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Refined Evaluation of Climate Suitability of Maize at Various Growth Stages in Major Maize-Producing Areas in the North of China

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Abstract: The Northeast region of China and Huang Huai Hai (3H) region are vital maize production bases in northern China that are crucial for national food security. The absence of phenological data hinders a detailed assessment of the alignment between maize development stages and climatic resources. This study combines the authors' maize phenology data with climate suitability modeling to evaluate maize's climate suitability at different developmental stages in both regions. This study shows that during the maize growth cycle, the average temperature, precipitation, sunshine, and comprehensive climate suitability were 0.77, 0.49, 0.87, and 0.65, respectively, in the Northeast. In contrast, the average temperature, precipitation, sunshine, and comprehensive climate suitability in the 3H region were 0.98, 0.53, 0.73, and 0.70, respectively. Precipitation is a major factor influencing maize growth, with temperature and sunshine impacting growth differently across regions. Temperature significantly affects maize in the Northeast, while sunshine plays a greater role in the 3H region. The Northeast is suitable for drought-resistant maize varieties, and implementing a late harvest policy in Liaoning could enhance maize yield. The 3H region generally has favorable climatic conditions. Apart from certain parts of Henan needing drought-resistant varieties, areas with ample growing seasons can adopt long-duration varieties to maximize thermal resource utilization. Our results have important implications for optimizing maize planting strategies and enhancing regional resilience, aiming to assess meteorological factors' impact on maize growth in key production areas.

Keywords: maize; climate suitability; planting strategy optimization; North China

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1. Introduction

Currently, global climate change threatens the stability of natural ecosystems and socio-economic sustainability [1,2]. Agriculture is one of the industries that are most susceptible to climate change. The increased volatility of climate resources impacts the order of agricultural production and the normal growth and development of crops, which in turn jeopardizes food production and security [3]. China is vast and climactically diverse, resulting in different cropping systems and management practices in each region [4]. Therefore, in the context of climate change, China's agricultural production will face greater challenges than other countries. The yields of the world's three major food crops, maize, rice, and wheat, are of great significance in ensuring global food security [5]. China is a large producer of maize, with its total output ranking second in the world. The Northeast and the (3H) region are China's maize production bases, and the stability of maize production in these two regions is of great significance in ensuring China's food security. Climate change has led to a further increase in the risk of meteorological disasters for crops such as maize [6,7], highlighting the importance of improving regional resilience. Improving the resilience of humans, plants, and animals to climate change has become the focus of present-day research. Historically, many scholars have carried out research on the climate suitability of maize growth stages based on phenological data and meteorological data. However, due to the influence of incomplete maize phenological data and other problems, the accuracy of climate suitability evaluation is limited to the whole growth process of maize or a small number of growth stages, and it is not possible to assess the various growth stages of maize exhaustively. Nonetheless, important studies on the impact of climate on maize have been carried out. Wang et al. selected factors such as soil, rainfall, temperature, irrigation, and soil erosion, and combined them with hierarchical analysis and sensitivity analysis to assess the crop suitability of rice, wheat, and maize, which helped to improve China's land allocation strategy [8]. He et al. entered data on frost-free periods, temperature, annual precipitation, and humidity inputs into the MaxEnt model to study the climatic suitability of maize cultivation and identified climatic thresholds for potential maize cultivation areas [9]. Zhao et al. established an average resource suitability index to evaluate the climate suitability of maize from germination to emergence, from emergence to jointing, from jointing to tasseling, and from tasseling to maturity, and concluded that the promotion of cold-resistant varieties in the middle and late stages of spring maize is conducive to reducing the adverse effects caused by climate change in Northeast China [10]. Zhang et al. established an integrated climate suitability model based on the temperature, precipitation, solar radiation, and wind demand of maize in Henan Province, China during different phenological periods from 1971 to 2020 and utilized the model to provide scientific support for grain yield prediction [11]. Zhao et al., based on future meteorological data, evaluated the suitability of maize in the North China Plain for the nutritive growth period, reproductive growth period, and the whole reproductive period [12]. The assessment of environmental conditions for crop growth based on fuzzy mathematical methods to build relevant climate models is one of the most commonly used methods in climate suitability studies [13]. For example, Zhao et al. established a composite climate suitability index of 0–1 as an assessment criterion based on this method and analyzed the climate suitability of potatoes at three growth stages in North China [14].

This study aims to assess the impact of meteorological factors on maize growth and development in the main production areas. This paper combines the existing results of maize phenological data, establishes a climate suitability evaluation model based on fuzzy mathematical methods, and finely evaluates the climate suitability of maize at different growth stages in the main producing areas under average conditions during the 2010–2020 period. This holistic approach is conducive to deepening our understanding of the relationship between agroclimatic resources and the production of maize.

2. Materials and Methods

2.1. Study Region

2.1.1. Northeast Region

The Northeast region of China covers Heilongjiang, Jilin, Liaoning, and the four eastern leagues of the Inner Mongolian Autonomous Region [15]. The region has a temperate monsoon climate with four distinct seasons and concentrated but uneven spatial distribution of precipitation, with annual precipitation of up to 1000 mm in the southeast, classified as a humid zone, and less than 300 mm in the northwest, classified as a semi-arid zone [16]. The soil types in Northeast China are diverse, mainly including black soils, dark brown forest soils, chestnut calcic soils, desert soils, meadow soils, and swamp soils, among which black soils are the dominant soil quality. These soil types reflect the differences in natural conditions such as climate, vegetation, topography, and hydrology in Northeast China [17]. The main grain crops are maize, rice, and soybeans, with maize production in the region accounting for about 40% of China's total maize production. Accumulated temperature status is used as the primary condition for judging whether a crop can be grown in a certain place. Therefore, to accurately assess climatic suitability for maize cultivation, the area in the region with annual ≥10 °C active cumulative temperatures of not less than 2300 °C·d was used as the study area for suitability evaluation (Figure 1a).

