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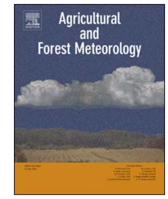

Modelling maize phenology, biomass growth and yield under contrasting temperature conditions

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ABSTRACT

Crop modelling has become an effective means to assess climate change impact on crop yield and to assist in development of adaptation strategies. Previous studies found large uncertainty in simulated crop yields, especially beyond optimal temperature range. In this paper, we combined the data reported in literature and our controlled-temperature experiment to derive the temperature response functions of phenological development and biomass growth of maize crop based on the Wang-Engel function *(Agricultural systems, 58(1):* 1–24), and compared them with those adopted in two mostly used maize growth models APSIM-Maize and CERES-Maize. Our results support the previous findings that leaf elongation, leaf appearance and the rate of development towards flowering have the same temperature response. Our results indicate that a curvilinear response with cardinal temperatures of 5 °C (base), 30 °C (optimum), and 41 °C (maximum) best describes the maize developmental response to temperature. For radiation use efficiency (RUE-biomass growth per unit intercepted radiation) of maize, the corresponding cardinal temperatures are likely to be 2 °C, 24 °C, and 38 °C respectively. All the cardinal temperatures are lower than what are used in current APSIM model. Replacing the default temperature responses with the newly derived ones led to contrasting differences in simulated flowering and maturity time across China's Maize Belt, while the differences in simulated maize yield were relatively smaller. This implies the importance to use the correct temperature response in maize growth modelling so that the genotype by environment interactions in response to rising temperature can be correctly captured.

1. Introduction

Extreme high temperature events occurred more frequently in the past decades and are projected to increase in magnitude, duration, and frequency (IPCC, 2012). Climate warming has had significant impacts on agricultural productions (Lobell et al., 2011, 2013; Piao et al., 2010; Wang et al., 2011). Accurately assessing the impacts of climate warming on crop yield is essential in developing effective adaptation strategies for agriculture adapting to climate change (IPCC, 2014; Parry et al., 2004; Rosenzweig and Wilbanks, 2010).

Maize is one of the most important grain crops, and has the largest total production (FAO, 2014). Maize production in China accounts for 17% of global total (Xiong et al., 2009). Previous studies showed that high temperature would lead to the decrease in maize growth period (Badu et al., 1983; Hunter et al., 1977; Warrington and Kanemasu, 1983) and final yield (Badu et al., 1983; Kiesselbach, 1950; Siebert et al., 2014). Accurate assessment of the impact of high temperature on maize growth and development could help develop appropriate options to ensure China's and global security of maize production (Tao and Zhang, 2010). Such assessment will require reliable predictions of maize yield in response to rising temperature.

Crop models have been recognized effective tools to evaluate the impacts of future climate change on crop production (Bassu et al., 2014). However, large uncertainties exist in simulated crop yield, particularly in response to rising temperature beyond the optimal range, which is the key finding of multi-model inter-comparison studies for wheat (Asseng et al., 2013), maize (Bassu et al., 2014), rice (Li et al., 2015), and potato (Fleisher et al., 2017). A more recent study by Wang et al. (2017) demonstrates that inaccuracies in temperature response functions of the key processes simulated in the wheat models explained more than 50% of the uncertainty in simulated wheat yield, and that improved temperature functions based on data could reduce the

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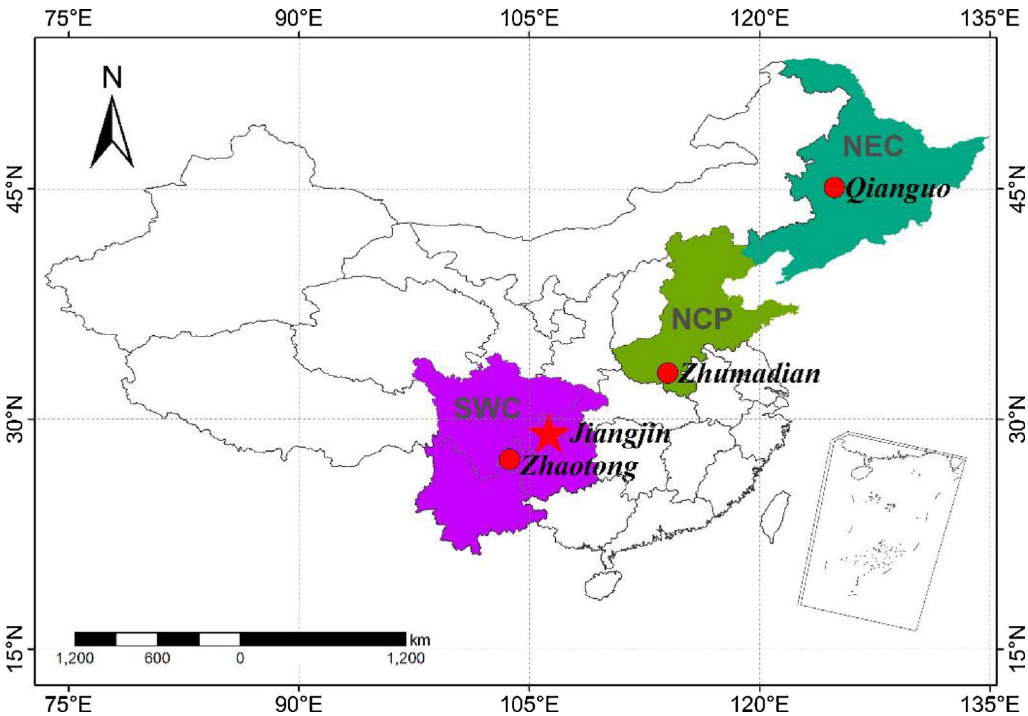

