

Original Research

Analysis of Temporal and Spatial Variation Characteristics of TPP and Yield Gap of Agricultural Land Grading Crops, Using Hohhot City in Inner Mongolia as an Example

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Abstract

Applying the step-by-step correction model, according to the method of “light and temperature” step-by-step attenuation, the agricultural land grading crops in Hohhot City from 2010 to 2020 is calculated daily: corn, wheat, soybean thermal production potential, and their light-temperature potential is calculated. yield gap, that is, the difference between the actual unit yield of the leading producing county and the TPP of the corresponding meteorological site. The results show that the solar radiation in Hohhot had an upward trend in the past ten years, and the spatial variation trend is high in the west and low in the east. The TPP of its agricultural land grading crops has shown an upward trend in the past ten years. Regarding spatial distribution, the TPP of farmland is higher in the south and lower in the north, and the city generally shows an increasing trend. In the past ten years, the actual yield per unit of farmland in the eastern part of Hohhot has been relatively low, and the production difference between light and temperature has decreased from south to north and east to west. This study can provide a reference for the rational use of light and temperature resources in Hohhot in the future, guide agricultural production, cultivate land evaluation, give full play to the potential of light and temperature products in the region, and improve regional productivity.

Keywords: Hohhot city, agricultural land grading crops, TPP, yield gap, step-by-step correction model

Introduction

In the Fifth Session of the 13th National People’s Congress, the concept of “digital agriculture” was highlighted, and digital agriculture was regarded as an

essential part of international agricultural cooperation during the “14th Five Year Plan” [1]. It was proposed in the “14th Five Year Plan” for International Cooperation in Agriculture and Rural Areas to enrich and expand cooperation areas, focusing on food security, digital agriculture, climate change response, animal and plant disease prevention and control and other cooperation. As the name suggests, digital agriculture is to apply geographic information systems, remote sensing,

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computer, network and other technologies to geography, climatology, botany, ecology, soil science and other basic disciplines, to make agricultural production technology and research more intelligent and truly achieve “self-sufficiency”.

Global warming has significantly changed the temporal and spatial distribution of global temperature in the past ten years. With the increase in greenhouse gas emissions, climate warming is expected to continue in the coming decades [2]. Climate change has a significant impact on the growth and production of crops. Light and heat resources are one of indispensable factors for plant growth. Photosynthesis of plants provided by light energy resources is the basis for crop growth. On the one hand, it depends on the utilization rate of light energy of plants themselves, and on the other hand, it depends on whether the light, temperature, water and gas required by plants meet the requirements [3]. The impact of climate change that we focus on is ultimately on yield. When the external conditions meet the optimal conditions for crop growth (such as soil nutrients, carbon dioxide, etc.) and make full use of light and heat climatic resources, the maximum biological yield or agricultural yield per unit area can be obtained as the Thermal Production Potential-TPP [4]. The process of calculating Thermal Production Potential is “digital agriculture”, which combines remote sensing, geographic information system, climatology and botany to improve agricultural production. This can not only guide actual local show, but also evaluate the utilization of local light and temperature resources. At present, models for calculating TPP are mainly divided into two categories. The first category is empirical models. Statistical models based on experimental data, such as the step-wise revised model [5], which is widely used in China, has been applied to the calculation of the TPP of China’s Heilongjiang soybean [6], Henan summer corn [7], Hunan spring corn [8], Yunnan apple [9], Inner Mongolia potato [10] and other crops. And the United Nations Food and Agriculture Organization (FAO) and the International Institute for Applied Systems Analysis (IIASA) jointly developed the Agro-Ecological Zones (AEZ) model [11]. M.I. Nazrul [12] et al. used AEZ model to calculate mung bean production potential in Sylhet, Robson A.[13] et al. used AEZ model to calculate sugarcane production potential in Minas Gerais. In China, AEZ model was used to calculate the TPP of sugarcane in Guangxi [14], potato in Yunnan [15], winter wheat in Henan [16], spring corn in Jilin [17] and other crops. The second type is the mechanism model, which applies mathematical methods to simulate various stages of crop growth and development and explain the physiological process of crop [18]. For example, Tan Hong et al. [19] used the DSSAT model [20] integrated with the CERES and CROPGRO models of the United States to calculate the TPP of cotton in Shihezi City of Xinjiang, and Qin Yaqian et al. [21] used the WOFOST model [22] of the Netherlands to calculate the TPP of spring wheat in the Qinghai-Tibet

Plateau. In addition to the above models, Australia’s APSIM model [23], Sweden’s COUPMODEL [24], France’s STICS model [25], and Sirius wheat growth model [26] developed by scientists from New Zealand and the United Kingdom, And Aquacrop crop model introduced by Food and Agriculture Organization of the United Nations (FAO) in recent years [27] et al. (Steduto et al.2009). Some decision systems with large model structures are now in their seventh or eighth generation, such as Australia’s APSIM 7.9, the Netherlands’ WOFOST 7.1, and France’s STICS8.5. Compared with the mechanism model, the empirical model needs less data and does not need parameter correction, so it is suitable for the calculation of light temperature production potential of a small range of multiple crops. The difference between potential yield and actual yield - yield gap. In 2009, Lobell [28] defined yield gap as the difference between potential yield and actual yield of farmers in a specific time and space. In 2010, Fischer [29] et al. Yang X.G. and liu Z.J. [30] summarized the definition of output difference between China and foreign countries in terms of actual output, potential output, output difference and relative output difference. In 2016, huang S.H. [31] and others proposed that the nutrient efficiency was poor, and compared the poor yield with the poor nutrient efficiency. Increasing the high yield potential of crops and reducing the yield gap are two important measures to improve the overall global food output and ensure global food security [32]. The calculation of yield gap can measure the degree of grain production and development and analyze provincial differences [33], and can also guide farmers to plant scientifically [34], providing reference for local agricultural policies [35].

