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Modelling the impact of heat stress on maize yield formation

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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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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

Table 1
Details of experiments used in the study.

Location	Experiment	Year	Heating treatment code	Heating treatment period	Air temperature measurement level
Argentina	A1	2006/2007	A1_GS1[a]	V11 to VT	Ear
	A2	2007/2008	A2_GS1	V11 to VT	Ear
		2007/2008	A2_GS2	VT to Silk + 15d	Ear
Spain	S1.1	2009	S1_PreS	Silk-15d to Mat	Ear and tassel
			S1_PostS	Silk + 15d to Mat	Ear and tassel
	S1.2	2010	S1_ PreS	Silk-15d to Mat	Ear and tassel
			S1_ PostS	Silk + 15d to Mat	Ear and tassel
	S2.1	2011	S2_ PreS	Silk-7d to Silk +9d	Ear and tassel
			S2_ PostS	Silk + 14d to Silk + 32	Ear and tassel
	S2.2	2012	S2_ PreS	Silk-7d to Silk +9d	Ear and tassel
			S2_ PostS	Silk + 14 to Silk + 32d	Ear and tassel

[a] Abbreviations: d, days; GS, Growing stage; Mat, Maturity; PostS, Post silking heating; PreS, Pre silking heating; Silk, Silking; VT, tasseling.

applied, whereas in A2, heating was applied for each of GS1 and GS2. The duration of heating periods in GS1 and GS2 (ca. 15–20 days) was based on dates of VT (tasseling) and silking of control plots. All silked plants in the shelters were hand pollinated with fresh pollen from non-heated plants, so that the effects of heat stress on pollen viability were not part of the experiment. Shoot biomass was estimated based on plants tagged before heating. Yield (Y) and yield components (kernel number per plant and individual kernel weight) were determined by harvesting ears with grains of each tagged plant, oven dried until constant weight and then weighed.

Temperature regime treatments were obtained by placing polyethylene shelters over two consecutive central rows of plots to increase the temperature using the greenhouse effect created by the shelters. In the heated treatments (H), the shelters reached close to the ground surface, except for one side that remained open to approximately 15 cm above ground level. For the control treatments (C), the South facing side remained open up to 1.4 m above the soil surface. The purpose of the open shelters in the C treatment was to avoid differences in solar radiation between treatments. Hourly records of air temperature in C and H plots were obtained by means of sensors (TC1047, Microchip Technologies, Chandler, AZ) installed at ear height and connected to dataloggers (Temp-Logger, Cavadevices, Buenos Aires, Argentina). The sensors were sheltered in white double-walled plastic cylinders with open ends, which had an internal diameter of 4.5 cm (innermost) or 10.5 cm (outermost), a total length of 18 cm. They were not aspirated. Solar radiation, wind speed and relative humidity data were collected from a weather station 500 m from the experimental site. The Argentine experiments were used for determination of the heat stress reduction factor, but not used for simulations with the canopy heat stress model, as only the air temperature at ear level (T_{air_ear}) was recorded in these experiments.

2.1.2. Spanish experiments

Datasets from two field experiments with controlled heating were used in the model evaluation. These two experiments were arranged into two studies, S1 and S2, each replicated for two consecutive growing seasons. The first year (2009) was conducted in Menarguens (41°43′48″N, 0°44′24″E) and the following three years (2010, 2011, 2012) in Algerri (41°48′36″N,0°38′24″E), both in Lleida, Spain (Table 1). Study S1 was carried out in 2009 (S1.1) and 2010 (S1.2) and S2 in 2011 (S2.1) and 2012 (S2.2). The cultivar Pioneer 31N28 (FAO 700) was used in S1.1, S1.2 and S2.1. For S2.2, Pioneer 33Y72 (FAO 700) was used. For each year and experiment, one value of yield and biomass were available for each treatment. PR33Y72 is similar to PR31N28 in all traits considered. Biomass was estimated by above-ground dry weight through oven drying the samples collected in each plot at maturity. Yield and its components were measured on these same samples. Additional details are reported in Ordoñez et al. (2015). Similar to the Argentine experiments, crop management ensured that there was minimal water, nitrogen or biotic stresses during the cropping season. The temperature regimes for S1 were (i) C: a control with no imposed heating, (ii) S1_Pre: heating imposed from 15 days before silking (Silk-15d) to maturity, and (iii) S1_Post: heating imposed from 15 days after silking (Silk + 15d) to maturity. Heating periods were about 76 days in S1. The temperature regimes for S2 were (i) C, as described above, (ii) S2_Pre: heating imposed from 7 days before silking (Silk-7d) to 9 days after silking (Silk + 9d), and (iii) S2_Post: heating imposed from 14 days after silking (Silk + 14d) to 32 days after silking (Silk + 32d). Heated treatments were established by means of polyethylene shelters mounted on structures of 3–3.5 m height (leaving the bottom 0.3 m open). As in the experiments from Argentina, elevated temperatures were obtained due to the greenhouse effect of the shelters. Plants in the shelters were hand pollinated as described for the Argentine experiments. Unlike the experiments in Argentina, the control (C) treatments were not covered by polyethylene film. Air temperature inside the shelters was measured at tassel (T_{air_tas}) and ear levels (T_{air_ear}) recorded with an Em5b Analog Data Logger (Decagon Devices USA), shielded with a cardboard cone with the bottom opened.

2.2. Model description

The maize heat stress model was developed and tested in SIMPLACE (Scientific Impact assessment and Modeling PLatform for Advanced Crop and Ecosystem management) modeling framework (Gaiser et al., 2013) together with the Lintul5 crop model (Wolf, 2012), the DRUNIR water balance model (Spitters and Schapendonk, 1990; Van Oijen and Leffelaar, 2008) and the CanopyT model (Webber et al., 2016). The combined model is SIMPLACE<Lintul5, DRUNIR, CanopyT, HeatStressHourly>, further referred to as SIMPLACE <Lintul5,HS,Tc>. The Lintul5 model is radiation use efficiency (RUE) based, that accounts for water and nutrient limitation. Crop development rates are a function of 24-h mean temperature above a base temperature, variety-specific parameters, and photoperiod sensitivity. Two parameters (TSUM1 and TSUM2) account for the thermal time required from emergence to anthesis and anthesis to maturity, respectively. Biomass growth is determined as the product of RUE and the amount of photosynthetically active radiation (PAR) that is intercepted by the crop (IPAR). IPAR is determined using Beer's Law as a function of the leaf area index (LAI). Initial LAI growth is exponential, while subsequent LAI is determined by leaf biomass accumulation and a time-varying specific leaf area (SLA). RUE also varies as a function of the crop development stage, and is reduced as a function of water stress. Water stress is defined as the ratio of actual crop transpiration to potential transpiration. Partitioning of biomass to roots, stems, leaves and grains varies with the crop development stage, with partitioning to roots increasing under water stress. Lintul5 also has a

RUE correction factor (RTMCO) that reduces RUE when daily mean temperature rises above 35 °C, which applies throughout the entire growing season. The RUE response to daily temperature follows that of the APSIM model (McCown et al., 1996; Keating et al., 2003).