Fig. 1. The geographic locations of Northeast China (NEC), North China Plain (NCP), Southwest China (SWC) and the three study sites (Qianguo, Zhumadian, Zhaotong). The controlled-temperature experiment was conducted at Jiangjin agrometeorological experimental station in Southwest China.

Table 1
Site information, maize cultivars and growing periods at three study sites. NEC = Northeast China, NCP = North China Plain, SWC = Southwest China.

Area	Site name	Latitude (°N)	Longitude (°E)	Altitude (m)	Growing season average temperature (°C)	Cultivar	Periods
NEC	Qianguo	45.08	124.87	136.2	19.8	Jidan_180	2007–2009 (calibration) 2010–2011 (validation)
NCP	Zhumadian	33.00	114.02	82.7	25.2	Zhengdan_958	2004–2006 (calibration) 2007–2009 (validation)
SWC	Zhaotong	27.35	103.72	1949.5	18.5	Tongdan_2	1994–1997 (calibration) 1998–2001 (validation)

Table 2
Temperature, photoperiod, relative humidity and CO_2 concentration maintained in the phytotron during the controlled experiment.

Temperature (°C)			Photoperiod (h)	Relative humidity (%)	CO_2 concentration (ppm)
Day	Night	Mean			
25	15	20	13	65	450
35	25	30			
35	35	35			
40	35	37.5			

simulation error by up to 50%. For maize, similar issues may also exist because response functions in current maize models may have been developed with the data from limited controlled-temperature and field experiments under a narrow range of temperatures (Brown and Bootsma, 1993; Gilmore and Rogers, 1958; Stewart et al., 1998; Yan and Hunt, 1999; Yin et al., 1995).

Parent and Tardieu (2012) found the Arrhenius-type curve could describe the response of crop development to a large range of temperature based on reviewing previous experimental data from the controlled-temperature and field experiments with contrasting climate conditions. However, the base and maximum temperatures for maize development could not be derived from Arrhenius-type curve. Parent and Tardieu (2014) further indicated that there may be a large uncertainty in the response function of radiation use efficiency (RUE) to temperature used in crop models. Such uncertainties warrant further work on temperature response of development, biomass growth and yield of maize crop.

The objectives of this study are to: (1) compare the temperature response functions for maize phenological development and biomass growth derived from data and those used in two maize crop models, i.e., APSIM and CERES, (2) derive new temperature response functions based on newest data and understanding, and (3) use APSIM model to investigate the impact of changed temperature response functions on simulated maize yield across contrasting maize growing regions of China under climate warming scenarios.

2. Materials and methods

2.1. Study sites

Three sites are selected in this study, including Qianguo in Northeast China (NEC), Zhumadian in North China Plain (NCP) and Zhaotong in Southwest China (SWC), where long-term maize data from an agrometeorological station at each site are available. The three sites cover the major climate types in China's Maize Belt (Fig. 1 and Table 1). Northeast China has a temperate monsoon climate where spring maize is sown on in early May and harvested in late September in a single-cropping system (one crop a year). The North China Plain is characterised by temperate humid/semi-humid climate where summer maize is sown in mid-June and harvested in late September in a winter wheat and summer maize double cropping system (two crops a year). Southwest China has a mixed subtropical and alpine frigid climate where maize is sown in early March to early May and harvest in late July to late September in a mixture of single-cropping system and