water

MDPI

Article

Study on the Water Supply and the Requirements, Yield, and Water Use Efficiency of Maize in Heilongjiang Province Based on the AquaCrop Model

Tangzhe Nie [1], Yang Jiao [1], Yi Tang [1], Na Li [1], Tianyi Wang [1,2], Chong Du [1,*], Zhongxue Zhang [2,3], Tiecheng Li [2,3], Shijiang Zhu [4], Zhongyi Sun [5] and Fengrui Li [6]

1 School of Water Conservancy and Electric Power, Heilongjiang University, Harbin 150080, China; 2019036@hlju.edu.cn (T.N.); jiaoyang0814@163.com (Y.J.); ty979794@163.com (Y.T.); L17863523371@163.com (N.L.); wangtianyi7176@163.com (T.W.)
2 School of Water Conservancy and Civil Engineering, Northeast Agricultural University, Harbin 150030, China; zhangzhongxue@163.com (Z.Z.); litiecheng1212@126.com (T.L.)
3 Key Laboratory of Agricultural Water Resource Use, Ministry of Agriculture, Harbin 150030, China
4 College of Hydraulic and Environmental Engineering, China Three Gorges University, Yichang 443002, China; zhusjiang@aliyun.com
5 College of Ecology and Environment, Hainan University, Haikou 570208, China; gis.rs@hainanu.edu.cn
6 Xingtai Hydrographic Survey and Research Center of Hebei Province, Xingtai 054000, China; 2191532@s.hlju.edu.cn
* Correspondence: duchong@hlju.edu.cn; Tel.: +86-136-3366-1083

Citation: Nie, T.; Jiao, Y.; Tang, Y.; Li, N.; Wang, T.; Du, C.; Zhang, Z.; Li, T.; Zhu, S.; Sun, Z.; et al. Study on the Water Supply and the Requirements, Yield, and Water Use Efficiency of Maize in Heilongjiang Province Based on the AquaCrop Model. *Water* **2021**, *13*, 2665. https://doi.org/10.3390/w13192665

Academic Editor: Junzeng Xu

Received: 23 July 2021
Accepted: 24 September 2021
Published: 27 September 2021

Abstract: Agricultural irrigation depends heavily on freshwater resources. Under the context of increasingly severe water shortages, studying the relationship among crop water requirements (ET_c), actual crop evapotranspiration (ET_a), irrigation water requirements (I_r), yield, and water use efficiency (*WUE*) would be beneficial to improve the agricultural application of irrigation water. Based on the daily data of 26 meteorological stations in Heilongjiang Province from 1960 to 2015, this study used the calibrated AquaCrop model to calculate the ET_c, ET_a, I_r, and yield of maize (*Zea mays* L.) in different hydrological years (extremely dry years, dry years, normal years, and wet years) along with *WUE* to evaluate the mass of yield produced per unit mass of crop evapotranspiration (*ET*) under rainfed and irrigated scenarios. The results showed that ET_c and ET_a decreased first and then increased from the west to the east during the four types of hydrological years. I_r exhibited a decreasing trend from the west to the east. Compared with the irrigation scenario, the rainfed scenario's average yield only decreased by 2.18, 0.55, 0.03, and 0.05 ton/ha, while the *WUE* increased by 0.32, 0.4, 0.33, and 0.21 kg/m^3 in the extremely dry years, dry years, normal years, and wet years, respectively. The results indicated that in the normal and wet years, the *WUE* was high in the central regions, and irrigation did not significantly increase yield; further, we determined that irrigation should not be considered in these two hydrological years in Heilongjiang Province. In the extremely dry and dry years, irrigation was necessary because it increased the yield, even though the *WUE* decreased. This study provides a theoretical basis for studying the regional irrigation schedule in Heilongjiang Province.

Keywords: maize; AquaCrop model; crop water requirements (ET_c); actual crop evapotranspiration (ET_a); irrigation water requirements (I_r); yield; water use efficiency (*WUE*); irrigation and rainfed scenario

1. Introduction

At present, the shortage of freshwater is regarded as one of the most critical global problems by scientists, policymakers, and even the general public [1]. According to an analysis of global water scarcity, two-thirds of the world's population will be affected by water scarcity in the next few decades. Water shortages in developing countries are also attributable to water distribution, poor management, and the inherent injustices and inequities of water distribution [2]. Agricultural water accounts for 70–75% of the total freshwater extracted. The available agricultural resources and the narrowing yield gaps of all crops play a crucial role in providing sufficient food for the rapidly growing global population [3]. According to Food and Agriculture Organization (FAO) projections, food production in irrigated areas will need to be increased by more than 50% by 2050, but only a 10% increase in water withdrawal for agriculture will be possible [4]. In addition, the large amount of agricultural irrigation has led to a rapid decline in the groundwater level over the past 20 years [5]. Some areas have experienced severe land subsidence, salt intrusion near the coast, degradation of ecosystems, and deterioration of groundwater quality [5].

Promoting sustainable agriculture, increasing crop productivity, and ensuring the effective management of limited water resources are indispensable for increasing global food production [6]. Maize (*Zea mays* L.) is one of the most important global food sources, accounting for 30% of the world's total grain production [7,8]. As the world's population continues to grow, by 2050, maize yield needs to increase by 66% to meet global demands [9]. As one of the arid countries, China is also the second-largest maize-producing country. Arid and semi-arid regions in the north of China make up 30% of the national land area but have less than 20% of total national available water resources because precipitation is low and evapotranspiration is high [10–12]. Using precipitation resources reasonably may become one of the fastest and most effective ways to alleviate water shortages and reduce unnecessary irrigation [7,13]. Moreover, numerous studies have shown a correlation between crop yields and water consumption in arid regions, as precipitation and crop adaptability directly impact the precipitation use efficiency of crops, thereby affecting crop yields [13–15]. In the north of China, droughts occur in maize growing stages frequently; in dry years, irrigation alleviates the reduction in maize production, while in wet years, precipitation meets maize water requirements [16]. Therefore, in order to explore the difference between maize under rainfed and irrigation scenarios, make full use of precipitation to reduce irrigation water requirements (I_r), study on maize evapotranspiration (ET) and yield may provide a basis for the regional balance on irrigation and rainfed.

As a significant component of the regional and global hydrological cycle, crop water requirements (ET_c) play an essential role in evaluating related I_r and crop water stress in agricultural ecosystems [17]. Exploring the relationship between ET_c and I_r will help maximize the use of rain resources and optimize the allocation of regional water resources. As precipitation directly affects the ET_c, actual crop evapotranspiration (ET_a), and I_r values of different crops, for maize, the precipitation in normal years and wet years can almost meet the ET_a, and irrigation is only required in dry years. However, irrigation significantly increases the wheat yield in semi-arid areas [18]. Irmak indicated that in maize growing season, there was an ununiform temporal distribution of precipitation, resulting in greater ET_c or ET_a losses. In these circumstances, full irrigation has a higher yield than rainfed [19]. In semi-arid China, irrigation could alleviate crop ET_a losses which are caused by the uneven distribution of precipitation, and in a dry year, irrigation would be more efficient to crop growth than in a wet year, though irrigation appears valuable in a wet year [20]. The relationship among ET_c, ET_a, and I_r varies depending on the crop, region, precipitation amounts, and distribution patterns, especially the changes in effective precipitation that affect ET_a, $ET_{c,}$ and I_r [21].

Water use efficiency (*WUE*) can be used to assess the relationship between water and crop yields. Many studies have used *WUE* to evaluate the practicality of irrigation management (rainfed, limited, or full irrigation). Crops in the northern Republic of Serbia are largely grown under rainfed conditions; due to the high variability of regional precipitation, and low crop yields are closely related to insufficient precipitation [22]. In Vojvodina, *WUE* was found to be higher during dry and normal years than during wet years. Moreover, lower *WUE* and higher yields were found for fully irrigated treatments compared to rainfed treatments [23]. In arid areas, to increase crop yields and *WUE*, irrigation at a fixed time is more effective than rainfed irrigation [24]. A previous study showed that crop *WUE* increased with an increase in irrigation until the additional irrigation no longer produced additional yield [25]. Moreover, because of differences in regional environmental conditions and seasonal precipitation fluctuations, irrigation may not improve *WUE* and yield continuously [26]. In eastern China, especially during dry years with little precipitation, rainfed farming provides insufficient water to crops, and irrigation is needed to reduce yield loss [27]. In the case of seasonal precipitation fluctuations and large inter-annual differences in precipitation, *WUE* provides a theoretical basis for regional water consumption and changes in the irrigation schedule under different circumstances.

