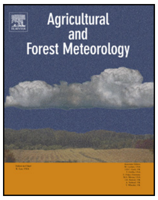
Agricultural and Forest Meteorology 222 (2016) 45–58

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Modelling the effects of heat stress on post-heading durations in wheat: A comparison of temperature response routines

Bing Liu[a,b], Leilei Liu[a], Senthold Asseng[b], Xiudong Zou[a], Jun Li[a], Weixing Cao[a], Yan Zhu[a,*]

[a] *National Engineering and Technology Center for Information Agriculture, Jiangsu Key Laboratory for Information Agriculture, Jiangsu Collaborative Innovation Center for Modern Crop Production, Nanjing Agricultural University, Nanjing, Jiangsu 210095, PR China*
[b] *Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL 32601, USA*

ARTICLE INFO

Article history:
Received 4 November 2015
Received in revised form 13 February 2016
Accepted 6 March 2016

Keywords:
Climate change
Heat stress
Temperature response routine
Senescence acceleration
Post-heading duration
Model evaluation

ABSTRACT

Crop yield simulations are highly correlated to reproductive phase duration simulations, which are often affected by heat stress. In this study, we evaluated four widely used temperature response routines of wheat phenology (Bilinear, Sin, Beta, and Trapezoidal routines) to simulate heat stress effects on post-heading durations with datasets from four years of environment-controlled phytotron experiments and multi-year field experiments across the main wheat production region in China. Significant reductions in post-heading duration were observed with increasing heat stress in phytotron experiments. A comparison of these temperature routines imbedded in the WheatGrow model showed that three of the routines could not predict post-heading durations under heat stress, while the Trapezoidal routine tended to overestimate high temperature impacts. Therefore, the three routines that could not simulate heat stress effects were extended by a senescence acceleration function. This function significantly improved the post-heading duration simulations under heat stress, regardless of the original temperature routine. However, the temperature threshold of initiating the senescence acceleration function varied depending on the original temperature response routine, between 27.3 and 30.1 °C. A new genotypic coefficient representing a cultivar-specific sensitivity to heat stress was introduced and ranged from 1.4 to 5.7 times of none heat-affected senescence per day. When evaluating the three temperature response routines linked with the added senescence acceleration function with independent phenology data (130 measurements), resulted in an average RMSE of 2.2 days for post-heading duration. The improved post-heading duration simulation is important for simulating current year-to-year yield variability due to frequent heat events, and it is even more critical for climate change impact assessments.

1. Introduction

Temperature is a crucial environmental factor for crop growth and development (Porter and Gawith, 1999). Future climate change will increase average temperature and temperature variability, resulting in more extreme temperature events, such as heat stress (IPCC, 2012). Recently, other studies have paid attention to extreme events, such as heat stress during crop development stages (Asseng et al., 2011; Gouache et al., 2012; Liu et al., 2014; Teixeira et al., 2013). Heat stress could result in dramatic yield reductions, particularly during the crop reproductive period (Liu et al., 2014; Lobell et al., 2011; Luo, 2011; Wardlaw and Moncur, 1995; Zhao et al., 2007). Many studies indicated that frequent heat stress events with a warming climate will pose great risks on crop yield stability (Koehler et al., 2013; Semenov, 2009; Semenov and Shewry, 2011; Siebert and Ewert, 2014; Teixeira et al., 2013). Therefore, quantifying the effects of heat stress on crop growth is important to create adaptation or mitigation strategies and to maintain a stable global food supply under future climate scenarios.

Process-based crop simulation models, which encompass knowledge of crop physiology and crop responses to environmental factors, have been used widely to predict crop productivity under future climates (White et al., 2011a). However, some recent studies expressed concerns about the accuracy of these simulation results when crop models were used to assess climate change impacts (Rötter et al., 2011; Semenov et al., 2012; Siebert and Ewert, 2014). One of the major concerns is that crop models cannot represent the effect of heat stress on crop yield adequately, especially during sensitive phases (Levis, 2014). One of the main weaknesses of using crop models to simulate crop production under future climate

---

* Corresponding author.
E-mail address: yanzhu@njau.edu.cn (Y. Zhu).

http://dx.doi.org/10.1016/j.agrformet.2016.03.006
0168-1923/

scenarios is that they underestimate the impacts of heat stress on crop growth (Lobell et al., 2012; Rötter et al., 2011; Semenov et al., 2012). Several researchers have addressed this problem by incorporating the effects of heat stress in crop models (Asseng et al., 2011; Hawkins et al., 2013a; Moreno-Sotomayor and Weiss, 2004). For example, Challinor et al. (2005) have developed a submodel to simulate the effects of high temperature events around flowering on peanut yield. Similar algorithms have been used to quantify the effect of heat stress on other crops, including wheat, soybean, and sunflower (Moriondo et al., 2010, 2011).