Consideration of canopy temperature (T_{can}) allows accounting for the feedback between crop water status and crop temperature. The CanopyT model calculates hourly T_{can} using daily weather data with an energy balance approach correcting for atmospheric stability conditions using the Monin-Obukhov Similarity Theory (Webber et al., 2016). The model makes simplifications about the canopy resistance term to avoid the need to calculate stomatal conductance. It is assumed that the upper (warm) temperature limit ($T_{can,upper}$) for particular weather conditions is reached when the crop does not transpire, as occurs under conditions of high water stress. Likewise, the lower (cool) temperature limit ($T_{can,lower}$) is reached when the crop is transpiring at its maximum potential rate, as occurs under non-water limiting conditions. Actual T_{can} is determined by interpolating between these two extremes as a function of hourly crop water stress. This simplification renders it suitable for application in crop models aimed at applications for field, regional and larger scales. The evaluated model approach compared very well to observations and other approaches used to simulate T_{can} (Webber et al., 2015).

The heat stress module developed here, HeatStressHourly, is based on an approach implemented in the APSIM crop model (Lobell et al., 2015), modified for hourly time steps with the possibility to use either simulated canopy (T_{can}) or air temperature (T_{air}). Daily minimum and maximum values of T_{air} are converted to hourly values using a sinusoidal function as in Goudriaan and van Laar (1994) and Nguyen et al. (2014). The module developed here reduces yield (Y) as a function of the hourly stress thermal time (TT_{hs}, in °Ch) (Blumenthal et al., 1991) accumulated above a critical high temperature threshold (T_{crit}) during the critical period for kernel number determination (between 300 °Cd before and 200 °Cd after silking, ca. 30 days bracketing silking).

2.3. Simulation steps

Model development and testing consisted of three main steps: (1) heat stress yield reduction factor determination (RedHS), (2) crop model calibration, and (3) model validation (see Fig. 1). Broadly speaking, the Argentine experiments were used in Step 1 to establish the RedHS, by comparing the control and heated treatments. The Spanish dataset was used in Steps 2 and 3, for calibration (using the experiments without heat stress) and validation of SIMPLACE <Lintul5,HS,Tc> with the heat stress experiments, respectively. Simulations were conducted twice using two different estimates of hourly temperature (T_h) to calculate hourly stress thermal time (TT_{hs}) (Eq. (1)); first using hourly $T_h = T_{air}$, and secondly with hourly $T_h = T_{can}$, as input:

$$TT_{hs,i} = T_{h,i} - T_{crit} \tag{1}$$

Step 1: The value of RedHS was determined after first specifying the critical temperature threshold for yield loss due to high temperature; air temperature at ear level (T_{ear}) was used, as it can be considered the actual temperature experienced by the ear. RedHS was calculated as the reduction in Y per TT_{hs} accumulated during the critical period, with $T_{crit} = 34$ °C as obtained by Cicchino et al. (2010b) for the same experiments. Y was normalized (Eq. (2)) with the Y obtained in the control treatment for each experiment/treatment combination, considering the Y in the control as the maximum Y that can be achieved in a particular year and site under the given conditions.

$$Y_{n,i} = \frac{Y_{o,i}}{Y_{m,i}} \tag{2}$$

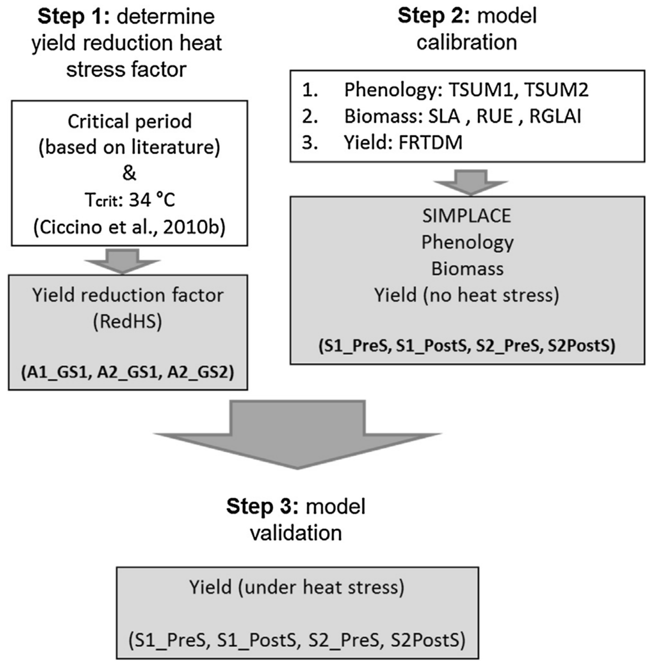

Fig. 1. Flowchart illustrating heat stress reduction function development and evaluation procedure. The heat stress reduction factor determination (Step 1) is followed by model calibration (Step 2), and model evaluation (Step 3). The experiment/treatment combinations (Table 1) considered in each step are shown in parentheses of the grey boxes.

where, $Y_{n,i}$ is normalized Y, $Y_{o,i}$ is the observed Y from the heated treatment and $Y_{m,i}$ is the maximum Y observed in the control experiment, and i representing the experiment/treatment combination.

With $TT_{hs,i}$ and Y_{ni} calculated, RedHS was calculated as:

$$RedHS = \frac{\sum_{i=1}^{N}\left(\frac{\Delta Y_{n,i}}{\Delta TT_{hs,i}}\right)}{N} \tag{3}$$

where, ΔY_n is the difference between $Y_{n,i}$ for the control (equal to 1) and $Y_{n,i}$ for the heated treatment for each experiment/treatment combination, and $\Delta TT_{hs,i}$ the difference between the hourly stress thermal time for the control treatment and the heated treatment, as the control experiments may also have experienced temperatures above T_{crit}. The index i indicates the experiment/treatment combination (e.g. 1 = A1_GS1, 2 = A2_GS1 and 3 = A2_GS2) and N the total number of experiment/treatments combinations.

