Field Crops Research 198 (2016) 226–237

Contents lists available at ScienceDirect

Field Crops Research

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

Modelling the impact of heat stress on maize yield formation

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ARTICLE INFO

Article history:
Received 8 April 2016
Received in revised form 4 August 2016
Accepted 9 August 2016

Keywords:
Heat stress
Maize
Zea mays (L)
Crop models

ABSTRACT

The frequency and intensity of extreme high temperature events are expected to increase with climate change. Higher temperatures near anthesis have a large negative effect on maize (*Zea mays*, L.) grain yield. While crop growth models are commonly used to assess climate change impacts on maize and other crops, it is only recently that they have accounted for such heat stress effects, despite limited field data availability for model evaluation. There is also increasing awareness but limited testing of the importance of canopy temperature as compared to air temperature for heat stress impact simulations. In this study, four independent irrigated field trials with controlled heating imposed using polyethylene shelters were used to develop and evaluate a heat stress response function in the crop modeling framework SIMPLACE, in which the Lintul5 crop model was combined with a canopy temperature model. A dataset from Argentina with the temperate hybrid Nidera AX 842 MG (RM 119) was used to develop a yield reduction function based on accumulated hourly stress thermal time above a critical temperature of 34 °C. A second dataset from Spain with a FAO 700 cultivar was used to evaluate the model with daily weather inputs in two sets of simulations. The first was used to calibrate SIMPLACE for conditions with no heat stress, and the second was used to evaluate SIMPLACE under conditions of heat stress using the reduction factor obtained with the Argentine dataset. Both sets of simulations were conducted twice; with the heat stress function alternatively driven with air and simulated canopy temperature. Grain yield simulated under heat stress conditions improved when canopy temperature was used instead of air temperature (RMSE equal to 175 and 309 $g\,m^{-2}$, respectively). For the irrigated and high radiative conditions, raising the critical threshold temperature for heat stress to 39 °C improved yield simulation using air temperature (RMSE: 221 $g\,m^{-2}$) without the need to simulate canopy temperature (RMSE: 175 $g\,m^{-2}$). However, this approach of adjusting thresholds is only likely to work in environments where climatic variables and the level of soil water deficit are constant, such as irrigated conditions and are not appropriate for rainfed production conditions.

Abbreviations: A_n, Argentine experiment *n*; DAS, days after sowing; GS_n, growing stage *n*; C, control plots; FRTDM, fraction of aboveground biomass to be translocated to seeds; H, heated plots; LAI, leaf area index; MBE, mean bias error; O, observed value; PAR, photosynthetically active radiation; IPAR, intercepted PAR; PostS, post-silking treatment; PreS, pre-silking treatment; RedHS, heat stress reduction factor; RGRLAI, maximum relative increase in LAI; RMSE, root mean square error; RUE, radiation use efficiency; RTMCO, correction factor for RUE; S_n, Spanish experiment *n*; T_{air}, air temperature; S, simulated value; SLA, specific leaf are; T_{can}, canopy temperature; $T_{can,lower}$, T_{can} lower limit; $T_{can,upper}$, T_{can} upper limit; T_{crit}, critical temperature; T_{air_ear}, air temperature at ear level; T_{air_tas}, air temperature at tassel level; Th, hourly temperature; TSUM1, thermal time from emergence to anthesis; TSUM2, thermal time from anthesis to maturity; TT_{hs}, hourly stress thermal time; Y, grain yield; Y_n, normalized Y.

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http://dx.doi.org/10.1016/j.fcr.2016.08.013
0378-4290/

1. Introduction

The frequency of extreme temperature (Alexander et al., 2006; IPCC, 2007; Orlowsky and Seneviratne, 2012) and drought (Alexander et al., 2006) events has increased across many world regions in the past 60 years, and is expected to further increase (Beniston et al., 2007; Seneviratne et al., 2012). Together with higher mean temperatures, these extreme events are expected to cause negative impacts on crop growth (Seneviratne et al., 2012; Gourdji et al., 2013). Large-scale observational studies analyzing maize yield and temperature records indicate that large yield losses are associated with even brief periods of high temperatures when crop-specific high temperature thresholds are surpassed. French maize yields over the past 50-years were found to have decreased as the number of days with maximum air temperature above 32 °C increased (Hawkins et al., 2013). Likewise, a panel analysis of maize yields in the US, determined that yield decreased with cumulative degree days above 29 °C (Schlenker and Roberts, 2009). Similarly, Lobell et al. (2011) detected maize yield losses across Sub-Saharan Africa ranging from 1 to 1.7% (depending on water availability) per each degree day above 30 °C.