For the convenience of agricultural planting, agricultural policy formulation, agricultural land development and consolidation, and the comparability of various work in various regions, the Ministry of Land and Resources issued the Regulations on Agricultural Land Classification (TD/T 1004-2003) [36] in 2003, which contains a quick check table of light temperature and climate productivity potential of agricultural land classification crops in various provinces of the country. However, it has been more than ten years since its calculation. The annual changes cannot be evaluated in real time, so this paper takes the main crops in the Agricultural Land Grading Regulations as the research object, uses the stepwise correction model, slope trend analysis method and geographic information system to quantify the annual “light and temperature” changes in Hohhot from 2010 to 2020, and analyzes the spatio-temporal evolution of the TPP, actual yield and potential difference of agricultural land grading crops to improve the understanding of grain production in Hohhot, the rational use of light and temperature resources in the future, to guide agricultural production, give full play to the region's TPP, improve regional productivity, ease the contradiction between local food security, regional

grain production policy formulation and implementation of ecological policy to provide some reference.

Material and Methods

Study Area

Hohhot is located in the central part of Inner Mongolia Autonomous Region, at 40°48' north latitude and 111°41' east longitude. It has jurisdiction over four districts (Saihan District, Xincheng District, Huimin District, Yuquan District), four counties (Tuoketuo County, Helinger County, Qingshuihe County, Wuchuan County), and one flag (Tumote Zuqi) [37]. The total area is 17224 km², with Daqing Mountain in the north, Manhan Mountain in the east, and Tumochuan Plain in the south and southwest. Hohhot is located in the temperate inland region, in the northern part of North China. It belongs to the typical Mongolian Plateau continental climate. The climate changes significantly in the four seasons, and the annual temperature difference and daily temperature difference are large. Its characteristics are: dry and windy in spring, with dramatic changes in temperature and temperature; short, hot summer with concentrated rainfall; rapid cooling in autumn with frequent frosts; long, cold, and less snowy winter. The annual average temperature is 6.8°C. The average annual precipitation is 335.2-534.6 mm, mainly concentrated in July-August; the total solar radiation in the growing season of crops is 35,592,828 MJ/km², which is 63% of the total annual solar radiation, with more than 1,600 hours of sunshine, accounting for 55% of the annual sunshine. The main crop varieties in Hohhot include 9 kinds,

52 varieties, including wheat, naked oats, barley, sorghum, corn, millet, millet, buckwheat, soybean and other grains. The agricultural land grading (TD/T 1004-2003) of Hohhot City includes corn, wheat and soybean.

Measure Method and Data Processing

Field survey and download on China Meteorological Science Data Sharing Service Network (<http://cdc.cma.gov.cn/home.do>) Daily meteorological data of 7 meteorological stations in Hohhot from 2010 to 2020 are selected, including daily average temperature, minimum temperature, maximum temperature and radiation. The distribution and names of stations are shown in Fig. 1. The actual unit yield data of corn, wheat and soybean for agricultural land classification in Hohhot from 2010 to 2020 are selected. The data are from the statistical yearbook of Inner Mongolia Autonomous Region and household survey.

Farmland production potential, also known as crop production potential of farmland, refers to the potential ability of farmland to continuously produce biological products needed by human beings under certain conditions. Excluding the influence of human socio-economic factors, farmland production potential is determined by light, heat, water, soil and crop biological characteristics. They restrict and influence each other, forming a ladder series of farmland TPP: Photosynthetic production potential. Light temperature production potential. Regarding the calculation of the light-temperature production potential, this paper adopts the traditional method of gradual correction of environmental factors, that is, the photosynthetic production potential is calculated first [38], and then

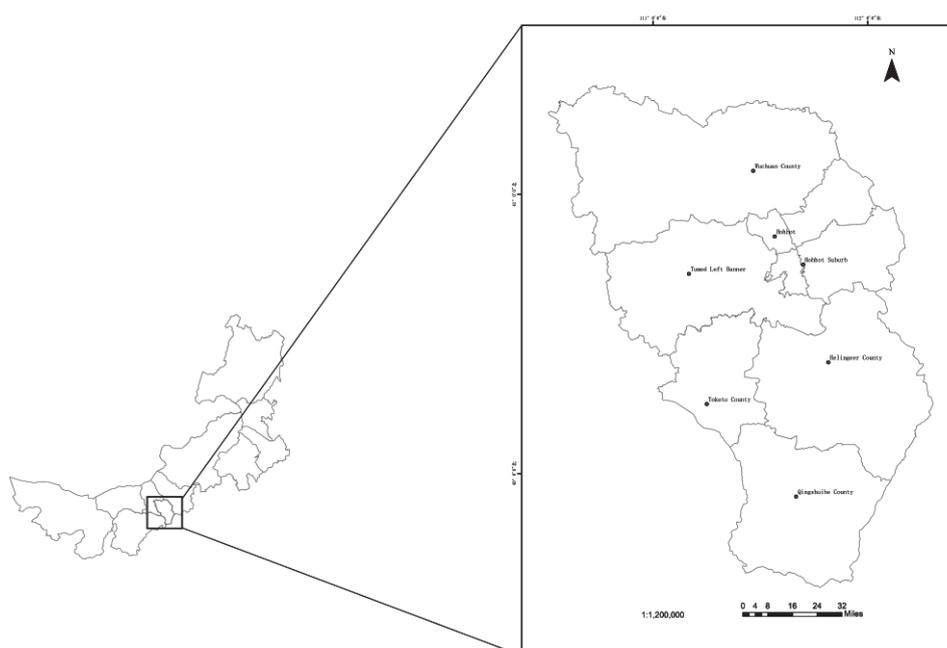


Fig. 1. Distribution of meteorological stations in Hohhot.

the light-temperature production potential of the crop is obtained by correcting the effect of temperature.

The formula for calculating the photosynthetic production potential:

$$Y_Q = Qf(Q) = CS\varepsilon\phi(1-\alpha)(1-\beta)(1-\rho)(1-\gamma)(1-\omega) \cdot Ef(L)\Sigma Q_i(1-\eta)^{-1}(1-\delta)^{-1}q^{-1} \tag{1}$$

Where Y_Q is the light and production potential (Kg/ha), C is the unit conversion factor, ΣQ_i is the total radiation sum of each month in the crop growing season (unit MJ/m²) [39], and the physical meanings and values of other parameters are shown in (Table 1) [40, 41].