Step 2: SIMPLACE <Lintul5,HS,Tc> was calibrated for conditions of no heat stress using the control treatments in the Spanish dataset following the procedure shown in Fig. 1. The first step was to calibrate the phenology routine (anthesis and maturity dates) with the parameters TSUM1 and TSUM2. Next, the biomass data were used to calibrate RUE, SLA and RGRLAI (maximum relative increase in LAI during juvenile stages). In a final step, Y was used to calibrate FRTDM (fraction of aboveground biomass to be translocated to seeds). Final Y was first simulated using the same T_{crit} for both T_{can} and T_{air}, and later increasing the T_{crit} for T_{air} based on the difference in temperatures within the maize canopy (Rattalino Edreira and Otegui, 2012).

Step 3: Validation of calibrated SIMPLACE <Lintul5,HS,Tc> was performed with the heated treatments from the Spanish datasets, considering the RedHS factor obtained in Step 1 and the crop parameters calibrated in Step 2.

Steps 2 to 3 were conducted with each T_{air} and T_{can}, and results compared. Additionally, simulated T_{can} for the Spanish experiments were compared with observed ear temperature values.

To estimate errors in the manual calibration process, root mean square error (RMSE), and mean bias error (MBE) were determined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \quad (4)$$

$$MBE = \frac{\sum_{i=1}^{n}(S_i - O_i)}{n} \quad (5)$$

where S_i is the simulated value and O_i the observed value, with i representing the experiment/treatment combinations.

3. Results

3.1. Step1. determination of yield reduction heat stress factor

$TT_{hs,i}$ calculated with T_{ear} from A1_GS and A2_GS experiments/treatment combinations (Table 1) and T_{crit} set at 34 °C showed a negative relationship with Y (Table 2). The Y reductions resulting from heating were larger for A2_GS1 than for A1_GS1, with a mean reduction in Y due to heating of 683 g m^{-2} (59.3% reduction in Y_n). Y reduction for A2_GS2 was intermediate between these values. The relative Y loss per unit TT_{hs} between the three experiment/treatment combinations was A1_GS1 > A2_GS2 > A1_GS2. The mean decrease in Y per unit TT_{hs} during the critical period, i.e. RedHS, was −0.0025 °Ch^{-1} (Table 2).

3.2. Step 2. model calibration

The crop parameters resulting in the lowest values of RMSE and MBE for simulation of the control treatments with SIMPLACE<Lintul5,HS,Tc> are presented in Table 3. The RUE parameter value from emergence to anthesis was 2.7 g MJ^{-1}, and then decreased linearly from 2.7 g MJ^{-1} to 2.5 g MJ^{-1} around mid-grain filling, to 1.3 g MJ^{-1} at maturity. The other parameters were kept constant throughout the crop cycle.

Phenological dates from the Spanish experiments were well simulated with SIMPLACE<Lintul5,HS,Tc> using the TSUM1 and TSUM2 parameters (Table 4). RMSE results for the anthesis and maturity date calibration were ca. 5 and 3 days, respectively.

After phenology calibration, the relationships between $T_{air\text{-}tas}$ (air temperature at tassel level), $T_{air\text{-}ear}$ (air temperature at ear level), and simulated T_{can} were evaluated using S1_PreS, S1_PostS, S2_PreS and S2_PostS experiments. Simulated T_{can} at 14.00 h from the Spanish experiments was similar to observed daily maximum $T_{air\text{-}ear}$ (Fig. 2a). During periods with heating, which did not entirely correspond with the critical period, the mean difference between simulated T_{can} and observed $T_{air\text{-}ear}$ was 0.1 °C. Both T_{can} and $T_{air\text{-}ear}$ were lower than air temperature at tassel height (Fig. 2b), with a mean difference between $T_{air\text{-}ear}$ and $T_{air\text{-}tas}$ of approximately 8.8 °C.

Simulated hourly $T_{air\text{-}tas}$ for 14:00 h (from daily measured temperature at tassel height) and simulated T_{can} at 14:00 h were compared for three different periods: (1) the entire growing season, (2) the critical period (−300 +200 °Cd around silking), and (3) the times when temperatures were above 34 °C within the critical period. Mean differences of around 5 °C were obtained between simulated T_{can} and $T_{air\text{-}tas}$ for the heated treatments (S1_PreS/PostS and S2_PreS/PostS) during the critical period (Table 5). This difference increased to around 5.7 °C when the temperatures exceeded 34 °C (Table 5).

After crop parameters calibration (Table 3), there was no difference in the model performance for simulating biomass and Y of control treatments with or without use of RedHS with T_{can}. Both models exhibited similar RMSE values for biomass with the critical threshold temperatures of T_{crit} = 34 °C (Table 6, Fig. 3), suggesting there was little heat stress in the control treatments when simulations were conducted with T_{can}. However, a larger RMSE value resulted when RedHS was computed with T_{air} as input (394 vs. 373 gm^{-2} for biomass and 260 vs. 234 gm^{-2} for Y), as T_{air} tended to be higher than T_{can} and measured T_{ear} (Table 5, Fig. 2). Nevertheless, the RMSE for all biomass and Y estimations did not vary when T_{crit} for T_{air} was increased to = 39 °C. This increase was due to the best match and the difference in temperature between T_{air} and T_{can} obtained during the critical period (Table 5).

3.3. Step 3. model evaluation

The model evaluation with treatments with heat stress from the Spanish dataset generated an overestimation of crop biomass when the heat stress module was not included in the analysis (no RedHS), with greater error for S_PreS than for S_PostS. This bias was reduced when the heat stress module was added (RMSE declined from 497 to 416 g m^{-2}). With the inclusion of the heat stress reduction module, biomass in both treatments (S_PreS and S_PostS) was slightly underestimated. Using the same T_{crit} (34 °C) for T_{air} and T_{can}, the error obtained using T_{air} as an input was higher than using T_{can} (RMSE: 557 vs 395 g m^{-2}); however, T_{crit} for T_{air} was increased to 39 °C the error was reduced, though still slightly greater than that obtained with T_{can} using T_{crit} = 34 °C (RMSE: 420 vs 395 g m^{-2}) (Fig. 4, Table 7).

Results for Y showed a similar trend to those for biomass, with the highest errors reported when the model without the RedHS module was used (Table 7). Inclusion of RedHS with T_{can} as the input temperature reduced errors for both heated periods (S_PreS and S_PostS), with a greater improvement in the S_PostS treatment than in the S_PreS. When T_{crit} with T_{air} was increased to 39 °C, the errors were lower compared to the model without RedHS, and slightly higher than using RedHS with T_{can} (Fig. 5, Table 7).

