Do Warming Temperatures Influence Yield Response to Higher Planting Density?

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Abstract

This study explores how warming temperatures influence corn yield response to planting density. Using 1990-2010 field trial data from Wisconsin and econometric models with a variety of specifications, we find that warming temperatures reduce the yield benefits of increasing planting density. However, these adverse warming effects are smaller for genetically-modified (GM) corn varieties with rootworm (RW) resistant traits. Consistent with previous studies, these results support the notion that varietal improvements through genetic modification may have paved the way for higher planting densities in US corn production. Moreover, our results imply that expected in-season temperatures are important considerations when making planting density decisions.

Keywords: Climate change, Corn yield response, Plant density, Warming

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1 Introduction

Since the development and diffusion of corn hybrids in the 1930s, commercial corn yields in the United States (US) have increased dramatically over the last 80 years. Data from the US Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) indicate that US corn yields have increased eight-fold from roughly 20 bu/acre in the mid-1930s to about 175 bu/acre in 2016. This tremendous growth implies a yield increase at a rate of about 1.8 bu/acre/year.

Previous literature has posited that a variety of factors, such as varietal improvement (i.e., through traditional plant breeding or genetic modification) and better agronomic practices, have contributed to this observed yield growth (Duvick (2005); Assefa et al. (2018)). However, a number of studies argue that the impressive yield increases seen in US corn can be mainly attributed to increases in planting density or plant population (i.e., the number of plants per acre), rather than to increases in per-plant yields (i.e., mainly through technological advances) (Tollenaar and Lee (2002); Tokatlidis and Koutroubas (2004); Duvick (2005)).

Growth in corn plant populations in the U.S. has roughly tracked the growth in corn yields from 1964-2016. In this period, yields have more than doubled, from approximately 60 bu/acre to 175 bu/acre, and at the same time plant population has also more than doubled, from about 14,000 plants/acre to close to 30,000 plants/acre. These figures suggest that yield per plant is only slightly higher in 2016 as compared to 50 years ago, and therefore support the notion that corn yield growth may be largely attributed to planting density increases. However, it is likely that the link between improved corn yields and higher plant densities over time is directly influenced by warming temperatures due to climate change, as well as varietal improvement and better agronomic practices (Lobell et al. (2014); Assefa et al. (2018)).

The objective of this study is to determine how the yield response of corn to increasing planting density is affected by warming temperatures. We are also interested in the role of genetically-modified (GM) corn varieties with regards to the impact of warming on the "yield-planting-density" relationship. To accomplish these objectives, we utilize plot-level field trial data collected by the University of Wisconsin over the period 1990-2010 (See Shi et al. (2013); Chavas and Shi (2015)), which is then merged with publicly available weather data. Yield regression models with a variety of specifications (and interaction terms) are then estimated to understand if and how warming temperatures impact corn yield response to increasing planting density.

There is now a robust literature about corn yield response to increasing planting density, and how varietal traits and agronomic practices influence this response (See Assefa et al. (2016); Stanger and Lauer (2006); Carlone and Russell (1987); Sangoi (2001); Lindsey and Thomison (2016); Van Roekel and Coulter (2011); Fromme et al. (2019); Porter et al. (1997)). For example, previous research such as Coulter et al. (2010), Brown et al. (1970), Beech and Basinski (1975), Cox (1996), Widdicombe and Thelen (2002), Nafziger (1994), Nielsen (1988), Varga et al. (2004) have examined the likely impacts of hybrids on a variety of corn agronomic responses to plant density. However, there have only been a handful of studies that specifically explored how the contribution of planting density to improved corn yields are affected by environmental factors and growing conditions. For example, papers such as Sangakkara et al. (2004), Abbas et al. (2012), Brown (1986), Van Averbeke and Marais (1992), and Muchow et al. (1990)) have examined the impact of soil characteristics (such as soil water availability and/or soil fertility) on the relationship between corn yields and planting density. Assefa et al. (2016) and Assefa et al. (2018) grouped observations into four hypothetical growth environments based on yield levels (e.g., low yield, medium yield, high yield, and very high yield environments), then estimated the corn-yield-planting-density relationship for each subgroup by utilizing maximum likelihood and least squares based statistical approaches. These studies found that increasing planting density has a larger positive effect on yield under a high yield environment than a low yield environment. Similarly, Chavas et al. (2014) and Chavas and Shi (2015) investigated the effect of planting density on corn yields for different yield levels. But note that these latter two studies utilized quantile regression techniques to estimate the "yield-planting-density" function (i.e., rather than defining specific yield level subgroups and using maximum likelihood or least squares to estimate the function for each subgroup). In addition, Chavas et al. (2014) and Chavas and Shi (2015) also explored how GM traits influence corn yield response to increases in planting density. They found that the yield benefits of increasing planting density would be further strengthened when GM varieties are used. We have not found any study that looked at how temperature changes may affect corn yield response to higher planting density using econometric methods and long-run field trial data.

Our main contribution is that we examine the role of a specific environmental factor — temperature changes — with respect to how planting density affects corn yields. This has important implications for corn farmers especially in a world with an increasingly warming climate and the need for climate change adaptation strategies. Although previous studies have explored how a "low-yield" environment generally influence corn yield response to planting density, none of these past studies have particularly investigated how increasing temperatures affect corn yield response to planting density. A better understanding of the effect of temperature on the "yield-planting-density" relationship would allow farmers to make better decisions at the start of the season (e.g., planting density and varietal choices) based on expected in-season temperatures during the growing period (Solomon et al. (2017)).

The second contribution is the exploration of whether GM traits would cause heterogeneity in the effect of warming on the "yield-planting-density" relationship. Specific interest is in the GM corn varieties with rootworm (RW) resistant traits since it is widely believed that below-ground rootworm protection allows for larger and healthier corn root balls. These larger and healthier roots then allow these RW resistant varieties to be more resilient to heat stress and higher temperatures. Even though there have been previous studies that examined the "triple" inter-relationship among corn yields, planting density, and GM traits (Chavas et al. (2014); Chavas and Shi (2015)), to the best of our knowledge, there have been no study that examined the "quadruple" inter-relationship among corn yields, planting density, GM traits, and warming temperatures. Hence, the present study contributes to further understanding of the so-called genotype (G), environment (E), and management (M) interactions (G $\times$ E $\times$ M) that determine crop yield outcomes (i.e., in our case, G is the GM trait, E is the warming temperatures, and M is the planting density choice).

Results from our study indicate that corn yield response to planting density varies with temperature, and the degree of variation with temperature is influenced by the GM traits. In general, the yield benefits of increasing planting density diminish as temperature increases. But note that the diminishing yield benefits of higher planting density (in the presence of warming) are mitigated by the use of GM crop varieties, especially those with RW resistance traits.

