Improving harvest efficiency of maize varieties via accumulated temperature in a certain planting area

Zhaofu Huang†, Liangyu Hou†, Jun Xue, Keru Wang, Ruizhi Xie, Peng Hou, Bo Ming, Shaokun Li*

(*Institute of Crop Sciences, Chinese Academy of Agricultural Sciences/Key Laboratory of Crop Physiology and Ecology, Ministry of Agriculture and Rural Affairs, Beijing 100081, China*)

Abstract: The ripening and drying of maize (*Zea mays* L.) grain are closely related to temperature. In accordance with maize grain drying characteristics, regional accumulated temperature (AT_0≥0°C) distribution is of great significance for a rational allocation of maize varieties, thus reducing grain moisture content (MC) to improve maize harvest efficiency. From 2016 to 2018, a multi-site trial was carried out in the spring maize production area of Northeastern China. In this study, under a guaranteed rate of 80% for AT_0, this area was divided into 15 accumulated temperature zones (ATZs) with an interval of 100°C based on climatic data of 78 local weather stations. Then the AT_0 demand of different maize varieties during different growth stages was calculated by combining experimental records with the established prediction model of MC, and then, the spatial partition for different types of maize varieties under different MCs was analyzed. The results showed that all the tested varieties could not reach physiological maturity (PM) at ATZs 13-15, hence, where maize planting is risky. With the increasing accumulated temperature demand of different types of maize varieties from planting to PM, to the MC of 25% and to the MC of 20%, the unplantable areas were gradually expanded from south to north while the region where the maize varieties could be harvested under different MCs was also moved southwardly. Additionally, at 1-2 ATZs, it is entirely possible to achieve mechanical kernel harvesting under the MC of 20%, even though the AT_0 requirements of the varieties are relatively high. Conclusively, on the grounds of AT_0 demand law of maize varieties and heat resource distribution in Northeastern China, the layout optimization for achieving different harvesting scenarios is conducive to providing a basis not only for selecting suitable varieties but also for promoting mechanical kernel harvesting in the spring maize production area of this region.

Keywords: grain, moisture content, accumulated temperature zone, cultivars' layout, Northeastern China

DOI: 10.25165/j.ijabe.20211404.6337

Citation: Huang Z F, Hou L Y, Xue J, Wang K R, Xie R Z, Hou P, et al. Improving harvest efficiency of maize varieties via accumulated temperature in a certain planting area. Int J Agric & Biol Eng, 2021; 14(4): 175–181.

1 Introduction

Grain drying is affected by genotype and environment, thereinto, the temperature is an important meteorological factor affecting grain drying during crop growth and development[1,2]. From planting to maturity, the total thermal requirement of various crops is named accumulated temperature, which is calculated as mean daily air temperature multiplied by the number of days to harvest[3]. Generally, the accumulated temperature ≥10°C is used to characterize the growth period of thermophilic crops and the number of regional heat resources[4,5]. However, the accumulated temperature above 0°C (AT_0) is more suitable for studying maize drying processes[6-10], probably because these active processes involve physical diffusion of sucrose and moisture content (MC)[11]. In 1976, for the first time, a study proposed the equation $y=c+dx^2$ to predict grain drying rate and then MC at harvest[12]. In order to avoid the influence of environmental conditions on the drying date of grains in different ripening stages, previous studies analyzed the AT_0 and MC after-silking with a more stable correlation[13-15], and established a regression model of the relationship between the two, so as to estimate the MC with the AT_0 after-silking.

With humid and semi-humid climatic characteristics, in the spring maize area of Northeastern China, winters are cold and dry, and summers are warm and short. The annual average temperature is generally between –5°C and 10°C, the AT_0 is between 2300°C·d and 4000°C·d. The annual precipitation is 500-800 mm, 60% of which occurs from July to September. The hotter season is also the rainy season, with sufficient sunshine suitable for maize growth and development. Whereas, the inharmony between heat resources and maize cultivars always leads to a yield gap between yield potential and actual yield[16-18]. The AT_0 of Northeastern China declines from south to north, and correspondingly, it is recommended that the maize cultivars are changed from

Received date: 2020-12-06 **Accepted date:** 2021-05-07

Biographies: Zhaofu Huang, PhD, research interest: grain quality of maize, Email: huangzhaofu123@126.com; **Liangyu Hou**, PhD candidate, Lecturer, research interest: high yield and high efficient maize cultivation, Email: 105948179@qq.com; **Jun Xue**, PhD, Assistant Researcher, research interest: maize lodging resistance, Email: xuejun5519@126.com; **Keru Wang**, PhD, Researcher, research interest: theory and technology of maize mechanization production, Email: wangkeru@caas.cn; **Ruizhi Xie**, PhD, Researcher, research interest: maize physiology and ecology, Email: xieruizhi@caas.cn; **Peng Hou**, PhD, Associate Researcher, research interest: physiology and ecology of maize high yield cultivation, Email: houpeng811125@163.com; **Bo Ming**, PhD, Associate Researcher, research interest: efficient utilization of environmental resources in crop production systems, Email: obgnim@163.com.

†These authors contributed equally to this study and should be regarded as co-first authors.

***Corresponding author: Shaokun Li**, PhD, Professor, research interest: physiology and ecology of maize high yield and high efficiency cultivation. Institute of Crop Sciences, Chinese Academy of Agricultural Sciences, Beijing 100081, China. Tel: +86-10-82108891, Email: lishaokun@caas.cn.

late-maturing to early-maturing from south to north[19-21]. The MC is high when harvesting, especially at high latitudes[22], which would result in a high mildewing risk that causes the quality reduction of maize grain. Due to climatic variation from north to south in Northeastern China, in some areas cold damage is severe in the early stages of maize growth in spring while light and heat resource is insufficient in the later stages of growth. In order to meet the huge market demand with limited farmland, in recent decades, selecting relatively late-maturing cultivars and making full use of regional heat resources has been universal strategies to improve yield. Maize usually reaches physiological maturity (PM) in a short time before the first frost, and therefore high MC on harvesting is common, which is an important factor affecting mechanical harvesting time, harvest quality, drying, grain storage and transportation, and commercial quality[23-27]. Internationally, the MC at harvest is generally 15%-25% and the peak harvesting period is 2-4 weeks later than PM[28,29]. For the past few years, in pursuit of high yield, many long-growing maize cultivars have been gradually planted in areas with less heat resources, further increasing the risk of maturity. Meanwhile, with the application of maize mechanical kernel harvesting technology, some cultivars with short growth period have been selected in areas with higher AT_0, which is a waste of regional heat resources.