In addition to the effect of RedHS reducing Y for hours when the respective T_{crit} was exceeded, a second reduction factor effects RUE (RTMCO) in response to daily mean temperatures rising above 35 °C, irrespective of the stage of crop development. While the effect of RTMCO is transient in that RUE on subsequent days is not affected by previous hot days, it will reduce new biomass production and resultant partitioning to yield due to heat stress. The relationship between these two sources of reduction in Y is shown in Fig. 6. Results showed equal reductions due to reductions in RUE (RTMCO) and the action of the RedHS response in most of the experiments. However, for the S_PreS of the years (2010, 2011 and 2012) when the critical and heating periods matched, yield reductions were more relevant (approximately 40 % higher) due to the heat stress (RedHS) than for RTMCO (Fig. 6).

4. Discussion

It has been emphasized that crop models must be improved to consider the effects of heat stress for both large (Ewert et al., 2015; Rezaei et al., 2015) and local (García-López et al., 2014; Gabaldón-Leal et al., 2015) scale assessments of climate change impacts on cropping systems. A challenge for model improvement is often the lack of field experiments with control trials to test model responses, in this case, of imposing high temperatures. A related challenge for simulating heat stress under field conditions and at larger scales is to account for the interaction between crop water status and heat stresses that cannot be accounted for by considering only air temperature (Webber et al., 2016). This is the first study we are aware of in which a heat stress response in a maize crop growth model has been tested with field data from two different datasets from two contrasting world regions, Argentina's Rolling Pampas (isohygrous) and the NE-E Spain (Mediterranean regime).

Table 2
Relationship between hourly stress thermal time (TT_{hs}) based on ear temperature and normalized maize grain yield (Y_n) for the Argentine experiments with a critical threshold temperature of 34 °C. The reduction heat stress factor (RedHS) represents the relationship.

		TT_{hs}(°Ch)	Y(g m^{-2})	Y_n	RedHS(°Ch^{-1})
A1_GS1	control	13.6	1015.5	1	−0.0030
	heated	186.8	480.3	0.473	
A2_GS1	control	194.5	1254	1	−0.0019
	heated	540.4	439.7	0.351	
A2_GS2	control	17.1	1161.6	1	−0.0025
	heated	261.2	461.6	0.397	
Mean					**−0.0025**

Table 3
Crop parameters for cultivar FAO 700. TSUM1: thermal time from emergence to anthesis, TSUM2: thermal time from anthesis to maturity, SLA: specific leaf area, RUE: Radiation use efficiency for biomass production, RGRLAI: maximum relative increase in LAI during juvenile stage and FRTDM: fraction of aboveground biomass to be translocated to seeds.

	TSUM1 (°Cd)	TSUM2 (°Cd)	SLA (m^2 g^{-1})	RUE[a] (g MJ^{-1})	RGRLAI (m^2 m^{-2} d^{-1})	FRTDM
FAO 700	850	1100	0.014	2.7–2.5–1.3	0.014	0.01

[a] Different values corresponding to different crop development stages: 2.7 g MJ^{-1} from emergence to anthesis; 2.7–2.5 g MJ^{-1} from anthesis to mid grain filling; 2.5 g MJ^{-1} to 1.3 g MJ^{-1} from mid grain filling to maturity.

Table 4
Performance of SIMPLACE <Lintul5,HS,Tc> to simulate phenological dates showing simulated (sim) and observed (obs) anthesis and maturity in days after sowing (DAS) for each treatment. The root mean square error (RMSE) and mean bias error (MBE) for each cultivar are shown.

		Anthesis (DAS)				Maturity (DAS)			
Year	Treatment	sim	obs	RMSE	MBE	sim	obs	RMSE	MBE
2010	C	87	83	4.7	1.0	159	161	2.8	0.00
2011		89	84			159	155		
2012		102	98			167	169		
2009	S1_PreS	63	71			–	–		
2009	S1_PostS	63	70			–	–		
2010	S1_ PreS	85	85			–	–		
2010	S1_ PostS	87	83			–	–		
2011	S2_ PreS	88	85			–	–		
2011	S2_ PostS	89	84			–	–		
2012	S2_ PreS	100	103			–	–		
2012	S2_ PostS	102	98			–	–		

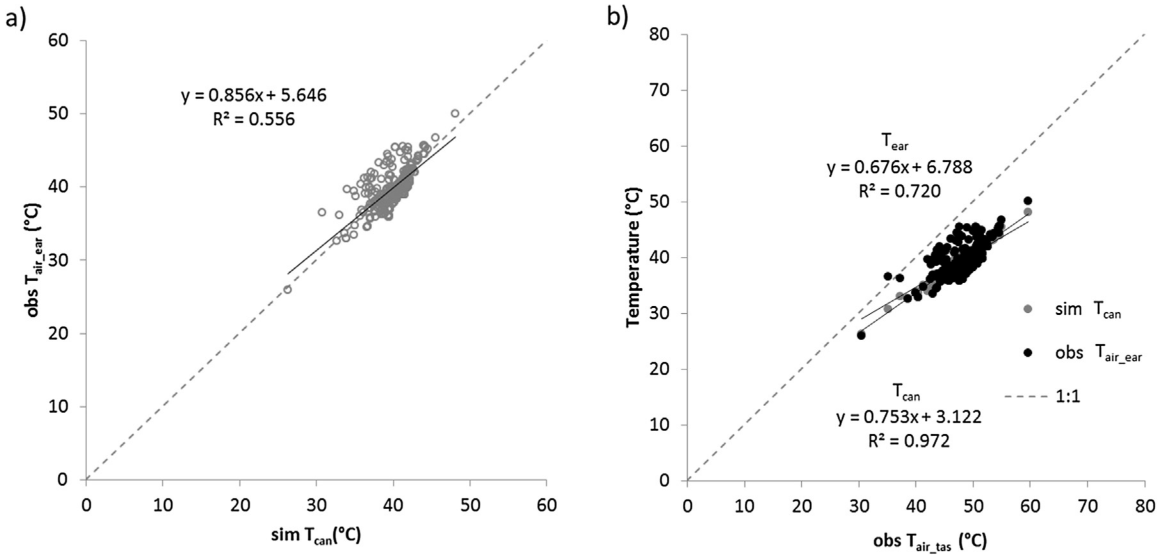

Fig. 2. Comparison of temperatures: a) Correlation between maximum observed air temperature at ear level (obs T_{air_ear}) and simulated canopy temperature (sim T_{can}). b) Correlation between maximum observed daily air temperature at tassel height (obs T_{air_tas}) and maximum observed temperature at ear level (obs T_{air_ear}) as well as simulated canopy temperature (sim T_{can}).