The rest of the paper proceeds as follows. First, we provide a detailed description of the data sources and our empirical approach that allows us to examine how corn yield responds to changes in plant density under different temperatures and/or GM traits. This is followed by a thorough discussion of estimation results and various robustness checks.

Lastly, conclusions, important implications, and potential avenues for future research are presented in the last section.

2 Data Sources and Empirical Approach

In this study, we use data from three sources: (1) annual corn field trial data collected by University of Wisconsin researchers over the period 1990-2010; (2) weather data drawn from the work of Schlenker and Roberts (2009), which includes interpolated daily minimum and maximum temperature information for 4 kilometer (km) grid cells within the United States from 1950 to 2017; and (3) county-level Palmer Drought Severity Index (PDSI) data from the Centers for Disease Control and Prevention(CDC).[1]

The University of Wisconsin field trial data includes information about plot-level yields (measured in bushels per acre) and farming inputs applied (e.g., fertilizer and insecticides). Input use and management practices (e.g., tillage, rotation) utilized in the trial plots are similar to neighboring commercial fields and are consistent with normal agronomic recommendations (Chavas and Shi (2015)). The management practices employed are typical of those used on corn farms practicing rainfed agriculture in the US corn belt. The experimental design for these field trials was a randomized complete block design in which each corn hybrid variety was grown in at least three separate plots (replicates) at each site (i.e., to account for field variability). These trials were conducted over the years for the purpose of evaluating the yield performance of different corn hybrids (e.g., conventional hybrids versus various GM hybrids). Hence, these trials were not explicitly designed to assess planting density. As such, management practices are typically the same for plots in each site-year (i.e., which has implications for our empirical specifications as discussed further below). Further note that this is the same data set used in Shi et al. (2013) and Chavas and Shi (2015) to mainly evaluate the production risk effects of various GM traits.

For the field trial data that spans crop years 1990-2010, a total of 4,748 hybrids were tested in which 2,653 were conventional hybrids and 2,095 were GM hybrids. Some hybrids were tested in multiple locations and/or for multiple years. The data includes 31,799 usable yield observations. However, for the present study, only 28,521 rainfed observations are utilized given the central role of warming in our analysis. Summary statistics and descriptions of the field-trial variables utilized in this study are provided in Table 1.

[1] The PDSI data is from Centers for Disease Control and Prevention. National Environmental Public Health Tracking Network. https://data.cdc.gov/Environmental-Health-Toxicology/Palmer-Drought-Severity-Index-1895-2016/en5r-5ds4/data. Accessed: 4/7/2019.

The corn field trials were conducted in 12 experimental sites (11 for rainfed corn), which are located in four production zones in the state of Wisconsin: South, South Central, North, and North Central (See Figure 1). All of the field trial sites are in what is commonly called the Northern Corn Belt. The South production zone includes three sites in the following cities/villages: Arlington, Janesville, and Lancaster. The South Central production zone includes sites in Fond Du Lac, Galesville, and Hancock. The Chippewa Falls, Marshfield, Seymour, and Valders filed trial sites are located in the North Central production zone. Lastly, the North production zone includes experimental sites in Spooner and Coleman. In general, the climatic conditions for the field trial sites within a particular production zone are similar. However, it should be noted that the sites in the Southern production zone tend to have a more favorable climate as compared to the sites located in the other zones. The field trial sites in the South Central, North Central and North production zones typically have a colder climate and a shorter growing season. Figure S1 and Figure S2 shows box-and-whisker plots of yield and plant density, respectively, for each of the four production zones. Notice that corn yields generally decrease as one goes further north, which is consistent with the observation that climate conditions of more southern sites are more favorable for corn. The temporal pattern of average yield and average planting density for all trial sites are presented in Figures S3 and Figure S4. The temporal yield and planting density patterns in the data are consistent with the national trend where corn plant population growth roughly track the growth in corn yield.[2]

The grid-level weather data drawn from the work of Schlenker and Roberts (2009) were aggregated up to the city (or village) where the field trial sites are located. After this aggregation, the monthly average daily minimum ($tmin$) and maximum ($tmax$) temperature data are then calculated. The monthly county-level PDSI data is also matched to the city (or village) where the field trial sites are located. For field trial sites wholly located in a single county, we use the PDSI value for the specific county where the trial site is located. However, for field trial sites that are in the border of two or more counties, we use a county-level average PDSI value for the corresponding counties near these trial sites. Given the nature of the weather data described above, it is important to note that all field trial plots within each site-year are assumed to have the same weather given that the $tmin$, $tmax$, and PDSI data are aggregated at the city (or village) where each

[2]In addition, temporal patterns of the number of plots in the filed trial data that planted conventional corn, GM hybrids with the RW resistance trait, and GM hybrids without the RW resistance trait are presented in Figures S6, S7, and S8, respectively.

field trial site is located. All weather variables are then merged with the plot-level field trial data. The summary statistics for relevant monthly minimum temperature, maximum temperature, and monthly PDSI are reported in Table 2. Moreover, the yearly changes in minimum temperatures, maximum temperatures, and PDSI for the period 1990-2010 are presented in Figures S9 and S10 for each production zone.

2.1 Empirical Specification and Estimation Strategies

The main empirical specification to determine how warming temperatures affect corn yield response to planting density is defined as follows:

$$\ln(y_{ilzt}) = \alpha_z + f(\mathbf{tmin}_{lzmt}, \mathbf{tmax}_{lzmt}, \mathbf{PDSI}^w_{lzmt}, \mathbf{PDSI}^d_{lzmt}, \mathbf{D}_{lzt}) + \gamma \mathbf{X}_{ilzt} + \eta t + \varepsilon_{ilzt} \quad (1)$$

where $\ln(y_{ilzt})$ is the natural log of corn yield in bushels per acre (bu/acre) for plot i, field trial location l, production zone z, and year t. We estimate equation (1) using ordinary least squares (OLS) regression that includes a production zone fixed effect α_z to eliminate any concerns about time-invariant unobservables at the production zone level.[3] We also include a linear time trend ηt to account for the technological improvement over time. Control variables that represent input use (or practices) are included in the vector $\mathbf{X}_{ilzt}$ (e.g., fertilizer, tillage, and other variables in Table 1).

We call $f(\cdot)$ in equation (1) the "weather-plant-density" function, which includes as arguments the following weather-related variables: $\mathbf{tmin}$, $\mathbf{tmax}$, $\mathbf{PDSI}^w$ and $\mathbf{PDSI}^d$ for field trial location l, production zone z, month m, and year t. Note that $\mathbf{PDSI}^w$ refers to positive PDSI values that measures the degree of wetness (w), while $\mathbf{PDSI}^d$ refers to the absolute value of negative PDSI values that reflects the degree of dryness (d). Large $\mathbf{PDSI}^d$ values usually reflects drought conditions, and large $\mathbf{PDSI}^w$ typically reflects extremely wet conditions (i.e., flooding).[4] The planting density variable (in '000s of plants per acre) is also included in $f(\cdot)$ and is represented by $\mathbf{D}_{lzt}$.

