Supplementary Data

Title: *Separating Heat Stress from Moisture Stress: Analyzing Yield Response to High Temperature in Irrigated Maize*

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**SD Methods**

**NCGA contest data structure.**

The NCGA National Yield Contest data has the following information for each contest entry: county of origin, farm ID (a NCGA assigned identifier), year, planting date, planting rate, tillage, previous crop, and cultivar.

**Figure S1: Structure of the NCGA irrigated Yield Contest data.** Within a given county (“County 1”), different farms (blue circles) submit yields (green circles) in different years. Within a farm, yields (green circles) may be submitted from different plots with different management treatments (red lines in blue circles). Some farms span multiple counties. Individual farms will submit multiple yield values from fields under different management. Farms will submit yield values with altered management from year to year.
NCGA contest locations and associated climate stations. Many counties with NCGA yield data did not have a climate station immediately within the county. For the most part, we used the climate station nearest the county with the NCGA yield data. For counties with more than one climate station in near equal proximity, we selected the climate station with a long-term average growing degree days (GDD) most similar to the county long-term average GDD reported by the US degree day mapping calculator (Coop, 2010; http://pnwpest.org/cgi-bin/usmapmaker.pl). Note that all GDD for this exercise were calculated using a base temperature of 10°C and maximum temperature of 30°C to be consistent with seed industry standards.
Figure S2. Locations of counties in the study area with yield contest entries (◼) and associated climate stations with hourly data available (◆) for the year 2012.

Growing degree days and crop growth stages. Maize is a facultative short day plant. In the U.S. Corn Belt, though, maize is functionally day-neutral, meaning that its development rate can be most accurately characterized by the accrual of thermal-time (growing degree days, GDD). Growing degree days, therefore, were used to define the crop growth stages used in the analyses. GDDs were calculated two ways: 1. Maximum temperature = 30°C / base temperature = 10°C; and 2. Maximum temperature = 34°C / base temperature = 8°C (1). Two methods were required because NCGA crop information on cultivar GDD to silking and physiological maturity uses 30°C / 10°C (86°F / 50°F), whereas research reporting maize responses to high temperature generally use
34°C / 8°C (2). We used 30°C / 10°C GDD to determine cultivar-specific dates of silking and maturity, and used 34°C / 8°C GDD to estimate the duration of crop growth stages.

Cultivars of different maturity classes require a different number of GDDs to reach distinct crop growth stages. NCGA data only provides the cultivar, not the thermal time to reach each growth stage. We used cultivar product descriptions available from seed companies to determine the GDD necessary to reach the silking stage and maturity (Fig. S3, note GDU is equivalent to GDD). With the cultivar-specific thermal-time to silking and maturity known, other growth stages were then determined as follows: ‘early growth’, emergence to the onset of kernel number (KN) development (silking GDD – 227 GDD); ‘reproduction’, onset of KN development to the beginning of the linear grain-fill period (silking GDD + 200 GDD); and ‘grain-fill’, onset of linear grain fill to physiological maturity for a given cultivar (silking GDD + 200 GDD - maturity) (2). Temperature indices, RAD and average VPD were calculated for each yield entry by growing season and by growth stage.

**Figure S3.** Schematic showing how the three crop growth stages were calculated using thermal-time (GDD). Detail at bottom is from a product description of a maize cultivar (P0448HR) from the Pioneer® Website ([www.pioneer.com](http://www.pioneer.com)) showing GDD to silking and to maturity (image provided courtesy of Dupont)
Canopy temperature. It is well established that daily maximum canopy temperatures in irrigated maize can differ from daily maximum air temperatures so we analyzed yield response to KDD calculated using air temperature and canopy temperature where canopy temperature was calculated from an empirical relationship among air temperature, VPD, and RAD (3). Figure S4 shows that
irrigated canopies experience fewer KDDs than would be expected if KDD had been calculated from air temperature alone.

**Figure S4.** Killing degree days (KDD) calculated using modeled canopy temperature (3) compared to KDD calculated from measured air temperature for the NCGA yield contest locations.

**Thermal time and intercepted radiation:** Because maize phenology can be described by cumulative GDD, a given cultivar will take longer to mature during a cool growing season, where GDD do not accumulate as rapidly, than during a warm growing season. In addition, the cumulative GDD required to reach silking and maturity is cultivar dependent (cultivar maturity class is a primary characteristic that growers use to select a cultivar for their region). The combination of maturity class, growing season temperature, planting date and
incident solar radiation interact to determine the cumulative incident solar radiation (RAD), the primary driver of irrigated crop production, for a given cultivar in a given year. Since these factors varied from year to year for a given cultivar, and varied among cultivars of different maturity classes in the NCGA irrigated maize data set, there was a broad range of growing season RAD. This can be seen in Figure S5 where RAD for all yield contest records over the 2005 – 2012 period are shown.