The objective of this study is, by reclassifying the ATZs of Northeastern China, to analyze the variety allocation for mechanical kernel harvesting based on regional heat resources, so as to provide the foundation for the selection and breeding of suitable varieties.

2 Materials and methods

2.1 Overview of the study area

From 2016 to 2018, field experiments were conducted at the Kailu Experimental Station (Kailu, Inner Mongolia Autonomous Region), the Tieling Technology Park (Tieling, Liaoning Province), and the experimental station of Bayi Agricultural University (Daqing, Heilongjiang Province, China). 78 standard meteorological stations spread over the maize planting area in Northeastern China were selected (Figure 1). Table 1 shows the geographical positions of test sites and their local climatic conditions during the maize growing season. As the latitude of the test site increases, the AT_0 and frost-free days gradually decreased. Compared with Kailu and Daqing, the precipitation in Tieling is more. The daily mean temperatures are similar at the Tieling and Kailu test sites. These three test sites are typical of the climatic characteristics in Northeastern China.

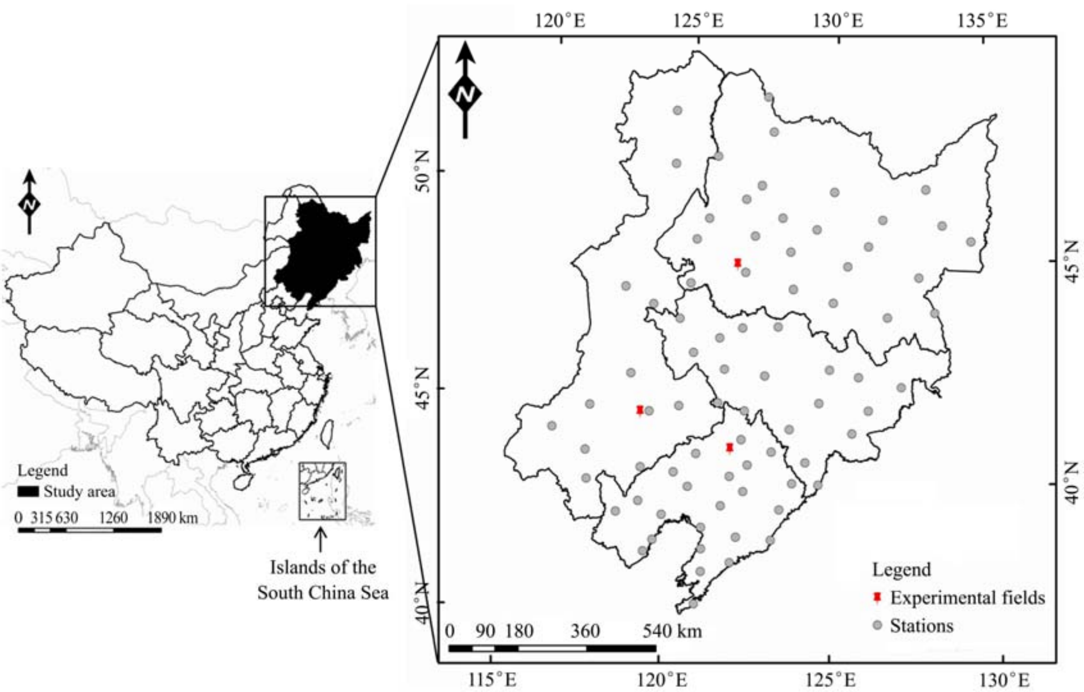


Figure 1 Location of test sites and representative meteorological stations in Northeastern China

Table 1 Locations of the three test sites and their climate conditions

Site	Location		Climatical conditions			
	Latitude/°N	Longitude/°E	Daily mean temperature/°C	AT_0/°C· d	Precipitation/mm	Frost-free days/d
Kailu	121.3	43.61	7.4	3876	325	177
Tieling	123.7	42.23	7.6	3894	714	170
Daqing	125.1	46.59	4.4	3431	473	163

Note: The ten-year mean value (2008-2017) of each variable was obtained by using data from the nearest meteorological station around each test site.

2.2 Maize cultivars and Climate data

From 2016 to 2018, 20 representative maize cultivars were selected for testing. Table 2 shows when each cultivar was planted and where they were planted. These cultivars were planted in a randomized complete block of 667 m^2 with a density of 6.75×10^4 plants/hm^2. From late April to mid-May, sowing was carried out mechanically in Kailu and Tieling but manually in Daqing. The fertilizer applied was as follows: 750 kg/hm^2 of organic fertilizer (organic matter ≥45%), 450 kg/hm^2 of water-soluble and slow-release Si organic fertilizer, and 150 kg/hm^2 of $N_{11}P_{17}k_9$ (37%). At all three sites, weeds, diseases, and insect pests were all well controlled with crop management.

In this study, the climate data was downloaded from the NASA, AgMIP Climate Forcing Datasets (https://data.giss.nasa.gov/impacts/agmipcf/agmerra/), which are consistent daily series covering the period 1980-2010 with a horizontal resolution of 0.25°×0.25° (25 km), including the mean, the minimum, and the maximum temperature (°C), precipitation (mm/d), solar radiation (MJ/m^2·d), wind speed (m/s), as well as relative humidity at the time of maximum temperature (%)[30].