[3]As mentioned above, plant density and other production inputs are the same for all plots for each site-year combination. Therefore, there is no variation in plant density for each field trial location and year. Therefore, we use production zone fixed effects rather than plot or field trial site fixed effect in our empirical specifications. This means that identification mainly comes from across production zone variation and variation across years.

[4]PDSI values range from -10 to +10. As alluded to above, negative PDSI values reflect dryness, while positive PDSI values reflect wetness. Typically, PDSI values of -4 or below represents extreme drought, while PDSI values of 4 or above reflects an extremely wet environment (i.e., flood conditions).

In particular, the "weather-plant-density" function is defined as follows:

$$\delta \mathbf{D}_{lzt} + \sum_{m=1}^{5} \beta_{1m} \mathbf{tmin}_{lzmt} + + \sum_{m=1}^{5} \beta_{2m} \mathbf{tmax}_{lzmt} + \sum_{m=1}^{5} \psi_{1m} (\mathbf{tmin}_{lzmt} \times \mathbf{D}_{lzt}) + \sum_{m=1}^{5} \psi_{2m} (\mathbf{tmax}_{lzmt} \times \mathbf{D}_{lzt}) + \sum_{m=1}^{5} \beta_{31m} \mathbf{PDSI}^{w}_{lzmt} + \sum_{m=1}^{5} \psi_{31m} (\mathbf{PDSI}^{w}_{lzmt} \times \mathbf{D}_{lzt}) + \sum_{m=1}^{5} \beta_{32m} \mathbf{PDSI}^{d}_{lzmt} + \sum_{m=1}^{5} \psi_{32m} (\mathbf{PDSI}^{d}_{lzmt} \times \mathbf{D}_{lzt}). \quad (2)$$

The growing season is specified as spanning 5-months ($m = 1, 2, ..., 5$) from May to September. The ψ parameters associated with the interaction terms in equation (2) give us insight into how weather variables affect corn yield response to planting densities.

The specification in equations (1) and (2) are consistent with previous studies that examined crop yield effects of weather variables (See Schlenker and Lobell (2010); Lobell et al. (2011); Lobell and Field (2007); Welch et al. (2010); Tack et al. (2015); Peng et al. (2004)). These studies typically use the following variables in their specifications: *tmin*, *tmax*, and a weather variable that reflects water-availability (e.g., typically quadratic functions of precipitation or rainfall). However, in contrast with these aforementioned studies, our specification above utilizes a drought index, specifically the PDSI, as a measure of water-availability rather than quadratic functions of precipitation or rainfall levels.[5] A drought index like PDSI is appropriate as a measure of water/moisture availability because its values are referenced to local climate, which allows one to calculate dryness or wetness relative to local norms (Xu et al. (2013); Kolář et al. (2014)). In addition, local soil attributes are partly accounted for when calculating drought indices, which is an important factor in a crop's ability to handle extreme dryness or wetness. Using both the positive and negative PDSI values in our specification also adequately account for nonlinearities in the effects of water availability (i.e., typically reflected by having a quadratic precipitation term in previous studies).

Another feature of the specification in equation (2) is the linear relationship between planting density (**D**) and crop yields. Previous studies have typically assumed a quadratic specification for planting density (See Assefa et al. (2018) for example). However, a linear specification is appropriate in our case given that the range of our planting density data do not usually reach the reported "optimal" planting density levels recommended for Wisconsin (i.e., the yield-maximizing planting density level where corn yields plateau (the "turning point") and consequently decreases in a quadratic specification). For example,

[5] Although we use PDSI in our main specification, we also conduct robustness checks below where we utilize a quadratic precipitation specification.

Stanger and Lauer (2006) suggests that the optimal planting densities for Wisconsin are approximately 39,984 plants per acre for non-GM corn and 42,290 plants per acre for GM corn with the Bt trait (for the period between 2002 and 2004). Based on field trial data locations across the corn belt, Assefa et al. (2018) indicates that optimal planting density ranges from 30,500 plants per acre (in 1987) to about 37,900 plants per acre in the 2007-2016 period. In our field trial data from 1990-2010, the range of planting density values is from about 18,250 plants per acre to around 33,409 plants per acre. This data range is more consistent with the upward sloping (and close to linear) part of the corn yield response function to planting density, which again supports our linear specification. Furthermore, a straightforward regression of the natural log of corn yield on planting density using our data set indicates a relationship that is very close to linear and without a turning point (See Figure S5).

2.2 Marginal Effects

To achieve the study objective of assessing how the yield impact of planting density changes with temperature, we calculate the marginal effect of planting density on corn yields under different temperature scenarios based on the empirical model specified in equations (1) and (2). The marginal percentage effect of increasing plant density is the percentage change in corn yields as a result of a 1 unit (in this case, 1000 plants per acre) increase in planting density. This marginal effect calculation can be expressed as follows:

$$\frac{\partial \ln(y_t)}{\partial \mathbf{D}_t} = \delta + \sum_{m=1}^{5} \psi_{1m}\mathbf{tmin}_{mt} + \sum_{m=1}^{5} \psi_{2m}\mathbf{tmax}_{mt} + \sum_{m=1}^{5} \psi_{31m}\mathbf{PDSI}_{mt}^{w} \tag{3}$$

if PDSI in each month is positive, and:

$$\frac{\partial \ln(y_t)}{\partial \mathbf{D}_t} = \delta + \sum_{m=1}^{5} \psi_{1m}\mathbf{tmin}_{mt} + \sum_{m=1}^{5} \psi_{2m}\mathbf{tmax}_{mt} + \sum_{m=1}^{5} \psi_{32m}\mathbf{PDSI}_{mt}^{d} \tag{4}$$

if all monthly PDSI's are negative.