The above factors underscore the need to identify irrigation patterns under rainfed and irrigated scenarios to maximize the utilization of available resources and improve productivity. However, due to time, funding, and resource constraints, it is not feasible to evaluate large combinations of various crop management options under field scenarios in many different regions and environmental contexts. To solve this issue, AquaCrop, as a fully tested, calibrated, and validated crop model, can be used to evaluate factors affecting maize yield and *WUE* [28]. López-Urrea et al. noted that AquaCrop correctly simulates the evolution of the harvest index, canopy cover (*CC*), ET_a, ET_c, yield, and aboveground biomass and is a better model than MOPECO for assessing the impact of a specific irrigation system on crops [29]. Nader Pirmoradian et al. found that AquaCrop can accurately simulate the I_r of a crop in wet, normal, and dry years [30]. Heng et al. further concluded that FAO's AquaCrop is an excellent crop growth model for designing and evaluating water management plans and studying the soil types and sowing dates of crops under rainfed or irrigated scenarios. The model was found to correctly simulate *ET* and production, and the measured and simulated values of *WUE* showed a high degree of fit [27]. However, when this model is implemented for practical purposes, it is necessary to use field measurements from different climate regions to verify the model under water-management scenarios to ensure the model's accuracy, as well as its potential limitation. Therefore, it is necessary to carefully test, calibrate, and validate the model for specific locations when simulating crop yields [31].

Heilongjiang Province is one of the main grain-producing areas [32]. As the main food crop, maize is a widely planted crop, and its planting area is increasing year by year. As of 2016, the planting area of maize was 7.72×10^6 hm^2, accounting for 52.2% of the province's crop planting area, and its yield was 3.544×10^7 t, accounting for 56% of the province's grain [33]. The East Asian summer monsoon controls precipitation in Heilongjiang Province, where the ET_c and irrigation are different over time and space [34]. Therefore, it is necessary to quantify the ET_c and I_r of maize, clarify the temporal and spatial changes and trends of ET_c and I_r, and determine the irrigation management methods necessary for different places and hydrological years. This assessment will provide essential information for irrigation strategies and sustainable water management to adapt to climate change in the region.

The purposes of this study were to (1) quantify the ET_c, ET_a, I_r, and yield of maize over four hydrological years in Heilongjiang Province (from 1960 to 2015) using AquaCrop; (2) clarify the temporal and spatial distribution of ET_c and ET_a in the growing seasons of maize; (3) determine the temporal and spatial variations in yield and *WUE* under irrigation and rainfed scenarios; and (4) further reveal the effects of rainfed and irrigated scenarios on the I_r and *WUE* of maize.

2. Materials and Methods

2.1. Study Area

This paper used the daily meteorological data from 26 stations in Heilongjiang Province from 1960 to 2015, including the maximum air temperature, minimum air temperature, average relative humidity, average wind speed, sunshine duration, precipitation, and longitude and latitude information of each station. All the above data were obtained from the China Meteorological Data Network (http://data.cma.cn, accessed on 22 July

2021), and the CO_2 data were obtained from the UK Greenhouse Gas Emissions database (https://www.gov.uk, accessed on 22 July 2021). Figure 1 shows the study area and the distribution of the site. Due to the different geographical locations of the meteorological stations in Heilongjiang Province, each station's division of annual accumulated temperature is different. According to the Heilongjiang Provincial Agricultural Commission's reports, "Heilongjiang Crop Variation Accumulative Temperature Zone" [35] and "Area Layout Planning of High-quality and High-yield Main Food Crops in Heilongjiang Province in 2015" [36], the sixth accumulative temperature zone is not suitable for maize planting. Therefore, the sixth temperature accumulation zone was not studied in this paper.

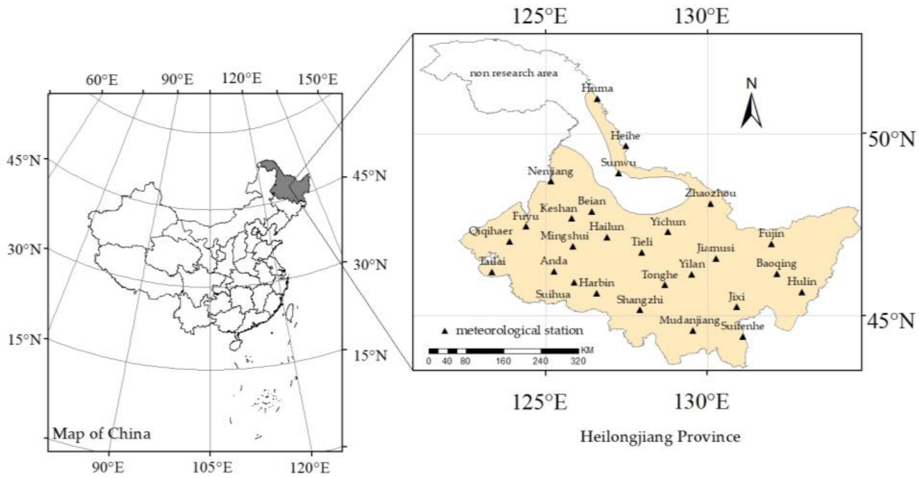


Figure 1. Map of the study area and distribution of meteorological stations in Heilongjiang Province.

2.2. Sources of Experimental Data

Data from three field experiments investigating maize planted in Heilongjiang Province, China, were used for the model calibration and verification (Table 1). The first experimental area was located at the Heilongjiang Province Hydraulic Research Institute, Harbin. The areas used for the second and third experiments were located at the Institute of Water Resources Science and Agricultural Technology Extension Center, Zhaozhou County, Daqing city [37–39].

Table 1. Crop management data obtained from three field experiments conducted in Heilongjiang Province, China, and used in the AquaCrop model calibration and verification.

	1st Experiment		2nd Experiment	3rd Experiment
Location	(126°36′35″ E, 45°43′09″ N)		(125°35′10″ E, 45°17′31″ N)	(125°17′57″ E, 45°42′57″ N)
Year	29 April–27 September 2014	28 April–24 September 2015	28 April–27 September 2014	3 May–27 September 2017
Treatment	Irrigation [1]	Irrigation [1]	Irrigation [2]	Rainfed [3]
Irrigation period	Seedling stage Jointing stage Tasseling stage Milk ripening stage	Seedling stage Jointing stage Tasseling stage Milk ripening stage	Tasseling stage Milk ripening stage Jointing stage	None
Irrigation limitation (%)	80 FC [4]	80 FC	none	0
Irrigation ceiling (%)	100 FC	100 FC	none	0

Table 1. *Cont.*

	1st Experiment		2nd Experiment	3rd Experiment
Irrigation quota (mm)	300~400	300~400	400	0
Data used in AquaCrop	Calibration	Verification	Verification	Verification

[1] Irrigation: when the maize soil water content reached 80% field capacity, with 100% field capacity achieved by the end of the day. [2] Irrigation: only irrigated three times during the maize growth period. [3] Rainfed: the growth of maize depended on precipitation. [4] FC: field capacity.

2.3. *AquaCrop Model Principle*

2.3.1. AquaCrop Model Description

The weather model included precipitation, reference crop evapotranspiration(ET_0), CO_2, and maximum air temperature, minimum air temperature, and daily ET_0 was calculated by the Penman–Monteith equation recommended by the FAO [40,41]. The crop model included crop growth, development, senescence, and yield. The management submodels included irrigation and field management practices; the soil models included soil and water balance management. The four main production processes were simulated using a daily time step and included crop development, transpiration (T_r), aboveground biomass production, and yield.

