test curve of maize $ET_c$ in Qiqihar



(c) Mann-Kendall test curve of maize $ET_c$ in Fuyu

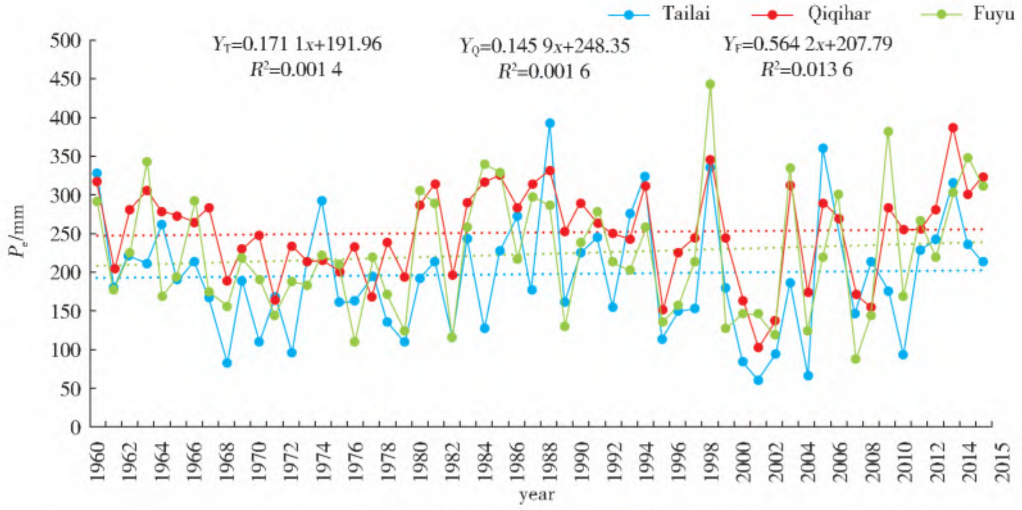
Fig. 3 Mann-Kendall test curve of maize $ET_c$ in study area during the maize growing seasons from 1960 to 2015

The highest $P_e$ was 442.60 mm and the highest $C_W$ was 19.62% in Fuyu in 1998 (Fig. 4 (a)). The climate tendency rates of $P_e$ in Tailai, Qiqihar, and Fuyu were respectively −1.71, 1.46, and 5.64 mm/(10 a), and those of $C_W$ in the three regions were respectively 1.5%/(10 a), 1.1%/(10 a), and 2.5%/(10 a). Overall, the climate tendency rates of $P_e$ and $C_W$ followed increasing trends in the study area.

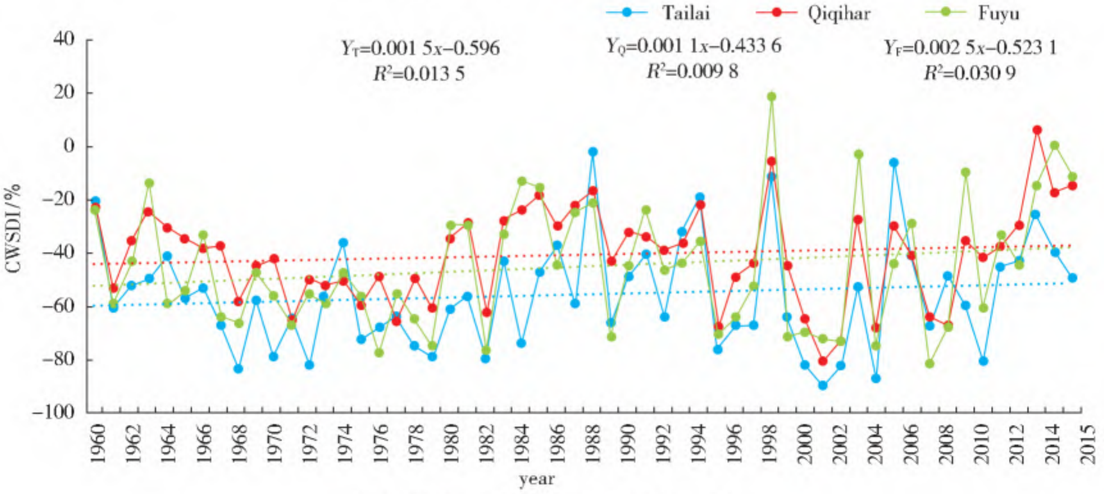
## 3.4 Temporal variation of $I_r$

$I_r$ values in Tailai, Qiqihar, and Fuyu were ranged within 164.80-504.60, 94.40-410.70, and 110.80-415.70 mm, with the average being 320.10, 240.74, and 260.77 mm, respectively. The study area had the average annual $I_r$ of 224.40 mm. Fig. 5 shows that the high $I_r$ values were mainly distributed in Tailai, and the highest value was 504.60 mm. The climate tendency rates of $I_r$ in Tailai, Qiqihar, and Fuyu were