Crop phenology is important for crop production management and agricultural decision-making, and crop phenology responses to climate change have been a key aspect in global warming studies (Ceglar et al., 2011; Li et al., 2008; Streck et al., 2007). In many process-based crop models, simulation of several critical processes during crop growth, such as biomass distribution and dynamic of leaf area index (LAI), directly depends on crop development. Precise prediction of phenological durations in response to climate change is important to evaluate the impact of climate change on agricultural yields (Craufurd et al., 2013). However, many recent studies revealed uncertainties in temperature responses of crop development. These findings suggest that urgent improvements are needed to enhance the ability of crop development predictions under various climates, especially under heat stress (Asseng et al., 2013). Lobell et al. (2012) showed that both CERES-Wheat and APSIM-Wheat exhibited poor performance in predicting the green season length of wheat under heat stress in India. Both Zhang et al. (2008) and van Oort et al. (2011) showed that the assumption of thermal time accumulation as a constant in crop phenology submodels could result in systematic errors in modelling the rice phenology during the long period. In addition, many other studies pointed out that existing crop models give wrong responses to temperature when above the optimal temperature threshold (Challinor and Wheeler, 2008; Challinor et al., 2009; Tao and Zhang, 2010; van Oort et al., 2011). White et al. (2011b) found that increasing the base and optimal temperatures in CERES-Wheat model can reduce the simulation errors of wheat anthesis and maturity dates within heating environments in temperature free-air controlled enhancement (T-FACE) experiments. Daily maximum temperature above the optimal temperature (i.e., >30 °C for wheat) is defined as heat stress, so the wrong responses of crop phenology submodels to temperature above optimal temperatures could be a result of heat stress events during crop cycles. In summary, although many studies have tried to improve crop models in simulating the effects of heat stress, there has been little progress in modelling the effects of heat stress on crop phenology. Therefore, improvements in phenology predictions of crop models under heat stress is essential for accurate future climate change assessments (White et al., 2011b; Zhang et al., 2012).

The objectives of this study were as follows: (1) to evaluate four widely used temperature response routines in wheat phenology submodels for simulating heat stress effects on post-heading durations; (2) to develop new functions for improving the predictions of post-heading durations under heat stress in wheat crops; (3) to calibrate and evaluate the new functions with observed phenology data under different temperature regimes.

2. Materials and methods

2.1. Data sources

For this study, we collected the observed wheat phenology datasets from both environment-controlled phytotron experiments and multi-year field experiments across the main wheat producing region of China to evaluate the performance of different temperature response routines in simulating heat stress effects on post-heading durations in wheat crops.

2.1.1. Experiment 1: environment-controlled phytotron experiments

In environment-controlled phytotron experiments, two winter wheat cultivars (Yangmai16 and Xumai30) were planted in plastic pots at Nanjing (118.78°E, 32.04°N) in growing season 2010–2013 and at Rugao (120.33°E, 32.23°N) in growing season 2013–2014 in Jiangsu Province of China. The height and inside diameter of pots were 30 cm and 25 cm. Plant density was 10 plants per pot. Sowing dates in the four growing seasons were November 1, November 6, November 4, and November 5, respectively. 0.9 g N, 0.5 g P_2O_5 and 0.9 g K_2O were applied in each pot before sowing, and another 0.9 g N were applied during jointing stage of wheat.

The wheat was grown in pots in a normal ambient environment before the heat stress treatments. Once the wheat developed into the appropriate growth stages, the wheat was transferred into phytotrons to expose to different heat stress conditions. The heat stress treatments were conducted at three wheat stages: anthesis, 10 days after anthesis (DAA10), and 20 days after anthesis (DAA20). The heat stress treatments included different temperature regimes (T_{min}/T_{max} were 17/27 °C (T1), 21/31 °C (T2), 25/35 °C (T3), 29/39 °C (T4), and 33/43 °C (T5)) and heat stress durations (3 days (D1), 6 days (D2) and 9 days (D3)). For each heat stress duration, we conducted several of the temperature regimes (T1–T4 in growing season 2010–2013, T1, T3, T4 and T5 in growing season 2013–2014). Table 1 summarizes the details of heat stress treatments in each growing season. The phytotrons were made of transparent glass, and the size of each phytotron was 3.4 m × 3.2 m × 2.8 m (length × width × height). Temperature and humidity in the phytotrons were controlled precisely to simulate the daily temperature and humidity fluctuations in the ambient environment to capture the actual response of wheat to heat stress in the field as true as possible. HOBO data loggers (Onset Computer Corp., Bourne, MA, USA) were used to measure the temperature and relative humidity during heat stress period every 5 min. The day-night temperature fluctuations, as shown in Fig. 1, followed a similar pattern of ambient temperature. Supplemental light was applied by halogen lamp to make sure that light condition in the phytotrons did not limit the wheat growth. Pots in phytotrons were randomly placed and rotated frequently to minimize positional effects. After the stress period, the plants were moved out of the phytotrons and maintained at normal ambient environmental conditions until harvest. All cultivation practices, such as irrigation, fertilization, herbicide and pesticide applications, were performed according to local standards of wheat cultivation to make sure that wheat was grown to avoid biotic and abiotic stresses. The meteorological data, including daily temperature, rainfall, and radiation during wheat growing season, was recorded by Dynamet-1K (Dynamet Inc., USA) near the experiment sites. Wheat phenology for each treatment was recorded accurately, including the dates of sowing, heading, anthesis, and maturity. The phenology observation was conducted according to the standard for observations of wheat phenology in the Observation Specification for Agricultural Meteorology: Crop Part (China Meteorological Administration, 1993). The heading date was determined when spikes were observed in 50% of plants, and the anthesis date was recorded when 50% of spikelet in the middle position of spike began to flower. To obtain accurate maturity date, wheat development stages were observed every day after anthesis. The maturity date was determined when the color of more than 80% of grains turn into yellow, all glumes and stems became yellow and only the first and second internode remained slightly green.