First, we used the green canopy cover (CC) in AquaCrop to simulate crop growth, development, and aging. CC was then used in conjunction with ET_0 and the transpiration coefficient (K_{cTr}) to calculate transpiration. Similarly, soil evaporation was calculated using the soil evaporation coefficient, CC, and ET_0 [31].

2.3.2. From the K_y Approach to the AquaCrop Model

The yield response to water (K_y) is used here to describe the relationship between crop yield and water stress due to the insufficient water supply by precipitation or irrigation during the growing period. In FAO.33, an empirical production function is used to assess the yield response to water [42]:

$$\left(1-\frac{Y}{Y_x}\right)=K_y\left(1-\frac{ET}{ET_x}\right) \quad (1)$$

where Y_x (ton/ha) and Y (ton/ha) are the maximum and actual yield, and $(1 - Y/Y_x)$ is the relative yield decline. ET_x (mm) and ET (mm) are the maximum and actual evapotranspiration, $(1 - ET/ET_x)$ is the relative water stress, and K_y is the proportionality factor between the relative yield decline and relative reduction in ET. When $K_y > 1$: crop response is very sensitive to water deficit with proportional larger yield reductions when water use is reduced because of stress. When $K_y < 1$: crop is more tolerant to water deficit and recovers partially from stress, exhibiting less than proportional reductions in yield with reduced water use. When $K_y = 1$: yield reduction is directly proportional to reduced water use.

2.3.3. Evapotranspiration and Yield

This model estimates transpiration and yield by establishing canopy growth and senescence models. For our study, ET_c was divided into transpiration and evaporation components to avoid the impact of the unproductive consumption (evaporation) of water [43–45]. Under the rainfed scenario, crops may be subjected to water stress, in which case, the crop evapotranspiration is ET_a. The Formulas (2) and (3) in AquaCrop for calculating crop transpiration (T_r, mm/ day), soil evaporation (E, mm/day), and final grain yield (Y, ton/ha) are as follows [46]:

$$T_r = K_s K_{s_{Tr}}\left(K_{c_{Tr,x}} CC^*\right) ET_0 \quad (2)$$

$$E = K_r(1 - CC^*)K_{ex} ET_0 \quad (3)$$

$$Y = f_{HI} HI_0 B \quad (4)$$

where CC^* is the actual canopy cover (%) adjusted for micro-advective effects, K_s is the crop coefficient, and K_{sTr} is temperature stress. $K_{cTr,x}$ is the maximum standard crop transpiration coefficient (dimensionless), ET_0 is the grass-reference evapotranspiration (mm/day), K_r is the evaporation reduction coefficient used to adjust for the effect of insufficient water in the topsoil layer, K_{ex} is the maximum soil evaporation coefficient, f_{HI} is the adjustment factor for water stresses, HI_0 is the reference harvest index, and B is the aboveground dry biomass (ton/ha).

2.4. Scenario Setting and Maize Irrigation Water Requirements

In this study, we developed two scenarios to explore the changes in irrigation water supply and the requirements and yield of maize in Heilongjiang Province:

1. Rainfed: The distribution of precipitation in Heilongjiang Province was uneven over the four seasons. Past studies showed that the distribution of precipitation in Heilongjiang Province has decreased in recent decades and that most of the maize planting in this region relies on rainfed farming [35]. The rainfed scenario involves the use of precipitation alone, without irrigation.
2. Irrigation: In this study, irrigation without a water shortage was used to compare the differences in maize ET_a, ET_c, I_r, yield, and *WUE* between the rainfed and irrigated scenarios. In the AquaCrop model, irrigation management was achieved through irrigation timing and the number of irrigation events during the crop growing season. In the irrigation scenario, maize was considered fully irrigated when the soil water content reached 80% field capacity, with 100% field capacity achieved by the end of the day to restore root zone moisture.

2.5. AquaCrop Model Data and Evaluation

The AquaCrop model provides default parameters for maize, but these default parameters cannot sufficiently reflect ET_a, ET_c, and yield during maize growing stages when used; the default parameters need to be verified (Table 2). The calibration procedure followed the guidelines outlined in the AquaCrop Reference Manual and FAO Irrigation and Drainage Document No.66, Crop Yield Responses to Water [46]. The experiments used for calibration and verification are shown in Table 1.

Table 2. Default and calibrated maize parameters for Aquacrop used in this study.

Parameter	Default	Calibrated
Conservative		
Base temperature (°C)	5.5	5.5
Cut off temperature (°C)	30	30
Canopy cover per seedling (cm^2 plant^{-1})	6.5	6.5
Crop transpiration (K_{cTr})	1.10	1.10
Canopy expansion stress coefficient (P_{upper})	0.25	0.25
Canopy expansion stress coefficient (P_{lower})	0.6	0.6
Crop water productivity (WP^*)	17	32
Initial canopy cover (CC_0)	1.2	0.36
Maximum canopy cover (%)	80	90
Reference harvest index	50	40
Non-conservative		
Time from sowing to emergence (day)	5	15
Time from sowing to max canopy cover (day)	70	80
Time from sowing to flowering (day)	87	99
Time from sowing to senescence (day)	120	134
Maximum effective rooting depth (cm)	1.0	1.0
Plant density (plants ha^{-1})	185,000	56,000

The output of the AquaCrop model compared to the field measurements was assessed using both qualitative and quantitative approaches. The qualitative approach involved the use of graphical interpretations of the results to evaluate the trends in simulated and measured data. The quantitative approach consisted of using statistical indicators such as the root mean square error (*RMSE*), the normalized root mean square error (*NRMSE*), the Nash–Sutcliffe model efficiency coefficient (*EF*), the coefficient of determination (R^2), and Willmott's index of agreement (*d*).

The *RMSE* measures the magnitude of difference between simulated and observed values and ranges from 0 to positive infinity, with 0 indicating good model performance and positive infinity indicating poor model performance [47]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - M_i)^2}{n}} \quad (5)$$

$$NRMSE = \frac{100RMSE}{\overline{O}} \quad (6)$$

where M_i and S_i (i = 1, 2, . . . , n) represent the measured and simulated values, and $\overline{O}$ is the average of the measured values. If *NRMSE* < 10%, the verification is considered to have a high degree of fit. If the *NRMSE* is between 10% and 20%, the fit is deemed good. If the *NRMSE* is between 20 and 30%, the verification is considered acceptable in terms of goodness-of-fit. If the value is greater than 30%, the verification fit is assumed to be poor [48].

The *EF* (ranging from 1 to negative infinity) determines the relative size of the residual value and the degree of fit between the observed data and the simulated data. An *EF* close to 1 indicates that the residual value is small and that the model offers a reasonable simulation. R^2 is the coefficient of determination (goodness-of-fit). The better the goodness-of-fit, the higher the independent variable's explanation for the dependent variable [49]. Here, *d* ranges from 0 to 1, indicating that the model performance is better when *d* is close to 1. The calculation formula is as follows:

$$EF = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(M_i - \overline{M})^2} \quad (7)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}\left(|S_i - O_i| + |O_i - \overline{O}|\right)^2} \quad (8)$$

where $\overline{M}$ represents the mean value, and R^2 and *EF* are used to quantify the predictive ability of the model, while the *RMSE* represents the model prediction error.

2.6. Division of Hydrological Years

The precipitation during the maize growing season at different sites levels from 1960 to 2015 was arranged in decreasing order of magnitude. Formula (9) was used to calculate the empirical frequency and draw the logarithmic normal distribution map to obtain the precipitation, precipitation values at F_a = 95%, 75%, 50%, 25% probability were defined as extremely dry year, dry year, normal year, and wet year [50] The average precipitation during the maize growing season in extremely dry, dry, normal, and wet year were 256.1, 333.6, 410.4, 487.9 mm in Heilongjiang Province. The precipitation varies in different regions, but we strictly follow the formula:

$$Fa = \frac{100m}{n+1} \quad (9)$$

where F_a is the empirical frequency of *m* items in the observation series, *m* is the sequence number of the observation series arranged from large to small, and *n* is the number of years in the observation series.