Table 2 Tested cultivars, test sites, and years

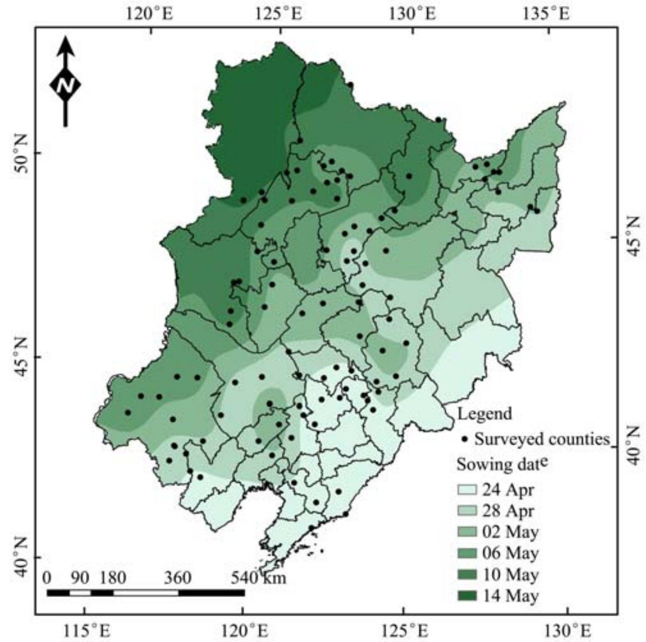
Cultivars	Experimental year	Experimental site
A6565 (A6565)	2017, 2018	Daqing, Tieling
Fengken139 (FK139)	2017, 2018	Tieling
Demeiya1 (DMY1)	2016, 2017	Daqing
Jingnongke728 (JNK728)	2017, 2018	Tieling
Hetian4 (HT4)	2016, 2017	Daqing
Huamei1 (HM1)	2017	Kailu, Tieling, Daqing
Dongdan913 (DD913)	2017	Kailu, Tieling
Deyu919 (DY919)	2017	Kailu, Daqing
Demeiya3 (DYM3)	2016, 2017	Daqing
Jidan66 (JD66)	2017	Tieling, Daqing
Shandan636 (SD636)	2016, 2017	Tieling, Daqing
Zeyu8911 (ZY8911)	2017, 2018	Kai, Tieling, Daqing
Dika159 (DK159)	2017, 2018	Kailu, Tieling, Daqing
Zeyu501 (ZY501)	2017	Kailu, Tieling, Daqing
Xiangyu998 (XY998)	2016, 2017	Daqing, Tieling
Danyu311 (DY311)	2017, 2018	Tieling
Tieyan388 (TY388)	2017, 2018	Tieling
Youdi919 (YD919)	2017	Kailu, Tieling
Dongdan1331 (DD1331)	2017, 2018	Kailu, Tieling
Liaodan575 (LD575)	2017, 2018	Tieling

2.3 Prediction model of grain moisture content

During the drying of maize grain in the field, the variation of MC is closely related to the atmospheric temperature. Previous studies have established prediction models for the MC of different cultivars[31,32]. In this study, a logistic model was established with the AT_0 after-spinning to predict the MC dynamics of the tested cultivars, thus calculating their AT_0 requirements to achieve different harvesting scenarios as a function of target MC.

2.4 Spatial distribution of accumulated temperature

The calculation of AT_0 is started from the spring maize sowing dates in all regions, by means of statistical analysis, which were collected from the 100 counties' survey data in Northeastern China of the National Maize Industrial Technology System in China (CARS-02-25) (Figure 2). Based on the multi-year meteorological data (2008-2017) of 78 major weather stations in Northeastern China, the geographic information analysis tool of the ArcGIS 10.3 software (Esri, Redlands, CA, USA), ArcMap was used to spatially interpolating and rasterizing the sowing dates of each county[33]. Additionally, with the Spatial Analyst Tools of ArcGIS, the annual planting schedule of each weather station was acquired and the mean annual AT_0 of each one was calculated starting from the perennial sowing day sequence. Afterwards, with the ordinary kriging method, AT_0 was interpolated and rasterized for its spatial distribution. In this study, due to a large inter-annual gap of AT_0, the spatial interpolation based on longitude and latitude was performed at a guaranteed rate of 80%.



Note: The black dots represent the location of the county selected for spatial interpolation (n=100).

Figure 2 Interpolation of spring maize's sowing date in Northeastern China

2.5 Data analysis

The experimental data were analyzed with Microsoft Excel 2010. The ArcGIS 10.3 software was used to perform the ordinary kriging method to construct the spatial distribution map of AT_0, and the Spatial Analyst Tools of ArcGIS were used to calculate the area of different accumulated temperature zones (ATZs).

3 Results

3.1 Different cultivars types of average AT_0 demand

According to the AT_0 requirements from Planting to PM, the tested cultivars were divided into four categories: LTD, low temperature demand (AT_0 demand less than 2900°C·d); LMTD, low and medium temperature demand (AT_0 demand range from 2900 to 3000°C·d); MTD, medium temperature demand (AT_0 demand range from 3000 to 3100°C·d); HTD, high temperature demand (AT_0 demand more than 3100°C·d) (Table 3). The results showed that, for the AT_0 required from planting to achieve MC of 25%, DD1331 was the highest (3525°C·d) and A6565 was the lowest (2896°C·d); for the AT_0 required from planting to achieve MC of 20%, DY311 was the highest (3945°C·d) and DMY1 was the lowest (3009°C·d); for the AT_0 required from PM to achieve MC of 25%, DD919 was the highest (342°C·d) and HT4 was the lowest (9°C·d); for the AT_0 required from PM to achieve MC of 20%, DY311 was the highest (756°C·d) and DMY3 was the lowest (136°C·d). By and large, the AT_0 required from PM to achieve MC of 25% was 73°C·d, 151°C·d, 158°C·d, and 217°C·d for LTD, LMTD, MTD, and HTD, respectively, with an average of 160°C·d, while the AT_0 required from PM to achieve MC of 20% for the four categories was 249°C·d, 378°C·d, 461°C·d, and 594°C·d, respectively, with an average of 451°C·d.