The results showed that the model tested in this study (SIMPLACE <Lintul5,HS,Tc>) was able to reproduce maize biomass growth and yield of maize grown under high temperature conditions near flowering. The model reduced yield as a function of accumulated stress thermal time during the critical period for Y formation bracketing silking. In the model, the direct heat stress effects on grain were accounted for in a heat stress reduction function, parameterized with the data from Argentina, and validated with

Table 5
Differences between simulated 14.00 h T_{air} (from daily measured data) and simulated 14.00 h T_{can} with SIMPLACE<Lintul5,HS,Tc> for the entire growing season, the critical period (from −300 to +200 °Cd around silking) and times when T_{air} was above 34 °C in the critical period. Standard deviation is in parenthesis.

Treatment period	Year	Difference between T_{air} and simulated T_{can}		
		Growing season °C	Critical period	Critical period with T_{air} > 34 °C
S1_PreS	2009	−5.7 (2.6)	−4.5 (2.3)	−5.8 (2.1)
S1_PostS	2009	−5.2 (2.6)	−3.7 (1.6)	−4.3 (1.4)
S1_PreS	2010	−5.6 (3.7)	−7.6 (2.4)	−8.6 (0.7)
S1_PostS	2010	−4.9 (3.6)	−4.1 (2.6)	−5.5 (1.6)
S2_PreS	2011	−2.7 (2.1)	−5.0 (3.3)	−8.2 (0.9)
S2_PostS	2011	−2.8 (1.9)	−2.7 (1.5)	−5.4 (1.9)
S2_PreS	2012	−2.9 (2.1)	−5.2 (3.2)	−8.1 (1.3)
S2_PostS	2012	−3.0 (2.3)	−2.5 (1.2)	−4.0 (1.5)
Mean		−4.1	−4.4	−6.3

Table 6
Root mean square error (RMSE) and mean bias error (MBE) for calibrations based on measurements performed on control treatments. Values were obtained without the heat stress module (no RedHS), or including the heat stress module (RedHS) with both T_{can} and T_{air}.

Trait	Error term	no RedHS	With RedHS and T_{can}	With RedHS and T_{air}	
			$T_{crit} = 34$ °C	$T_{crit} = 34$ °C	$T_{crit} = 39$ °C
		g m^{-2}			
Biomass	RMSE	373	373	394	373
	MBE	−3	−3	110	−3
Grain yield	RMSE	234	234	260	234
	MBE	25	25	−88	25

Table 7
Root mean square error (RMSE) of simulated biomass and grain yield for treatments heated during the pre-silking (S_PreS) or the post-silking (S_PostS) periods, obtained with the model excluding (no RedHS) and including the heat stress module (RedHs). For the latter, results based on canopy (T_{can}) or air (T_{air}) temperatures are present, considering T_{crit} for T_{air} and T_{can} equal to 34 °C, and T_{crit} for T_{air} increased to 39 °C and T_{crit} for T_{can} equal to 34 °C. Data correspond to the heated treatments.

RMSE	Treatment period	no RedHS	RedHS with T_{can}	RedHS with T_{air}	
			$T_{crit} = 34$ °C	$T_{crit} = 34$ °C	$T_{crit} = 39$ °C
		g m^{-2}			
Biomass	S_PreS	606	557	685	579
	S_PostS	387	233	428	260
	Mean	497	395	557	420
Grain yield	S_PreS	917	235	258	235
	S_PostS	257	116	361	207
	Mean	587	175	309	221

the experimental data from Spain. The difference in RedHS between Argentine treatments could be both due to the calculation procedure as well as to the photothermal environment. The difference introduced by the former is reduced when considering absolute rather than standardized values (results not shown). The variation in photothermal environment (ratio between radiation and temperature) is generally accounted for in crop simulation models (Kiniry and Ritchie, 1985), as variability in photothermal conditions affects plant growth rate and consequently grain set (Vega et al., 2001; Cicchino et al., 2010b). In the current research, the variability in photothermal environments arose due to (i) years, due to differences in climate, and (ii) control and heated plots, due to delayed silking of the latter. A final source of error is that different cultivars were used in the Argentine and Spanish experiments, though neither the RedHS factor nor T_{crit} were re-calibrated between experiments. Despite these differences between the datasets, as well as the potential of small amount of double counting due to the reduction in RUE when daily mean temperature is greater than 35° C (discussed below), the model performed well with a slight underestimation of the effects of heat stress in the Spanish experiments (Figs. 4 and 5). Therefore, these parameters may be considered to have general validity for long cycle maize varieties and be appropriate for use in large area climate change impact assessments.

The heat stress reduction factor using T_{can} performed better than that using T_{air} when the critical threshold temperature determined in Cicchino et al. (2010a) was used. This critical threshold is also close to values reported in other studies on the sensitivity of maize yield formation to high temperature (Herrero and Johnson 1980; Dupuis and Dumas, 1990). However, in the conditions of the Spanish validation experiments, evaporative cooling was high due to irrigation combined with high radiation and a high vapor pressure deficit, similar to the conditions of Arizona reported in Kimball et al. (2015). As a result, the crop was consistently several degrees cooler than the ambient air, such that T_{crit} used in RedHS with T_{air} could be increased to 39 °C to account for this cooling. In this case, yield simulations had a similar performance as compared to using $T_{crit} = 34$ °C in RedHS with T_{can}, with only slightly larger error. Therefore, under irrigated conditions and environmental conditions like those tested in the Spanish conditions (Webber et al., 2016), if estimation of T_{can} is not possible, it may be reasonable to increase T_{crit} when T_{air} is used to determine heat stress effects. This approach is not expected to be valid under rainfed conditions when both water availability and the atmospheric demand are more variable. Collectively, using T_{air} to simulate heat stress effects, T_{crit} would need to be increased after rainfall events on clear, dry days, but decreased on hot humid days, or when soil water was limiting. The variability in response depending on environmental conditions highlights the need to increase the number of field experiments combining heat stress with water availabil-