−4.83, 1.84 and −4.50 mm/(10 a), respectively. The climate tendency rate of $I_r$ exhibited decreasing trends in Tailai and Fuyu but an increasing one in Qiqihar.



(a) Distribution of average $P_e$ and its trend



(b) Distribution of average $C_W$ and its trend

Fig. 4 Distribution of average $P_e$ and $C_W$ and their trends in the study area from 1960 to 2015

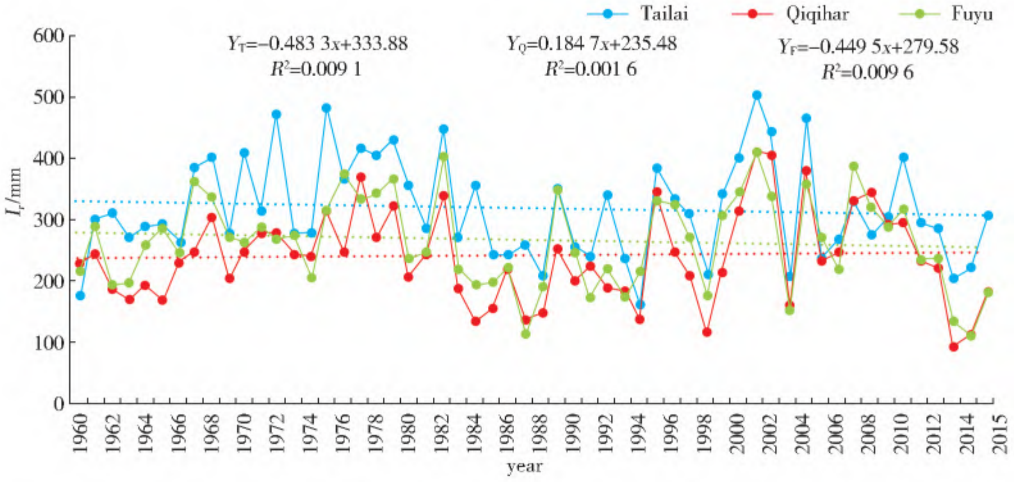


Fig. 5 Distribution of average $I_r$ and its trends in the study area from 1960 to 2015

### 3.5 Irrigation schedule of maize in different hydrological years

During the formulation of the irrigation schedule by the CROPWAT model, the wetting layer depth was designed as 30, 80, 80, and 70 cm in the early, rapid, middle, and late growth stages, respectively. In this paper, the total available soil moisture was 180.0 mm/m, initial soil moisture depletion 32%, and initially available soil moisture 122.4 mm/m. The above data were sourced from the China Meteorological Data Sharing Service System[22], and the unavailable data were set as the default values in FAO-56[5]. The soil moisture content suitable for maize growth was 55%-80% of field capacity. 80% of field capacity was selected for irrigation when the water content reached the lower limit of readily available water. The simulation result of irrigation schedule in different hydrological years is displayed in Tab. 2. The net irrigation quota and irrigation times increased gradually with the increase in hydrological frequency. The net irrigation quota ranged from 122.7 to 428.6 mm, and Tailai had the highest level compared with Qiqihar and Fuyu in different hydrological years. The formulated irrigation schedule was recommended to sprinkler irrigation.