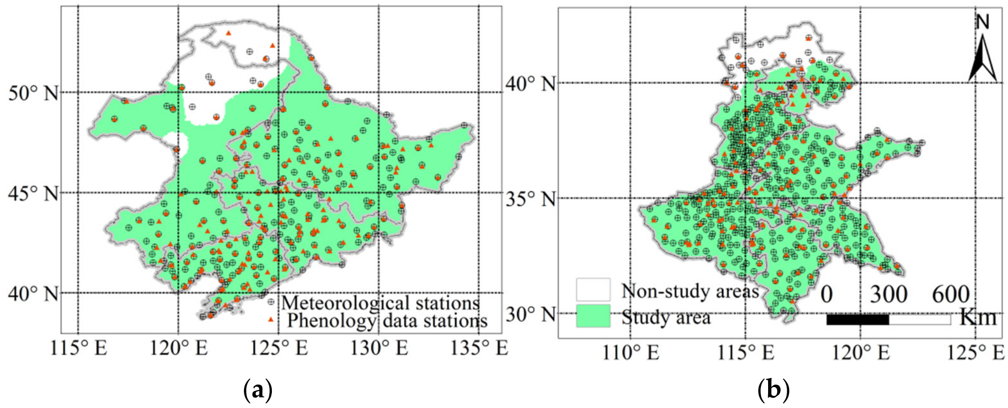

Figure 1. Spatial distribution of meteorological and phenology data locations in (**a**) Northeast China and (**b**) Huang Huai Hai Region. White areas represent non-study areas and green areas represent study areas.

2.1.2. Huang Huai Hai Region

The Huang Huai Hai region includes Beijing, Tianjin, Shandong, most of Hebei and Henan provinces, and the northern parts of Jiangsu and Anhui provinces [18]. The climate type of the region is a temperate monsoon climate with abundant light and heat resources, and the average annual precipitation is 500–700 mm, which is mainly concentrated in the summer, with strong fluctuation of annual precipitation [19]. The soil types in the Huang Huai Hai region are mainly brown earths, fluvisols, and cinnamon soils. The region has abundant arable land resources, with deep soil layers and good tillage [17]. The main cropping method is the rotation of winter wheat and summer maize, and the maize production in the region accounts for about 30% of China's total maize production. An area of the region with annual ≥10 °C active cumulative temperature not less than 3700 °C·d was used as the study area for suitability evaluation (Figure 1b).

2.2. Data Sources

2.2.1. Maize Phenological Data

The maize phenological data were derived from the authors' previous research [20,21]. This dataset was generated by the authors, using maize phenological period data from various sources. The method employed was founded on the connection between the phenological period and its adjacent phenological periods, along with latitude, longitude, and altitude. Subsequently, the corresponding phenological period model was created, resulting in the acquisition of the constructed phenological dataset for the average period from 2010 to 2020. Consequently, the developmental day sequences of the maize phenological period in each region were obtained and are presented in Table 1.

Table 1. Range of the average time of the year (in days) for each phenological period in the Northeast and Huang Huai Hai region from 2010 to 2020.

Study Area	Sowing Stage (SW)	Emergence Stage (VE)	Three-Leaf Stage (V3)	Seven-Leaf Stage (V7)	Jointing Stage (JT)	Tasseling Stage (VT)	Flowering Stage (FR)	Silking Stage (R1)	Maturity Stage (R6)
Northeast	110–149 d	126–159 d	133–169 d	146–182 d	168–197 d	189–216 d	192–219 d	194–221 d	245–285 d
Huang Huai Hai	142–178 d	148–185 d	156–192 d	No data	173–218 d	197–235 d	199–237 d	200–238 d	236–285 d

The number of days for each developmental stage of maize in Northeast China and the Huang Huai Hai region was derived from the average number of days for the two adjacent phenological periods (Table 2).

Table 2. Duration of the stages of maize development in the Northeast and Huang Huai Hai regions (in days).

<table>
<tr><th>Study Area</th><th>SW-VE</th><th>VE-V3</th><th>V3-V7</th><th>V7-JT</th><th>JT-VT</th><th>VT-FR</th><th>FR-R1</th><th>R1-R6</th></tr>
<tr><td>Northeast</td><td>16</td><td>7</td><td>15</td><td>20</td><td>20</td><td>3</td><td>2</td><td>58</td></tr>
<tr><td>Huang Huai Hai</td><td>7</td><td>5</td><td colspan="2">23</td><td>21</td><td>2</td><td>1</td><td>42</td></tr>
</table>

2.2.2. Meteorological Data

The meteorological data in this paper were obtained from the National Meteorological Science Data Center of China, and the specific data attributes are shown in Table 3.

Table 3. Meteorological datasets from 2005 to 2015.

<table>
<tr><th>Time Range</th><th>Data Precision</th><th>Meteorological Elements</th><th>Unit</th></tr>
<tr><td rowspan="8">2005–2015</td><td rowspan="8">day</td><td>Average temperature</td><td>°C</td></tr>
<tr><td>Maximum temperature</td><td>°C</td></tr>
<tr><td>Minimum temperature</td><td>°C</td></tr>
<tr><td>Average relative humidity</td><td>%</td></tr>
<tr><td>Precipitation</td><td>mm</td></tr>
<tr><td>Average wind speed</td><td>m/s</td></tr>
<tr><td>Sunshine hours</td><td>hour</td></tr>
<tr><td>Percentage of sunshine hours</td><td>%</td></tr>
</table>

2.3. Climate Suitability Evaluation Methods

The suitability of climatic conditions determines crop growth and yield [22]. During the normal growth and development of maize, high or low temperatures lead to heat or cold damage, too much or too little precipitation leads to flooding or drought, and the adequacy of sunshine hours has an important impact on the rate of maize photosynthesis and the process of male-female differentiation, etc. Very high yield is thus determined by the combined effect of the three factors. Therefore, single-factor evaluation of temperature, precipitation, and light conditions in the main production area was conducted by using the temperature suitability model, precipitation suitability model, and light suitability model; the sunshine, temperature, and water composite factor evaluation was conducted by combining the comprehensive climate suitability model.

2.3.1. Single-Factor Evaluation

(a) Temperature suitability model

Temperature suitability refers to the degree to which the ambient temperature is favorable to the growth and development of maize. Maize is a warm-season crop, and the temperature of the three base points is different at different growth stages [23]. The temperature suitability model is constructed as follows:

$$St(i) = \begin{cases} 0 & T_i \leq T_1 \ or \ \ T_i \geq T_2 \\ \frac{(T_i - T_1)(T_2 - T_1)^B}{(T_0 - T_1)(T_2 - T_0)^B} & T_1 < T < T_2 \\ 1 & T_i = T_0 \end{cases} \tag{1}$$

$$B = \frac{(T_2 - T_0)}{(T_0 - T_1)} \tag{2}$$

where i is a growth stage, $St(i)$ is temperature suitability for a growth stage, T_i is the average daily temperature within a growth stage, T_1 is the lower temperature limit for a growth stage, T_0 is the optimum temperature, T_2 is the upper temperature, and B is the constant calculated based on the triple base point temperature.

Since there are significant differences in the climate and planting systems in the Northeast and Huang Huai Hai regions, and differences in the actual conditions of maize planting in different regions and related information [24–27], the three base point temperatures (Table 4) for each growth stage of maize in the Northeast and Huang Huai Hai regions were determined as follows:

Table 4. Temperature and B value of three basis points at each growth stage of maize.