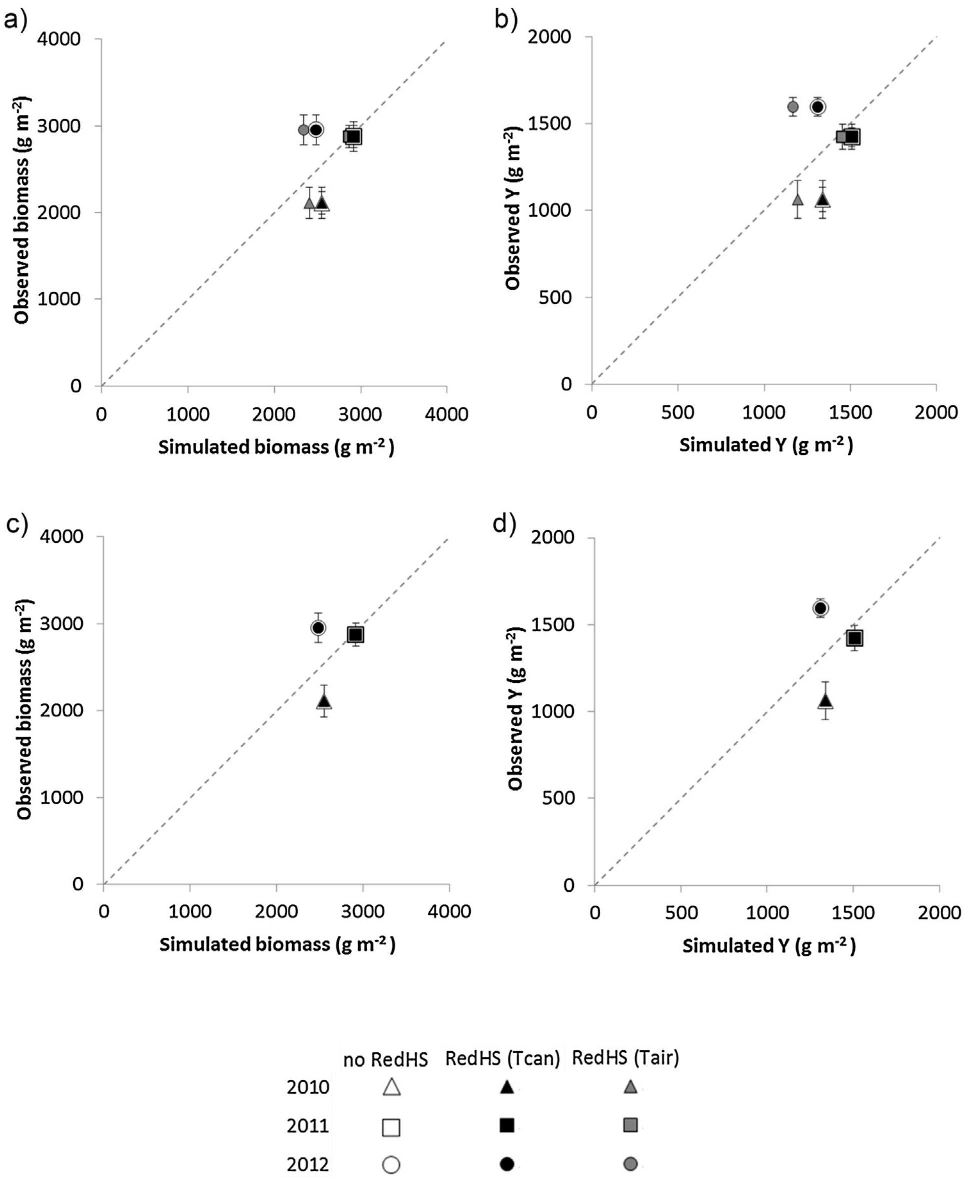

Fig. 3. Observed and simulated values of above ground biomass (a, c) and grain yield (Y) (b, d) for the control treatments using the model without the heat stress module (no RedHS, white symbols) (a and b), and with heat stress module (RedHS) (c and d) with T_{can} (black symbols) or T_{air} (grey symbols). T_{crit} is equal to 34 °C in panels (a and b) for both T_{can} and T_{air}, whereas T_{crit} for T_{air} was equal to 39 °C and T_{crit} for T_{can} equal to 34 °C in panels (c and d). Each data-point for the observed data is the average of three reps (and vertical bars on each symbol stand for the standard error of the mean). The line in each figure represents the 1:1 relationship.

ity in order to obtain an accurate approach valid for any weather conditions and crop water status.

The aim of the study was to develop a heat stress response function together with a canopy temperature model for application in regional climate change impact and adaptation assessment studies, rather than to explicitly simulate the detailed mechanism of heat stress. However, a brief reflection on the main processes causing large yield losses in field trials with controlled heating compared to processes captured in the model in response to high temperature is offered in what follows. Rattalino Edreira et al. (2011) and Rattalino Edreira and Otegui (2012, 2013) indicated that reduction in yield is explained by both a reduction in RUE (−3 to 33% of final biomass) as well as a failure of reproductive processes such as ovary pollination and fertilization together with an increased kernel abortion, all conducive to a reduction in kernel numbers of approximately 60%. It should be noted that the warmer plants of all experiments were hand pollinated with pollen from outside the chambers such that the effects of high temperature on pollen viability are not accounted for. The model proposed here potentially double counted some of the effects of high temperature with the heat stress reduction function RedHS as it is calculated based on the reduction in yield in the heated treatments as a function of the accumulation of TT_{hs} above T_{crit} in the experiments from Argentina, in which Y losses were due to both a failure of reproductive processes and a reduction in RUE. As explained above, in SIMPLACE <Lintul5,HS,Tc> RUE is already reduced when daily mean temperature is greater than 35 °C through the RTMCO factor, and the current approach did not consider possible double counting of yield loss from RTMCO and RedHS. Therefore, a next step for further model improvement is to examine how the response of RUE to average 24-h temperature greater than 35 °C correlates with TT_{hs} and to adjust RedHS considering the amount of high temperature stress that is already accounted for in RTMCO. However, this relationship between the high temperature dependence of RTMCO and RedHS is expected to vary with the environment depending on the magnitude of diurnal temperature variation. Another process known to