2.7. Water Use Efficiency

Increasing crop *WUE* is the key to increasing agricultural productivity under limited water resources. *WUE* refers to the amount of assimilated matter produced per unit of water consumed during crop production, reflecting the relationship between the yield and *ET* of crops [37]. The calculation method is as follows:

$$WUE = \frac{Y}{ET} \tag{10}$$

where *WUE* is expressed in kg/m^3 based on units of water volume, *ET* is evapotranspiration (mm), and *Y* is grain yield (ton/ha).

2.8. Data Processing

In this paper, we used the spatial analysis function of ArcMap 10.5 toolbox to interpolate the spatial distribution maps of ET_c, ET_a, I_r, yield, and *WUE* in different hydrological years.

3. Results

3.1. Calibration and Verification of the AquaCrop Model

3.1.1. Crop Water Requirement

Figure 2 illustrates a comparison between the measured and simulated values of ET_c at all growth stages, based on a calibration of AquaCrop in Harbin 2014. The corrected model underestimated the ET_c with values 15~30 mm in the late growth period (Figure 2). However, the model showed a high degree of fit overall, with low *RMSE* (19.56 mm) and *NRMSE* (14.25%) and acceptable *EF* (0.87) and *d* (0.67) values.

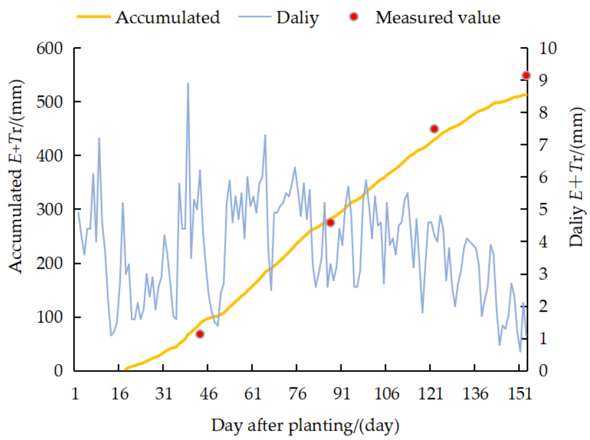
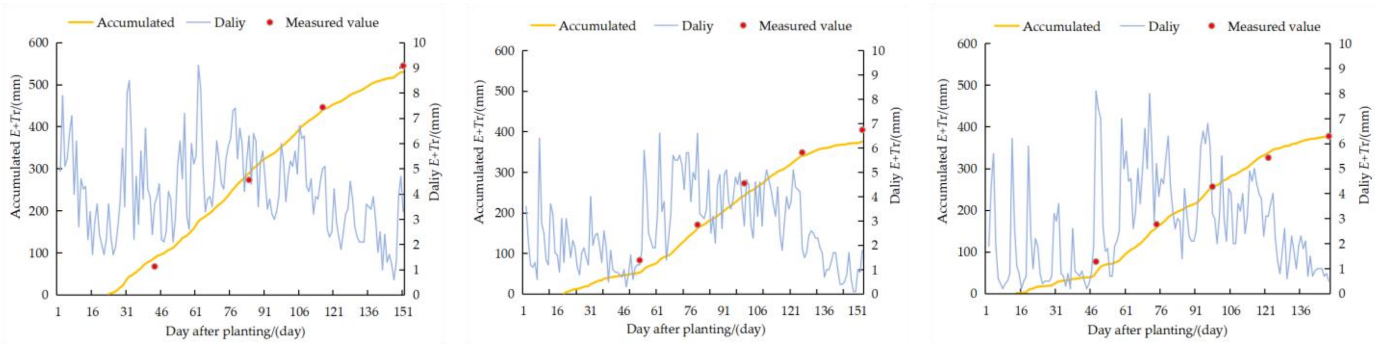


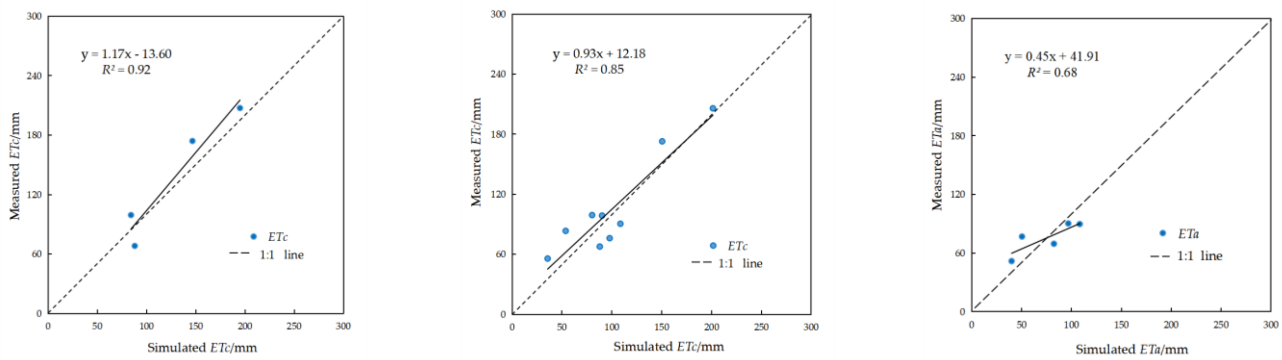
Figure 2. Simulated and measured accumulated ET_c ($E + T_r$) during the growing season in Harbin, 2014. *ET*: soil evaporation, T_r: crop transpiration, same as below.

The measured and simulated values of ET_c at different growth stages were compared and verified by the data for Harbin in 2015 and Zhaozhou in 2014 and 2017 (Figure 3). In the verification process, AquaCrop was used to simulate the growth trend of maize during the growth seasons. However, as the model underestimated the ET_c with the value of 10~30 mm in the later growth stage, the degree of underestimation was less than that of the calibration 50~60 mm. Figure 4 illustrates a comparison between all the measured and simulated values listed in Table 3; these values provided the goodness-of-fit parameters for model calibration and verification in all years and locations. AquaCrop underestimated the ET_c during calibration, and the results showed an overestimation of ET_c though R^2 close to 1, during verification, especially for the verified ET_a (R^2 = 0.68) in Figure 4. In general, the model provided a high degree of fit between the simulated and measured values.



(**a**) Harbin, 2015 (**b**) Zhaozhou, 2014 (**c**) Zhaozhou, 2017

Figure 3. Simulated and measured accumulated ET_c ($E + T_r$) and ET_a ($E + T_r$) from model verification during the growing seasons in (**a**) Harbin (2015), (**b**) Zhaozhou (2014), and (**c**) Zhaozhou (2017).



(**a**) (**b**) (**c**)

Figure 4. Calibration for (**a**) Harbin (2014) and verification of the measured and simulated ET_c for (**b**) Harbin (2015) and Zhaozhou (2014); (**c**) ET_a for Zhaozhou (2017) under the irrigation and rainfed scenarios. ET_c: crop water requirements, ET_a: actual crop evapotranspiration, same as below.

Table 3. The goodness-of-fit indexes from the growing-season model simulation: yields in 2014, 2015, and 2017.

	Location (Year)	**The Goodness-of-Fit Parameters**			
		RMSE **(mm)**	***NRMSE*** **(%)**	***EF***	***d***
Calibration	Harbin (2014)	19.56	14.25	0.87	0.67
Verification	Harbin (2015)	15.79	11.59	0.92	0.94
	Zhaozhou (2014)	19.85	24.51	−0.66	0.66
	Zhaozhou (2017)	16.70	22.08	0.60	0.64

3.1.2. Yield

The yields of four experiments were used for calibration and verification. The measured and simulated yields are shown in Figure 5. The model results indicate that the simulated yield overestimated the actual yield less than 0.6 ton/ha with R^2 (0.9) close to 1. The model had low *RMSE* (0.595 ton/ha) and *NRMSE* (4.2%) values and acceptable *EF* (0.98), *d* (0.9), and R^2 (0.901) values.