Study Area	Growth Stage	T_1 (°C)	T_0 (°C)	T_2 (°C)	B
Northeast	SW-VE	6	12	22	1.7
	VE-V3	6	18	35	1.4
	V3-V7	8	20	35	1.3
	V7-JT	10	22	35	1.1
	JT-VT	16	22	35	2.2
	VT-FR	18	24	32	1.3
	FR-R1	20	26	32	1.0
	R1-R6	15	25	30	0.5
Huang Huai Hai	SW-VE	14	25	35	0.9
	VE-V3	14	26	35	0.8
	V3-JT	17	27	35	0.8
	JT-VT	17	27	34	0.7
	VT-FR	15	26	34	0.7
	FR-R1	15	26	34	0.7
	R1-R6	10	23	32	0.7

(b) Precipitation suitability model

Maize, as a dryland crop, has high requirements for moisture conditions, requiring 500–800 mm of precipitation throughout its growth cycle. Since maize has different water requirements at different growth stages, a precipitation suitability model was constructed by combining the FAO's revised Penman-Monteith formula [28,29]. The precipitation suitability model [30] is constructed as follows:

$$Sp(i) = \begin{cases} r_i/ET_i & r_i < ET_i \\ ET_i/r_i & r_i \geq ET_i \end{cases} \tag{3}$$

$$ET_i = K_{ci} \cdot ET_0 \tag{4}$$

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{5}$$

where i is a growth stage, $Sp(i)$ is a growth stage precipitation suitability, ET_i is a growth stage crop water demand, r_i represents different growth stage effective precipitation (mm), K_{ci} is a growth stage crop coefficients, the specific value of Table 4, ET_0 is the reference evapotranspiration (mm), R_n is the canopy surface net radiation (MJ·m^{-2}·d^{-1}), G is the soil heat flux (MJ·m^{-2}·d^{-1}), T is the mean air temperature (°C), e_s is the saturation water vapor pressure (kPa), e_a is the actual water vapor pressure (kPa), Δ is the slope of the saturation vapor pressure-temperature curve at T (kPa·°C^{-1}), γ is the psychrometric constant (kPa·°C^{-1}), and U_2 is the wind speed at 2 m above ground level (m·s^{-1}).

(c) Sunshine suitability model

Maize is a short light-tolerant crop. When the percentage of sunshine reaches more than 70%, it can be considered suitable for maize. The sunshine suitability model [31] is constructed as follows:

$$Ss(i) = \begin{cases} e^{-[(s_i - s_0)/b]^2} & s_i < s_0 \\ 1 & s_i \geq s_0 \end{cases} \tag{6}$$

where i is a growth stage, $Ss(i)$ is a growth stage of sunshine suitability, s_i is a growth stage of the actual sunshine hours (h), s_0 is a sunshine percentage $\geq$ 70% of the average value of sunshine hours, and b represents sunshine constants, with the relevant information and b value shown in Table 5.

Table 5. Crop coefficients and sunshine constant b values at each growth stage of maize.

	SW-VE	VE-V3	V3-V7	V7-JT	JT-VT	VT-FR	FR-R1	R1-R6
Kc	0.3	0.3	0.3	0.75	1.2	1.2	1.2	0.6
b	4.77	5.08	5.08	5.08	5.17	5.17	5.17	5.17

2.3.2. Composite Factor Evaluation

The geometric mean method [32] was used to construct an integrated impact model of sunshine, temperature, and precipitation:

$$Sc(i) = \sqrt[3]{St(i) \times Sp(i) \times Ss(i)} \tag{7}$$

where i is a growth stage, $Sc(i)$ is the comprehensive climate suitability for a growth stage, $St(i)$ is the temperature suitability for a growth stage, $Sp(i)$ is the precipitation suitability for a growth stage, and $Ss(i)$ is the sunshine suitability for a growth stage.

2.4. Climate Suitability Evaluation Standard

Given that temperature, precipitation, and sunshine affect maize growth and development to different degrees, the evaluation criteria for these variables at various stages of maize growth and development are shown in Table 6. The evaluation standard for comprehensive climate suitability evaluation is shown in Table 7.

Table 6. Single factor suitability evaluation standard.

Condition Level	Numerical Range		
	Temperature	Precipitation	Sunshine
High	0.8–1.0	0.7–1.0	0.6–1.0
Middle	0.5–0.8	0.4–0.7	0.3–0.6
Low	0–0.5	0–0.4	0–0.3

Table 7. Composite factor suitability evaluation standard.

Suitability Level	Unsuitable	Less Suitable	Suitable	Most Suitable
Numerical range	0–0.3	0.3–0.5	0.5–0.7	0.7–1.0

3. Results

3.1. Northeast China

3.1.1. Temperature Suitability

Figure 2 shows the spatial distribution of temperature suitability at each growth stage of maize in Northeast China. There is a risk of heat shortage, mainly in the pre-growth stage and the late growth stage of maize. Conversely, during the other growth stages, the heat is sufficient, which is favorable to the normal growth and development of maize. This result is consistent with the findings of a previous study [33]. From the point of view of each growth stage, the average SW-VE temperature suitability of maize was 0.86, due to the relatively early sowing time of maize in Liaoning and the southern part of Inner Mongolia. This means that the regions have lower temperature suitability than other regions. Regarding the VE-VT growth and development stage, the average temperature suitability of the entire Northeast region was above 0.9, which is conducive to maize's nutrient growth. Finally, the VT-FR, FR-R1 and R1-R6 temperature suitability means were 0.89, 0.62, and 0.60, respectively. Influenced by latitude and climate from the VT-FR stage, the temperature suitability from north to south declines through time. Thus, the northern and central parts of the Northeast should be carefully managed to guard against the impact of the lack of heat on the growth and development of maize.

