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

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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$_0$) 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

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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[12].

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...
late-maturing to early-maturing from south to north\textsuperscript{19-21}. The MC is high when harvesting, especially at high latitudes\textsuperscript{22}, which would result in a high mildew 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\textsuperscript{23-27}. Internationally, the MC at harvest is generally 15%-25% and the peak harvesting period is 2-4 weeks later than PM\textsuperscript{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\textsubscript{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\textsubscript{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.

| Site   | Location | Climatic conditions |
|--------|----------|---------------------|
| Kailu  | 121.3    | 43.61               |
| Tieling| 123.7    | 42.23               |
| Daqing | 125.1    | 46.59               |

Daily mean temperature/°C | AT\textsubscript{0}/°C·d | Precipitation/mm | Frost-free days/d |
---|---|---|---|
| 7.4 | 3876 | 325 | 177 |
| 7.6 | 3894 | 714 | 170 |
| 4.4 | 3431 | 473 | 163 |

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

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\textsuperscript{2} with a density of 6.75×10\textsuperscript{4} plants/hm\textsuperscript{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\textsuperscript{2} of organic fertilizer (organic matter ≥45%), 450 kg/hm\textsuperscript{2} of water-soluble and slow-release Si organic fertilizer, and 150 kg/hm\textsuperscript{2} of N\textsubscript{11}P\textsubscript{17}K\textsubscript{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/m²·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 |
| Jinyongke728 (JNK728) | 2017, 2018 | Tieling |
| Hetian4 (HT4) | 2016, 2017 | Daqing |
| Huaimei1 (HME1) | 2017 | Kailu, Tieling, Daqing |
| Dongdan913 (DD913) | 2017 | Kailu, Tieling |
| Deya919 (DY919) | 2017 | Kailu, Daqing |
| Demeiya3 (DY3M) | 2016, 2017 | Daqing |
| Jidan66 (JD66) | 2017 | Tieling, Daqing |
| Shandan636 (SD636) | 2016, 2017 | Tieling, Daqing |
| Zeya9811 (ZY9811) | 2017, 2018 | Kailu, Tieling, Daqing |
| Dika159 (DK159) | 2017, 2018 | Kailu, Tieling, Daqing |
| Zeya501 (ZY501) | 2017 | Kailu, Tieling, Daqing |
| Xiangyu998 (XY998) | 2016, 2017 | Daqing, Tieling |
| Danyu311 (DY311) | 2017, 2018 | Tieling |
| Tieyan388 (TY388) | 2017, 2018 | Tieling |
| Youd919 (YD919) | 2017 | Kailu, Tieling |
| Dongdan1331 (DD1331) | 2017, 2018 | Kailu, Tieling |
| Liaodian575 (LD575) | 2017, 2018 | Tieling |

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

### 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 AT₀, 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 AT₀ demand

According to the AT₀ requirements from Planting to PM, the tested cultivars were divided into four categories: LTD, low temperature demand (AT₀ demand less than 2900°C·d); LMTD, low and medium temperature demand (AT₀ demand range from 2900 to 3000°C·d); MTD, medium temperature demand (AT₀ demand range from 3000 to 3100°C·d); HTD, high temperature demand (AT₀ demand more than 3100°C·d) (Table 3). The results showed that, for the AT₀ 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 AT₀ 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 AT₀ required from PM to achieve MC of 20%, DY311 was the highest (342°C·d) and HT4 was the lowest (9°C·d); for the AT₀ 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 AT₀ 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 AT₀ 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 AT₀ 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         | 3072             | 86               | 262              |
|      | DMY1     | 2850         | 3009             | 76               | 159              |
|      | FK139    | 2884         | 3209             | 56               | 325              |
|      | Average  | 2848         | 3097             | 73               | 249              |
|      | JNK728   | 2926         | 3411             | 121              | 485              |
|      | HT4      | 2934         | 3084             | 9                | 136              |
|      | HM1      | 2947         | 3428             | 234              | 481              |
|      | DMY3     | 2948         | 3084             | 63               | 136              |
|      | DD913    | 2977         | 3323             | 139              | 326              |
|      | Average  | 2955         | 3333             | 151              | 378              |
| LMTD | JN66     | 3057         | 3393             | 101              | 336              |
|      | SD636    | 3066         | 3416             | 128              | 350              |
|      | ZY891    | 3084         | 3626             | 153              | 542              |
|      | DK159    | 3092         | 3709             | 250              | 617              |
|      | Average  | 3075         | 3536             | 158              | 461              |
| MTD  | ZY501    | 3108         | 3606             | 204              | 498              |
|      | XY998    | 3187         | 3580             | 125              | 393              |
|      | DY311    | 3189         | 3945             | 295              | 756              |
|      | TY388    | 3194         | 3929             | 223              | 735              |
|      | YD919    | 3239         | 3856             | 232              | 617              |
|      | DD1331   | 3251         | 3838             | 274              | 587              |
|      | LD575    | 3282         | 3857             | 164              | 575              |
|      | Average  | 3207         | 3802             | 217              | 594              |
|      | Total    | 3041         | 3484             | 160              | 451              |