In order to examine how temperature changes influence the yield response to planting density, we calculate marginal effects under two warming scenarios: (1) a warming scenario where both **tmin** and **tmax** change by 1°C increments, and (2) a warming scenario where **tmin** and **tmax** changes separately by 1°C increments. To calculate the marginal effects of planting density under the first warming scenario, we first assume that both the monthly **tmin** and **tmax** variables deviate from their means by the following amounts: −1°C, −2°C, −3°C, −4°C, +1°C, +2°C, +3°C, +4°C. This calculation structure allows us to see how corn yield response to planting density changes as both the minimum and maximum temperatures change (holding PDSI constant at its mean).[6] The marginal effect of planting density under the first warming scenario can then be expressed as follows:

$$\frac{\partial \ln(y_t)}{\partial \mathbf{D}_t} = \delta + \sum_{m=1}^{5} \psi_{1m}(\overline{\mathbf{tmin}}_{mt} + k) + \sum_{m=1}^{5} \psi_{2m}(\overline{\mathbf{tmax}}_{mt} + k) + \sum_{m=1}^{5} \psi_{31m} \overline{\mathbf{PDSI}}_{mt} \quad (5)$$

where $\overline{\mathbf{tmin}}_{mt}$, $\overline{\mathbf{tmax}}_{mt}$, and $\overline{\mathbf{PDSI}}_{mt}$ are set at the means in month m and year t, and the nine assumed temperature deviations are where $k = -4, -3, .., 0, .., +3, +4$.[7]

Under the second warming scenario, the marginal effects of planting density are calculated assuming that **tmin** and **tmax** separately changes in 1°C increments (where $k = -4, -3, .., 0, .., +3, +4$). The marginal effect of planting density when only **tmin** changes can be calculated as follows:

$$\frac{\partial \ln(y_t)}{\partial \mathbf{D}_t} = \delta + \sum_{m=1}^{5} \psi_{1m}(\overline{\mathbf{tmin}}_{mt} + k) + \sum_{m=1}^{5} \psi_{2m} \overline{\mathbf{tmax}}_{mt} + \sum_{m=1}^{5} \psi_{31m} \overline{\mathbf{PDSI}}_{mt}, \quad (6)$$

where **tmax** and the PDSI's are held at their mean values. On the other hand, the marginal effect of planting density when only **tmax** changes can be expressed as follows:

$$\frac{\partial ln(y_t)}{\partial \mathbf{D}_t} = \delta + \sum_{m=1}^{5} \psi_{1m} \overline{\mathbf{tmin}}_{mt} + \sum_{m=1}^{5} \psi_{2m}(\overline{\mathbf{tmax}}_{mt} + k) + \sum_{m=1}^{5} \psi_{31m} \overline{\mathbf{PDSI}}_{mt} \quad (7)$$

where **tmin** and the PDSI's are held at their mean values.

The marginal effect calculations above assume that changes in temperature occur in all months of the season. However, previous literature has argued that the June to August months are the critical months for corn growth. During this period, crop growth is frequently affected by environmental stresses such as high temperatures (McWilliams et al. (1999)). Since silking occurs in the summer time, stress conditions that happen two weeks before or after silking typically lead to substantial reductions in yield (see McWilliams et al. (1999)). Therefore, we also calculate the marginal effects of increasing planting density under both the warming scenarios described above, but only imposing changes in the temperatures for the June to August months (i.e., and where temperatures in the other months are set at their means).

Another issue of interest in this study is to determine the role of GM corn varieties,

[6] We understand that changes in temperatures also likely affects PDSI (i.e., increasing temperature may result in more drier conditions (and lower PDSI's)). Hence, the marginal effect calculation where we hold PDSI's constant at the mean can be considered a lower bound for the effect of warming temperatures on the corn yield response to planting density.

[7] For the purpose of calculating the marginal effect in equation (5), as well as in equations (6), (7), (9), (10), and (11), the term $\overline{\mathbf{PDSI}}_{mt}$ is calculated by taking the average over all PDSI's in the data (i.e., both negative and positive) and the mean PDSI value used is XX. Thus, the superscript for the PDSI variable (e.g., w or d) has been omitted in these marginal effect expressions.

especially those that have RW resistant traits, with regards to how corn yield responds to planting density under different warming scenarios (i.e., the "quadruple" inter-relationship among corn yields, planting density, GM traits, and warming temperatures). Given this interest, we modify the "weather-planting-density" function in (2) to allow for "triple" interaction terms among the planting density variable, the weather variables, and GM corn varietal dummy variables. In this case, the corn varieties in the field trial data set are categorized into three groups: conventional varieties, GM-RW hybrids, and other GM hybrids. Note that GM-RW hybrids are those varieties that have RW resistance, either as a single-trait GM crop with only RW resistance, or a "multi-stack" variety with RW resistance combined with other traits (i.e., such as a double-stack GM with combined above-ground corn borer resistance together with below-ground RW resistance). The "other GM hybrids" category includes those GM varieties with GM traits, but specifically without the RW resistance trait (e.g., single-trait Bt corn with resistance only to European corn borers).

With the GM variety categorization above, the "weather-planting-density" specification in (2) is modified as follows (to include the GM variety dummies and triple interaction terms):

$$
\begin{aligned}
&\delta \mathbf{D}_{lzt} + \sum_{r=1}^{2} \zeta_r \mathbf{V}^r_{ilzt} + \sum_{r=1}^{2} \eta_r (\mathbf{D}_{lzt} \times \mathbf{V}^r_{ilzt}) + \sum_{m=1}^{5} \beta_{1m} \mathbf{tmin}_{lzmt} + \sum_{m=1}^{5} \beta_{2m} \mathbf{tmax}_{lzmt} + \\
&\sum_{m=1}^{5} \beta_{31m} \mathbf{PDSI}^w_{lzmt} + \sum_{m=1}^{5} \beta_{32m} \mathbf{PDSI}^d_{lzmt} + \sum_{r=1}^{2}\sum_{m=1}^{5} \theta_{1rm} (\mathbf{tmin}_{lzmt} \times \mathbf{V}^r_{ilzt}) + \\
&\sum_{r=1}^{2}\sum_{m=1}^{5} \theta_{2rm} (\mathbf{tmax}_{lzmt} \times \mathbf{V}^r_{ilzt}) + \sum_{r=1}^{2}\sum_{m=1}^{5} \theta_{31rm} (\mathbf{PDSI}^w_{lzmt} \times \mathbf{V}^r_{ilzt}) + \\
&\sum_{r=1}^{2}\sum_{m=1}^{5} \theta_{32rm} (\mathbf{PDSI}^d_{lzmt} \times \mathbf{V}^r_{ilzt}) + \sum_{m=1}^{5} \psi_{1m} (\mathbf{tmin}_{lzmt} \times \mathbf{D}_{lzt}) + \\
&\sum_{m=1}^{5} \psi_{2m} (\mathbf{tmax}_{lzmt} \times \mathbf{D}_{lzt}) + \sum_{m=1}^{5} \psi_{31m} (\mathbf{PDSI}^w_{lzmt} \times \mathbf{D}_{lzt}) + \sum_{m=1}^{5} \psi_{32m} (\mathbf{PDSI}^d_{lzmt} \times \mathbf{D}_{lzt}) + \\
&\sum_{r=1}^{2}\sum_{m=1}^{5} \kappa_{1rm} (\mathbf{tmin}_{lzmt} \times \mathbf{D}_{lzt} \times \mathbf{V}^r_{ilzt}) + \sum_{r=1}^{2}\sum_{m=1}^{5} \kappa_{2rm} (\mathbf{tmax}_{lzmt} \times \mathbf{D}_{lzt} \times \mathbf{V}^r_{ilzt}) + \\
&\sum_{r=1}^{2}\sum_{m=1}^{5} \kappa_{31rm} (\mathbf{PDSI}^w_{lzmt} \times \mathbf{D}_{lzt} \times \mathbf{V}^r_{ilzt}) + \sum_{r=1}^{2}\sum_{m=1}^{5} \kappa_{32rm} (\mathbf{PDSI}^d_{lzmt} \times \mathbf{D}_{lzt} \times \mathbf{V}^r_{ilzt})
\end{aligned}
\tag{8}
$$