Tab. 2　Irrigation schedule for different hydrological years

| Hydrological years | Region | Net irrigation quota/mm | Irrigation times | Irrigation quota in each irrigation time/mm | Irrigation dates/Month. Day (The irrigation time fluctuates for 5 days) |
|---|---|---|---|---|---|
| Rainy year ($P=25\%$) | Tailai | 177.3 | 3 | 50—60/60—65/55—60 | 6.19/7.29/8.14 |
| | Qiqihar | 157.3 | 3 | 20—30/55—65/60—70 | 5.20/8.07/8.31 |
| | Fuyu | 122.7 | 3 | 20—30/30—40/60—70 | 5.18/6.01/7.27 |
| Normal year ($P=50\%$) | Tailai | 277.0 | 5 | 20—30/30—40/40—50/60—70/60—70 | 5.14/5.27/6.06/6.27/7.14 |
| | Qiqihar | 191.8 | 3 | 50—60/50—60/70—80 | 6.25/8.16/9.14 |
| | Fuyu | 240.2 | 5 | 20—30/30—40/60—65/50—60/60—70 | 5.15/5.29/7.21/8.24/9.03 |
| Dry year ($P=75\%$) | Tailai | 304.6 | 6 | 20—30/40—45/40—50/60—65/60—70/60—70 | 5.18/6.02/6.11/6.23/7.20/8.28 |
| | Qiqihar | 239.0 | 5 | 20—25/40—50/50—60/60—65/60—65 | 5.16/6.13/6.24/7.08/8.13 |
| | Fuyu | 286.0 | 5 | 40—45/60—65/60—65/60—65/60—70 | 6.11/6.26/7.10/8.06/9.06 |
| Extremely dry year ($P=90\%$) | Tailai | 428.6 | 8 | 20—30/30—40/40—50/60—70/60—70/60—70/60—70/70—75 | 5.13/5.25/6.05/6.24/7.05/8.07/8.19/9.04 |
| | Qiqihar | 243.5 | 4 | 50—60/60—70/60—70/60—70 | 6.27/7.20/7.29/8.22 |
| | Fuyu | 388.3 | 8 | 20—25/30—35/40—45/40—50/50—60/60—65/60—65/60—65 | 5.15/6.01/6.10/6.19/7.01/7.21/8.14/8.24 |

## 4　Discussion

In previous studies, Zhao et al.[27] found that $ET_0$ was enhanced with the increase in net radiation and air temperature. Yanjun et al.[28] also reported that the temperature rising and various crop planting structures were mainly responsible for the increase in maize $ET_0$. However, we previously discovered that increasing temperature did not influence $ET_0$ in Heilongjiang Province, while wind speed and sunshine hours were the main impact factors. Wu et al.[29] pointed out that the decrease in wind speed, vapor pressure, and sunshine hours diminish the $ET_0$. Xinran et al.[30] found that with the increasingly severe air pollution, the short-wave radiation was blocked by pollutants, which made the atmosphere more stable, reduced the momentum transport near the ground, and lowered the ground wind speed. Nie et al.[31] held that warming clouds and greenhouse gases are more conducive to capturing heat, weakening solar radiation, and thus reducing crop evapotranspiration. To sum up, not only temperature but also other factors should be considered during the investigation of maize $ET_0$ change.

The results indicated that $ET_0$ and $ET_c$ declined in western Heilongjiang Province. Wang et al.[32] pointed out that the maize $ET_c$ was 381 mm in the case of sufficient irrigation in 2004. The Collaboration Group on Isoline Map of Water Demand of Main Crops in China reported that the average

$ET_c$ of maize was 427 mm in 17 regions of Heilongjiang Province from 1961 to 1980 [33]. The average $ET_c$ was 438.13 mm, 2.5% higher than the above, as the western region had the highest water deficit during maize growth periods. Jiang et al. [8] stated that the west region had the highest $ET_c$ than other regions of Heilongjiang. Gao et al. [34] calculated the climate tendency rate of maize $ET_c$ to be 1.2 mm/(10 a) in northeast China from 1961 to 2010. The climate tendency rate of maize $ET_c$ was −5.561 mm/(10 a) in western Heilongjiang Province. Especially, the lowest precipitation and the highest $ET_c$ in Tailai entail the highest $I_r$. Despite the decrease in maize water requirement, it was still higher than that in other regions of Heilongjiang Province. Thus, coordinated regional water distribution becomes crucial at high maize $ET_c$.

East Asian monsoon impacts the precipitation in Heilongjiang Province, increasing the extreme droughts and waterlogging events since the 1970 s [35]. Zhai et al. [36] pointed out that more droughts occurred in China during the past 20 years. Zhang et al. [37] found an increasing water deficit in the northeast region of China. et al. [6] indicated that precipitation decreased by 2.4 mm every decade from 1961 to 2017 in Heilongjiang Province. However, it was increasing in western Heilongjiang Province. Qiqihar and Tailai were the regions with the lowest precipitation in literature[6]. $P_e$ and $C_W$ showed increasing trends in all regions. In spite of the increase in precipitation, we should also pay attention to the drought situation in western Heilongjiang Province.