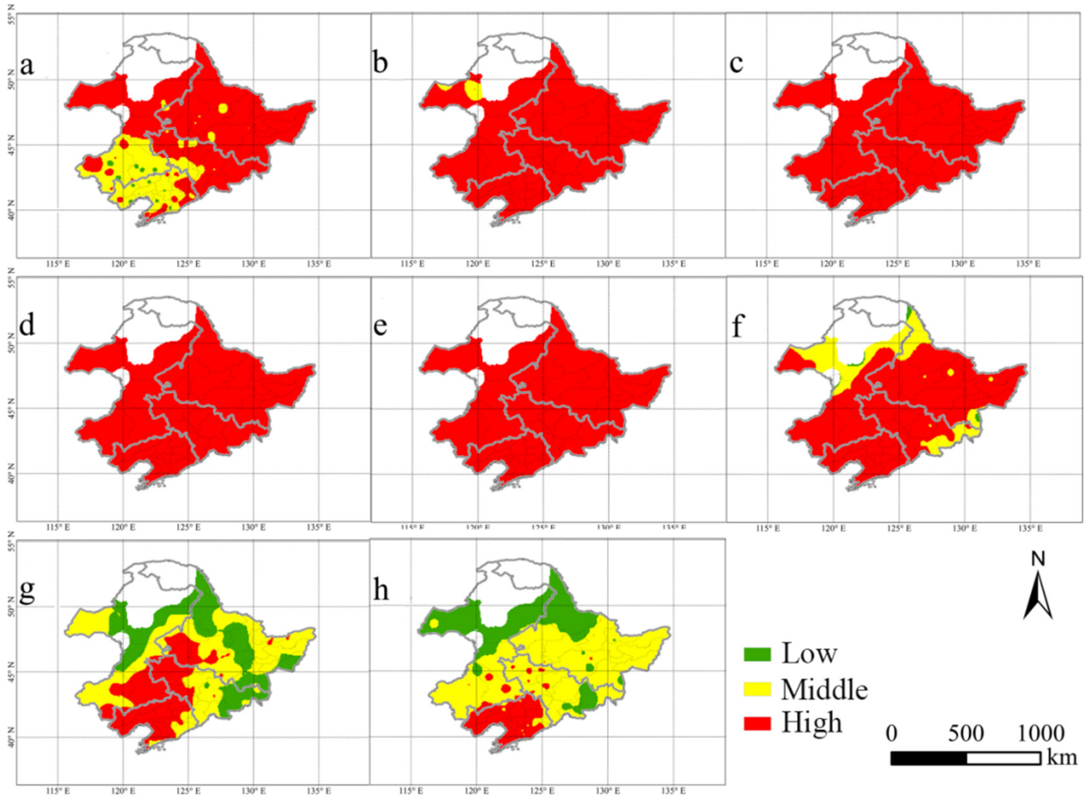

Figure 2. Temperature suitability of maize at various growth stages in Northeast China: (**a**) SW-VE, (**b**) VE-V3, (**c**) V3-V7, (**d**) V7-JT, (**e**) JT-VT, (**f**) VT-FR, (**g**) FR-R1, and (**h**) R1-R6.

3.1.2. Precipitation Suitability

Figure 3 shows the spatial distribution of precipitation suitability at each growth stage of maize in Northeast China. The characteristics of the distribution of precipitation suitability at each growth and development stage of maize are consistent with the monthly distribution of annual precipitation in Northeast China [34]. Precipitation conditions were poor during the early stages of maize growth and development, and relatively good during the remainder of the growth phase. Regarding SW-VE and VE-V3, the average precipitation suitability was 0.21 and 0.20, respectively. Thus, in the Northeast region during this period, weather conditions should be monitored, with sowing undertaken soon after irrigation. In addition, the field emergence rate situation must also be monitored to prevent drought that could lead to a large-scale seedling shortage. After maize entered the three-leaf stage, with the advent of the rainy season in Northeast China, the precipitation suitability of each growth stage appeared to increase to different degrees, and the average values of the precipitation suitability of each growth stage from V3-R6 were 0.45, 0.51, 0.59, 0.47, and 0.54, respectively. Overall, the middle and late stages of maize development in Northeast China had suitable precipitation conditions, which were conducive to high yields of maize.

3.1.3. Sunshine Suitability

Figure 4 shows the spatial distribution of sunshine suitability for each growth stage of maize in Northeast China. Based on this, it can be concluded that there is sufficient sunshine in Northeast China to meet the growth and development requirements of maize in both its whole growth and development stages. The sunshine requirements are also met at each stage. The average values of sunshine suitability in stages (a)–(h) (Figure 4) were 0.84, 0.87, 0.85, 0.80, 0.89, 0.90, 0.91, and 0.90, respectively. Suitable sunshine conditions are conducive to improving the development rate of maize in the pre-growth stage, avoiding the problem of prolonged maize growth cycle due to the lack of sunshine hours. The conditions are also conducive to guaranteeing efficient photosynthesis in the mid- and late-stage of maize growth to create and accumulate more organic matter.

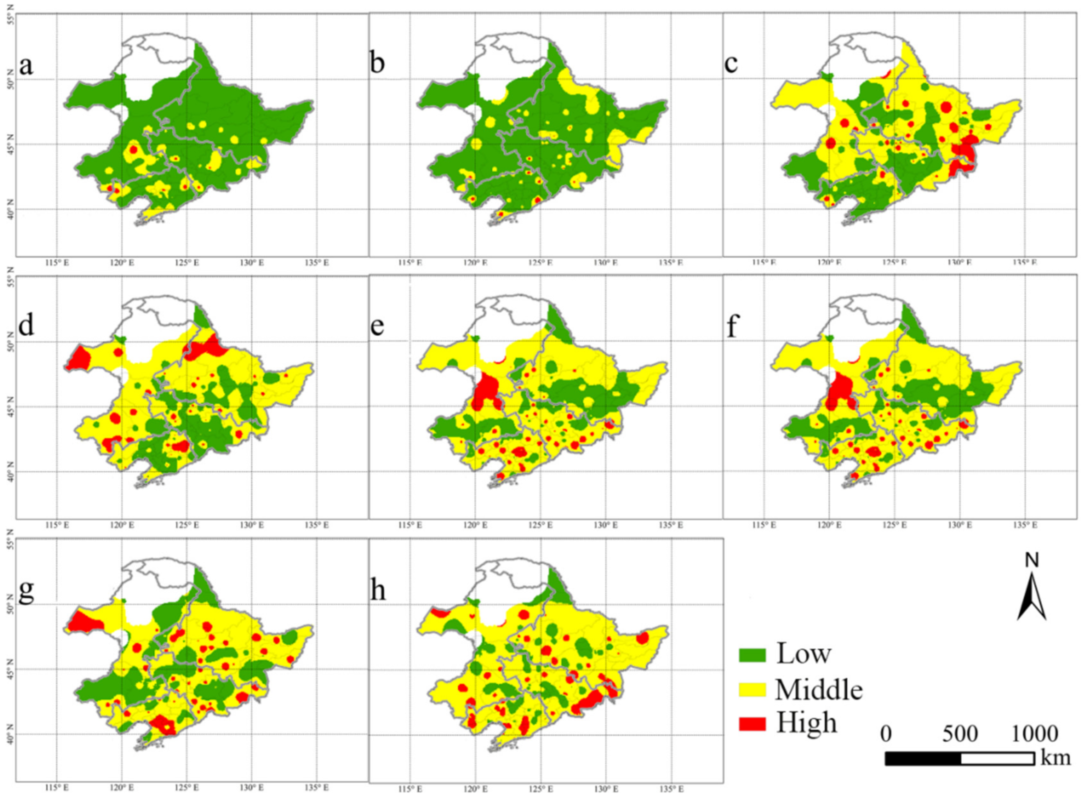

Figure 3. Precipitation suitability of maize at various growth stages in Northeast China: (**a**) SW-VE, (**b**) VE-V3, (**c**) V3-V7, (**d**) V7-JT, (**e**) JT-VT, (**f**) VT-FR, (**g**) FR-R1, and (**h**) R1-R6.