3.2 Accumulated temperature zones and the area covered by them

According to the daily mean temperature measured at 78 weather stations in Northeastern China, the average value of AT_0 during 2008-2017 was calculated. Starting from the southern region of Northeastern China, it can be divided into fifteen ATZs (Figure 3).

Table 3 Accumulated temperature requirements of different maize cultivars at different growth stages

Type	Cultivar	PD-PM /°C·d	PD-MC 25% /°C·d	PD-MC 20% /°C·d	PM-MC 25% /°C·d	PM-MC 20% /°C·d
LTD	A6565	2810	2896	3072	86	262
	DMY1	2850	2926	3009	76	159
	FK139	2884	2940	3209	56	325
	Average	2848	2921	3097	73	249
LMTD	JNK728	2926	3047	3411	121	485
	HT4	2934	2943	3084	9	150
	HM1	2947	3181	3428	234	481
	DMY3	2948	3011	3084	63	136
	DD913	2977	3136	3323	139	326
	DY919	2997	3319	3669	342	692
	Average	2955	3106	3333	151	378
MTD	JD66	3057	3158	3393	101	336
	SD636	3066	3194	3416	128	350
	ZY8911	3084	3237	3626	153	542
	DK159	3092	3342	3709	250	617
	Average	3075	3233	3536	158	461
HTD	ZY501	3108	3312	3606	204	498
	XY998	3187	3312	3580	125	393
	DY311	3189	3484	3945	295	756
	TY388	3194	3417	3929	223	735
	YD919	3239	3471	3856	232	617
	DD1331	3251	3525	3838	274	587
	LD575	3282	3446	3857	164	575
	Average	3207	3424	3802	217	594
	Total	3041	3201	3484	160	451

Note: PD: planting date; PM: physiological maturity; MC: grain moisture content.

Heilongjiang Province is mainly situated at ATZ7-ATZ15 and Jilin Province, at ATZ4-ATZ14, except for the southeastern Jilin Province where the hinterland of Changbai Mountain is covered by ATZ13. With the highest AT_0 observed in the southeastern part, Liaoning Province is mainly situated at ATZ1-ATZ8. The four leagues of Eastern Inner Mongolia belong to ATZ3-ATZ15, with the highest AT_0 of 3600°C·d-3900°C·d observed in Liao River Basin and the lowest AT_0 of 2500-2700°C·d observed in the Great Khinan Mountains. ATZ10 and ATZ11 both take up more than 100 000 km^2, accounting for 11.3% and 12.5% of Northeastern China's total area, respectively, while ATZ1 covers less than 10 000 km^2, only accounting for 0.2%. With their area around less than 30 000 km^2, ATZ2 and ATZ3 make up 2.8% and 2.9% of the total area, respectively. Besides, the rest of the ATZs occupy a proportion between 50 000 km^2 and 95 000 km^2 of Northeastern China's total area. Major cities or regions located in each ATZ are shown in Table 4.

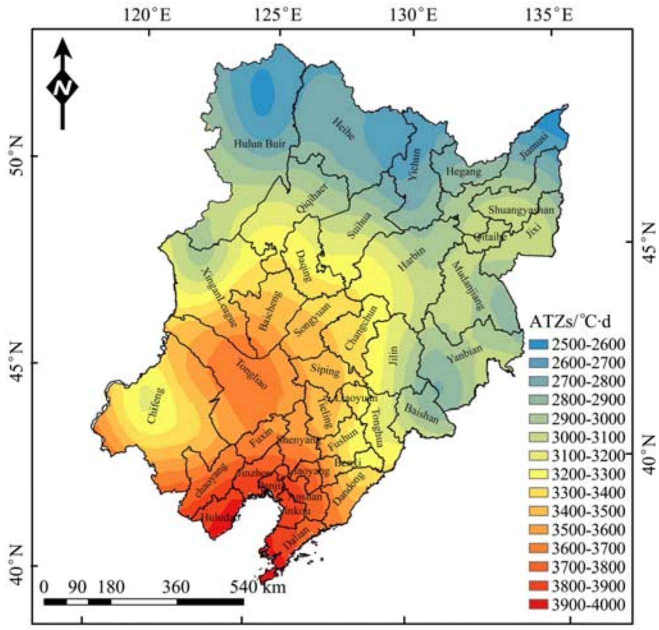


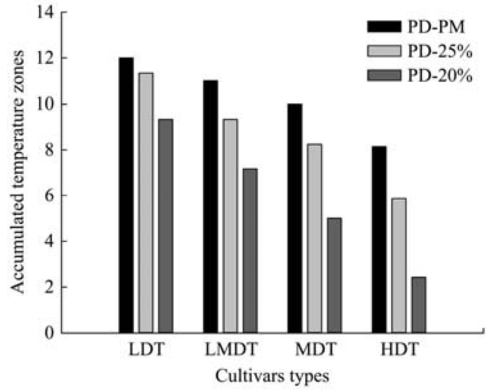
Figure 3 Schematic diagram of AT_0 in Northeastern China (guarantee rate of 80%)

Table 4 Classification of different accumulated temperature zones (ATZs) and their coverage