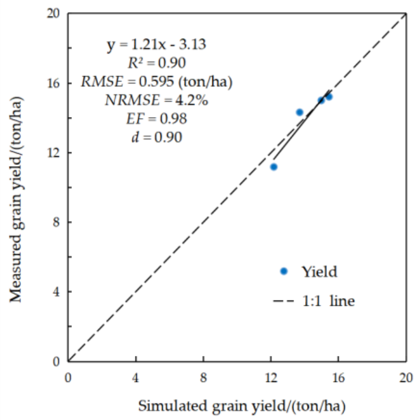


Figure 5. Calibration and verification results for the measured and simulated yields in all years (Zhaozhou (2014), Harbin (2014–2015), and Zhaozhou (2017).

3.2. Comparison of ET_c and ET_a in Different Hydrological Years

The characteristics of ET_a and ET_c in the growing season of maize were then determined. The spatial distribution patterns of ET_a and ET_c were generally similar over the four hydrological years—first decreasing and then increasing from west to east. High ET_c and ET_a with values greater than 500 and 400 mm were located along the strip extending from the west to the south (Figure 6). As a whole, the average ET_c decreased from the extremely dry years to wet years, with values of 499, 464, 453, and 423 mm, respectively. The value of the average ET_a increased from the extremely dry years to normal years and varied weakly from normal years to wet years. The average ET_a values were 144, 82, 52, and 31 mm lower, respectively, than the average ET_c values.

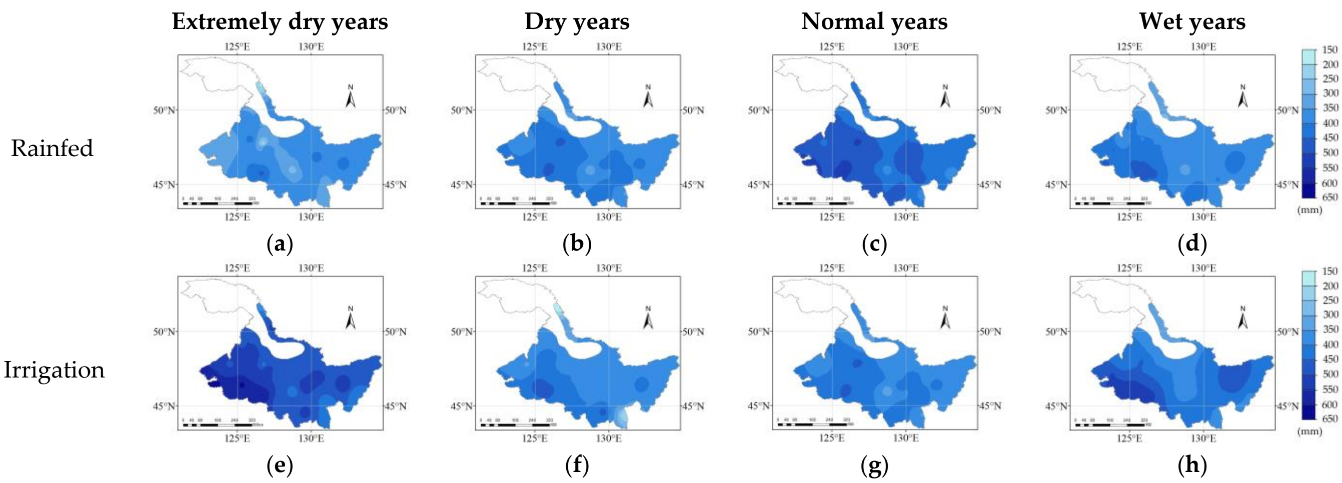


Figure 6. Spatial distribution of ET_a and ET_c in extremely dry years (**a**,**e**), dry years (**b**,**f**), normal years (**c**,**g**), and wet years (**d**,**h**) under rainfed and irrigation scenarios.

3.3. Spatial Distribution of I_r in Different Hydrological Years

Weak variations in I_r trends were observed between the four hydrologic years in the different regions, with a decreasing trend from west to east over the four hydrological years (Figure 7). The average I_r values were 289, 212, 141, and 80 mm, and high values were mainly distributed in the west, similar to the locations of ET_c, greater than 400, 300, 200, 100 mm in the extremely dry years, dry years, normal years, and wet years, respectively.

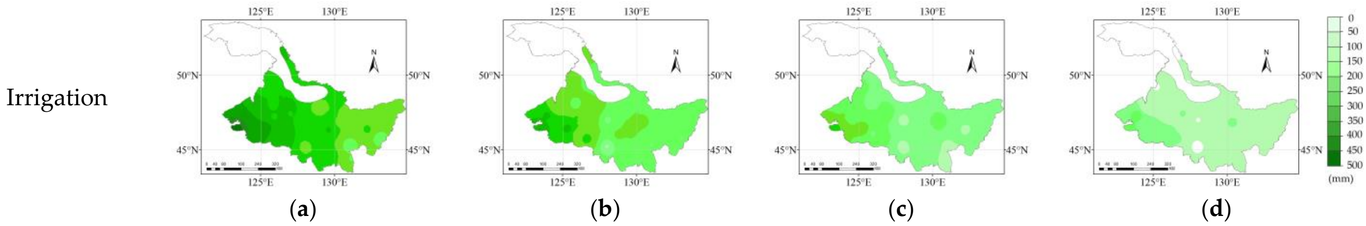


Figure 7. Spatial distribution of I_r in extremely dry years (**a**), dry years (**b**), normal years (**c**), and wet years (**d**) under irrigation scenario.

3.4. Spatial Distribution of Yield in Different Hydrological Years under Rainfed and Irrigation Scenarios

The average yields under the rainfed scenario during the extremely dry years, dry years, normal years, and wet years were 9.59, 11.32, 11.73, and 11.71 ton/ha, respectively. Irrigation increased maize yield in most areas during the extremely dry and dry years by 2.18 and 0.55 ton/ha, respectively, especially in the regions where ET_c and I_r were high. However, in the normal and wet years, irrigation only increased the yield by 0.03 and 0.05 ton/ha, respectively (Figure 8). The high yield values greater than 13.0 ton/ha were mainly distributed in the southwest, while the low yield values less than 8.5 ton/ha were primarily distributed in the eastern regions.

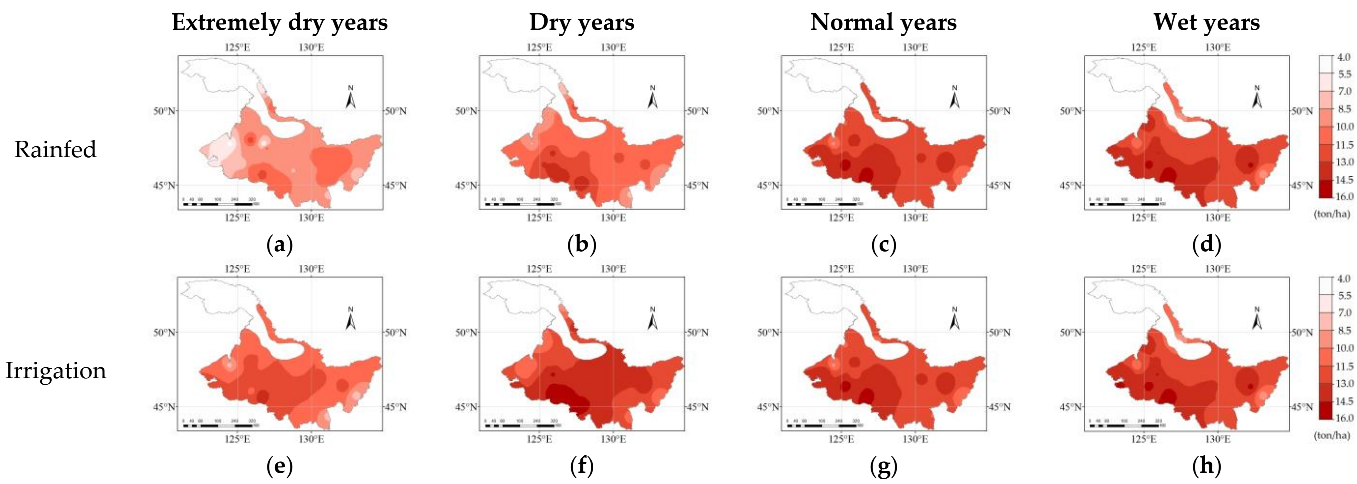


Figure 8. Spatial distribution of yield in extremely dry years (**a**,**e**), dry years (**b**,**f**), normal years (**c**,**g**), and wet years (**d**,**h**) under the rainfed and irrigation scenario.