where V^r_{ilzt} represents the GM variety dummy variables for plot i, field trial location l, production zone z, and year t. In the specification above, conventional corn hybrids are designated as the base group (e.g., the omitted category) and V^r are dummy variables that represent the two GM varietal groups, where $r = 1$ corresponds the GM-RW hybrids, and $r = 2$ refers to the other GM hybrids. Among the 28,521 plots in the field trial data, there are 17,680 with conventional corn, 4,044 with GM-RW hybrids, and 6,797 with the other GM hybrids. The change in varietal adoption rate over time for the four production zones are shown in Figure S6, Figure S7 and Figure S8.

Given the "weather-planting-density" specification in equation (8), the marginal yield effect of increasing planting density for conventional corn under the first warming scenario (for $k = -4, -3, .., 0, .., +3, +4$) can then be calculated as follows:

$$\frac{\partial \ln(y_t)}{\partial \mathbf{D}_t} = \delta + \sum_{m=1}^{5} \psi_{1m}(\overline{\mathbf{tmin}}_{mt} + k) + \sum_{m=1}^{5} \psi_{2m}(\overline{\mathbf{tmax}}_{mt} + k) + \sum_{m=1}^{5} \psi_{31m}\overline{\mathbf{PDSI}}_{mt} \quad (9)$$

where the weather variables are set at their mean values in all 5 months of the growing season. On the other hand, the marginal effect of increasing planting density for the GM-RW hybrids can be written as:

$$\begin{aligned} \frac{\partial \ln(y_t)}{\partial \mathbf{D}_t} = \delta + \eta_1 + \sum_{m=1}^{5} \psi_{1m}(\overline{\mathbf{tmin}}_{mt} + k) + \sum_{m=1}^{5} \psi_{2m}(\overline{\mathbf{tmax}}_{mt} + k) + \\ \sum_{m=1}^{5} \kappa_{11m}(\overline{\mathbf{tmin}}_{mt} + k) + \sum_{m=1}^{5} \kappa_{21m}(\overline{\mathbf{tmax}}_{mt} + k) + \sum_{m=1}^{5} \psi_{31m}\overline{\mathbf{PDSI}}_{mt} + \\ \sum_{m=1}^{5} \kappa_{311m}\overline{\mathbf{PDSI}}_{mt} \end{aligned} \quad (10)$$

where the weather variables are again set at their mean values in all 5 months of the growing season. Similarly, the marginal effect of increasing planting density for the other GM hybrids can be calculated as follows:

$$\begin{aligned} \frac{\partial \ln(y_t)}{\partial \mathbf{D}_t} = \delta + \eta_2 + \sum_{m=1}^{5} \psi_{1m}(\overline{\mathbf{tmin}}_{mt} + k) + \sum_{m=1}^{5} \psi_{2m}(\overline{\mathbf{tmax}}_{mt} + k) + \\ \sum_{m=1}^{5} \kappa_{12m}(\overline{\mathbf{tmin}}_{mt} + k) + \sum_{m=1}^{5} \kappa_{22m}(\overline{\mathbf{tmax}}_{mt} + k) + \sum_{m=1}^{5} \psi_{31m}\overline{\mathbf{PDSI}}_{mt} + \\ \sum_{m=1}^{5} \kappa_{312m}\overline{\mathbf{PDSI}}_{mt} \end{aligned} \quad (11)$$

where the weather variables are again set at their mean values in all 5 months of the growing season. Although not shown here, similar marginal effect calculations can also be computed for the second warming scenario, and for the case where we only consider temperature changes in the June to August months.

3 Estimation Results and Marginal Effects

The main empirical model as specified in equations (1) and (2) are estimated by OLS and, in the spirit of conciseness, the parameter estimates are presented in the Appendix (See Table S1).[8]

3.1 Warming Effects

To determine the influence of warming on the yield effects of planting density, we calculate the marginal effects of increasing planting density under the two warming scenarios described in the previous section and present results in Table 3. For the first warming scenario, where both **tmin** and **tmax** are assumed to change by 1°C increments, we find that the yield benefit of increasing planting density is reduced by 1.86% for every 1°C increase in the minimum and maximum temperatures in each month of the cropping season. This result suggests that the yield benefits of increasing planting density diminish in the presence of warming.

As described in the previous section, we also calculate the marginal effect of increasing planting density as temperature deviates from the mean by 1°C increments (see equation (5)). The results of these marginal effect calculations are graphically presented in Figure 2. The mean temperature result in Figure 2 indicates that, for average weather conditions in the study area (e.g., average minimum and maximum temperatures, as well as average PDSI), increasing planting density would negatively affect corn yields (albeit by a relatively small percentage amount). Moreover, as the minimum and maximum temperatures increase relative to the mean, increasing planting density becomes more detrimental to corn yields (e.g., a 1000 plants per acre increase in planting density results in more than 5% yield reduction when minimum and maximum temperatures increase by more than 3°C from the mean). On the other hand, note that increasing planting density has a positive marginal effect on yield when temperatures are lower than the mean. The diminishing marginal effect of increasing planting density in a warming environment is consistent with the idea that inter-plant competition for nutrients and resources (i.e., water) intensifies as planting density increases, and this competition escalates further when temperatures increase.

[8] Consistent with equation (1), results presented here is for the case where $\ln(y_{ilzt})$ is the dependent variable. We also ran all the models where the dependent variable is the actual yield in bu/acre (i.e., not taking the natural logarithms) Results for those runs are consistent with what is presented here and is available from the authors upon request.

Results from the second warming scenario, where we assume that **tmin** and **tmax** increases separately in 1°C increments in all months, are fairly consistent with the marginal effect estimates calculated in the first warming scenario described above (See Table 3). But we note that increases in **tmax** tend to have a larger negative impact on the yield effects of increasing planting density (as compared to the impact of increases in **tmin**). This suggests that increases in daytime temperatures are more likely to negatively influence yield response to increasing planting density.

For the case where the two warming scenarios are applied only to the critical growth months of June to August, the marginal effect estimates are still largely consistent with the results from the earlier results where warming affects all growing season months (See Table 3 and Figure 3). The general pattern of results in Figure 3 is almost the same as in Figure 2. However, the magnitudes of the warming effects are relatively smaller for the case where warming is only felt in the June to August months.