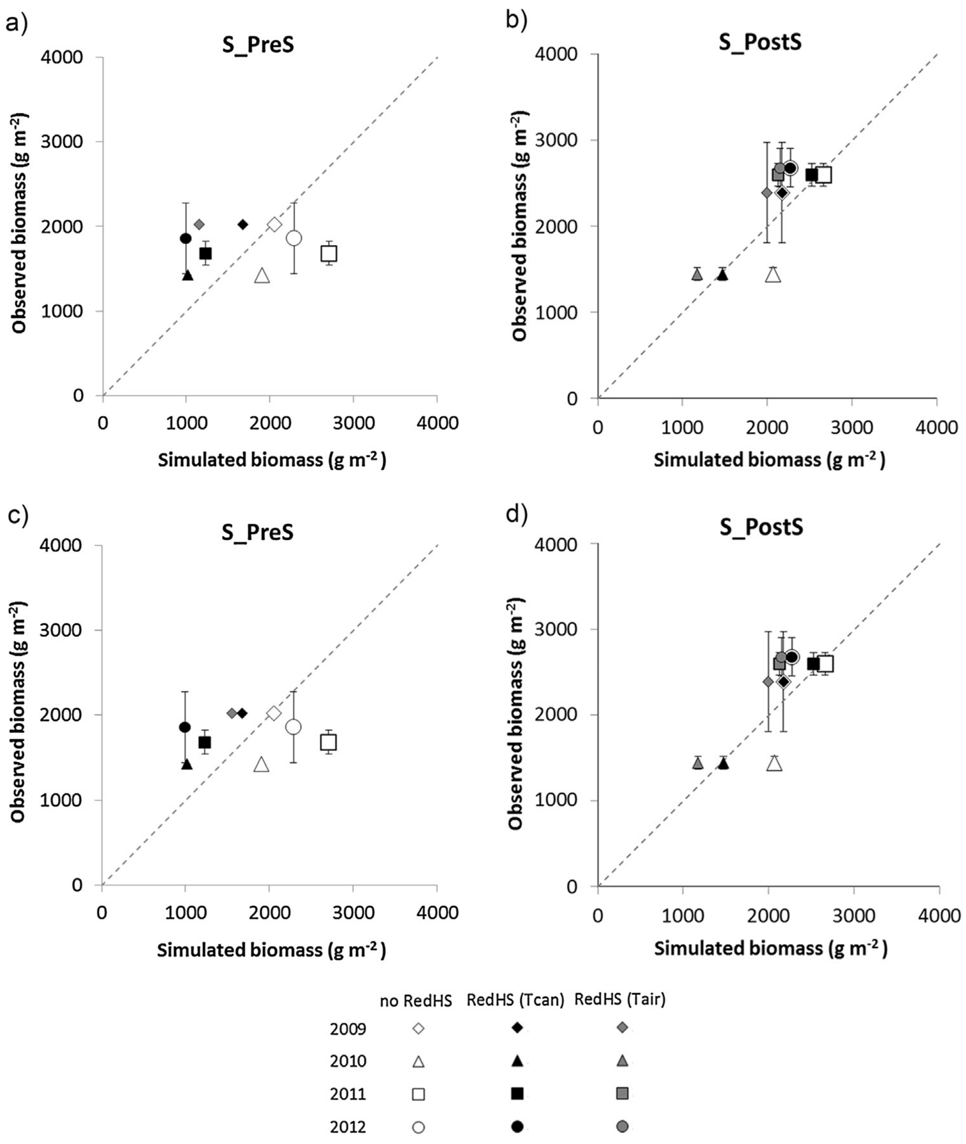

Fig. 4. Observed and simulated values of biomass for pre-silking heating (a, c), and post-silking heating (b, d) using the model without the heat stress module (no RedHS) (white symbols) and with heat stress module (RedHS) with T_{can} (black symbols) or T_{air} (grey symbols) (c and d). Panels (a, b) have T_{crit} equal to 34 °C, while panels (c and d) have T_{crit} for T_{air} increased to 39 °C and T_{crit} for T_{can} equal to 34 °C. Each data-point for the observed data is the average of three reps (and vertical bars on each symbol stand for the standard error of the mean). The line in each figure represents the 1:1 relationship.

be affected by high temperatures is the rate of crop development. For temperature above the optimum for a given development stage, crop development can be delayed, for example flowering (Cicchino et al., 2010a). In the current study, the observed development stages show a delay for the heated as compared to the control treatments, which is not reproduced by the model, indicating a limitation of the model that requires improvement to better simulate the critical period of anthesis.

Beyond the processes captured in the model, two other limitations of the present study are discussed. Firstly, the model was only tested using irrigated trials. Using our canopy temperature model, we hypothesized to be able to account for interaction between crop temperature and transpiration rate. Further model testing and experimental datasets are critical for extending the model rainfed conditions and other locations, as many world regions with the largest food security challenges (e.g. Sub-Saharan Africa) rely on rainfed production, and high temperatures and drought events are likely to coincide. A related limitation is that the trials were conducted under non-nutrient limiting conditions, which are not the case for many rainfed maize systems, particularly in tropical regions. A second limitation is related to the data used for model development and model testing. While these experiments are unique for maize in imposing controlled heat stress under field grown conditions, they did present challenges for model testing. The reduction in incident solar radiation due to the polyethylene film was not a severe artifact. Polyethylene shelters slightly affect crop incident radiation and RUE; however there is usually compensation between both effects (pers. comm. with Cicchino et al., 2010a, b authors). Therefore, observed differences were mainly attributable to temperature. However, reduced wind speed and increased relative humidity may represent an important bias from many natural conditions. To some extent these variables were measured in the experiments, and reliable estimates generated when required. Ideally for modeling studies, weather stations would be installed for each heat treatment.

This raises the more general need for increasing collaboration between modelers and experimentalists – from physiologist to agronomists and engineers. The current experiments from

