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Temporal and spatial variation in accumulated temperature requirements of maize

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ABSTRACT

Temperature, especially accumulated temperature, is an important environmental factor that plays a fundamental role in agricultural productivity. To examine temporal and spatial variation in accumulated temperature requirements of maize as indicated by ≥10 °C accumulated temperature and growing degree days (GDD), we conducted experiments during 2007–2012 at 35 locations in seven provinces in the north spring maize region between 35°11′ N and 48°08′ N and 6 locations in four provinces in the Huanghuaihai maize region between 32°52′ N and 41°05′ N in China. The most widely cultivated maize hybrids of ZD958 and XY335 were used in this study. We found that the coefficients of variation for ≥10 °C accumulated temperature and GDD requirements were different during different growth periods, with a descending rank order of sowing to emergence > silking to maturity > emergence to silking > sowing to maturity and greater in the north spring maize region than in the Huanghuaihai maize region. The coefficients of variation were lower for ≥10 °C accumulated temperature than GDD requirements for both cultivars in both planting regions. Significant differences existed between locations and years for the ≥10 °C accumulated temperature and GDD requirements. These have implications for appropriate maize cultivars recommendation, and high and stable yield achieving by reasonably using accumulated temperature across different regions of China.

1. Introduction

The north spring maize (*Zea mays* L.) and Huanghuaihai maize regions of China (hereafter, NM and HM, respectively) are the largest and second largest maize production regions in China spanning latitudes from 32°00′ N to 50°50′ N. The total maize acreage in these two regions accounts for 79.7% of the maize-planted area in China and 16.5% of the world planted area, and represents about 82% and 15.2% of total Chinese and global maize grain production, respectively (Li and Wang, 2010; FAO, 2011). Maize production in these regions plays a significant role in ensuring food security, but their climates vary dramatically, with the annual accumulated temperature above 10 °C, total sunshine hours, and total precipitation of 2000–4700 °C day, 2100–2900 h, and 400–800 mm, respectively (Li and Wang, 2010). These climatic differences have a significant influence on maize growth and development (Li and Wang, 2010; Liu et al., 2013a,b).

Temperature is an important climate factor that plays a fundamental role in agricultural production. The agricultural effects of temperature include determination of emergence, flowering, and maturity dates (Skaugen and Tveito, 2004; Iannucci et al., 2008). As a source of heat energy, temperature plays a key role in plant development and growth. Each plant species has a base temperature below which growth stops and above which most biological processes and growth continue (Major et al., 1983; Stevens et al., 1986; McMaster and Smika, 1988; Hodges et al., 1994; Bonhomme et al., 1994; Olivier and Annandale, 1998; Kadioğlu and Şaylan, 2001; Berti and Johnson, 2008; Sacks and Kucharik, 2011). Field studies have shown that maize has a base temperature of 5–10 °C (Major et al., 1983; Stevens et al., 1986; Hodges et al., 1994; Bonhomme et al., 1994; Sacks and Kucharik, 2011). For maize an upper temperature threshold exist. The upper temperature threshold of maize has been reported to be 30 °C by McMaster and Wilhelm (1997), 32 °C by Nielsen and Hinkle (1996), and 34 °C by Birch et al. (1998).

Thermal conditions are important for regulating crop growth (Olivier and Annandale, 1998; Dong et al., 2009). Since Reaumut

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first introduced the concept of heat units or thermal time in 1730, many methods for calculating thermal time have been used successfully in agricultural sciences (McMaster and Wilhelm, 1997). In 1837, Boussingault used a method in which mean daily air temperature was multiplied by the number of days during the crop-growing period to calculate the total thermal requirement of various crops from sowing to maturity, i.e., accumulated temperature. This concept was subsequently introduced to geobotany by de Candolle (1855) and began to be used in agricultural meteorology in Britain in 1878 (Gregory, 1954; Yan et al., 2011). Since the mid 1950s, the concept has been widely used in several research fields in China (Feng and Tao, 1991). In China, the ≥10 °C accumulated temperature is used as an important indicator of thermal conditions in crop ecology (Qiu and Lu, 1980; Bai et al., 2008). The ≥10 °C accumulated temperature is the sum of the mean daily temperatures during a growth period in which the mean daily temperature is above 10 °C each day. The ≥10 °C accumulated temperature is routinely used to determine crop planting schedules, crop varieties, and crop patterns in China (Zheng et al., 2008; Yan et al., 2011).

Growing degree days (GDD) is another representation of accumulated temperature calculated as the accumulated temperature above a base level (Wang, 1960). GDD is used to estimate plant development and growth during the growing season and can be used to assess flowering, maturity, and harvest dates of crops and to predict the suitability of a region for the production of a particular crop. Many studies have estimated the relationship between GDD and crop growth including the phenological development of crops (Stewart et al., 1998; Craufurd et al., 1998; Bartholomew and Williams, 2005). Thermal parameters are also used in simulation models of crop growth based on the growth rate of crops driven by the daily temperature (Huang et al., 1998; Caton et al., 1998; Liu et al., 1998; Yang et al., 2004, 2006).