3.1.4. Composite Climate Suitability

Figure 5 shows the spatial distribution of the composite climatic suitability of maize at each growth stage in Northeast China. In terms of the overall growth stage, the composite climate suitability in the early stage of growth is low due to the double influence of precipitation and low temperature suitability. In the late stage of growth, the composite climate suitability is low due to the influence of low temperature suitability, and the composite climate suitability of the remaining stages of growth and development is relatively high. In terms of maize's growth and development stages, SW-VE composite climate suitability mean has a value of 0.49, but, in the Heilongjiang region, suitability is poor; VE-V3 composite climate suitability has a mean value of 0.51, which is an improvement on the previous growth stage of the composite climatic conditions. The mean values of the composite climatic suitability of V3-R6 are 0.70, 0.73, 0.79, 0.71, 0.62, and 0.66, respectively. Therefore, it can be concluded that the composite climatic suitability of the JT-VT stage is the highest, which is mainly because the period coincides with the "rainy season" of the Northeast region, and because the temperature and sunshine are suitable.

3.2. Huang Huai Hai Region

3.2.1. Temperature Suitability

Maize requires high heat throughout its growth and development stages. Figure 6 shows the spatial distribution of the temperature suitability of maize at each growth stage in the Huang Huai Hai region. Based on this, it can be concluded that there is sufficient heat in the Huang Huai Hai region to meet the heat demand of maize at each growth stage. The mean value of temperature suitability at each growth stage was about 0.98. Suitable temperature in the early growth stage helped to increase the germination rate of maize and promote its growth and development. Suitable temperature at the FR-R1 stage helped to maintain the activity of pollen grains and increase the success rate of pollination and fertilization. At the end of the growth period, the temperature was suitable for ensuring the rate of maize grouting, improving the rate of dry matter accumulation, and ensuring a high yield.

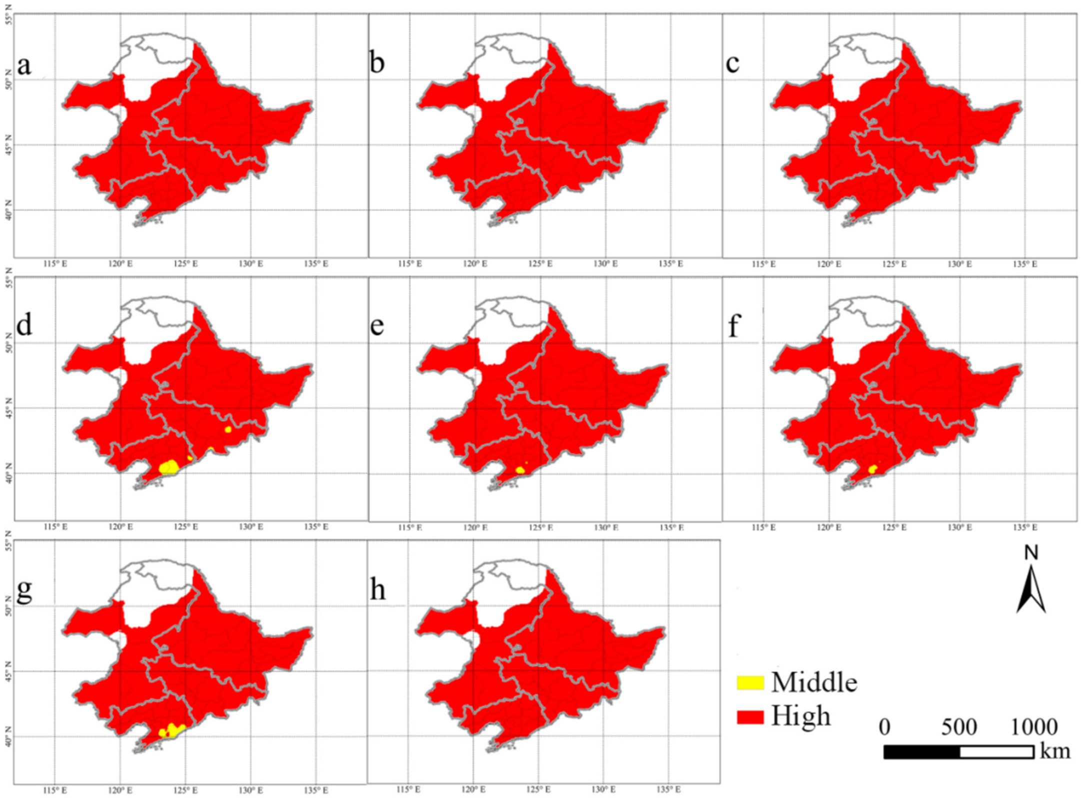

Figure 4. Sunshine suitability of maize at various growth stages in Northeast China: (**a**) SW-VE, (**b**) VE-V3, (**c**) V3-V7, (**d**) V7-JT, (**e**) JT-VT, (**f**) VT-FR, (**g**) FR-R1, and (**h**) R1-R6.

3.2.2. Precipitation Suitability

Figure 7 shows the spatial distribution of precipitation suitability at each growth stage of maize in the Huang Huai Hai region. In terms of the whole growth and development stages of maize, these results are consistent with the monthly distribution of annual precipitation in the region, in which the overall poor precipitation conditions mainly occur in the early and late stages of maize growth and development, while for the rest of the growth stage, precipitation conditions are relatively adequate. In terms of the various stages of maize fertility, the average values of SW-VE and VE-V3 stage precipitation were 0.37 and 0.39, respectively. Precipitation suitability is poor, due to the region's heat sufficiency; thus, the maize should be watered immediately after the emergence of seedlings to avoid high temperatures, which would lead to a reduction in the rate of germination, resulting in seed death and poor quality seeds. It would also prevent a reduction in seedlings and breakage. After maize entered the three-leaf stage, with the gradual arrival of the rainy season in the Yellow and Huaihai regions, the rainfall suitability of each growth stage increased to varying degrees. From V3-R6, the average rainfall suitability of each growth stage was 0.59, 0.74, 0.49, 0.42, and 0.69, respectively. When maize enters the FR-R1 stage in Henan, soil moisture must be monitored to avoid spitting due to drought, which can prevent maize from reaching the flowering stage.