**Figure S5:** Scatterplot of incident RAD by season length, where season length was calculated for each individual yield record using cultivar-specific thermal time (GDD). Color scale for growing season average daily maximum temperature.
**Identifying temperature stress mechanisms.** An alternative to using statistical relationships between yields and high temperatures to project yield response to climate change has been to use crop process models to predict yield response to climate change. A limitation to this approach is that some maize crop process models do not parameterize for high temperature stress impacts beyond increased phenological development - which is associated with a decrease in intercepted radiation and photosynthetic capacity over the cropping season - and heat related moisture stress. In our statistical analyses, we have controlled for accelerated phenological development by calculating all climate variables, including solar radiation, over entry-specific thermal-growth defined periods, both seasonally and by crop growth stage. Crop moisture stress was controlled by examining only irrigated yield contest entries. By controlling for water stress using only irrigated contest entries, and controlling for temperature impacts on crop phenology by modeling duration of crop growth using thermal-time, we have the ability to use observational data to explore evidence for currently under-parameterized high temperature impacts on yield formation that occur at broad spatial scales.

**SD Results**

**Mixed model summaries and output.** The following tables and figure are to provide detail on the nested mixed effects models used in the analyses
presented here. Tables S1, S2, and S3 are the model output summary from the `lme4::lmer` function in R for the base (management only, Table S1), crop growth stage (base + radiation and TT34 by crop growth stage, Table S2), and management interactions (climate + climate and management crossed effects, Table S3) models. Figure S6 is included to demonstrate the relative magnitudes of significant effects and crossed effects in the crop growth stage model.

**Figure S6.** Coefficient plot of the crop growth stage model (left) with prediction-plot details illustrating relative magnitude of crossed effects in terms of projected standardized yield impacts (right). Regression estimates describe the change in standard deviations of yield (1.76 MT ha$^{-1}$) per standard-deviation change in predictor variable (RAD, planting rate, planting date, cultivar GDD to maturity) or one-unit change in log-transformed TT34. Note: the model has a negative intercept; “0” yield does not represent population mean.
Table S1. Base model summary.

Formula: Yield = Planting rate + Planting date + Planting rate:Planting date + Cultivar GDD to maturity + Previous crop + (location + location:farm ID + cultivar + year[inter-annual])

|            | AIC  | BIC  | logLik | deviance | df.resid |
|------------|------|------|--------|----------|----------|
|            | 4419 | 4485.8 | -2197.5 | 4395 | 1917 |

Scaled residuals:

|            | Min | 1Q  | Median | 3Q  | Max  |
|------------|-----|-----|--------|-----|------|
|            |-3.2366 | -0.5239 | 0.0227 | 0.5425 | 2.9781 |

Random Effects:

| Groups               | Name   | Variance | Std.Dev. |
|----------------------|--------|----------|----------|
| location:farmID      | (Intercept) | 0.22824 | 0.4777 |
| cultivar             | (Intercept) | 0.0608 | 0.2466 |
| location             | (Intercept) | 0.04826 | 0.2197 |
| inter-annual         | (Intercept) | 0.11972 | 0.346 |
| Residual             |        | 0.35616 | 0.5968 |

Number of obs: 1929, groups: csv:farmID, 990; cultivar, 312; csv, 66; year, 8

Fixed Effects:

|                      | Estimate  | Std. Error | df | t value | Pr(>|t|) |
|----------------------|-----------|------------|----|---------|---------|
| (Intercept)          | -0.36522  | 0.1338     | 10.8 | 2.73   | 0.01983 * |
| planting rate        | 0.28756   | 0.02164    | 1589.4 | 13.286 | <2.00E-16 *** |
| planting date        | -0.03688  | 0.01443    | 1624.1 | -1.509 | 0.131391 |
| Cultivar GDD to maturity | 0.08004  | 0.02642    | 328 | 3.029  | 0.002648 ** |
| Prev. Crop: Other    | 0.14709   | 0.0805     | 1852.8 | 1.827 | 0.067822 . |
| Prev. Crop: Soy/Beans | 0.13209  | 0.04038    | 1920.9 | 3.271 | 0.001091 ** |
| Planting rate: planting date | -0.05434 | 0.01601    | 1707.6 | -3.394 | 0.000704 *** |

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Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1
**Table S2.** Crop growth stage model summary. This model was constructed to look at interactions among high temperature indices, and between high temperature indices and RAD occurring at different crop growth stages. EGrad, Grad: RAD during the ‘early-growth’ and ‘grain-fill growth stages, respectively. EGTT34, GTT34: cumulative degree-hours over 34°C during the ‘early-growth’ and ‘grain-fill growth stages, respectively.