Two opposite points of view exist about the heat units (≥10 °C accumulated temperature and GDD) requirements of maize. One is that maize always requires the same amount of heat units and depends only on the cultivar to reach a certain developmental stage (Wang, 1960; Sacks and Kucharik, 2011). The opposite view is that the number of heat units required for the completion of a given growth period of a particular maize cultivar is not constant but may vary with other environmental conditions (Tataryn, 1974; Major et al., 1983; Liu et al., 2013b). For example, Liu et al. (2013b) showed that for maize cultivar of ZD958, the GDD requirements during the vegetative growth period increased significantly but the GDD requirements during the reproductive growth period decreased significantly with latitudes northward in China. However, few studies have focused on variation in ≥10 °C accumulated temperature and GDD requirements of widely cultivated maize cultivars, particularly during different growth stages, on a large scale.

The Zhengdan 958 (ZD958) and Xianyu335 (XY335) maize varieties, which are characterized by high yield, high quality, multi-resistance, and extensive adaptability, have been the leading maize hybrids in China in recent years. They are planted widely in the NM and HM regions of China. The planting areas of ZD958 and XY335 were increased to 4,540,000 ha and 1,270,000 ha, respectively, in 2009 (Chinese Agriculture Technology and Popularization Center). Because of global warming (IPCC, 2007), the planting areas of both varieties have expanded northward. The northern line for safe planting of ZD958 has shifted to 47° N in the northeast (You et al., 2008; Bai et al., 2010) and ZD958 can be planted in most regions of NM. This provides the opportunity to study the variation in thermal requirements of widely planted maize cultivars under different ecological conditions across a large region.

In the present study, we investigated the variation in ≥10 °C accumulated temperature and GDD requirements for ZD958 and XY335 between different regions and during different growth periods (sowing to emergence, emergence to silking, silking to maturity, and sowing to maturity). We also assessed the differences in ≥10 °C accumulated temperature and GDD requirements between experimental sites and years during different growth periods. This will be helpful for appropriate maize cultivars recommendation, and high and stable yield achieving by reasonably using accumulated temperature across different regions of China.

2. Materials and methods

2.1. Site description and experimental design

Experiments were conducted from 2007 to 2012 at 35 locations in seven provinces (Heilongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Shanxi, and Shaanxi) between 35°11′ N and 48°08′ N in NM, and from 2010 to 2012 at 6 locations in four provinces (Shandong, Henan, Shaanxi, and Anhui) between 32°52′ N and 41°05′ N in HM (Fig. 1 and Table 1). Details of the geographical positions and ecological conditions are given in Table 1. NM is in a cold-temperature zone with humid and semi-humid climates. The winters are cold and dry and the summers are warm and short. HM is in a warm-temperature zone with semi-humid and semi-arid climates. In these two regions, the annual accumulated temperature above 10 °C, total sunshine hours, and total precipitation are 2000–4700 °C day, 2100–2900 h, and 400–800 mm.

The maize cultivars ZD958 and XY335, which are widely grown in both regions, were chosen for this study. Maize was planted at a density of 6.0×10^4 plants ha^{-1} with four replications. Each plot was 15 m long, 6.5 m wide, and consisted of 10 rows with an inter-row spacing of 0.65 m.

One maize harvest per year was defined as continuous maize cultivation in NM and a winter wheat–summer maize double-cropping rotation in HM. Maize was sown by hand in the soil depth of about 5 cm at all sites (from late April to early May in NM and in mid-June in HM) and harvested from late September to early October. All sites were well managed and weeds, diseases, and insect pests were well controlled. Many different nutrient management treatments (in terms of fertilizer applications) were applied: 138–380 kg ha^{-1} nitrogen (N), 0–177 kg ha^{-1} phosphorus (P, in the form of P_2O_5), and 0–112 kg ha^{-1} potassium (K, in the form of K_2O) in NM, and 126–300 kg ha^{-1} N, 45–207 kg ha^{-1} P, and 45–78.75 kg ha^{-1} K in HM. These amounts were based on existing levels of N, P, and K in plots, as determined by soil tests.

2.2. Database

The dates of sowing, emergence, silking, and maturity were recorded. An emergence date was taken when 60% of the plants had emerged, a silking date when 60% of the ears showed silk emergence and a physiological maturity date when the black layer appeared. Climate data (maximum temperature, mean temperature, minimum temperature) were obtained from the nearest meteorological station (CMA Archives, 2013) which, on average, was located about 17 km away from each experimental site ranging from 3 to 39 km.

The ≥10 °C accumulated temperature is the sum of the mean daily temperatures during the growing period in which the mean daily temperature is above 10 degrees Celsius (≥10 °C) each day (Yan et al., 2011).

GDD was defined using the following equation, where $T_{\max}$, $T_{\min}$, and T_{base} are the maximum temperature, minimum temperature, and 10 °C base temperature, respectively (McMaster and Wilhelm, 1997; Yang et al., 2004); because GDD for maize is normally