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

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

| ATZs | AT/°C·d | City                                                                 | Area/km² |
|------|---------|----------------------------------------------------------------------|----------|
| ATZ1 | 3900–4000 | Dalian                                                                | 2375     |
| ATZ2 | 3800–3900 | Dalian, Panjin, Yingkou, Jinzhou, Chaoyang, Huiluado               | 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, Songyuan, Baicheng, Xingan League, Tongliao, Chifeng | 79 950   |
| ATZ7 | 3300–3400 | Dandong, Benxi, Fushun, Tieling, Songyuan, Baicheng, Daqing, Xingan League, Tongliao, Chifeng | 87 500   |
| ATZ8 | 3200–3300 | Benxi, Tonghua, Liaoyuan, Changchun, Jilin, Harbin, Suihua, Daqing, Qihaer, Xingan League, Chifeng | 94 325   |
| ATZ9 | 3100–3200 | Tonghua, Baishan, Jilin, Harbin, Suihua, Daqing, Qihaer, Xingan League, Chifeng | 70 075   |
| ATZ10 | 3000–3100 | Baishan, Jilin, Harbin, Linjiang, Mudanjiang, Qitaibei, Shuangyashan, Jixi, Jiamusi, Suihua, Qihaer, Xingan League, Chifeng | 115 025   |
| ATZ11 | 2900–3000 | Baishan, Jilin, Yanbian, Mudanjiang, Jixi, Shuangyashan, Jiamus, Harbin, Suihua, Qihaer, Xingan League, Hulun Buir | 126 500   |
| ATZ12 | 2800–2900 | Baishan, Jilin, Yanbian, Jixi, Shuangyashan, Jiamus, Hegang, Yichun, Suihua, Qihaer, Heihe, Hulun Buir | 87 675   |
| ATZ13 | 2700–2800 | Shuangyashan, Jiamus, Hegang, Yichun, Suihua, Qihaer, Heihe, Hulun Buir | 81 750   |
| ATZ14 | 2600–2700 | Jiamus, Yichun, Heihe, Hulun Buir                                    | 70 975   |
| ATZ15 | 2500–2600 | Jiamus, Hulun Buir                                                    | 11 465   |

### 3.3 Spatial distribution of tested cultivars

According to tested cultivars' AT0 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

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 AT0 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 AT0 of 3600°C·d-3900°C·d observed in Liao River Basin and the lowest AT0 of 2500-2700°C·d observed in the Great Khinan Mountains. ATZ10 and ATZ11 both take up more than 100 000 km², accounting for 11.3% and 12.5% of Northeastern China’s total area, respectively, while ATZ1 covers less than 10 000 km², only accounting for 0.2%. With their area around less than 30 000 km², 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 km² and 95 000 km² of Northeastern China’s total area. Major cities or regions located in each ATZ are shown in Table 4.
reach PM are ATZ1-ATZ12, ATZ1-ATZ11, ATZ1-ATZ10, and ATZ1-ATZ7, respectively, covering 850 950 km², 763 275 km², 636 775 km², and 357 350 km², namely, accounting for 83.83%, 75.19%, 62.73%, and 35.20% of Northeastern China. With the increase of AT₀ 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 km²), 62.73% (636 775 km²), 35.20% (357 350 km²), and 26.58% (269 850 km²) 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 km²), 26.58% (269 850 km²), 5.91% (60 025 km²), and 3% (30 450 km²) 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

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, however, heat resources have significantly increased. Heat resources are very important for maize growth and development, as well as its grain drying after maturity. In Northeastern China, air temperature decreases dramatically with latitude increase, resulting in the shortening of heat resources. 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. 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 AT0 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 AT0 values of 2500-3300°C·d, Jilin Province was divided into nine ATZs with AT0 values of 2600-3500°C·d, and that Liaoning Province was divided into eight ATZs with AT0 values of 3200-4000°C·d.

In consistence with previous studies, the AT0 shows a significant latitude distribution, gradually declining from south to north, with each AT moving northwardly and expanding eastwardly. Although late-maturing cultivars may contribute a higher yield, this always brings about a higher MC on harvesting. 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. 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. 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. 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. 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.

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 AT0, 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. 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. 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.

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