Maize yield is largely determined during a rather narrow window of time of four to five weeks bracketing silking (Fischer and Palmer, 1984; Otegui and Bonhomme, 1998). It is during this time that crop growth rates strongly determine the number of grains set (Otegui and Bonhomme, 1998), a key determinant of final grain yield (Fischer and Palmer, 1984). This is why this period is referred to as "critical" for maize yield determination with a high sensitivity to abiotic stress (Fischer and Palmer, 1984; Kiniry and Ritchie, 1985; Grant et al., 1989; Lizaso et al., 2007). The mechanisms of yield reduction with high temperatures are associated with reductions in both source and sink capacity. Equally crop development rate, photosynthesis and respiration rates also respond non-linearly to high temperatures (Lobell et al., 2011), but the reducing effects on these processes are reversed when temperatures return to optimal ranges (Rattalino Edreira and Otegui, 2012; Ordóñez et al., 2015). Nevertheless, reductions in net assimilation (photosynthesis plus respiration) that produce a marked decrease in plant growth rate can result in large yield reductions if they occur during the critical period for kernel number determination (Andrade et al., 1999, 2002). The reduction in sink capacity can be caused by direct high temperature effects on flowering dynamics, ovary fertilization or grain abortion, with resulting losses in grain number being irreversible (Herrero and Johnson, 1980; Rattalino Edreira et al., 2011; Ordóñez et al., 2015).

Evidence from field trials has demonstrated that when heating was performed during the critical period, reductions in maize yield were very large (Cicchino et al., 2010a, 2010b; Rattalino Edreira and Otegui, 2012; Ordóñez et al., 2015). These reductions were independent of the negative effects of heat on pollen viability (Rattalino Edreira et al., 2011; Ordóñez et al., 2015), and were predominantly driven by reduced ovary fertilization of pollinated spikelets exposed to temperatures above 35 °C (Dupuis and Dumas, 1990). The reduction in grain number due to kernel abortion was the main effect of high temperatures during flowering in other works (Rattalino Edreira and Otegui, 2013; Ordóñez et al., 2015).

Various studies identified the upper maximum of the optimum temperature range to be about 30 °C (Gilmore and Rogers, 1958; Tollenaar et al., 1979) to 35 °C (Jones and Kiniry, 1986) for maize. In field trials with controlled heating, Cicchino et al. (2010b) determined this critical upper optimum temperature at flowering in two years as 35.5 ± 1.3 °C and 32.2 ± 1.1 °C with the same temperate hybrid. Porter and Semenov (2005) reported that temperatures above 36 °C reduced pollen viability in this species. Finally, Sánchez et al. (2014) reported 37.3 and 36 °C for the flowering and grain filling period, respectively, as the threshold optimum temperature.

Some evidence suggests that the crop canopy temperature better explains yield reductions associated with surpassing high temperature thresholds better than air temperature (Craufurd et al., 2013; Siebert et al., 2014; Webber et al., 2016). The differences between air temperature and the temperature of the canopy surface can differ significantly depending on the irrigation conditions as irrigation has a cooling effect that reduces canopy temperatures (Lobell et al., 2008) by as much as 10 °C (Kimball et al., 2015). However under rainfed conditions when soil water is limiting, or when transpiration rates are low due to low vapor pressure deficit, crop canopy temperature can increase above air temperature leading to yield loss from high crop temperatures (Lobell et al., 2015). The difference between air and crop canopy temperature is thought to be critical for heat stress responses as the difference of 1–2 °C can lead to large over or underestimation of yield loss from heat stress (Webber et al., 2016). While temperature gradients exist within the vertical plant profile (Rattalino Edreira and Otegui, 2012), it may be sufficient to capture the difference between the canopy surface and air temperature for simulations at the field and larger scales.

Currently, only a few published crop models include the effects of heat stress on maize yield and its physiological determinants, such as GLAM (Challinor et al., 2005, 2004), Aquacrop (Raes et al., 2009; Steduto et al., 2012), a modified Cropsyst (Moriondo et al., 2011) or APSIM maize (Lobell et al., 2015). Additionally, other research groups are currently developing heat stress modules specific for maize such as Lizaso et al. (2016). However, no published studies have evaluated model performance under heat stress using field trials with controlled heating. Consequently, heat stress model development and testing has been limited by a lack of data from field experiments with the application of high temperatures compared to a non-heated control. This applies even more so for modelling the effect of canopy temperature as compared to air temperature. Without such data, correct attribution of heat stress is difficult to distinguish from other growth limiting factors.

This study makes use of four independent datasets collected at Argentina and Spain in which controlled heating was applied to field grown maize crops. These datasets are used to parametrize and evaluate the performance of a canopy heat stress approach to account for the negative effects of extreme high temperatures on maize grain yield. The model performance is evaluated using both air and simulated canopy temperature as inputs to the heat stress module. These functions are suggested to be included in crop models applied at field and larger scales.

2. Material and methods

2.1. Experimental data

2.1.1. Argentine experiments

To develop a relationship to reduce grain yield with high temperature, two experimental datasets from Pergamino (33°56′ S, 60°34′ W), Argentina were used. Crops were cultivated under field conditions, but with controlled heat stress. These two experiments were carried out during two growing seasons (Table 1), in 2006/2007 (A1) and 2007/2008 (A2). Details of crop husbandry can be found in Cicchino et al. (2010a, 2010b). Briefly, the cultivar used was the temperate hybrid Nidera AX 842 MG, classified as 119 for relative maturity (Peterson and Hicks, 1973). The experiments were fully fertilized and irrigation was supplied to avoid water stress. Crop management ensured minimal weed, pest and disease pressure. Two temperature regimes were applied (C: control plots; H: heated plots). The timing of heating was an experimental treatment with two levels: GS1 heating between the appearance of the 11th leaf (V11 of Ritchie and Hanway, 1982) and tasseling and GS2 with heating from tasseling to 15 days after silking. In A1, only GS1 has