ATZs	AT/°C· d	City	Area/km^2
ATZ1	3900–4000	Dalian	2375
ATZ2	3800–3900	Dalian, Panjin, Yingkou, Jinzhou, Chaoyang, Huludao	28 075
ATZ3	3700–3800	Dalain,Yinkou, Anshan, Liaoyang, Shenyang, Jizhou, Chaoyang	29 575
ATZ4	3600–3700	Dandong, Anshan, Liaoyang, Shenyang, Fuxin, Chaoyang, Chifeng, Tongliao, Xingan League	53 325
ATZ5	3500–3600	Dandong, Benxi, Fushun, Shenyang, Fuxin, Chaiyang, Chifeng, Tongliao, Xingan League, Baicheng	76 550
ATZ6	3400–3500	Dandong, Benxi, Fushun, Tieling, Siping, Songyuan, Baicheng, Xingan League, Tongliao, Chifeng	79 950
ATZ7	3300–3400	Dandong, Benxi, Fushun, Tieling, Liaoyuan, Siping, Changchun, Songyuan, Baicheng, Daqing, Xingan League, Tongliao, Chifeng	87 500
ATZ8	3200–3300	Benxi, Tonghua, Liaoyuan, Chuangchun, Jilin, Harbin, Suihua, Daqing, Qiqihaer, Xingan League, Chifeng	94 325
ATZ9	3100–3200	Tonghua, Baishan, Jilin, Harbin, Suihua, Daqing, Qiqihar, Xingan League, Chifeng	70 075
ATZ10	3000–3100	Baishan, Jilin, Harbin, Linjiang, Mudanjiang, Qitaihe, Shuangyashan, Jixi, Jiamusi, Suihua, Qiqihaer, Xingan League, Chifeng	115 025
ATZ11	2900–3000	Baishan, Jilin, Yanbian, Mudanjiang, Jixi, Shuangyashan, Jiamusi, Harbin, Suihua, Qiqihaer, Xingan League, Hulun Buir	126 500
ATZ12	2800–2900	Baishan, Jilin, Yanbian, Jixi, Shuangyashan, Jiamusi, Hegang, Yichun, Suihua, Qiqihaer, Heihe, Hulun Buir	87 675
ATZ13	2700–2800	Shuangyashan, Jiamusi, Hegang, Yichun, Suihua, Heihe, Hulun Buir	81 750
ATZ14	2600–2700	Jiamusi, Yichun, Heihe, Hulun Buir	70 975
ATZ15	2500–2600	Jiamusi, Hulun Buir	11 465

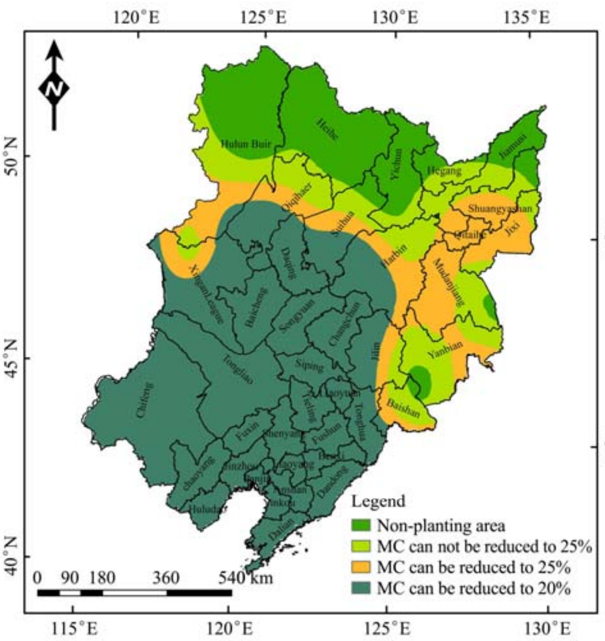
3.3 Spatial distribution of tested cultivars

According to tested cultivars' AT_0 requirements at different stages of grain maturation and its drying, the tested cultivars were matched with regional heat resources, and the results are shown in Figure 4. In line with the four categories of cultivars, LTD, LMTD, MTD and HTD, the ATZs in which these cultivars can reach PM are ATZ1-ATZ12, ATZ1-ATZ11, ATZ1-ATZ10, and ATZ1-ATZ7, respectively, covering 850 950 km^2, 763 275 km^2, 636 775 km^2, and 357 350 km^2, namely, accounting for 83.83%, 75.19%, 62.73%, and 35.20% of Northeastern China. With the increase of AT_0 demand, the ATZs where tested cultivars barely reach PM extend southwardly from ATZ 15. The ATZs where the MC of LTD, LMTD, MTD, and HTD can drop to 25% are ATZ1-ATZ11, ATZ1-ATZ10, ATZ1-ATZ7, and ATZ1-ATZ6, respectively, accounting for 75.19% (763 275 km^2), 62.73% (636 775 km^2), 35.20% (357 350 km^2), and 26.58% (269 850 km^2) of Northeastern China. Moreover, for a better quality of mechanical kernel harvesting, the ATZs where the MC of LTD, LMTD, MTD, and HTD can drop to 20% are ATZ1-ATZ10, ATZ1-ATZ6, ATZ1-ATZ3, and ATZ1-ATZ2, respectively accounting for 62.73% (636 775 km^2), 26.58% (269 850 km^2), 5.91% (60 025 km^2), and 3% (30 450 km^2) of Northeastern China.

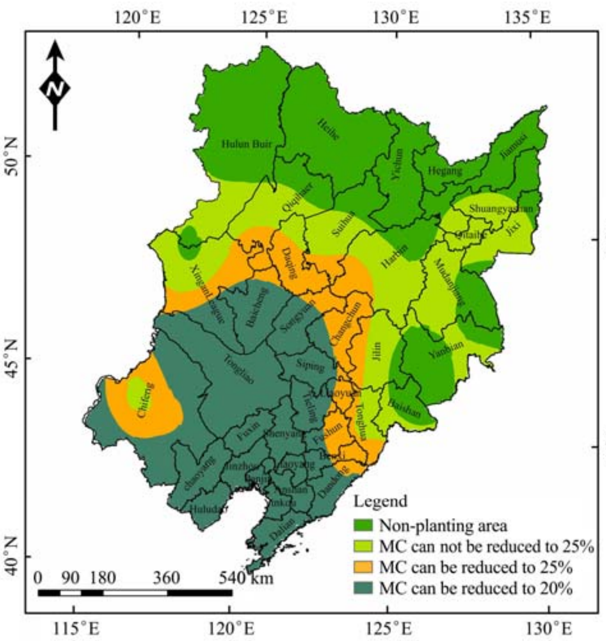


Note: PD-PM is from sowing date to physiological maturity; PD-25% is from sowing date to the grain moisture content of 25%; PD-20% is from sowing date to the grain moisture content of 20%.