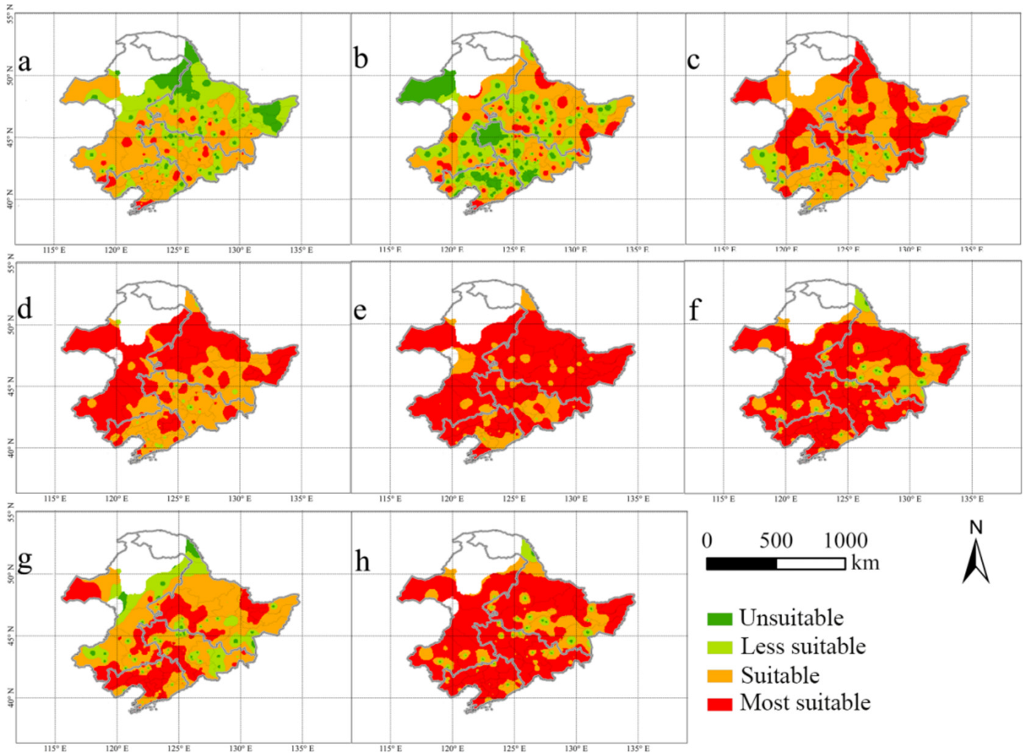

Figure 5. Composite suitability of maize at various growth stages in Northeast China: (**a**) SW-VE, (**b**) VE-V3, (**c**) V3-V7, (**d**) V7-JT, (**e**) JT-VT, (**f**) VT-FR, (**g**) FR-R1, and (**h**) R1-R6.

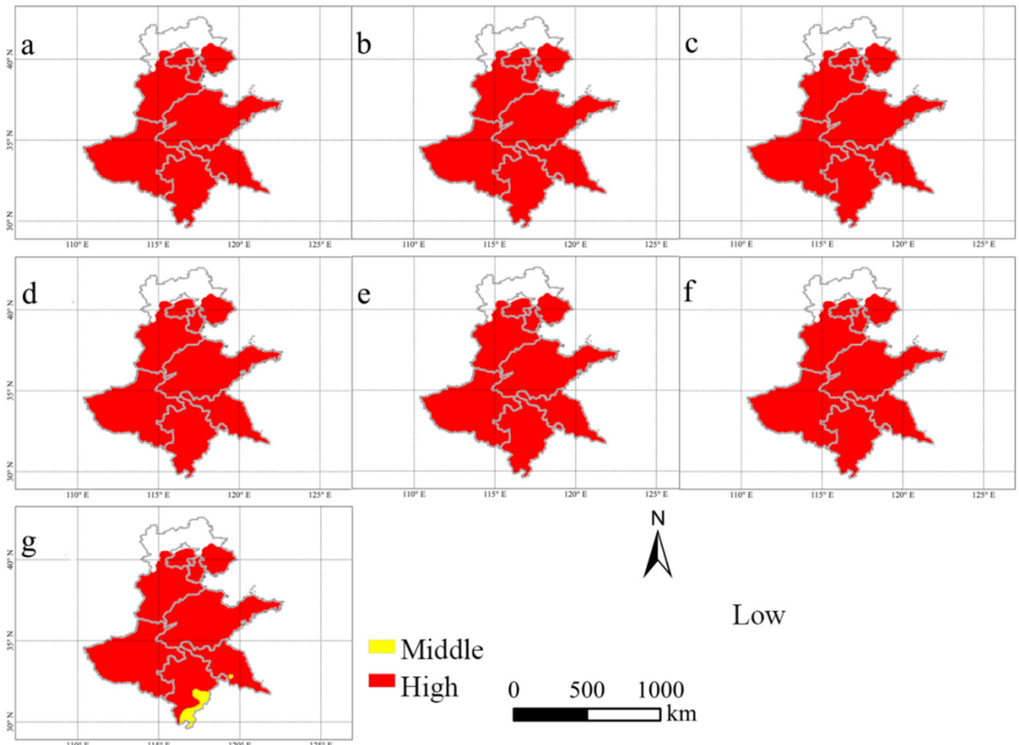

Figure 6. Temperature suitability of maize at various growth stages in Northeast China: (**a**) SW-VE, (**b**) VE-V3, (**c**) V3-JT, (**d**) JT-VT, (**e**) VT-FR, (**f**) FR-R1, and (**g**) R1-R6.