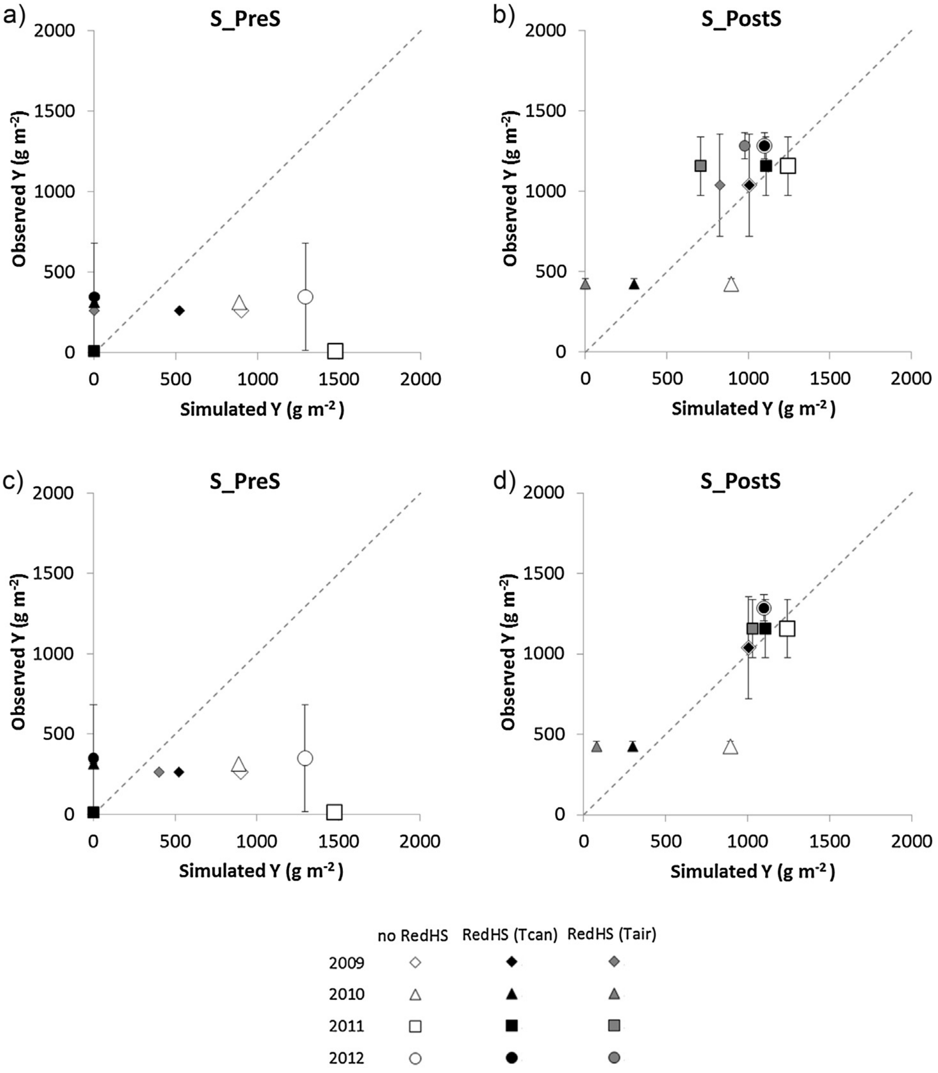

Fig. 5. Observed and simulated values of grain yield (Y) with pre-silking heating (a, c) and post-silking heating (b, d) using the model without the heat stress module (no RedHS) (white symbols) and with heat stress module (RedHS) with T_{can} (black symbols) or T_{air} (grey symbols). Panels (a and b) have T_{crit} equal to 34 °C, while panels (c and d) have T_{crit} for T_{air} increased to 39 °C and T_{crit} for T_{can} equal to 34 °C. Each data-point for the observed data is the average of three reps (and vertical bars on each symbol stand for the standard error of the mean). The line in each figure represents the 1:1 relationship.

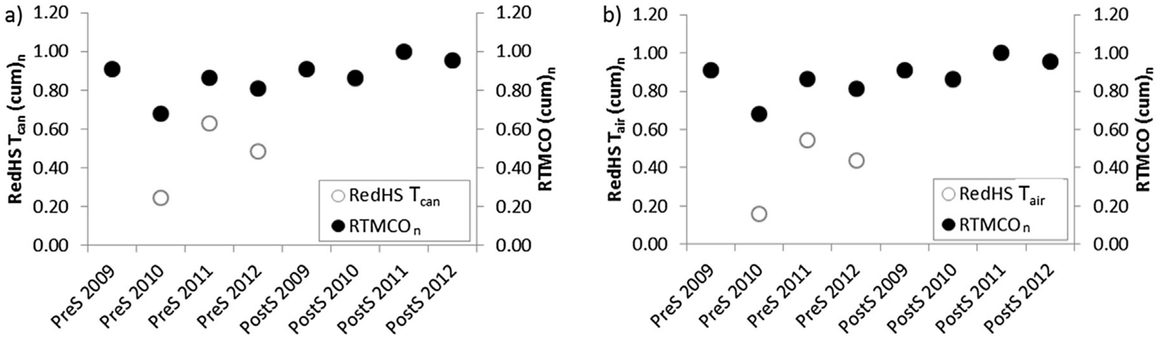

Fig. 6. Variation of the heat stress reduction factor (RedHS, in normalized units) across heat stress treatments, and its response to the introduction of a correction factor applied to the radiation use efficiency values during critical phase in LINTUL5 (RTMCOn, normalized) for (a) T_{can} and (b) T_{air}.

Argentina and Spain, and associated analysis from Rattalino Edreira and Otegui (2012, 2013) were very useful for crop growth simulation model development. These studies analyzed the effects of high temperature on concepts common to crop models, such as intercepted PAR, RUE, partitioning and harvest index, final biomass and yield. As such, it was very easy to understand what effects should be accounted for in the model response. However, in current study, we identified two areas in which greater and earlier collaboration between modellers and experimentalists could improve crop models and, ultimately, their usefulness in impact assessments. The first is the need measurement of key weather variables representative of the crop environment (i.e. inside the shelters) needed to drive crop growth models, such as air temperature, wind speed, solar radiation, vapor pressure, etc. More generally, experimentalists often focus on determining treatment effects whereas modellers generally need to produce absolute effects. Exchange between modellers and experimentalists in the early stages of experimental design should enable much of this information to be collected with minimal extra effort and designs achieved to also serve crop modelling. The second challenge we note is related to making incremental improvements to existing crop models. Existing models in many cases were developed for other purposes, that may not be completely compatible with new experimental evidence and/or environmental realities (i.e. more frequent heat stress with climate change). For example, many crop models, including Lintul5, include a 24-h mean temperature dependence of RUE that is determined with air temperature. These crop models have been developed and evaluated for decades using air temperatures. Results from the Argentine experiment indicated that reductions in RUE explained close to 50% of the reductions in kernel number and final grain number of maize exposed to high temperature. However, both the current physiological understanding and the data used to quantify this effect in the current research are based on plant temperature exceeding a threshold (not the 24-h mean air temperature) (Craufurd et al., 2013). In current study, we left the temperature response to RUE and included all effects of heat stress reducing yield in our reduction factor, though there will be some small degree of double counting. Perhaps modellers need to engage in critical discussions with stress physiologists and experimentalists to reconcile new process understanding with existing modelling approaches. Such collaboration can inform and support model development, as well as support experimental design such that datasets are more fully useful and valid for model improvement (Kersebaum et al., 2015). The synergistic relationship extends beyond the sharing of data for model improvement to enabling better science by bringing both sets of knowledge together and systemizing what is known about crop response to climatic factors. This collaboration should be strengthened and facilitated, particularly in joint proposals and experiment planning.

5. Conclusion

It is only recently that crop models for cereals have included heat stress responses, with few, if any, tested against experimental data. This study presented a model improvement to simulate the impact of high temperatures on maize yield. The model estimated grain yield reductions based on accumulated hourly stress thermal time above a critical threshold temperature in the critical period around flowering. The model was developed and tested with six experiments that used controlled heating conditions in Argentina and Spain. The model performance was better when simulated canopy temperature as compared to air temperature was used as an input to the heat stress reduction function. For satisfactory performance with air temperature, the critical threshold for heat stress was increased from 34 °C, which is a physiologically meaningful threshold, to 39 °C, as the crops were considerably cooler than the air due to ambient cooling caused by irrigation. Increasing the critical temperature is an alternative option for using air temperature with the heat stress reduction function in irrigated conditions, but is not expected to be suitable under rainfed conditions. This study has reinforced the potential for greater collaboration between modelers and experimentalists.

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