The formula for calculating the light-temperature production potential Y_T is as follows:

$$Y_T = f(t) \cdot Y_Q \tag{2}$$

where $f(t)$ is the temperature correction coefficient [42], calculated as follows:

$$f(t) = \begin{cases} 0, t < t_{\min}, t > t_{\max} \\ \frac{t-t_{\min}}{t_s-t_{\min}}, t_{\min} \leq t < t_s \\ \frac{t_{\max}-t}{t_{\max}-t_s}, t_s \leq t < t_{\max} \end{cases} \tag{3}$$

t is the monthly average temperature, and t_{\min} , t_s , and t_{\max} are the three base-point temperatures in the

crop development period, which are the lower limit temperature [43], the optimum temperature and the upper limit temperature (Table 2).

Statistical analysis of the research data was carried out with Excel, and the change trend analysis was carried out with linear tendency rate [44] and SLOPE trend [45, 46] analysis; the spatial distribution map was obtained by the inverse distance weight method of GIS.

Results and Analysis

Analysis of Solar Radiation Characteristics

Figs 2a), 2b), and 2c) show the temporal and spatial variation characteristics of the total solar radiation in the 2010-2020 crop growth period (May-September) at seven observation stations in Hohhot. The lowest solar radiation in the crop growth period from 2010 to 2020 appeared in 2010 (3127.813 MJ/m²), and the highest appeared in 2019 (3361.584 MJ/m²), showing an upward trend. From 2010 to 2020, the spatial distribution of the average solar radiation in the crop growth period was higher in the south and lower in the north. The total solar radiation in Qingshuihe, Tuoketuo and Helinger counties was higher, and the total solar radiation in Wuchuan County was the lowest. Its overall change trend is on the rise, and the solar radiation in Tuoketuo County has the largest upward trend, rising by 19 (MJ/m²) per year.

Analysis of Temperature Characteristics

Figs 3a), 3b), and 3c) show the temporal and spatial variation characteristics of temperature during the crop

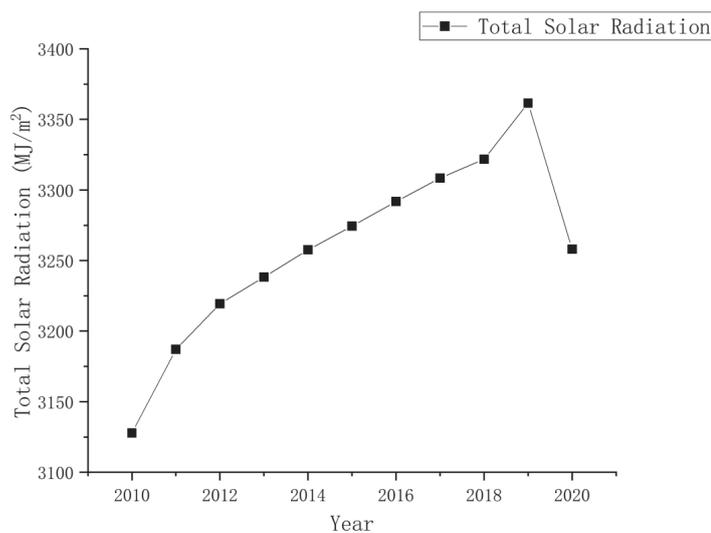
Table 1. Significance and value of parameters of photosynthetic productivity of crops in farmland.

Parameter	Physical Meaning	Corn	Wheat	Soybean
S	Ratio of crop photosynthetic fixation CO ₂ capacity	1	0.85	0.6
ϕ	Efficiency of photosynthetic quantum conversion	0.224	0.224	0.224
ε	Ratio of PAR to total global solar radiation	0.49	0.49	0.49
α	Reflectance of vegetation population	0.08	0.1	0.1
β	Transmittance of Luxuriant plant group	0.06	0.07	0.1
γ	Ratio of light over light-saturation points	0.01	0.05	0.1
ω	Ratio of respiration consumption to photosynthates	0.3	0.33	0.35
ρ	Intercepted radiation ratio of non-photosynthetic organs	0.1	0.1	0.1
E	Crop economic coefficient	0.35	0.36	0.35
ζ	Ratio of ash content in plants	0.08	0.08	0.08
η	Moisture content of mature grain	0.15	0.14	0.15
q	Heat content of per unit dry matter (MJ/Kg)	17.2	17.58	23.1
$f(L)$	Corrected value of crop leaf area dynamic change	0.58	0.61	0.5

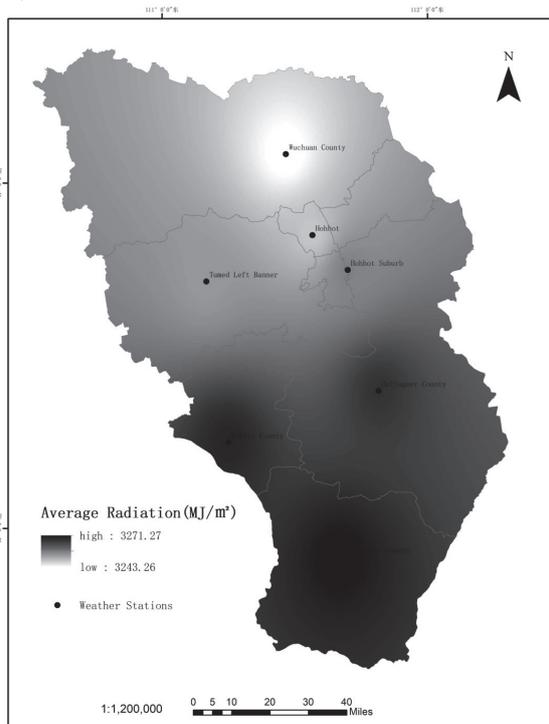
Table 2. lower limit, upper limit and optimum temperature of different development stages of crops in farmland.