Water deficit has become the primary restraint to agricultural development in the western Heilongjiang Province[38]. The climate tendency rate of $I_r$ in Qiqihar and Tailai presented increasing trends. Liu et al. [39] pointed that $I_r$ in Heilongjiang Province was 10-200 mm. However, the range is extensive, and thus the result is not suitable for guiding farmers' production. We calculated the $ET_c$ and net $I_r$ of maize in different hydrological years in the western region of Heilongjiang Province. The average $I_r$ was 273.87 mm. Formulating irrigation schedule with limited water is critical for sustainable water resources management[40]. CROPWAT model comprehensively considers $K_c$, the soil water change at the maximal rooting depth, and drainage to estimate $ET_0$. Changing the interval and irrigation depth frequently is not practical[41], as the CROPWAT model can extend actual findings to conditions not tested in the field[42]. When recommended this new irrigation schedule, researchers should take into account many additional factors, such as water supply plan in the irrigation region, input for $I_r$, and environmental impact of irrigation[43].

## 5 Conclusions

In the past 55 years, $ET_0$ in western Heilongjiang Province was decreased, with an average of 639.64 mm. The decrease in $ET_0$ lowered $ET_c$, whose average was 438.13 mm. The range of $P_e$ became wider and its average was 224.40 mm. The range of $I_r$ was narrowed, with an average of 273.87 mm. The highest $ET_0$, $ET_c$, and $I_r$ were found in the westernmost region (Tailai). The $C_W$ went up in western Heilongjiang Province. However, the water deficit was severe during maize growth periods. The formulated irrigation schedule can alleviate this situation in agricultural water management. The net irrigation quota ranged from 122.7 to 428.6 mm, and Tailai had the highest irrigation quota in the study area in different hydrological years.

**References:**

[1] LIU M, XU X, JIANG Y, et al. Responses of crop growth and water productivity to climate change and agricultural water-saving in arid region[J]. Science of The Total Environment, 2020, 703. DOI: 10.1016/j.scitotenv.2019.134621.

[2] IPCC AR5. Intergovernmental panel on climate change climate change fifth assessment report (AR5)[M]. Cambridge: London Cambridge University Press, 2013.

[3] DENMAN K, BRASSEUR G. The physical science basis. contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change [J]. Computational Geometry, 2007, 18(2): 95-123. DOI: 10.1016/S0925-7721(1)00003-7.

[4] SHEFFIELD J, Wood EF, RODERICK ML. Little change in global drought over the past 60 years[J]. Nature, 2012, 491(7424): 435-438. DOI: 10.1038/nature11575.

[5] FAO. Adaptation to climate change in agriculture, forestry and fisheries: perspective, framework and priorities[M]. Food & Agriculture Organization of the United Nations, 2007.

[6] ZHANG H L, WANG B, LIU H N, et al. Summer precipitation in Heilongjiang from 1961 to 2017: Climatic characteristics[J]. Chinese Agricultural Science Bulletin, 2019, 35(25): 115-122. (in Chinese)

[7] WANG T, DU C, NIE T, et al. Spatiotemporal analysis of maize water requirement in the Heilongjiang Province of China during 1960-2015[J]. Water, 2020, 12(9), 2472. DOI: https://doi.org/10.3390/w12092472.

[8] JIANG Q X, FU Q, WANG Z L, et al. Research on spatial variability of soil water characteristics in western semi-arid area of Heilongjiang Province[J]. Journal of Soil and Water Conservation, 2007, 21(5): 118-122. (in Chinese)

[9] ZHANG H, WANG B, LIU H, et al. Summer precipitation in Heilongjiang from 1961 to 2017: climatic characteristics[J]. Chinese Agricultural Science Bulletin, 2019, 35(25): 115-122. (in Chinese)

[10] YAO J, ZHANG H, QUE L, et al. Spatial and temporal pattern analysis of drought in crop growing season in Heilongjiang Province based on the standardized precipitation evapotranspiration index (SPEI) [J]. Journal of Inner Mongolia University for Nationalities (Natural Sciences), 2019, (5): 424-430. (in Chinese) DOI: 10.14045/j.cnki.15-1220.2019.05.011.