3.2 GM traits and Warming Effects

The role of GM traits is examined based on the empirical specification in equations (1) and (8). Parameter estimates for the specification that includes the GM dummy variables (and the corresponding interactions) are presented in Table S2. Similar to the results in Table S1, the planting density effect on corn yields is positive if GM traits and weather variables are not taken into account.

The marginal effects of increasing planting density that considers GM traits under our two warming scenarios are presented in Table 2. Results from these marginal effect calculations generally suggest that the negative effect of warming is more strongly felt for conventional corn varieties, as compared to the GM-RW hybrids and other GM hybrids. That is, the marginal yield effect of increasing planting density is more negatively affected by warming when conventional varieties are used.

To better visualize the role of GM traits, we also graph the marginal effects of increasing planting density under the first warming scenario (i.e., increasing both **tmin** and **tmax** in all months), but separating it out by the hybrid type – conventional, GM-RW, and other GM (See Figure 4). First, at the mean temperature levels, it is important to note that increasing planting density results in a negative yield impact for conventional corn yields. In contrast, for GM-RW hybrids and other GM hybrids, the marginal yield effect of increasing planting density is positive at mean temperature levels. Second, the positive marginal effect of increasing planting density is higher for GM-RW hybrids as compared to the other GM hybrids. Moreover, even at temperatures above or below the mean level, the positive marginal effect of planting density for GM-RW hybrids is still consistently larger than the other GM hybrids. Lastly, the slope of the marginal effect line for the conventional hybrids is steeper than those of the GM-RW and other GM hybrids, suggesting that the marginal effect of increasing planting density diminishes more rapidly (as temperature rises) for conventional corn, relative to the GM-RW and other GM hybrids. Overall, these results provide some evidence that the typical yield benefits of increasing planting density can be more easily maintained under warming conditions if corn varieties with GM traits are used. This outcome suggests that corn varieties with GM traits (especially GM-RW hybrids) may be more efficient in utilizing nutrients and moisture even under intensified inter-plant competition due to increasing planting density and higher temperatures. Moreover, the GM trait results here support the idea that the use of GM varieties may have facilitated the increases in planting density over time.

4 Robustness Checks

To verify the strength and stability of our results, we conduct several robustness checks that consider the following alternatives to our main empirical specification (as described in equations (1) and (2)): (a) the main specification without including the managerial inputs and practices ($\mathbf{X}_{ilzt}$) as control variables, (b) the main empirical specification that includes interaction term between the time trend and the plant density, and (c) the main specification but using a quadratic form of precipitation of the May-September growing season as a measure of water availability (instead of PDSI).

We conduct the first robustness check, which excludes the managerial inputs, to account for concerns that input choices in the production process may be endogenous. However, note that this endogeneity concern may be largely mitigated by the fact the data set used in this study is based on field trial data rather than actual farm-level production data collected through a survey. Estimation results for the first robustness check are presented in Table S3, and the corresponding marginal effects of increasing planting density for our two warming scenarios are reported in Table 5. Figure 5 shows the marginal percentage impact of increasing planting density for the warming scenario where both **tmin** and **tmax** of each month change by 1°C increments when managerial inputs are not considered in the specification. Results from this first robustness check are largely consistent with our main warming results reported in the previous section. The magnitudes of the warming effects on the corn yield response to increasing planting density are very similar to the original results above. Overall, the first robustness check still strongly supports the notion that yield effects of increasing planting density diminish as temperature levels increase.

The second robustness check aims to show whether our results still hold when one assumes that the marginal effect of increasing planting density is not constant through time. Parameter estimates for the second robustness check that include interaction terms between the time trend and planting density are presented in Table S4, and the corresponding marginal effects are presented in Table 6. Moreover, Figure 6 graphically shows the marginal impacts of increasing planting density under the first warming scenario in five-year increments (from 1990-2010). Again, the second robustness check validates our results from the main specification in the previous section. The patterns of results in Figure 6 (for all years) are consistent with our main specification result in Figure 2. An interesting pattern to note in Figure 6 is that the marginal yield impact of increasing planting density (for all temperature levels) shifted upward through time. This is consistent with the observation that GM adoption has increased through time, which in turn may have brought about better yield response to increasing planting density even in warming temperatures (see section 3.2 above).

Lastly, we conduct a third robustness check where we replace PDSI as a measure of water availability with a quadratic function of precipitation (e.g., we added $prec$ and $prec^2$, instead of the PDSI variables in equations (1) and (2)).[9]. For this last robustness check, the parameter estimates are reported in Table S5 for the case where GM traits are not yet considered, and the corresponding marginal effects of increasing planting density for this specification are presented in Table 7. The visual representation of the marginal planting density effects for this last robustness check (under the first warming scenario) is presented in Figure 7. All of the results for this last robustness check are fairly consistent with the direction and magnitudes of the marginal impacts of increasing planting density using the main specification. Even when we use precipitation as a measure of water availability, the marginal yield response to increasing planting density deteriorates when temperature levels increase.

Parameter estimates for the specification where a quadratic form of precipitation is

[9]For this robustness check, we use the mean of monthly cumulative precipitation for the whole growing season. But further note that we also ran an additional specification that uses monthly cumulative precipitation. The results are similar to what is presented here. Results for the specification that uses monthly precipitation are available from the authors upon request

used and GM traits are considered can be seen in Table S6. Moreover, the marginal effects associated with this specification is presented in Table 8. A corresponding graphical representation of the marginal effects of increasing planting density under the first warming scenario, and separated out by GM type, are shown in Figure 8. These robustness check results with precipitation used as a measure of water availability are still consistent with the results from the main specification above. At mean temperatures, the marginal effect of increasing planting density is still the strongest for GM-RW hybrids and is higher than both the conventional and other GM hybrids. At larger positive deviations from mean temperatures, this pattern still holds (as before). But note that, for mean temperatures, the marginal effect of increasing planting density for conventional corn is still positive (as compared to it being negative in the main specification). Lastly, note that the slope of the marginal effect line for conventional corn is still the steepest among the three hybrid groups. However, in contrast to the main specification results (with PDSI), the slope of the marginal effect line for GM-RW is flatter than the other GM hybrids. Nonetheless, even when precipitation is used as a measure of water availability, these robustness check results still support the notion that yield benefits of increasing planting density are better maintained under warming conditions when corn varieties with GM traits are utilized.

5 Conclusions

This study aims to explore how yield response to planting density is influenced by warming temperature and to understand the role of GM traits in this situation. Plot-level field trial data from Wisconsin over the period 1990-2010, as well as the corresponding weather data for these field trial locations, are used to fulfill the study objectives. Yield regression models are then developed with interaction terms among planting density, weather variables, and GM hybrid dummy variables to ascertain the impact of warming and GM traits on the corn yield response to increasing planting density. Results from these models suggest that the yield benefits of increasing planting density largely diminish as temperature levels increase, and the rate of deterioration is larger for conventional corn hybrids without GM traits. Corn varieties with RW resistance GM traits generally are better able to maintain the yield benefits of increasing planting density under warming conditions. These results indicate that inter-plant competition for resources (e.g., nutrients and moisture) is further intensified as planting density increases and when temperatures rise, which results in the diminishing benefits. But corn hybrids with GM traits may be more efficient in utilizing these resources such that they perform better than conventional varieties even in situations with increasing planting density and warming temperatures.