3.5. Spatial Distribution of WUE in Different Hydrological Years under Rainfed and Irrigation Scenarios

WUE showed a trend of increasing first and then decreasing from the western to the eastern regions over the four hydrological years (Figure 9). The average *WUE* under the rainfed scenario in the respective extremely dry years, dry years, normal years, and wet years was 2.70, 3.00, 2.95, and 2.99 kg/m^3. The average *WUE* under the irrigation scenario was 0.32, 0.4, 0.33, and 0.21 kg/m^3 lower than that under the rainfed scenario in the extremely dry years, dry years, normal years, and wet years. Overall, irrigation reduced the *WUE* over the four hydrological years, especially during normal and wet years. Irrigation did not significantly improve the *WUE* and yield in most areas; thus, rainfed farming could be employed as an alternative schedule.

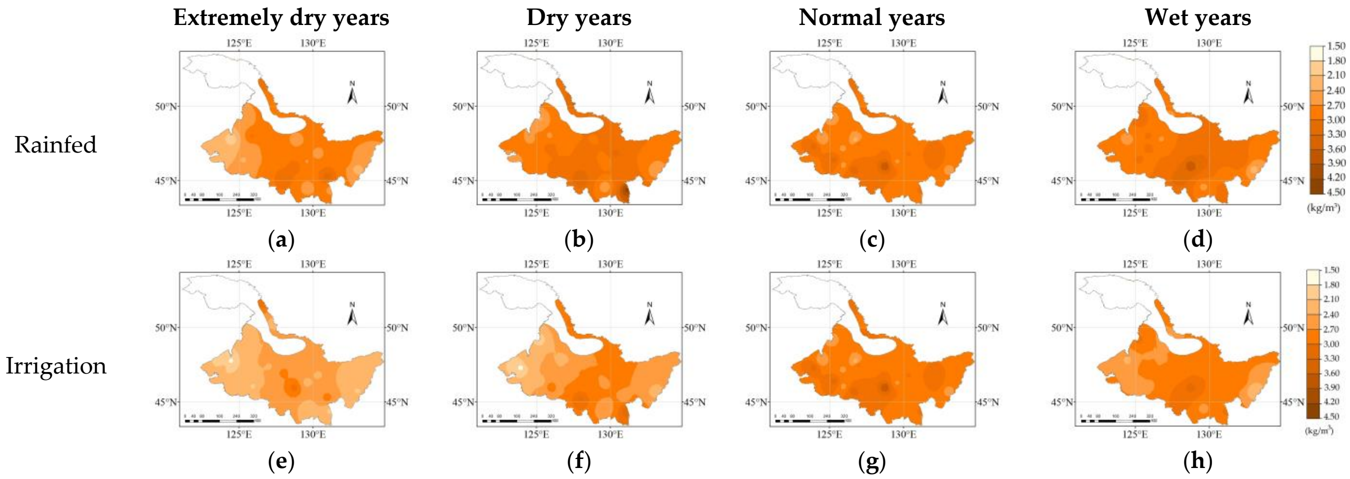


Figure 9. Spatial distribution of *WUE* in extremely dry years (**a**,**e**), dry years (**b**,**f**), normal years (**c**,**g**), and wet years (**d**,**h**) under the rainfed and irrigation scenarios.

4. Discussion

The results demonstrated that AquaCrop performed well in simulating ET_c and maize yield (Figures 4 and 5), with acceptable *RMSE*, *NRMSE*, *EF*, and *d* values (Table 3). However, AquaCrop underestimated ET_c in the final simulation (Figures 3 and 4). Ultimately, the result for ET_c was lower than the actual result. Rupinder indicated that under irrigation and rainfed scenarios, the AquaCrop model consistently underestimates the trends of ET_c [31]. Thus, the observed bias in simulated values was most likely due to insufficient parameterization of the crop parameters during later growth stages, as the model was highly impacted by crop senescence stress coefficients [27,51]. In this study, due to the limited data, adjustments in the canopy decline may have affected the correction of ET_c for the later growth stages.

Many previous studies indicated that high values of ET_c are mainly distributed in the western regions [52,53], with an average of 401.64 mm, while low values are primarily distributed in the eastern regions [34]. In [34], the spatial distribution of ET_c was the same as that in this study, but the value of ET_c was greater than 401.64 mm, which may have been caused by the use of different models and methods. The previous study used a single crop coefficient to calculate ET_c. However, the present study used the AquaCrop model with two crop coefficients (E and T_r) and considered the impact of CO_2 on ET_c [45]. Studies have shown that the use of two crop coefficients offers more accuracy than the use of a single crop coefficient and that predicting ET_c using two crop coefficients provides better performance than predicting ET_c using a single crop coefficient [54]. In the present study, the AquaCrop model was calibrated and verified using experimental data from the field. The results obtained through this method may be more reliable than those acquired by calibrating K_c in the CropWAT model using the FAO-56 method. Furthermore, a more reliable localized AquaCrop model will require more experimental data for calibration and verification. In future studies, we will further optimize the AquaCrop model to make it more accurate and applicable to more crop simulations.

The present study demonstrated that, in the west, I_r was high while the yield and *WUE* were low. Nie indicated that ET_c and I_r in each accumulated temperature zone are increased with increasing temperature, confirming the spatial distribution trend of ET_c and I_r in this study [51]. Sun showed that precipitation in the maize growing season fluctuates strongly in the west [55], which may be one reason for the large amount of irrigation in these regions. Moreover, due to the high accumulated temperature, relatively low air humidity, strong solar radiation, and high maize ET_c, drought frequently occurred in the west [56]. Past research has shown that the increase in greenhouse gases in Heilongjiang Province has affected radiation to a certain extent, thereby increasing ET_0. However, the

ET_0 in the northeast slightly decreased. This trend reduced the ET_c and the potential I_r for *ET* [57]. Moreover, research has shown that the water shortage in the west improved from 1960 to 2015 [34]. Based on this trend, the ET_0 will alleviate drought in the west, which will be beneficial for employing a rainfed schedule during normal and wet years in Heilongjiang Province.

Under the studied irrigation scenarios, the *WUE* was lower than that under the rainfed scenario. In extremely dry and dry years, irrigation alleviated drought and increased maize yields in most regions. Moreover, the water supply increased as the *ET* increased, and the *WUE* was low, possibly because the additional water supply contributed to biomass production rather than an increase in the yield [58]. During normal and wet years, irrigation did not significantly increase the yield. The results further demonstrate that excess irrigation may be lost through deep percolation. Therefore, except for the *WUE* being lower under the irrigation scenario, there was no significant difference in the spatial distribution between the two hydrological years. In the future, based on the water-saving principle, irrigation should not be considered during normal and wet years. When irrigation is necessary during extremely dry years and dry years, a water-saving irrigation schedule (such as drip irrigation under mulch or the use of sprinklers) needs to be implemented under appropriate agricultural management strategies to improve *WUE*. These measures are essential to increase the yields of similar crops under the same climate regions and provide a basis for optimizing the allocation of water resources and improving the *WUE* of maize planted in Heilongjiang Province.

5. Conclusions

In this study, the data from three field experiments on maize were used to calibrate and validate the AquaCrop model in Heilongjiang Province. The ET_c, ET_a, I_r, and yield were correctly simulated under rainfed and irrigation scenarios over four hydrological years. The results demonstrated that in the west, the ET_c, ET_a, and I_r were high, but the yield was low. Moreover, irrigation increased the yield in extremely dry years, while there were no significant changes during normal and wet years. The *WUE* under irrigation was lower than that under the rainfed scenario. Notably, in normal and wet years, irrigation did not increase yield but instead reduced *WUE*. Therefore, the planting area may not require irrigation during normal and wet years, but the drought in the western area of Heilongjiang Province cannot be ignored.