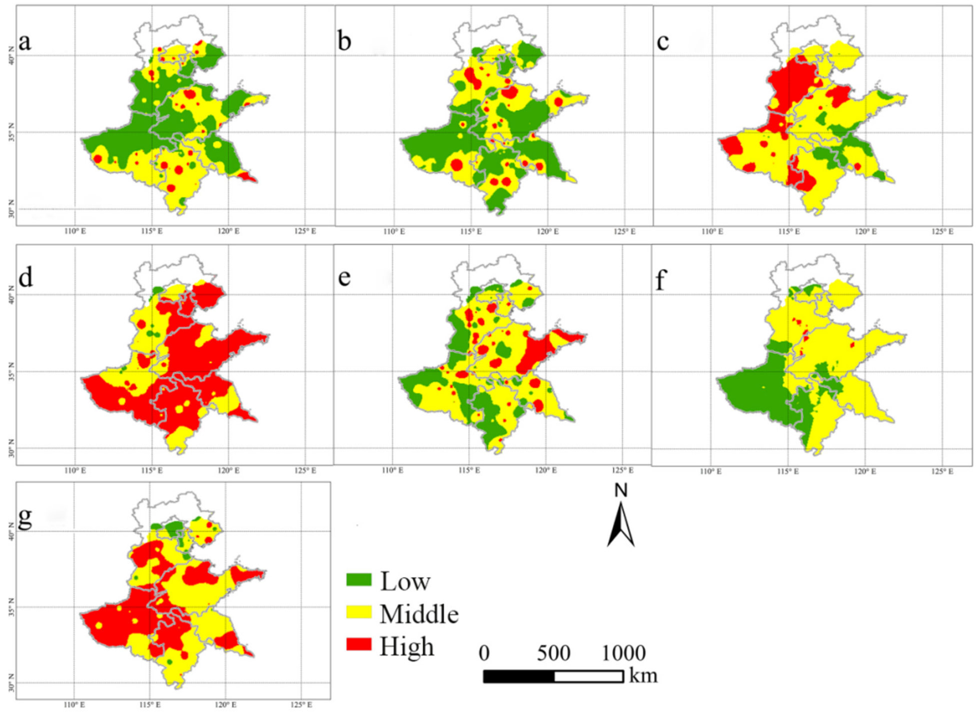

Figure 7. Precipitation suitability of maize at various growth stages in Northeast China: (**a**) SW-VE, (**b**) VE-V3, (**c**) V3-JT, (**d**) JT-VT, € VT-FR, (**f**) FR-R1, and (**g**) R1-R6.

3.2.3. Sunshine Suitability

Figure 8 shows the spatial distribution of light suitability for each growth stage of maize in the Huang Huai Hai region. In terms of the whole growth and development stage, most of the areas have sufficient sunshine to meet the demand for maize growth and development. In terms of sunshine conditions in each growth stage, the average values of light suitability during the SW-JT period were 0.85, 0.82, and 0.74, respectively. These values were maintained at a high level and satisfied the requirements of maize at the nutrient growth stage. Maize growth and development in the JT-R1 stage, during the "rainy season", was characterized by relatively low sunshine suitability. The average values were 0.56, 0.62, and 0.74, respectively. Low-value areas were mainly concentrated in Henan. Based on this finding, steps must be taken to mitigate prolonged raw and low light, which prevents synchronization between the female and male flowering periods and can cause poor fruiting and other problems. The average value of sunshine suitability in the R1-R6 stage is 0.82. A high amount of sunshine is conducive to drying the cob, which is convenient for post-harvest storage.

3.2.4. Composite Climate Suitability

Figure 9 shows the spatial distribution of the composite climatic suitability of maize at each growth stage in the Huang Huai Hai region. The pre-growth stage of maize is affected by low precipitation suitability, resulting in low composite climate suitability. The late growth stage is affected by both low precipitation and sunshine suitability, resulting in low composite climate suitability, while the composite climate suitability of other growth and development stages maintains a high level. Specifically, from the SW-V3 stage, the mean values of integrated climate suitability were 0.62 and 0.65, respectively, and the low-value areas were mainly distributed in the northwestern region of Henan. During the V3-VT stages, the mean values of integrated climate suitability were 0.75 and 0.74, respectively, and the overall climatic conditions were better, laying a good foundation for strong plants with large spikes. The average value of integrated climate suitability in the VT-R1 stage was about 0.65. Some areas in Henan were affected by precipitation and sunshine insufficiency, resulting in lower integrated climate suitability, which could easily affect the quality of maize pollination, and therefore yield. The mean value of the integrated climate suitability of the R1-R6 stages was 0.81, and the overall climate conditions were good, conducive to ensuring a higher grouting rate. Therefore, late maturity should be performed according to the agricultural calendar of each region to increase the dry matter accumulation and improve the yield.

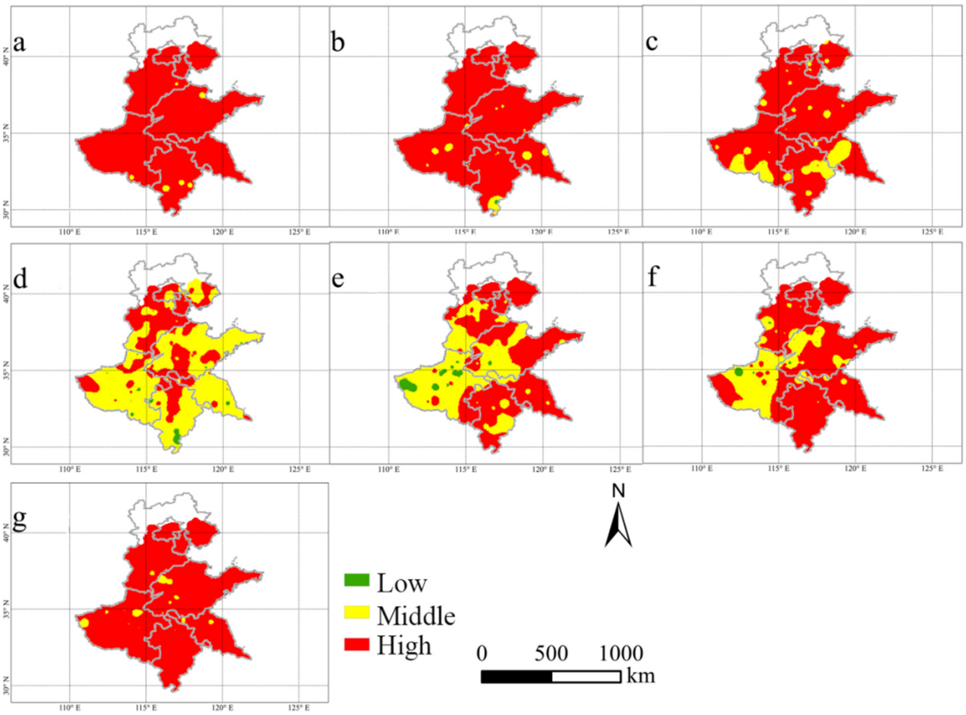

Figure 8. Sunshine suitability of maize at various growth stages in Northeast China: (**a**) SW-VE, (**b**) VE-V3, (**c**) V3-JT, (**d**) JT-VT, (**e**) VT-FR, (**f**) FR-R1, and (**g**) R1-R6.