Findings from the present study point to a couple of important implications. First, results from the study highlight the important role that expected growing season temperatures should play when farmers make planting density decisions and varietal choices at the start of the season. Increasing planting density does not necessarily result in yield benefits even at mean temperatures when conventional corn hybrids are used. And yield increases from higher planting density still diminish under warming temperatures. Hence, growers would likely benefit from optimizing planting density and variety choices by partly conditioning these decisions on temperature forecasts for the growing season (Solomon et al. (2017)). For example, if forecasted summer season temperature is higher than normal, then based on our results it may be prudent to not increase planting density for conventional corn production (or only increase it slightly for GM varieties). Second, the study findings also imply that further research investments in developing corn varieties that are more tolerant to higher temperatures would likely facilitate higher optimal planting densities going forward. Not only will more heat-tolerant varieties directly reduce heat-related losses, but these types of varieties may also indirectly provide planting density induced yield benefits. Therefore, public and private research investments for developing heat-tolerant corn varieties (i.e., either through genetic modification or traditional plant breeding) would be important to continue the trend of increasing planting density and yields into the future, especially if climate change continues to result in warmer temperatures.

Although the present study provides important insights regarding the role of warming and GM traits on the yield response to increasing planting density, there are study limitations that need to be acknowledged. First, the geographical scope of the current study is limited to the Northern corn belt and the data is from experimental field trial data rather than actual farmer data from commercial corn production. Future studies may consider using actual farm production data (i.e., data collected through farm surveys or through precision agriculture technologies) and expanding the geographical scope to more areas in the corn belt (or other locations and other corn-producing countries). Exploring the "yield-planting density" relationship in warmer climates (e.g., tropical locations) may also be beneficial. Second, the empirical analysis here would also be further improved if we had a true panel data set at the plot (or trial location) level. This would allow for using plot (or location) fixed effects and better identification of the planting density and warming effects on yields. In addition, a long-term field trial data explicitly aimed to examine how planting density influence yields (e.g., field trials designed specifically to explore planting density effects (instead of variety effects) on yields) would also help in more precisely teasing out the warming and GM trait effects. Lastly, having data for a longer period (i.e., more than 30 years) would also allow one to more accurately estimate the long-run effects of warming on the yield response to increasing planting density. We leave all these potential extensions for future work.

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Table 1: Descriptive statistics of variables for Wisconsin data

Variable	Unit	Mean	SD	Median	Min	Max
Yield	bu/acre	176.46	40.26	178.53	21	289.81
plant density	1000 plants per acre	28.44	1.95	28.18	18.25	33.41
pcorn	1 if previous crop is corn	0.29	0.46	0	0	1
psoy	1 if previous crop is soybean	0.61	0.49	1	0	1
palf	1 if previous crop is alfalfa/hay	0.07	0.26	0	0	1
pwhe	1 if previous crop is wheat	0.02	0.13	0	0	1
plup	1 if previous crop is lupine	0	0.06	0	0	1
ft	Fall tillage, 1 if yes, 0 if no	0.51	0.5	1	0	1
st	spring tillage, 1 if yes, 0 if no	0.92	0.27	1	0	1
ic	apply insecticide, 1 if yes, 0 if no	0.38	0.49	0	0	1
fertilizer N	lbs $acre^{-1}$	122.86	41.76	130	0.5	201.5
conventional	1 if conventional corn is planted	0.62	0.49	1	0	1
RW	1 if expressing Bt trait for corn rootworm	0.14	0.35	0	0	1
other GM	1 if without Bt trait for corn rootworm	0.24	0.43	0	0	1

Table 2: Summary statistics of weather variables

Month	Variable	Mean	SD	Median	Min	Max
May.	tmin(°C)	7.03	2.153	7.01	1.58	12.26
	tmax(°C)	19.60	2.092	19.60	13.76	24.74
	PDSI	0.78	1.676	0.96	-4.11	5.53
	prec(mm)	98.65	47.23	90.43	23.73	310.79
Jun.	tmin(°C)	12.82	1.748	13.08	7.95	16.47
	tmax(°C)	24.96	1.732	24.93	20.36	29.46
	PDSI	0.95	2.060	1.09	-4.72	7.06
	prec(mm)	122.89	58.20	117.34	20.42	355.04
Jul.	tmin(°C)	14.97	1.754	15.10	9.88	19.07
	tmax(°C)	26.98	1.778	26.98	22.07	31.20
	PDSI	0.98	2.246	1.03	-4.95	6.99
	prec(mm)	102.46	49.64	94.27	18.28	268.96
Aug.	tmin(°C)	14.23	1.891	14.28	9.45	19.74
	tmax(°C)	26.08	1.629	26.34	21.56	29.96
	PDSI	0.81	2.127	0.73	-5.05	7.17
	prec(mm)	105.92	58.41	92.95	20.86	367.83
Sep.	tmin(°C)	9.54	1.634	9.57	4.47	12.87
	tmax(°C)	21.85	1.981	21.81	16.39	26.75
	PDSI	0.52	2.147	0.31	-3.74	6.59
	prec(mm)	83.50	44.75	75.75	8.17	235.18

Table 3: Estimated changes in the effects of plant density on yield as a result of 1°C warming

	All Months		Jun-Aug	
	Estimates	P-value	Estimates	P-value
tmin & tmax	-0.0186	0.000	-0.0055	0.000
tmin	-0.0066	0.000	0.0116	0.000
tmax	-0.0121	0.000	-0.0170	0.000

Notes: (1) The results here are estimated through our main specification in equations (1) and (2). (2) The first column indicates what weather variables the marginal effects of plant density are based on. The first row indicates a 1°C increase in both **tmin** and **tmax**. The second row refers to a warming scenario where only **tmin** increases by 1°C. The third row refers to a 1°C increase in **tmax**. (3) The second and the third column report coefficients and p-values of the changes in the marginal effects of plant density as a result of warming scenarios (both **tmin** and **tmax**, and **tmin** and **tmax** separately) where temperature of each month of the May-September growing season increases by 1°C. The last two columns provide coefficients and p-values of the changes in the marginal effects of warming scenarios where the temperature of each month from June to August increases by 1°C.