The results obtained by the localized AquaCrop model may provide a reference for areas with similar phenology in Heilongjiang Province. Due to limited experimental data used for calibration and verification in this study, the AquaCrop model still has a deviation. In the future, we will focus on calibrating the AquaCrop model with more field experiments, dividing rainfed and irrigation districts, and formulating irrigation schedules for irrigation districts to guide agricultural irrigation in Heilongjiang Province.

Author Contributions: T.N. collected the data; Y.J. and T.N analyzed data; Y.J. wrote the paper; Y.T., N.L., T.W. and C.D. drew the figures for this paper; Z.Z., T.L., S.Z., Z.S. and F.L. reviewed and edited the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This work was fund by the Basic Scientific Research Fund of Heilongjiang Provincial Universities, grant number RCCXYJ201912&2018-KYYWF-1570, National Natural Science Foundation Project of China, grant number 51809042.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: We thank the Chinese meteorological data sharing service (http://data.cma.cn, accessed on 22 July 2021) for providing the meteorological data. We thank the anonymous reviewers and the editor for their suggestions, which substantially improved the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. UNEP. Global Environmental Outlook. 2000. Available online: http://www.unep.org/geo/geo2000/english/index.htm (accessed on 7 July 2021).
2. Rijsberman, F.R. Water scarcity: Fact or fiction? *Agric. Water Manag.* **2006**, *80*, 5–22. [CrossRef]
3. Crow, B. Contesting water injustice: The Santa Cruz Declaration on the global water crisis. *Water Int.* **2014**, *39*, 246–261. [CrossRef]
4. Tittonell, P.; Giller, K.E. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Res.* **2013**, *143*, 76–90. [CrossRef]
5. FAO. FAO Statistical Yearbook 2007: World Food and Agriculture. Available online: http://www.fao.org/docrep/018/i3107e/i3107e00.htm (accessed on 7 July 2021).
6. Beshir, S. Review on Estimation of Crop Water Requirement, Irrigation Frequency and Water Use Efficiency of Cabbage Production. *J. Geosci. Environ. Prot.* **2017**, *5*, 59–69. [CrossRef]
7. Sandhu, R.; Irmak, S. Performance of AquaCrop model in simulating maize growth, yield, and evapotranspiration under rainfed, limited and full irrigation. *Agric. Water Manag.* **2019**, *223*, 105687. [CrossRef]
8. Kehlenbeck, K.; Jamnadass, R. Food and Nutrition—Fruits, Nuts, Vegetables and Staples from Trees. In *Treesilience: An Assessment of the Resilience Provided by Trees in the Drylands of Eastern Africa*; De, L.J., Njenga, M., Wagner, B.I., Eds.; ICRAF: Nairobi, Kenya, 2014; Chapter 6.2.1; p. 166. ISBN 978-92-9059-352-2.
9. Alexandratos, N.; Bruinsma, J. *World Agriculture towards 2030/2050: The 2012 Revision*; ESA Working Paper No. 12-03; FAO of UN: Rome, Italy, 2012; Chapter 2.1.2; pp. 32–33.
10. Zhang, Q.S.; Shi, Q.L.; Chen, C.; Shi, Q. Impacts of land use and land cover changes on surface energy and water balance in the Heihe River Basin of China, 2000–2010. *Phys. Chem. Earth* **2015**, *79–82*, 2–10. [CrossRef]
11. Qian, X.; Wei, S.A.; Ying, Z.C. Forecast and optimal allocation of production, living and ecology water consumption in Zhangye, China. *Phys. Chem. Earth* **2016**, *96*, 16–25. [CrossRef]
12. Deng, X.P.; Lun, S.; Zhang, H.; Turner, N.C. Improving agricultural water use efficiency in arid and semiarid areas of China. *Agric. Water Manag.* **2006**, *80*, 23–40. [CrossRef]
13. Yang, X.L.; Chen, Y.Q.; Pacenka, S.; Steenhuis, T.S.; Sui, P. Managing food and bioenergy crops with declining groundwater levels in the North China Plain. *Field Crops Res.* **2019**, *234*, 1–14. [CrossRef]
14. Ammar, M.E.; Davies, E. On the accuracy of crop production and water requirement calculations: Process-based crop modelling at daily, semi-weekly, and weekly time steps for integrated assessments. *J. Environ. Manag.* **2019**, *238*, 460–472. [CrossRef]
15. Adeboye, O.; Schultz, B.; Adekalu, K.O.; Prasad, K. Performance evaluation of AquaCrop in simulating soil water storage, yield, and water productivity of rainfed soybeans (*Glycine max* L. merr) in Ile-Ife, Nigeria. *Agric. Water Manag.* **2019**, *213*, 1130–1146. [CrossRef]
16. Nie, T.Z.; Liang, Q.Z.; Wang, T.Y.; Chu, L.L.; Chen, X.; Li, F.R. Water requirement and supply and irrigation schedule formulation for maize in the western region of Heilongjiang Province. *South-to-North Water Transfers and Water Sci. Technol.* **2021**, 1–13. Available online: http://kns.cnki.net/kcms/detail/13.1430.TV.20210628.1130.002.html (accessed on 7 July 2021).
17. Allen, R.G.; Walter, I.A.; Elliott, R.L. *The ASCE Standardized Reference Evapotranspiration Equation*; ASCE: Reston, VA, USA, 2005; pp. 46–47. [CrossRef]
18. Sun, H.Y.; Shen, Y.J.; Yu, Q.; Flerchinger, G.N. Effect of precipitation change on water balance and *WUE* of the winter wheat–summer maize rotation in the North China Plain. *Agric. Water Manag.* **2010**, *97*, 1139–1145. [CrossRef]
19. Djaman, K.; Irmak, S.; William, R.R.; Martin, D. Maize evapotranspiration, yield production functions, biomass, grain yield, harvest index, and yield response factors under full and limited irrigation. *Trans. ASABE* **2013**, *56*, 273–293. [CrossRef]
20. Qin, S.; Li, L.; Wang, D.; Zhang, J.L. Effects of Limited Supplemental Irrigation with Catchment Rainfall on Rain-fed Potato in Semi-arid Areas on the Western Loess Plateau, China. *Am. J. Potato Res.* **2013**, *90*, 33–42. [CrossRef]
21. Acharjee, T.K.; Halsema, G.; Ludwig, F.; Hellegers, P. Declining trends of water requirements of dry season Boro rice in the north-west Bangladesh. *Agric. Water Manag.* **2017**, *180*, 148–159. [CrossRef]
22. Kresovic, B.; Matovic, G.; Gregoric, E.; Djuricin, S.; Bodroza, D. Irrigation as a climate change impact mitigation measure: An agronomic and economic assessment of maize production in Serbia. *Agric. Water Manag.* **2014**, *139*, 7–16. [CrossRef]
23. Kresovi' ca, B.; Tapanarova, A.; Tomić, Z.; Zixotic, L. Grain yield and water use efficiency of maize as influenced by different irrigation regimes through sprinkler irrigation under temperate climate. *Agric. Water Manag.* **2016**, *169*, 34–43. [CrossRef]
24. Attia, A.; El-Hendawy, S.; Al-Suhaibani, N.; Alotaibi, M. Evaluating deficit irrigation scheduling strategies to improve yield and water productivity of maize in arid environment using simulation. *Agric. Water Manag.* **2021**, *249*, 106812. [CrossRef]
25. Djaman, K.; Irmak, S. Soil water extraction patterns and crop, irrigation, and evapotranspiration water use efficiency of maize under full and limited irrigation and rainfed settings. *Trans. ASABE* **2012**, *55*, 1223–1238. [CrossRef]
26. Zou, Y.F.; Saddique, Q.; Ajaz, A.; Xu, J.T. Deficit irrigation improves maize yield and water use efficiency in a semi-arid environment. *Agric. Water Manag.* **2020**, *243*, 106483. [CrossRef]
27. Heng, L.; Hsiao, T.C.; Evett, S.; Howell, T.A. Validating the FAO AquaCrop Model for Irrigated and Water Deficient Field Maize. *Agron. J.* **2009**, *101*, 488–498. [CrossRef]
28. Sandhu, R.; Irmak, S. Performance assessment of Hybrid-Maize model for rainfed, limited and full irrigation conditions. *Agric. Water Manag.* **2020**, *242*, 106402. [CrossRef]