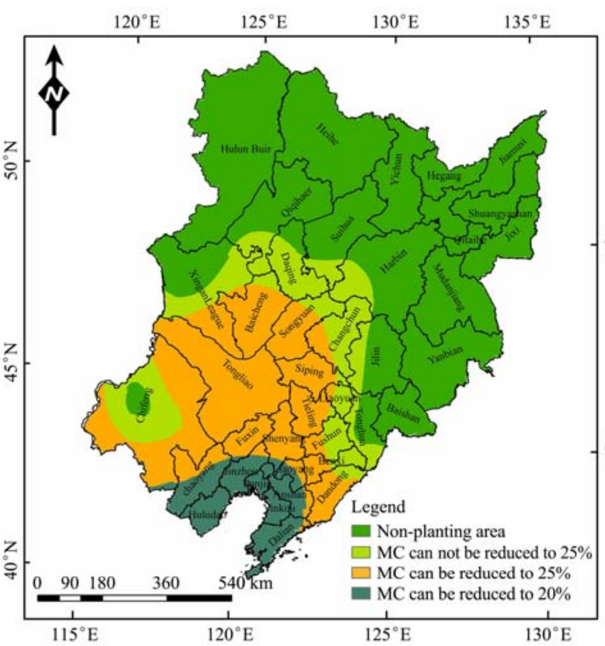
Figure 4 Accumulated temperature zones (ATZs) where maize cultivars can complete different growth processes



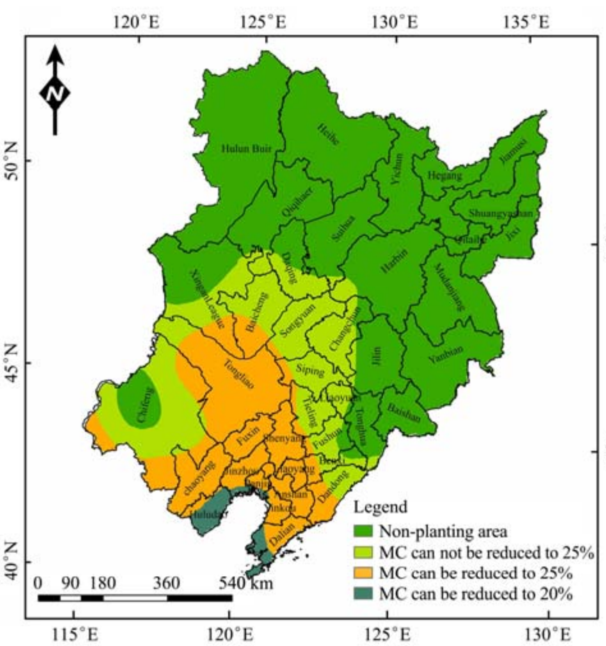
a. LTD



b. LMTD



c. MTD



d. HTD

Figure 5 Spatial distributions of maize cultivars categorized as LTD, LMTD, MTD, and HTD

4 Discussion

4.1 Distribution of heat resources in northeastern China

Due to climate change, solar radiation in China has declined for the past 40-50 years[34], however, heat resources have significantly increased[35]. Heat resources are very important for maize growth and development, as well as its grain drying after maturity[19,36]. In Northeastern China, air temperature decreases dramatically with latitude increase, resulting in the shortening of heat resources[20-22,37,38]. Therefore, it is very essential to coordinate the growth and development maturity of maize cultivars with accumulated temperature distribution under different climatic conditions. Bai et al.[39] divided Northeastern China into eleven ATZs based on GDD (growing degree days required for the growth and development of maize) at an interval of 200°C·d, which was 1800-3800°C·d. Yet, in this study, based on the AT_0 required for grain drying, the ATZs in Northeastern China were renewed under a guaranteed rate of 80% that Heilongjiang Province was divided into eight ATZs with AT_0 values of 2500-3300°C·d, Jilin Province was divided into nine ATZs with AT_0values of 2600-3500°C·d, and that Liaoning Province was divided into eight ATZs with AT_0 values of 3200-4000°C·d.

In consistence with previous studies, the AT_0 shows a significant latitude distribution, gradually declining from south to north, with each ATZ moving northwardly and expanding eastwardly. Although late-maturing cultivars may contribute a higher yield, this always brings about a higher MC on harvesting[40]. Therefore, in ATZ8-ATZ15, farmers should choose LTD or LMTD cultivars with a quick-drying rate to reduce frost damage and avoid high MC at harvest time[41]. Geographically, Northeastern China is situated at the same latitude as the maize belt of the United States, in which, maize grain is directly harvested with combine and the harvesting begins since 2-3 weeks after PM, when the MC of maize grain has reduced to less than 20% at harvest[29]. In Northeastern China, the temperature is higher in the early stage of grain filling but drops rapidly after autumn, causing a lack of heat conditions for grain ripening and drying. Currently, in Northeastern China, the MC of maize grain is between 20%-25% on harvesting, which is relatively higher than that in the United States.

4.2 Spatial distribution of maize cultivars

In virtue of its lower accumulated temperature demand and rapid drying rate, LTD, is capable of fulfilling PM in ATZ1-ATZ12. If only LTD cultivars were planted in ATZs with better heat conditions in the south of Northeastern China, it would inevitably issue a yield reduction. Nonetheless, its yield can be guaranteed by appropriately increasing its planting density[42]. Overall, taking full advantage of local heat resources, selecting cultivars fitting to local ecological conditions, and rational close-planting are primary measures to ensure high yield and facilitate mechanical kernel harvesting while planting longer maturity cultivars is also elemental to make use of heat resources for improving maize yield, especially in regions with better heat conditions[43]. For instance, for utilizing heat resources as more as possible, in the Huanghuaihai summer-maize area of China, a rotation system of summer-maize and winter-wheat is taken and adopted since the output under this double-cropping system is evidently higher than that of planting maize once a year[38].