Month	Growth period	Corn			Wheat			Soybean		
		t_{min}	t_{max}	t_s	t_{min}	t_{max}	t_s	t_{min}	t_{max}	t_s
5	Emergence	8	27	20.5	9	28	21	7.5	26	18.5
6	Vegetative growth period	11.5	30	24.5	12	32	25	10	30	23.5
7	Vegetative and reproductive growth period	14	33	27	15	33	27.8	13	32	26
8	Flowering and filling period	14	32	25.5	15	33	26.3	14	30.5	24.5
9	Filling and maturity period	10	30	19	10	30	19.3	10	30	18

a)



b)



c)

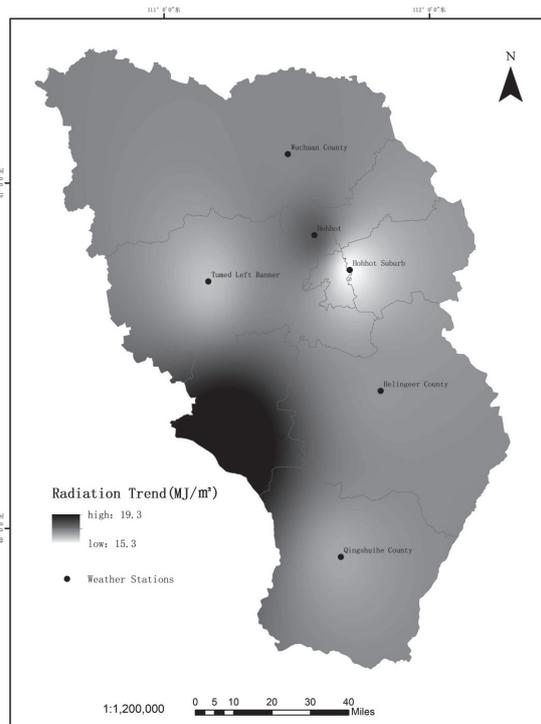


Fig. 2. Temporal a) spatial b) distribution map and trend c) distribution map of temperature during crop growth period in Hohhot from 2010 to 2020.

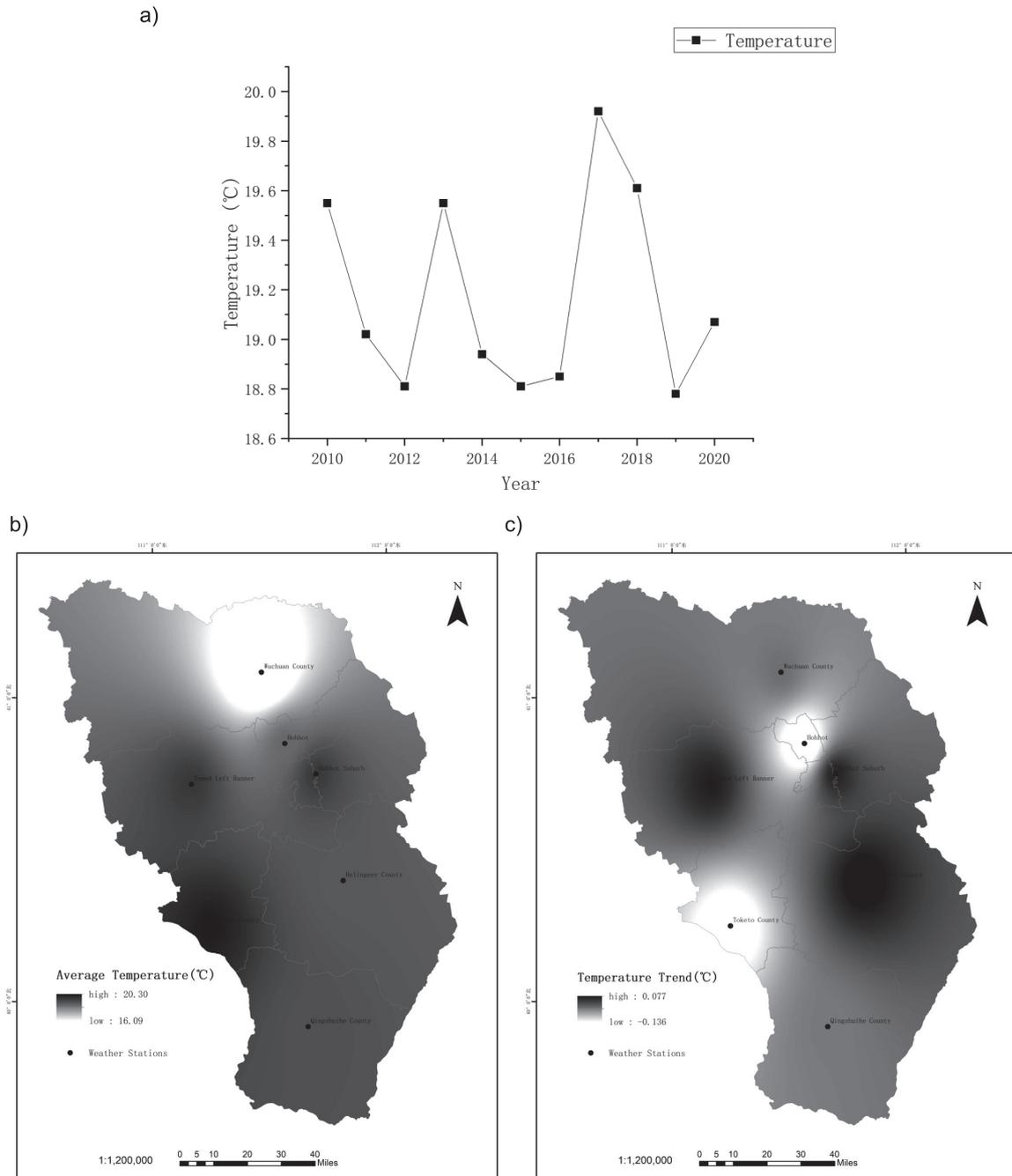


Fig. 3. Temporal a) spatial b) distribution map and trend c) distribution map of temperature during crop growth period in Hohhot from 2010 to 2020.

growth period (May-September) at seven observation stations in Hohhot from 2010 to 2020. During the 2010-2020 crop growth period, the lowest temperature appeared in 2019 (18.78°C), and the highest appeared in 2017 (19.92°C), showing a downward trend. The spatial distribution of temperature in the crop growth period from 2010 to 2020 was higher in the south and lower in the north, higher in Tuoketuo County, Tumote Zuoqi and suburban stations of Hohhot City, and the lowest in Wuchuan County. The overall trend of change is not obvious, with an average annual fluctuation of -0.136-0.077°C.