[11] ZHAO J, YANG X, LIU Z, et al. Greater maize yield improvements in low/unstable yield zones through recommended nutrient and water inputs in the main cropping regions, China[J]. Agricultural Water Management, 2020, 232, 106018. DOI: 10.1016/j.agwat.2020.106018.

[12] ADRIAN P, DUMITRU M, LILIANA G, et al. Spatiotemporal distribution of reference evapotranspiration in the Republic of Moldova[J]. Theoretical and Applied Climatology, 2016, 124(3-4): 1133-1144. DOI: 10.1007/s00704-015-1490-2.

[13] GONG L, XU C, CHEN D, et al. Sensitivity of the Penman-Monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) basin[J]. Journal of Hydrology. 2006, 329, 620-629.

[14] WANG R, ZHANG J, WANG C, et al. Characteristic analysis of droughts and waterlogging events for maize based on a new comprehensive index through coupling of multisource data in midwestern Jilin Province, China[J]. Remote Sensing, 2019, 12(1): 60. DOI: 10.3390/rs12010060.

[15] ESPADAFOR M, GAVILAN P, BERENGENA J. An analysis of the tendency of reference evapotranspiration estimates and other climate variables during the last 45 years in southern spain[J]. Agricultural water management, 2011, 98, 1045-1061. DOI: 10.1016/j.agwat.2011.01.015.

[16] COHEN S, IANETZ A, STANHILL G, et al. Evaporative climate changes at Bet Dagan, Israel, 1964-1998 [J]. Agricultural and Forest Meteorology, 2002, 111 (2): 83-91. DOI: 10.1016/S0168-1923(02)00016-3.

[17] CROITORU AE, PITICAR A, DRAGOTA CS, et al. Recent changes in reference evapotranspiration in Romania[J]. Global and Planetary Change, 2013, 111: 127-136. DOI: 10.1016/j.gloplacha.2013.09.004.

[18] CHANDHOK S, WILLIAMS JL, SCHWARTZMAN D. Anatomical analysis of recurrent conduction after circumferential ablation[J]. Journal of Interventional Cardiac Electrophysiology, 2010, 27(1): 41-50. DOI: 10.1007/s10840-009-9442-3.

[19] NIE T, ZHANG Z, QI Z, et al. Characterizing spatiotemporal dynamics of $CH_4$ fluxes from rice paddies of cold region in Heilongjiang Province under climate change[J]. International journal of environmental research and public health, 2019, 16(5). DOI: 10.3390/ijerph16050692.

[20] URETA C, GONZALEZ E J, ESPINOSA A, et al. Maize yield in Mexico under climate change[J]. Agricultural Systems, 2020, 177: 102697. DOI: 10.1016/j.agsy.2019.102697.

[21] LIU Z, YANG X, HUBBARD KG, et al. Maize potential yields and yield gaps in the changing climate of northeast China[J]. Global Change Biology, 2012, 18(11): 3441-3454. DOI: 10.1111/j.1365-2486.2012.02774.x.

[22] China meteorological data sharing service system[OL]. Available online: https://data.cma.cn/ (accessed on 2 September 2020)

[23] STANHILL G, COHEN S, METEOROLOGY F. Global dimming: A review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences[J]. Agricultural and Forest Meteorology, 2001, 107(4): 255-278. DOI: 10.1016/S0168-1923(00)00241-0.

[24] MORIONDO M, JONES GV, BOIS B, et al. Projected shifts of wine regions in response to climate change [J]. Climatic Change, 2013, 119(3-4): 825-839. DOI: 10.1007/s10584-013-0739-y.

[25] Smith, M. CROPWAT: Manual and Guidelines[M], FAO of UN: Rome, Italy, 1991.

[26] GAO X, WANG C, ZHANG J. Crop water requirement and temporal-spatial variation of drought and flood disaster during growth stages for maize in northeast during past 50 years[J]. Transactions of the Chinese Society of Agricultural Engineering. 2012, 28, 101-109. (in Chinese)

[27] ZHOU L, WANG Y, JIA Q, et al. Evapotranspiration over a rainfed maize field in northeast China: How are relationships between the environment and terrestrial evapotranspiration mediated by leaf area? [J]. Agricultural Water Management, 2019, 221, 538-546. DOI: 10.1016/j.agwat.2019.05.026.