Based on the accumulated temperature requirements of grain moisture content falling to 25% and 20%, this study was conducted to match maize cultivars with regional heat resources in Northeastern China. As shown in Figure 4, with increasing AT_0 demand for PM, the non-planting areas is expanded while the areas that MC could be reduced to 25% is gradually extended to the southern region with sufficient heat resource. The same trend was observed when MC falls to 20%, however, the non-planting area is narrower. As the main maize cultivars planted in the Southern, HTD is suitable in coastal areas for harvesting at low MC (20%), even though it could not reach this MC in the normal harvesting period in other areas of Northeastern China. With an accumulated temperature of 3400°C-3600°C, heat resource in the central region of Northeastern China is comparatively rich, in which HTD can be harvested at 25% MC, but would be hardly harvested if MC were lower. In the northern and eastern area, the heat resource is scarce with an accumulated temperature of 2500°C-2800°C, often, in which the farmers choose maize varieties with long growing period because they think the growth period of maize varieties means high yield without viewing the high grain MC on harvesting, consequently, debasing the quality of mechanical kernel harvesting[44]. Additionally, there also may be frost risk in the production of maize varieties with a long growth period, undoubtedly coming out quality degradation or production shortfall. Therefore, the tradeoff between the potential frost risk before PM and cultivar selection to make most of the heat resources should be given consideration. Firstly, farmers should sow early, on the other hand, the breeders should develop new maize varieties with the accumulated temperature demand of 2500°C·d-2800°C·d and a faster drying rate. With the rise of labor costs, the mechanical kernel harvesting technology of maize, which has been widely used in developed countries in Europe and America, is becoming increasingly popular in China[45]. The spatial diversification of climatic conditions has a great impact on the growth and development of maize, hence, from the perspective of production management and varieties' ripe stage, the harmonization between local heat resource and the accumulated temperature demand of maize cultivars is requisite, in addition, the sowing time of cultivars should also be reasonably scheduled. Other than the integration of agronomy and agricultural equipment by improving the efficiency of machinery, a reasonable configuration of mechanical capacity and labor demand can likewise mitigate the risks involved in maize production, hereby giving full play to the characteristics of cultivars and enhancing maize production.

As a comprehensive project, the layout of maize varieties is supposed to take into account not only heat resources, but also extreme weather such as rainfall and light radiation, local agricultural production, as well as government policies.

5 Conclusions

In this study, it is proved by a multi-year and multi-site experiment that the accumulative temperature requirements of different varieties vary greatly when drying to the target moisture content. By calculating the accumulated temperature of maize planting area and allocating maize cultivars according to their accumulated temperature demands, heat resources can be effectively conserved for reducing the moisture content of maize grain at harvest time. For advancing the mechanical kernel harvesting of maize in China, the ideal layout of maize varieties oriented to mechanical kernel harvesting should be formulated by the accumulative temperature requirements for drying to the target moisture content and the available heat resource.

Acknowledgements

The present study was supported by the National Key Research and Development Program of China (Grant No. 2018YFD0100206), the China Agriculture Research System (Grant No. CARS-02-25), and the Agricultural Science and Technology Innovation Project of the Chinese Academy of Agricultural Sciences.

[References]

[1] Borrás L, Zinselmeier C, Senior M L, Westgate M E, Muszynski M G. Characterization of grain-filling patterns in diverse maize germplasm. Crop Science, 2009; 49: 999–1009.

[2] Carter M W, Poneleit C G. Black layer maturity and filling period variation among inbred lines of corn (*Zea mays* L.). Crop Science, 1973; 13: 436–439.

[3] Gao S, Ming B, Li L L, Xie R Z, Xue J, Hou P, et al. Relationship between grain dehydration and meteorological factors in the Yellow-Huai-Hai rivers summer maize. Acta Agronomica Sinica, 2018; 44: 1755–1763. (in Chinese)

[4] Skaugen T E, Tveito O E. Growing-season and degree day scenario in Norway for 2021-2050. Climate Research, 2004; 26: 221–232.

[5] Warrington I J, Kanemasu E T. Maize growth response to temperature and photoperiod. II. Leaf initiation and leaf appearance rates. Agronomy Journal, 1983; 75: 755–761.

[6] Gregory S. Accumulated temperature maps of the British. Isles Trans Paper, 1954; 20: 59–73.

[7] Bai J S, Chen X P, Dobermann A, Yang H S, Cassman K G, Zhang F S. Evaluation of NASA satellite-and model-derived weather data for simulation of maize yield potential in China. Agronomy Journal, 2010; 102: 9–16. (in Chinese)

[8] Mao Z Q, Yu Z R, Liu H. Experimental research on thermal requirement forwinter wheat and its leaves. Journal of China Agricultural University, 2002; 7(5): 14–19. (in Chinese)

[9] Muchow R C. Effect of high temperature on grain-growth in field-grown maize. Field Crops Research, 1990; 23(2): 145–158.

[10] Stewart D W, Dwyer L M, Carrigan L L. Phenological temperature response of maize. Agronomy Journal, 1998; 90(1): 73–79.

[11] Brooking I R. Maize ear moisture content during grain filling, and its relation to physiological maturity and grain-drying. Field Crops Research, 1990; 23(1): 55–68.

[12] Daynard T B, Kannenberg L W. Relationships between length of the actual, and effective grain filling periods and grain yield of corn. Canada Journal Plant Science, 1976; 56: 237–242.

[13] Daynard T B. Relationships among black layer formation, grain moisture percentage, and heat unit accumulation in corn. Agronomy Journal, 1972; 64: 716–719.

[14] Russelle M P, Wilhelm W W, Olson R A, Power J F. Growth analysis based on degree days. Crop Science, 1984; 24: 28–32.

[15] Cross H Z, Zuber M S. Prediction of flowering dates in maize based on different methods of estimating thermal units. Agronomy Journal, 1972; 64: 351–355.

[16] van Ittersum M K, Leffelaar P A, van Keulen H, Kropff M J, Bastiaans L, Goudriaan J. On approaches and applications of the Wageningen crop models. European Journal of Agronomy, 2013; 18: 201–234.

[17] Meng Q F, Hou P, Wu L, Chen X P, Cui Z, Zhang F S. Understanding production potentials and yield gaps in intensive maize production in China. Field Crops Research, 2013; 143: 91–97.