Characteristic Analysis of Thermal Potential Productivity

Fig. 4a) shows the changes in TPP of seven observation stations in Hohhot from 2010 to 2020, and the average value is shown in Fig. 4b). It can be seen from the figure that the high value of TPP in Hohhot is distributed in the southern regions, such as Tuoke. Tuo County, Tumote Zuoqi, Qingshuihe County, Helinger County, Yuquan District and Saihan District. Its low value is distributed in the northerly areas, such as Huimin District, Xincheng District and Wuchuan

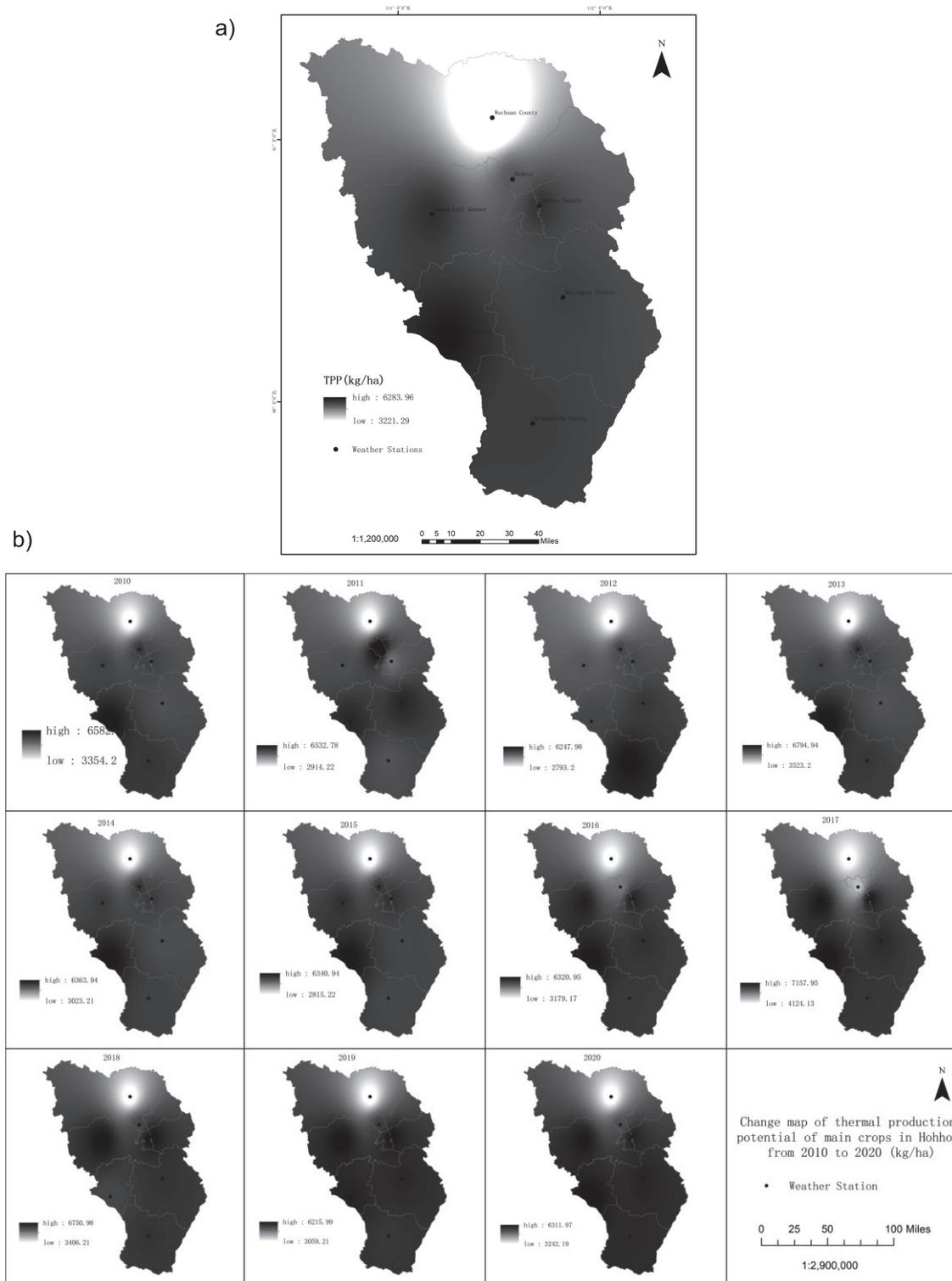


Fig. 4. Spatial a) and b) distribution map of farmland thermal production potential in Hohhot from 2010 to 2020.

County. The specific reason is that the northern part of Hohhot City is close to the Daqingshan Mountains. The shielding effect of the mountains on solar radiation makes its cold, warm, dry and wet conditions lower than in other places.