**Eliminated variables (in order of elimination):**

| Eliminated Variable       | Coefficient Estimate | Standard Error | Chisq | DF | Pr(>Chisq) |
|---------------------------|----------------------|----------------|-------|----|-------------|
| SenTT34:GTT34             | -4.62E-04            | 3.26E-03       | 0.02  | 1  | 0.888       |
| Senrad:SenTT34            | 2.30E-03             | 8.14E-03       | 0.08  | 1  | 0.779       |
| Senrad                    | -6.18E-03            | 3.02E-02       | 0.04  | 1  | 0.839       |
| EGTT34:SenTT34            | -2.67E-03            | 3.08E-03       | 0.75  | 1  | 0.387       |
| SenTT34                   | 7.18E-03             | 9.47E-03       | 0.56  | 1  | 0.455       |
| Egrad:EGTT34              | 9.36E-03             | 5.63E-03       | 2.75  | 1  | 0.097       |

**Final Model:**

Formula: Yield = Planting rate + Planting date + Planting rate:Planting date + Cultivar GDD to maturity + Previous crop + EGTT34 + GTT34 + EGTT34:GTT34 + EGrad + Grad + Grad:GTT34 + (location + location:farm ID + cultivar + year['inter-annual']).
Appendix B: (Radiation by TT34(model

Linear mixed model fit by maximum likelihood ' [merModLmerTest

Formula: 'yield' ~ 'Planting rate' + 'Planting date' + 'Planting rate:' 'Planting date' + 'Cultivar GDD to mat' + 'Previous crop' + '''

EGTT34' + 'GTT34' + 'EGTT34:GTT34+

EGrad' + 'Grad' + 'Grad:' 'GTT34' +'

(1|location)' + (1|location: farmID)' + (1|'cultivar)' + (1|'year)

Data:

AIC  BIC  logLik  deviance  df.resid
4381.5  4481.7  -2172.8  4345.5  1911

Scaled residuals:

Min 1Q Median 3Q Max
-3.13408 -0.53224 0.02155 0.52396 2.8972

Random Effects:

| Groups           | Name       | Variance  | Std.Dev.  |
|------------------|------------|-----------|-----------|
| location: farmID | (Intercept)| 0.22813   | 0.4776    |
| cultivar         | (Intercept)| 0.05492   | 0.2343    |
| location         | (Intercept)| 0.03364   | 0.1834    |
| inter-annual     | (Intercept)| 0.10226   | 0.3198    |
| Residual         |            | 0.34822   | 0.5901    |

Number of obs: 1929, groups: csv: farmID, 990; cultivar, 312; csv, 66; year, 8

Fixed effects:

|                  | Estimate | Std. Error | df | t value | Pr(>|t|) |
|------------------|----------|------------|----|---------|---------|
| (Intercept)      | -3.93E-01| 1.43E-01   | 1.80E+01 | -2.759  | 0.012906 * |
| planting rate    | 2.97E-01 | 2.15E-02   | 1.58E+03 | 13.817  | <2.00E-16 *** |
| planting date    | -2.01E-02| 2.88E-02   | 1.12E+03 | -0.698  | 0.485525  |
| Cultivar GDD to maturity | 6.42E-02 | 2.75E-02 | 3.96E+02 | 2.334  | 0.020116 * |
| Prev. Crop: Other | 1.28E-01 | 7.95E-02 | 1.85E+03 | 1.61  | 0.107601  |
| Prev. Crop: Soy/Beans | 1.40E-01 | 4.00E-02 | 1.92E+03 | 3.493  | 0.000489 *** |
| EGrad            | 1.11E-01 | 3.15E-02 | 6.26E+02 | 3.515  | 0.000472 *** |
| Grad             | 1.66E-01 | 5.04E-02 | 1.45E+03 | 3.283  | 0.001051 ** |
| EGTT34           | -1.94E-02| 1.56E-02 | 1.74E+03 | -1.246  | 0.212999 |
| GTT34            | -1.53E-02| 1.16E-02 | 1.34E+03 | -1.323  | 0.186088 |
| Planting rate: planting date | -5.67E-02 | 1.58E-02 | 1.72E+03 | -3.593  | 0.000336 *** |
| EGTT34:GT34      | 7.51E-03 | 2.21E-03 | 1.58E+03 | 3.399  | 0.000692 *** |
| Grad:GT34        | -1.81E-02| 6.59E-03 | 1.72E+03 | -2.751  | 0.006004 ** |

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Table S3. Management model summary. Note that this model is considered improved relative to the crop growth stage model, based on the AIC; but is considered overfit, relative to the crop growth stage model, based on the increase in BIC.