[18] Chen X Z, Cui M, Fan P, Vitousek M, Zhao W, Ma W P, et al. Producing more grain with lower environmental costs. Nature (London), 2014; 514: 486–498.

[19] Dong J, Liu J, Tao F, Xu X, Wang J. Spatio-temporal changes in annual accumulated temperature in China and the effects on cropping systems, 1980s to 2000s. Climate Research, 2009; 40: 37–48. (in Chinese)

[20] Liu Y E, Hou P, Xie R Z, Li S K, Zhang H Z, Ming B, et al. Spatial adaptabilities of spring maize to variation of climatic conditions. Crop Science, 2013; 53(4): 1693–1703.

[21] Liu Y E, Xie R Z, Hou P, Li S K, Zhang H B, Ming B, et al. Phenological responses of maize to changes in environment when grown at different latitudes in China. Field Crops Research, 2013; 144: 192–199.

[22] Jennings M V. Genotypic variability in grain quality of maize (*Zea mays* L.). America, Iowa State University, 1974; 171p.

[23] Plett S. Corn kernel breakage as a function of grain moisture at harvest in a prairie environment. Canadian Journal of Plant Science, 1994; 74(3): 543–544.

[24] Chai Z W, Wang K R, Guo Y Q, Xie R Z, Li L L, Ming B, et al. Current status of maize mechanical grain harvesting and its relationship with grain moisture content. Scientia Agricultura Sinica, 2017; 50(11): 2036–2043. (in Chinese)

[25] Wang K R, Li S K. Progresses in research on grain broken rate by combine harvesting maize. Scientia Agricultura Sinica, 2017; 50(11): 2018–2026. (in Chinese)

[26] Xie R Z, Lei X P, Wang K R, Guo Y Q, Chai Z W, Hou P, et al. Research on maize mechanically harvesting grain quality in Huanghuaihai Plain. Crops, 2014; 2: 76–79. (in Chinese)

[27] Zhao M, Li S K, Dong S T, Zhang D X, Wang P, Xue J Q, et al. The key technology of American maize production and the development of modern maize production in China—A study report after visiting the United States. Crops, 2011; 5: 1–3. (in Chinese)

[28] Li S K. Characteristics and enlightenment of maize production technologies in the U.S. Journal of Maize Sciences, 2013; 21: 1–5. (in Chinese)

[29] Ruane A C, Goldberg R, Chryssanthacopoulos J. Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. Agriculture and Forest Meteorology, 2015; 200: 233–248.

[30] Li L L, Ming B, Gao S, Xie R Z, Hou P, Wang K R, et al. Study on grain dehydration characters of summer maize and its relationship with grain filling. Scientia Agricultura Sinica, 2018; 51(10): 1878–1889. (in Chinese)

[31] Huang Z F, Ming B, Wang K R, Xie R Z, Yang F, Wang Z G, et al. Characteristics of maize grain dehydration and prediction of suitable harvest period in Liao River Basin. Acta Agronomia Sinica, 2019; 45(5): 732–741. (in Chinese)

[32] Li J, You S C, Huang J F. Spatial interpolation method and spatial distribution characteristics of monthly mean temperature in China during 1961-2000. Ecology and Environmental Sciences, 2006; 15(1): 109–114. (in Chinese)

[33] Yang Y W, Yu Q, Wang J. Spatio-temporal variations of principal climatic factors in north china and part of East China within past 40 years. Res. Sci., 2004; 26(4): 45–50. (in Chinese)

[34] Yang P Y, Hu Q, Ma X Q, Hu L T, Ren F Y, Yan M L, et al. Spatiotemporal variation of heat and solar resources and its impact on summer maize in the North China Plain over the period 1961−2015. Chinese Journal of Agrometeorology, 2018; 39(7): 431–441. (in Chinese)

[35] Olivier F C, Annandale J G. Thermal time requirements for the development of green pea (*Pisum sativum* L.). Field Crops Research, 1998; 56: 301–307.

[36] Li S K, Wang C T. Potential and ways to high yield in maize. Science Press, Beijing, China, 2010.

[37] Liu Z J, Yang X G, Chen F, Wang E L. The effects of past climate change on the northern limits of maize planting in Northeast China. Climmate Change, 2013; 117(4): 891–902.

[38] Meng Q F, Hou P, Lobell D B, Wang H F, Cui Z L, Zhang F S, et al. The benefits of recent warming for maize production in high latitude China. Climmate Change, 2014; 122: 341–349.

[39] Bai C Y, Li S K, Zhang H B, Bo J H, Xie R Z, Meng L. Ecological adaptability of Zhengdan958 hybrid in northeast of China. Acta Agronomia Sinica, 2010; 36(2): 296–302. (in Chinese)

[40] Dwyer L M, Ma B L, Evenson L, Hamilton R I. Maize physiological traits related to grain yield and harvest moisture in mid- to short-season environments. Crop Science, 1994, 34: 985–992.

[41] Liu Y E, Hou P, Xie R Z, Hao W P, Li S K, Mei X R. Spatial variation and improving measures of the utilization efficiency of accumulated temperature. Crop Science, 2015; 55: 1806–1817.

[42] Li S K, Wang K R, Xie R Z, Hou P, Ming B, Yang X X, et al. Implementing higher population and full mechanization technologies to achieve high yield and high efficiency in maize production. Crops, 2016; 4:1–6. (in Chinese)

[43] Tsimba R, Edmeades G O, Millner J P, Kemp P D. The effect of planting date on maize: Phenology, thermal time durations and growth rates in a cool temperate climate. Field Crops Research, 2013; 150: 145–155.

[44] Wang K R, Li S K. Analysis of influencing factors on kernel dehydration rate of maize hybrids. Scientia Agricultura Sinica, 2017; 50(11): 2027–2035. (in Chinese)

[45] Baute T, Hayes A, Mc Donald I, Reid K. Agronomy guide for field crops. Publ. 811. The Ontario Ministry of Agriculture, Food and Rural Affairs. Guelph, ON, 2002.