The temporal variation of TPP of Hohhot farmland from 2010 to 2020 at meteorological observation stations is shown in Fig. 5a), and the inter-annual

variation is between 5452 kg/ha (2011) and 6563 kg/ha (2017), showing an upward trend, and the reason is related to the obvious increase in the amount of solar radiation. Fig. 5b) shows the spatial variation trend of TPP of farmland in Hohhot City. The TPP of Hohhot Observation Station shows an obvious downward trend (the downward trend is 10-79 kg/ha/a). The change trend of production potential is not obvious ($-9 \leq \text{change}$

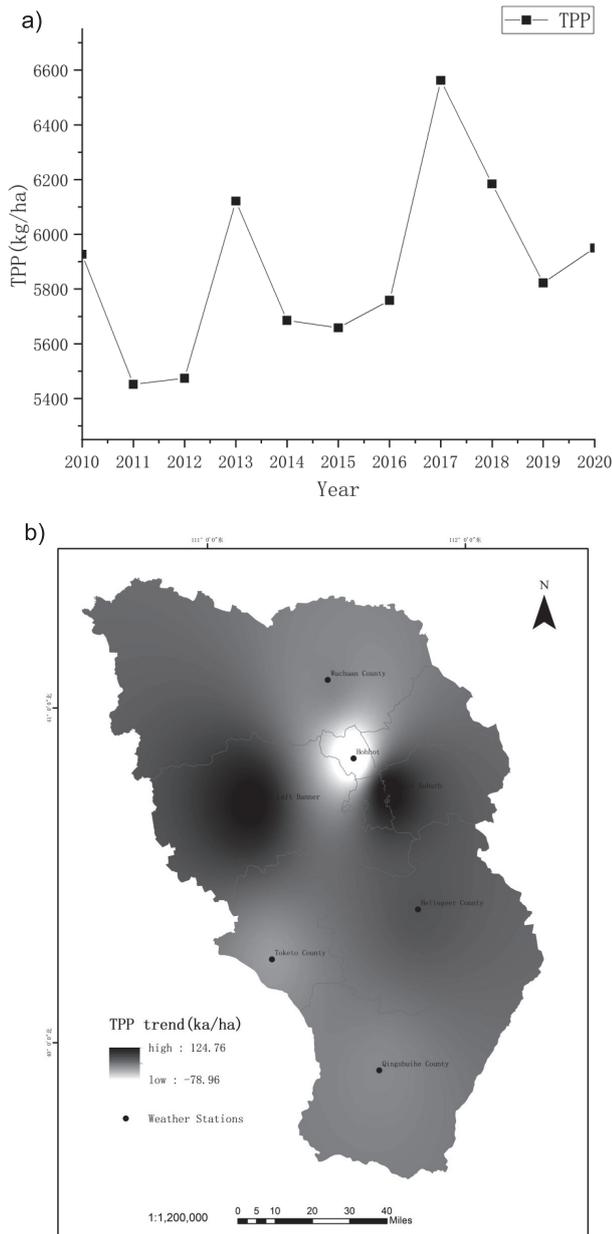


Fig. 5. Time a) distribution map and change trend b) map of farmland thermal production potential in Hohhot.

trend \leq 23), and other regions have obvious increasing trends (the increasing trend is 24-125 kg/ha/a).

Analysis of Actual Yield Characteristics

Fig. 6a) shows the time change of the actual farmland yield of seven observation stations in Hohhot from 2010 to 2020. The year with the lowest actual yield was 1494 kg/ha in 2010, and the year with the highest actual yield was 4137 kg/ha in 2020, which showed an overall upward trend. The spatial distribution of the average farmland yield in Hohhot from 2010 to 2020 is shown in Fig. 6b). The average farmland yield per unit area (2814-4068 kg.hm²) is the highest in Tumut Zuoqi, followed by Tuoketuo County (2123-2813 kg/ha)

and Linger County (1637-2123 kg/ha), the main reason is that Tumote Zuoqi, Tuoketuo County, and Linger County focus on the development of green food. The average unit yield of farmland in Wuchuan County (1166-1636 kg/ha), Qingshuihe County Station, Hohhot City Station and Hohhot Suburban Station (67-1165 kg/ha) is relatively low. The reason is that Wuchuan County is a dry farmer. The Qingshuihe County is located in the northern edge of the Loess Plateau, with the most mountains and fewer beaches, characterized by long winters and short summers, cold and dry, windy and rainy, not suitable for the growth of crops, while Hohhot Station and Hohhot the suburban station area belongs to the central urban area of Hohhot, and mainly develops cultural tourism, modern service industry, and logistics hub. The change trend of actual unit yield is shown in Fig. 6c). The change trend of the actual unit yield of crops in Hohhot generally shows an increasing trend. Only the Hohhot station and the suburban station of Hohhot show a decreasing trend. The main reason is that they are located in the central urban area.

Analysis of Yield Gap Characteristic

Fig. 7a) shows the average time change of cropland light temperature yield gap in Hohhot from 2010 to 2020. The year with the smallest yield gap was 2012 (3850 kg/ha), and the year with the largest yield gap was 2017 (4967 kg/ha). increasing trend. The main reason is that the increasing trend of TPP of farmland in Hohhot from 2010 to 2020 is far greater than the increase trend of actual unit yield. The spatial distribution of light-temperature yield gap of farmland in Hohhot from 2010 to 2020 is shown in 7b). The places with the smallest light-temperature yield gap are Tumutzuoqi Station and Wuchuan County Station (1759-2847 kg/ha). The main reason is that Tumochuan Plain is relatively close to ideal production compared with other mountainous areas. The largest places are Qingshuihe County Station, Hohhot City Station, and Hohhot Suburban Station (4590-5618 kg/ha). The variation trend of light-temperature yield gap is shown in Fig. 7c). The light-temperature yield gap of crops in Hohhot generally shows an increasing trend. Only the light-temperature yield gap of Hohhot City Station, Tuoketuo County Station and Helinger County Station decreased. The reason is that although the TPP of Hohhot Station is decreasing, its actual unit yield decreases more, and the increasing trend of TPP in Tuoketuo County and Helinger County is higher than that of the actual unit yield.

The relative yield gap of light and temperature of main crops in Hohhot in recent ten years is shown in Fig. 7d), and its relative yield gap is 24%-31%. The minimum relative output difference in 2017 was 24%, the highest relative output difference in 2019 was 31%, and the relative output difference in 2020 increased by 1% compared with 2010.