29. López-Urrea, R.; Domínguez, A.; Pardo, J.J.; Montoya, F. Parameterization and comparison of the AquaCrop and MOPECO models for a high-yielding barley cultivar under different irrigation levels. *Agric. Water Manag.* **2020**, *230*, 105931. [CrossRef]
30. Pirmoradian, N.; Davatgar, N. Simulating the effects of climatic fluctuations on rice irrigation water requirement using AquaCrop. *Agric. Water Manag.* **2019**, *213*, 97–106. [CrossRef]
31. Sandhu, R.; Irmak, S. Assessment of AquaCrop model in simulating maize canopy cover, soil-water, evapotranspiration, yield, and water productivity for different planting dates and densities under irrigated and rainfed conditions. *Agric. Water Manag.* **2019**, *224*, 105753. [CrossRef]
32. Bai, J.; Chen, X.; Dobermann, A.; Yang, H.S.; Kenneth, G.; Cassman, K.G.; Zhang, F.S. Evaluation of NASA Satellite and Model-Derived Weather Data for Simulation of Maize Yield Potential in China. *Agron. J.* **2010**, *102*, 9–16. [CrossRef]
33. Heilongjiang Bureau of Statistics. *Heilongjiang Statistical Yearbook*; China Statistics Press: Beijing, China, 2016. Available online: http://tjj.hlj.gov.cn/tjsj/tjnj/ (accessed on 7 July 2021).
34. Wang, T.Y.; Du, C.; Nie, T.; Sun, Z.Y.; Liang, Q.Z. Spatiotemporal Analysis of Maize Water Requirement in the Heilongjiang Province of China during 1960–2015. *Water* **2020**, *12*, 2472. [CrossRef]
35. Heilongjiang Provincial Agriculture Committee. Division of Accumulated Temperature Zones of Crop Varieties in Heilongjiang Province. Available online: http//www.hljagri.gov.cn/nygk/nzwpzjwqh/ (accessed on 7 July 2021).
36. Accumulated Temperature Zone of Crop Varieties in Heilongjiang Province. Available online: http://www.hljagri.gov.cn/ (accessed on 7 July 2021).
37. Li, H. *Experimental Study on Water Consumption Law and Irrigation Scheme Evaluation of Corn under Regulated Deficit Irrigation*; Agricultural University: Harbin, China, 2016. (In Chinese)
38. Wang, D. *Experimental Study on Coupling Effect of Water and Fertilizer of Corn Sprinkler Irrigation in Semi-Arid Area of Heilongjiang Province*; Agricultural University: Harbin, China, 2016. (In Chinese)
39. Chen, S. *Experimental Research on Corn Irrigation System and Water and Nitrogen Utilization in Semi-Arid Area of Western Heilongjiang*; Northeast Agricultural University: Harbin, China, 2019. (In Chinese)
40. Bottazzi, M.; Bancheri, M.; Mobilia, M.; Bertoldi, G.; Rigon, R. Comparing Evapotranspiration Estimates from the GEOframe-Prospero Model with Penman–Monteith and Priestley-Taylor Approaches under Different Climate Conditions. *Water* **2020**, *13*, 1221. [CrossRef]
41. Zotarelli, L.; Dukes, M.D.; Romero, C.C.; Migliaccio, K.W.; Morgan, K.T. *Step by Step Calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method)*; Institute of Food and Agricultural Sciences, University of Florida: Gainesville, FL, USA, 2010; pp. 1–10.
42. Doorenbos, J.; Kassam, A.H. *FAO Irrigation and Drainage Paper No. 33*; FAO of UN: Rome, Italy, 1979; pp. 37–55. ISBN 925-10-0744-6.
43. Doorenbos, J.; Kassam, A.H. Yield Response to Water 1. *Irrig. Agric. Dev.* **1986**, *33*, 257–280. [CrossRef]
44. Steduto, P.; Hsiao, T.C.; Fereres, E. On the conservative behavior of biomass water productivity. *Irrig. Sci.* **2007**, *25*, 189–207. [CrossRef]
45. Steduto, P.; Hsiao, T.C.; Raes, D.; Fereres, E. AquaCrop-The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agron. J.* **2009**, *101*, 426–437. [CrossRef]
46. FAO. Crop yield response to water. In *FAO Irrigation and Drainage Paper No. 66*; Steduto, P., Hsiao, T.C., Raes, D., Eds.; FAO of UN: Rome, Italy, 2012; ISBN 978-92-5107274-5.
47. Kontoyiannis, H.; Jacovides, C.P. Statistical procedures for the evaluation of evapotranspiration computing models. *Agric. Water Manag.* **1995**, *27*, 365–371. [CrossRef]
48. Jamieson, P.D.; Porter, J.R.; Wilson, D.R. A test of the computer simulation model ARCWHEAT1 on wheat crops grown in New Zealand. *Fields Crops Res.* **1991**, *27*, 337–350. [CrossRef]
49. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models. *J. Hydrol.* **1970**, *10*, 282–290. [CrossRef]
50. Smith, M. *CROPWAT: A Computer Program for Irrigation Planning and Management*; FAO of UN: Rome, Italy, 1992; pp. 69–73. ISBN 92-5-103106-1.
51. Nie, T.; Zhang, Z.; Qi, Z.; Chen, P.; Sun, Z.; Liu, X.C. Characterizing Spatiotemporal Dynamics of CH_4 Fluxes from Rice Paddies of Cold Region in Heilongjiang Province under Climate Change. *Int. J. Environ. Res. Public Health* **2019**, *16*, 692. [CrossRef] [PubMed]
52. Nie, T.Z.; Zhang, Z.; Lin, Y.; Chen, P.; Sun, Z. Spatial and Temporal Distribution Characteristics of Maize Water Requirement in Heilongjiang Province during 1959–2015. *T Chin. Soc. Mach.* **2018**, *49*, 218–227. (In Chinese)
53. Gao, X.; Wang, C.; Zhang, J.; Xue, X. Crop water requirement and temporal-spatial variation of drought and flood disaster during growth stages for maize in Northeast during past 50 years. *Trans. CSAE* **2012**, *28*, 101–109. (In Chinese)
54. Akhavan, S.; Kanani, E.; Dehghanisanij, H. Assessment of different reference evapotranspiration models to estimate the actual evapotranspiration of corn (*Zea mays* L.) in a semiarid region (case study, Karaj, Iran). *Theor. Appl. Climatol.* **2018**, *137*, 1403–1419. [CrossRef]
55. Sun, Y.; Gao, S.; Cao, Y.; Xu, J.Q.; Wang, Z. Study on the suitability of maize planting in Heilongjiang Province based on precipitation. *J. Northeast Agric. Univ.* **2017**, *48*, 33–41. (In Chinese)
56. Hu, X.; Chen, M.; Liu, D.; Li, D.; Luo, Y. Reference evapotranspiration change in Heilongjiang Province, China from 1951 to 2018: The role of climate change and rice area expansion. *Agric. Water Manag.* **2021**, *253*, 106912. [CrossRef]

57. Wang, Z.; Ye, A.; Wang, L.; Liu, K.; Cheng, L. Spatial and temporal characteristics of reference evapotranspiration and its climatic driving factors over China from 1979–2015. *Agric. Water Manag.* **2019**, *213*, 1096–1108. [CrossRef]
58. Irmak, S.; Djaman, K.; Rudnick, D.R. Effect of full and limited irrigation amount and frequency on subsurface drip-irrigated maize evapotranspiration, yield, water use efficiency and yield response factors. *Irrig. Sci.* **2016**, *34*, 271–286. [CrossRef]