Eliminated variables (in order of elimination):

| Rejected Variable          | Coefficient Estimate | Standard Error | Chisq | DF | Pr(>Chisq) |
|----------------------------|----------------------|----------------|-------|----|-------------|
| EGTT34:GTT34:PD            | 2.01E-03             | 2.19E-03       | 0.02  | 1  | 0.878       |
| EGrad:CultGDD              | -1.13E-02            | 2.32E-02       | 0.23  | 1  | 0.628       |
| EGTT34:PD                  | 3.53E-03             | 6.95E-03       | 0.25  | 1  | 0.615       |
| Grad:GTT34:CultGDD         | 3.70E-03             | 6.55E-03       | 0.32  | 1  | 0.573       |
| EGTT34:GTT34:PR            | 1.81E-03             | 2.18E-03       | 0.69  | 1  | 0.406       |
| Grad:GTT34:PD              | -6.69E-03            | 8.19E-03       | 0.67  | 1  | 0.415       |
| Grad:GTT34:PR              | -5.94E-03            | 6.61E-03       | 0.81  | 1  | 0.369       |
| Grad:PR                    | 1.15E-03             | 2.08E-02       | 0.00  | 1  | 0.956       |
| GTT34:PR                   | 3.57E-02             | 1.97E-02       | 0.39  | 1  | 0.531       |
| EGrad:PD                   | -2.35E-02            | 2.11E-02       | 1.24  | 1  | 0.265       |
| EGrad:PR                   | -2.61E-02            | 2.08E-02       | 1.56  | 1  | 0.211       |
| EGTT34:PR                  | -7.64E-03            | 6.24E-03       | 1.49  | 1  | 0.222       |

Final Model:

Formula: Yield = Planting rate + Planting date + Planting rate:Planting date + Cultivar GDD to maturity + Previous crop + EGrad + Grad + EGTT34:GTT34 + Grad:GTT34 + Planting date:GTT34 + Planting date:Grad:GTT34 + Cultivar GDD to maturity:EGTT34 + Cultivar GDD to maturity:GTT34 + Cultivar GDD to maturity:Grad:GTT34 + (location + location:farm ID + cultivar + year["inter-annual"]).
Components of yield variance. Variables which had the largest impact on yields included “Other genetics”, “Planting Rate and Planting Date”, and “Farm-level” random effects. Combined, these three variables accounted for approximately 35 – 40% of the yield variance, suggesting that even on the highest-performing farms, there is significant room for yield improvements. In hierarchal linear mixed effects models, addition of a significant fixed effect into a model should reduce the unexplained variance in the response variable, which is
then distributed among random effects. Comparing the distribution of variance partitioning between nested models, where one contains the fixed effect (or group of fixed effects) which are being analyzed and the other does not, can give critical insight into the nature of the response variable’s response to these fixed effects. Table S4 shows how addition of significant climate interactions modified variance partitioning among random effects in the model. Comparing the “climate” model (which contains all significant RAD and TT34 interactions in addition to all management and random effects terms in the “base” model) to the “base” model allows for the examination of how much inter-annual variance, location-level variance, farm-level variance, and genetic variance are explained by climate factors. Accounting for all significant RAD and temperature impacts on yields only explained 14% of original inter-annual yield variance, suggesting that in irrigated maize, 86% of inter-annual yield anomaly is due to other factors (such as pests, disease, or unanalyzed climate variables). Nearly 10% of cultivar performance variability can be explained by temperature interactions.
Table S4. Climate impact on variance components partitioning.

| Groups           | Base Model | Rad and TT34: | % Explained by Climate |
|------------------|------------|---------------|------------------------|
| farm-level       | 0.23       | 0.23          | 0.05%                  |
| cultivar         | 0.06       | 0.05          | 9.67%                  |
| location-level   | 0.05       | 0.03          | 30.29%                 |
| inter-annual     | 0.12       | 0.10          | 14.58%                 |
| residual         | 0.36       | 0.35          | 2.23%                  |
| Total variance*  | 0.81       | 0.77          | 5.66%                  |

*left over from yield variance explained by fixed effects

All RAD and climate variables, which included an interaction term that suggested acclimation to heat stress, reduced the small amount of yield variance partitioning to location by over 30%, though the amount of yield variance described by a location random effect was small to begin with (about 4%).

Supplemental References

1. Kiniry, J.R. 1991. Maize phasic development. *Modeling Plant and Soil Systems* eds Hanks J, Ritchie JT (American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc.,) pp 55-70.

2. Otegui ME, Bonhomme R (1998) Grain yield components in maize: I. Ear growth and kernel set. *Field Crops Research* 56(3):247-256.
3. Payero JO, Irmak S (2006) Variable upper and lower crop water stress index baselines for corn and soybean. *Irrigation Science*, 25(1): 21-32.