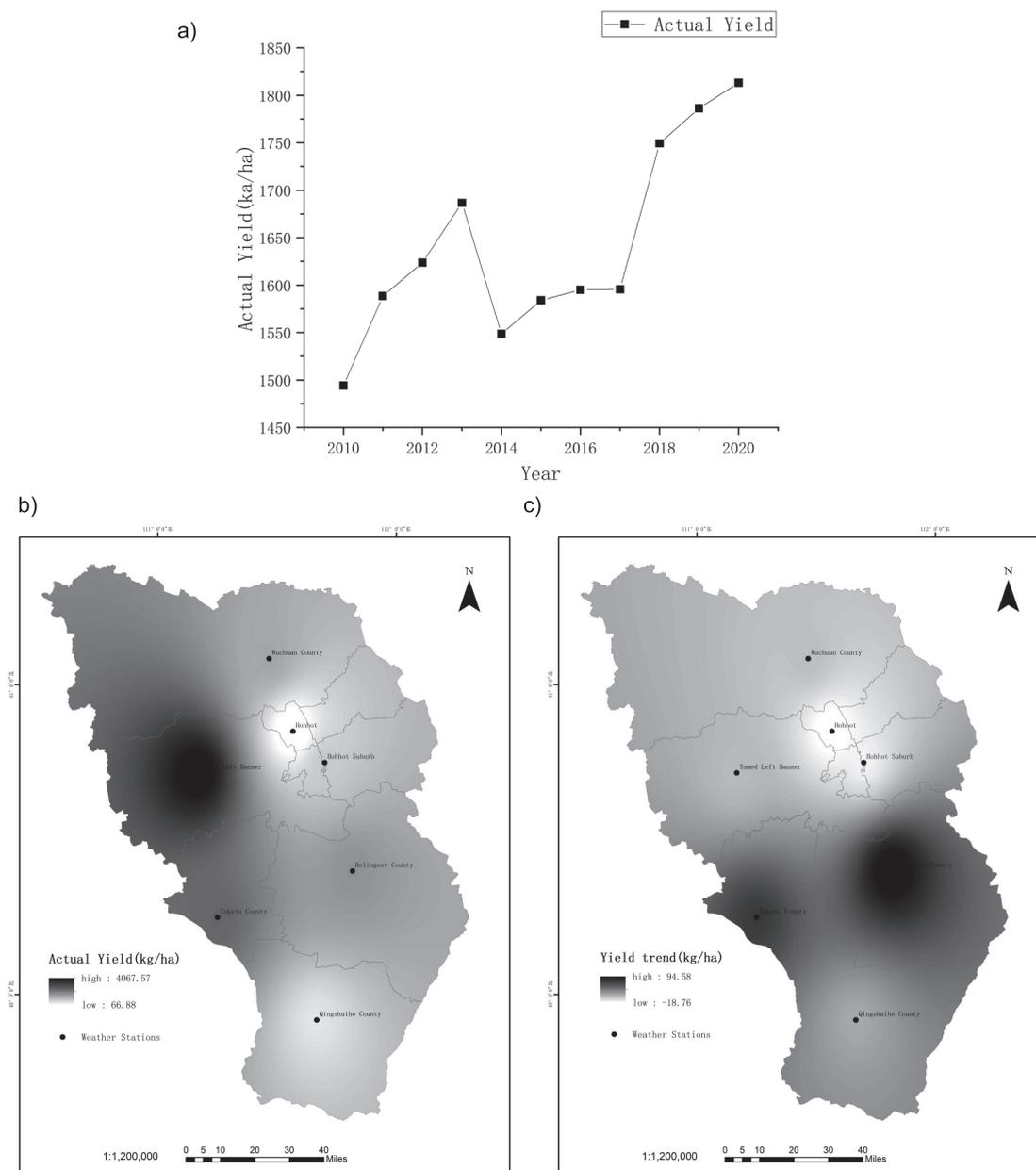


Fig. 6. Time a) space b) distribution and change trend c) of actual yield of farmland in Hohhot from 2010 to 2020.

Discussions

Crop production has the most direct impact on agriculture, and climate change is one of the most important factors affecting crop production. Because of China’s vast territory, climate change in China has obvious regional differences, and the characteristics of climate change in different regions are different. Therefore, the types of crop cultivation in different regions are also different, and their relevant policies should also be adapted to local conditions. This study analyzed the variation characteristics of ‘light and temperature’ factors of 7 stations in Hohhot from 2010 to 2020, quantified the changes of ‘light and temperature’ in Hohhot, and provided a reference for Hohhot to cope with climate change and make rational

use of ‘light and temperature’ resources to fully develop the light and temperature potential of the region. The results show that the solar radiation in Hohhot is high in the south and low in the north, which is the same as the law that the solar radiation decreases with the increase of latitude, and the overall trend is increasing. The temperature in the south is higher than that in the north, which is consistent with the law that the lower the latitude, the higher the temperature, and the decreasing trend. This is consistent with Meng Y.J’s [47] conclusion that the temperature in Inner Mongolia is temporarily slowing down.

The light and temperature production potential is the highest yield achieved under the condition that the conditions of agricultural production are fully guaranteed and the local light and heat resources.