[28] YANJUN S, YANING C, YONGQING Q, et al. Estimation of regional irrigation water requirement and water supply risk in the arid region of northwestern China 1989-2010[J]. Agricultural water management, 2013, 128(2013) 55-64. DOI: 10.1016/j.agwat.2013.06.014.

[29] WU X, WANG P, HUO Z, et al. Crop Drought identification index for winter wheat based on evapotranspiration in the Huang-Huai-Hai Plain, China[J]. Agriculture, Ecosystems & Environment, 2018, 263: 18-30. DOI: 10.1016/j.agee.2018.05.001.

[30] WANG X R. Effects of air pollution on radiation budget and meteorological elements in Beijing[D]. Beijing: China Academy of Meteorological Sciences, 2016. (in Chinese)

[31] NIE T, ZHANG Z, LIN Y, et al. Spatial and temporal distribution characteristics of maize water requirement in Heilongjiang Province[J], Transactions of the Chinese Society for Agricultural Machinery, 2018, 49(7): 217-227. (in Chinese)

[32] WANG D, ZHANG Z, LIANG Q, et al. Experimental study on water and fertilizer coupling effect of maize spray irrigation in semi-arid area of Heilongjiang Province [J]. Water Save Irrigation, 2016, 6, 15-18. (in Chinese)

[33] Collaboration Group on Isoline Map of Water Demand of Main Crops in China. Study on isoline map of water demand of main crops in China[M]. Agricultural Science and Technology Press: Beijing, China, 1993.

[34] GAO X, WANG C, ZHANG J. Crop water requirement and temporal-spatial variation of drought and flood disaster during growth stages for maize in northeast during past 50 years[J]. Transactions of the Chinese Society of Agricultural Engineering, 2012, 28, 101-109. (in Chinese)

[35] DING Y, WANG Z, SUN Y. Inter-decadal variation of the summer precipitation in east China and its association with decreasing Asian summer monsoon, Part I: Observed evidences[J]. International journal of climatology, 2008, 28, 1139-1161. DOI: 10.1002/joc.1615.

[36] ZHAI J, SU B, KRYSANOOVA V, et al. Spatial variation and trends in PDSI and SPI indices and their relation to streamflow in 10 large regions of China[J]. Journal of Climate, 2010, 23(3): 649-663. DOI: 10.1175/2009JCLI2968.1.

[37] ZHANG S, ZHANG Y, CAI F, et al. Changes of water budget and their effects and responses in northeastern China from 1961 to 2007[J]. Resources Science. 2010, (04): 79-86. DOI: 10.1016/S1001-0742(9)60222-9.

[38] ZHANG S, ZHANG Y, JI R, et al. Analysis of spatio-temporal characteristics of drought for maize in northeast China[J]. Agricultural Research in the Arid Areas, 2011, (01): 231-236. (in Chinese)

[39] LIU Y, WANG L, NI G, et al. Spatial distribution characteristics of irrigation water requirement for main crops in China[J]. Transactions of the Chinese Society of Agricultural Engineering, 2009, 25(12): 6-12. DOI: 10.3969/j.issn.1002-6819.2009.12.002.

[40] ZHOU H, ZHAO. Modeling soil water balance and irrigation strategies in a flood-irrigated wheat-maize rotation system: A case in dry climate, China[J]. Agricultural Water Management, 2019, 221: 286-302. DOI: 10.1016/j.agwat.2019.05.011.

[41] MLADEN T. Crop water requirements and irrigation scheduling[J]. Encyclopedia of Water, 2019, 12(29). DOI: 10.1002/9781119300762.wsts0204.

[42] MANJUNATHH S B, THIMME G P, SATYAREDDI S A, et al. Study on water requirement of maize (Zea mays L.) using CROPWAT Model in northern transitional zone of Karnataka[J]. Journal of Environmental Science, 2013, 2(1): 105-113.