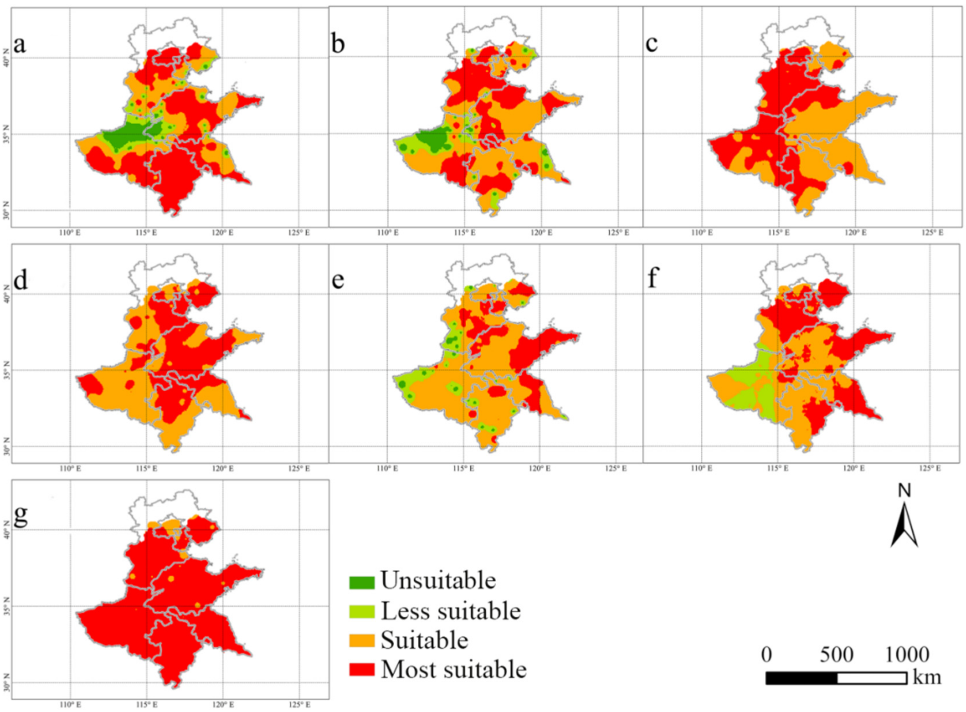

Figure 9. Composite suitability of maize at various growth stages in Northeast China: (**a**) SW-VE, (**b**) VE-V3, (**c**) V3-JT, (**d**) JT-VT, (**e**) VT-FR, (**f**) FR-R1, and (**g**) R1-R6.

4. Discussion

This paper shows that maize in Northeast China is susceptible to the risk of heat deficit in the pre-growth period and at the end of the growth period, which is mostly consistent with related studies [35,36]. In addition, precipitation is a major factor affecting maize growth and development in this region, especially in the early stages of maize growth. Song et al. showed that Northeast China is the region with the highest risk of drought in China's maize growing areas, and notably in the context of climate change, the risk of drought increases by 110% for every 1 °C temperature increase [37]. In this paper, it was found that maize in Northeast China entered the flowering and tasseling stage in some areas with poor precipitation conditions. Notably, Li et al. found that maize in Northeast China had already experienced high temperatures and drought [38]. This in turn suggests that the region has poor precipitation moderation, which is consistent with the results of this paper. In the composite climate suitability evaluation of maize at all growth stages in the Northeast region, it was found that the level of precipitation conditions had a greater impact. In addition, the main reason for low precipitation suitability was that the amount of precipitation was less than the amount of evapotranspiration, which was consistent with the findings of similar studies [39]. The Huang Huai Hai region is rich in heat resources [40], which is affected by precipitation and insufficient sunshine hours, resulting in low integrated climate suitability at some growth stages. For example, in Shandong Province, rainfall has a much greater impact on maize yield increase than light and temperature [41]. In the context of limited land resources, the goal of increasing maize yield can be achieved by supporting suitable moisture conditions [42]. Crucially, the precipitation conditions of maize at various stages in the Huang Huai Hai region derived in this paper can lay a theoretical foundation for the implementation of this measure.

When evaluating temperature suitability, the authors based their evaluation on the quantitative relationship between the temperatures at the three base points of each growth stage and the average daily temperatures within the time frame of each growth stage; however, due to the differences in maize varieties and management practices in different regions, there are certain differences in the temperatures at the three base points of each growth stage of maize [36]. Therefore, future research should determine the three base point temperatures at each growth stage of maize in different regions based on field experiments in order to accurately assess the suitability of temperatures at each growth stage in different regions. In addition, in this paper, when evaluating the suitability of precipitation, the water requirement of maize at each growth stage was calculated according to the crop coefficients recommended by the Food and Agriculture Organization of the United Nations (FAO), which has a certain degree of universality. Nonetheless, it is worth highlighting variations in meteorological conditions and field management in different regions every year. Therefore, during future research, crop growth conditions, soil moisture, and heat in different regions should be taken into account to conduct comprehensive simulations and obtain accurate crop coefficients to improve the accuracy of the precipitation suitability results. In this paper, the weights of temperature, light, and moisture are the same by default in the comprehensive climate suitability evaluation process, and the weighted average method is used to calculate the comprehensive climate suitability. Due to the many differences in climate, management, and varieties in different regions, the impacts of light, temperature, and moisture on various growth stages of maize vary. It is, therefore, critical to accurately assess the weights of light, temperature, and moisture in different growth stages of maize in different regions. Weighting is thus one of the issues which must be considered in future climate suitability evaluation work.

5. Conclusions

Precipitation holds primary significance as the key meteorological factor influencing maize growth in main production areas, followed by temperature and sunshine. However, regional variations in climatic characteristics and geographic locations result in differential effects of temperature and sunlight on maize growth stages. The Northeast region experiences a stronger influence from temperature than sunshine on maize growth and development. The risk of heat shortage is observed in the early and late growth stages, while sunshine remains consistently adequate. Conversely, in the Huang Huai Hai region, sunshine has a greater impact than temperature on late-stage maize growth, posing a risk of insufficient light.

Analyzing meteorological factors and overall climate suitability, the findings suggest the Northeast region is conducive to promoting drought-resistant maize varieties during the seedling stage. Additionally, implementing a late harvest policy in Liaoning would enhance maize yield. The Yellow and Huaihai regions generally exhibit favorable climatic conditions, except for certain parts of Henan, favoring the adoption of drought-resistant varieties. In the remaining areas, selecting maize varieties with extended reproductive life is recommended to optimize the utilization of regional heat resources while avoiding agricultural season constraints.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14020344/s1, Supplementary Materials-1: Maize phenological stage dataset in Northeast China, Supplementary Materials-2: Maize phenological stage dataset in Huang Huai Hai.

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