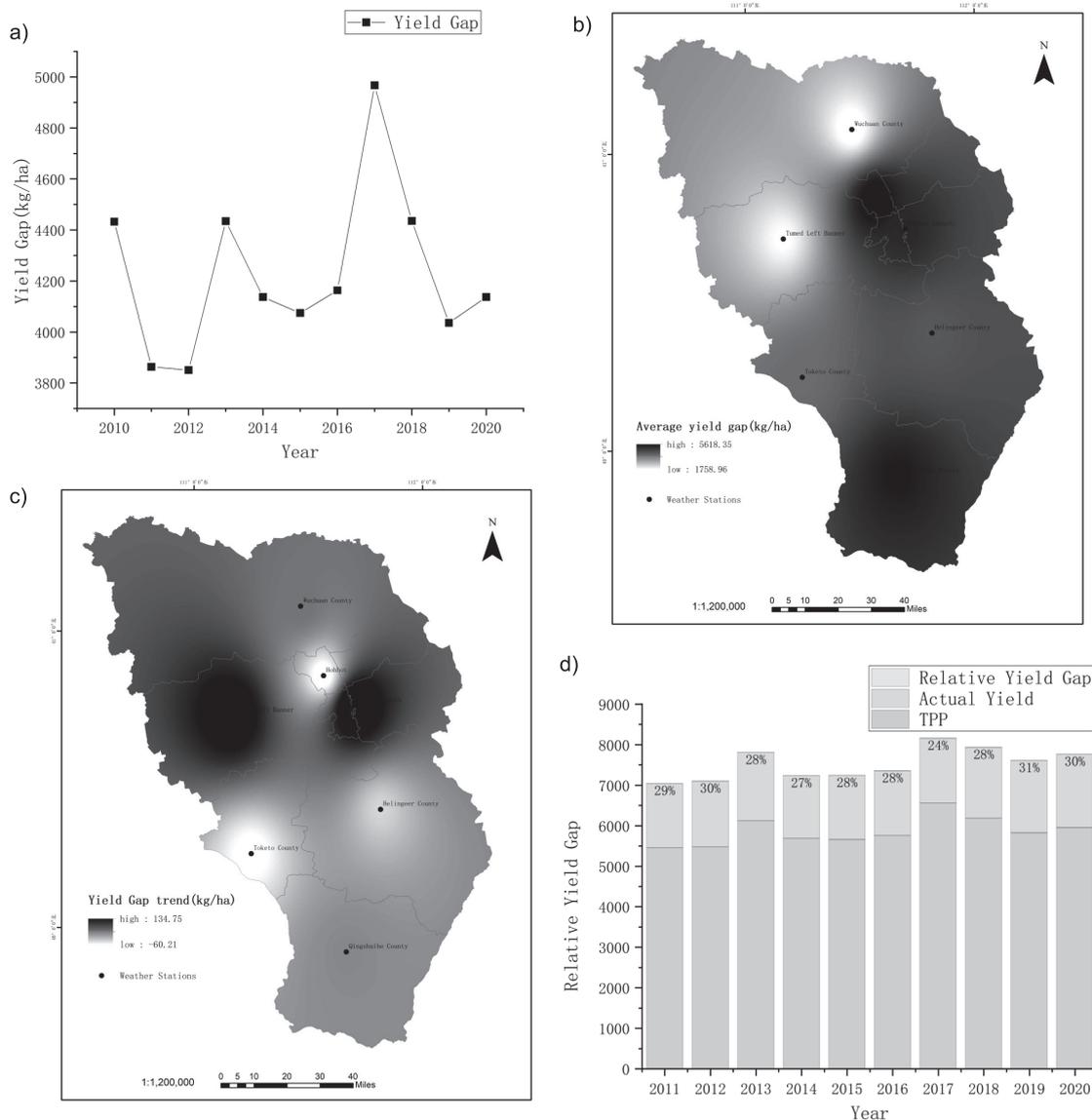


Fig. 7. Temporal a) spatial b) distribution and change trend c) of thermal potential gap in Hohhot from 2010 to 2020, d) the relative yield gap of light and temperature of main crops in Hohhot in recent ten years.

Crop light and temperature production potential is the basis for studying the comprehensive grain production capacity and land classification and grading. It can provide some reference for the evaluation of cultivated land quality, the adjustment of agricultural structure, the improvement of regional productivity, the alleviation of local food security contradictions, the formulation of regional grain production policies and the implementation of ecological restoration policies. This study found that the light and temperature production potential of Hohhot is high in the south and low in the north, and the influencing factors of solar radiation account for a large proportion, showing an increasing trend.

This study selected the most widely used crop production potential assessment model in China, that is, the step-by-step correction model, and studied the

light and temperature production potential of the main crops of agricultural land classification in Hohhot, corn, wheat and soybean. Using the first two steps of the model, namely ‘light, temperature’ two indicators affecting crop yield, calculate the light and temperature productive potentiality. The basic data of the model are easy to obtain and the theoretical results are simple. A large number of studies and large-scale application of the former fully prove that the results can better reflect the light and temperature productive potentiality of crops in different regions. But in the actual agricultural production. There is a big gap between the potential productivity of light and temperature and the actual productivity. The potential productivity of light and temperature is the productivity of crops under ideal conditions, and the actual yield of crops is affected by many factors in reality. In addition to the

natural environment's own resources and uncertain natural disasters, such as multiple cropping index, planting structure, cultivated land area [48], factors of human management of farmland and soil [49, 32], nitrogen fertilizer utilization rate and early sowing [50], etc.

Conclusions

Based on the analysis of the variation characteristics of 'light and temperature' elements in Hohhot, this study analyzed the spatial and temporal distribution characteristics of the TPP of the main crops in Hohhot based on the stepwise correction model and the characteristics of yield gap were analyzed. The results showed that :

(1) In the past ten years, the amount of solar radiation in Hohhot has shown an upward trend. The spatial variation trend is higher in the west and lower in the east. The average temperature shows a downward trend, and the spatial variation of temperature is not obvious. The TPP of its farmland shows an upward trend in time. In terms of spatial distribution, the TPP of farmland is higher in the south and lower in the north. The whole city generally shows an increasing trend. This is because the production potential of light and temperature is positively correlated with the influence of solar radiation. With the increase of solar radiation, the production potential of light and temperature will also increase. Because the surveyed years are only in the past ten years, the calculated trend is only a trend over a period of time, and cannot be said to be an overall trend.

(2) In the past ten years, the actual yield per unit of farmland in the eastern part of Hohhot is relatively low, and the production difference between light and temperature decreases from south to north, and from east to west. In order to achieve the purpose of increasing production, it is necessary to start from two aspects: the internal factors affecting crops and the external environment. Among them, the internal factors are mainly considered from the crop varieties. The improvement of external conditions, on the one hand, is to solve the limitation of water, soil, etc., and on the other hand, to improve the cultivation methods and techniques, so as to minimize the influencing factors, thereby increasing the crop yield.

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Mechanism of Wind Power Station on Vegetation in Grassland Area of Northern, China [2018MS04009].

Conflicts of Interest

The authors declare no conflict of interest.

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