[43] DU C, WANG T, NIE T, et al. Water surplus deficit and irrigation schedule of maize based on CROPWAT model[J]. Water Saving Irrigation, 2020(8): 91-97. (in Chinese)

# 黑龙江省西部地区玉米需水量与灌溉制度制定

聂堂哲[1]，梁契宗[1,2]，王天倚[1]，褚丽丽[1]，陈选[3]，李奉锐[4]

（1. 黑龙江大学水利电力学院，哈尔滨 150080；2. 中山大学土木工程学院水资源与环境研究中心，广州 510275；
3. 宁海县水务局，浙江 宁波 315600；4. 河北省邢台水文勘测研究中心，河北 邢台 054000）

**摘要：**黑龙江省西部地区频发的干旱情况影响该地区农业水循环与粮食安全，研究玉米水分供需关系对于理解该地区干旱机理有重要意义。根据 FAO-56 单作物系数法，计算玉米生育期参考作物蒸散量（$ET_0$）、作物需水量（$ET_c$）和灌溉需水量（$I_r$），依托 CROPWAT 模型制定灌溉制度，并通过计算作物水分盈亏指数（$C_W$）分析玉米水分盈余情况。结果表明：1960—2015 年黑龙江省西部玉米生育期 $ET_0$ 和 $ET_c$ 呈下降趋势，有效降水量（$P_e$）、$I_r$ 和 $C_W$ 呈上升趋势；平均 $ET_0$、$ET_c$、$P_e$ 和 $I_r$ 分别为 639.64、438.13、224.40 和 273.87 mm；由于不同水文年干旱条件不同，$P_e$ 并不能在所有年份满足玉米水分需求，丰水年、平水年、枯水年和特枯水年的平均净灌溉定额分别为 152.43、236.33、276.53 和 353.47 mm。黑龙江省西部玉米生育期水分供需关系的研究和灌溉制度的制定有助于区域水资源调控和农业发展。

**关键词：**参考作物蒸散量；作物需水量；作物水分盈亏指数；有效降雨量；灌溉需水量；灌溉制度

（上接第 959 页）

winter wheat yield into climatic yield and trend yield, to screen the years with high yield variability, i. e. , three high yield years and three low yield years, and to reveal the main meteorological factors affecting yields, and then to analyze the relationship between winter wheat yield and climate change.

The results showed that the average temperature (0.05 ℃ • $a^{-1}$), maximum temperature (0.03 ℃ • $a^{-1}$) and minimum temperature (0.07 ℃ • $a^{-1}$) in wheat season increased significantly, the average wind speed decreased significantly (−0.01 m • $s^{-1}$ • $a^{-1}$), and the multi-year mean value of total $ET_0$ was 600 mm with a not clear increasing trend. The multi-year average of actual winter wheat yield was 5 330 kg • $ha^{-1}$. Both the actual and trend yields showed a significant increasing trend with Sen's slopes of 136 kg/($hm^2$ • $a^{-1}$) and 139 kg/($hm^2$ • $a^{-1}$), respectively. Though the climatic yield trend did not show a clear change trend, it varied from −1 245 to 1 376 kg • $ha^{-1}$ (−41%～26%), indicating a great variation in different years. The climate variables in big low yield and high yield seasons were analyzed and the main factors to influence wheat yield were summarized. Generally, extremely low temperature during the sowing-regreening period (for example December 8 and 9, 1986, the daily minimum temperature reached −21.2 ℃, and the average minimum temperature from January 14 to 25, 1993 reached −14.1 ℃), un-sufficient irrigation during a jointing-heading period (1993) and excessive precipitation in late planting period (2008) would lead to wheat yield reduction. The increases in sunshine hours and temperature are beneficial to wheat production.

The trends of climate elements are consistent with the findings of most studies in the north China plain, indicating that climate change in the study area is consistent with the trends of climate change at larger spatial scales. Yields in the study area increased at a faster rate in the 1990's, indicating a significant increase in the level of winter wheat cultivation during that period. The influence of climate factors on winter wheat yield in low yield years shows that extremely low temperatures during the sowing-regreening period, un-sufficient irrigation during the jointing-heading period, and excessive precipitation in the late planting period can all lead to wheat yield reduction. The main meteorological factors causing yield reduction varied with growth seasons, indicating the complexity of climate effects on wheat yield production. The influence of climate factors on winter wheat yield in high-yielding years shows that the increase in sunshine hours is more beneficial to wheat yield under the condition that the temperature remains consistent with the multi-year average. The main meteorological factors causing yield increase are similar in different years, indicating the consistency of climate factors on wheat yield increase.

**Key words:** climatic yield; winter wheat; typical low yield year; typical high yield year