Table 4: Estimated changes in the effects of plant density on yield as a result of 1°C warming

		All months		Jun-Aug	
		Estimates	P-value	Estimates	P-value
tmin & tmax	Conventional	-0.0279	0.000	-0.0069	0.000
	GM-RW	-0.0127	0.227	0.0123	0.388
	Other GM	-0.0019	0.490	-0.0002	0.960
tmin	Conventional	-0.0194	0.000	0.0118	0.000
	GM-RW	-0.1480	0.000	0.0458	0.000
	Other GM	-0.0016	0.620	-0.0240	0.000
tmax	Conventional	-0.0085	0.000	-0.0186	0.000
	GM-RW	0.1353	0.000	-0.0334	0.030
	Other GM	-0.0004	0.908	0.0238	0.000

Notes: (1) The table displays coefficients and p-values of the changes in the marginal effects of plant density as a result of 1° warming. The results are calculated from the estimated results of the model specification in equations (1) and (8) (the specifications including interactions among the weather, plant density and GM varietal dummy variables). (2) The first column indicates what weather variables the marginal effects of plant density are based on. The first row of the first panel indicates a 1°C increase in both **tmin** and **tmax**. The first row of the second panel refers to a scenario where only **tmin** increases by 1°C. The first row of the third panel refers to a situation where only **tmax** increases by 1°C. (3) The second column indicates the hybrid groups: "RW" is GM hybrids expressing Bt trait for corn rootworm. "other GM" refer to GM hybrids without Bt trait for corn rootworm. (4)The third and fourth column report coefficients and p-values of the changes in marginal effects of plant density as a result of warming scenarios (both **tmin** and **tmax**, and **tmin** and **tmax** separately) where the temperature of each month of the May-September growing season increases by 1°C. The last two columns provide coefficients and p-values of the changes in marginal effects of warming scenarios where the temperature of each month from June to August increases by 1°C.

Table 5: Estimated changes in the effects of plant density on yield as a result of 1°C warming

	All Months		Jun-Aug	
	Estimates	P-value	Estimates	P-value
tmin & tmax	-0.0195	0.000	-0.0056	0.000
tmin	-0.0042	0.000	0.0154	0.000
tmax	-0.0153	0.000	-0.0209	0.000

Notes: (1) The table shows the results of the first robustness check (the main specification without including managerial inputs and practices as control variables). (2) The first column indicates what weather variables the marginal effects of plant density are based on. The first row indicates a 1°C increase in both **tmin** and **tmax**. The second row refers to a warming scenario where only **tmin** increases by 1°C. The third row refers to a 1°C increase in **tmax**. (3) The second and the third column report coefficients and p-values of the changes in the marginal effects of plant density as a result of warming scenarios (both **tmin** and **tmax**, and **tmin** and **tmax** separately) where the temperature of each month of the May-September growing season increases by 1°C. The last two columns provide coefficients and p-values of the changes in the marginal effects of warming scenarios where the temperature of each month from June to August increases by 1°C.

Table 6: Estimated changes in the effects of plant density on yield as a result of 1°C warming

	All Months		Jun-Aug	
	Estimates	P-value	Estimates	P-value
tmin & tmax	-0.0191	0.000	-0.0053	0.000
tmin	-0.0069	0.000	0.0110	0.000
tmax	-0.0122	0.000	-0.0163	0.000

Notes: (1) The table shows the results of the second robustness check (the model specification includes the interaction term between plant density and the time trend in addition to the independent variables of the main specification). (2) The first column indicates what weather variables the marginal effects of plant density are based on. The first row indicates a 1°C increase in both **tmin** and **tmax**. The second row refers to a warming scenario where only **tmin** increases by 1°C. The third row refers to a 1°C increase in **tmax**. (3) The second and the third column report coefficients and p-values of the changes in the marginal effects of plant density as a result of warming scenarios (both **tmin** and **tmax**, and **tmin** and **tmax** separately) where the temperature of each month of the May-September growing season increases by 1°C. The last two columns provide coefficients and p-values of the changes in the marginal effects of warming scenarios where the temperature of each month from June to August increases by 1°C.

Table 7: Estimated changes in the effects of plant density on yield as a result of 1°C warming

	All Months		Jun-Aug	
	Estimates	P-value	Estimates	P-value
tmin & tmax	-0.0161	0.000	-0.0030	0.000
tmin	-0.0049	0.000	0.0190	0.000
tmax	-0.0112	0.000	-0.0220	0.000

Notes: (1) The table shows the results of the third robustness check which replaces PDSI as a measure of water availability with a quadratic form of the mean of monthly cumulative precipitation for the whole growing season. (2) The first column indicates what weather variables the marginal effects of plant density are based on. The first row indicates a 1°C increase in both **tmin** and **tmax**. The second row refers to a warming scenario where only **tmin** increases by 1°C. The third row refers to a 1°C increase in **tmax**. (3) The second and the third column report coefficients and p-values of the changes in the marginal effects of plant density as a result of warming scenarios (both **tmin** and **tmax**, and **tmin** and **tmax** separately) where the temperature of each month of the May-September growing season increases by 1°C. The last two columns provide coefficients and p-values of the changes in the marginal effects of warming scenarios where the temperature of each month from June to August increases by 1°C.

Table 8: Estimated changes in the effects of plant density on yield as a result of 1°C warming

		All months		Jun-Aug	
		Estimates	P-value	Estimates	P-value
tmin & tmax	Conventional	-0.0104	0.000	0.0084	0.000
	GM-RW	0.0018	0.547	0.0051	0.331
	other GM	-0.0053	0.030	-0.0151	0.000
tmin	Conventional	0.0086	0.000	0.0280	0.000
	GM-RW	-0.0282	0.000	-0.0222	0.001
	other GM	-0.0176	0.000	-0.0456	0.000
tmax	Conventional	-0.0190	0.000	-0.0197	0.000
	GM-RW	0.0300	0.000	0.0272	0.000
	other GM	0.0123	0.000	0.0305	0.000

Notes: (1) The table displays coefficients and p-values of the change in the marginal effect of plant density as a result of 1° warming. The results are calculated from the estimated results of the model specification in equations (1) and (8) that replaces monthly PDSI as a measure of water availability with a quadratic form of the mean of monthly cumulative precipitation for the whole growing season. (2) The first column indicates what weather variables are the marginal effects of plant density based on. The first row of the first panel indicates a 1°C increase in both **tmin** and **tmax**. The first row of the second panel refers to a scenario where only **tmin** increases by 1°C. The first row of the third panel refers to a situation where only **tmax** increases by 1°C. (3) The second column indicates the hybrid groups: "RW" is GM hybrids expressing Bt trait for corn rootworm. "other GM" refer to GM hybrids without Bt trait for corn rootworm. (4)The third and fourth column report coefficients and p-values of the change in marginal effect of plant density as a result of warming scenarios (both **tmin** and **tmax**, and **tmin** and **tmax** separately) where temperature of each month of the May-September growing season increases by 1°C. The last two columns provide coefficients and p-values of the change in the marginal effect of warming scenarios where the temperature of each month from June to August increases by 1°C.

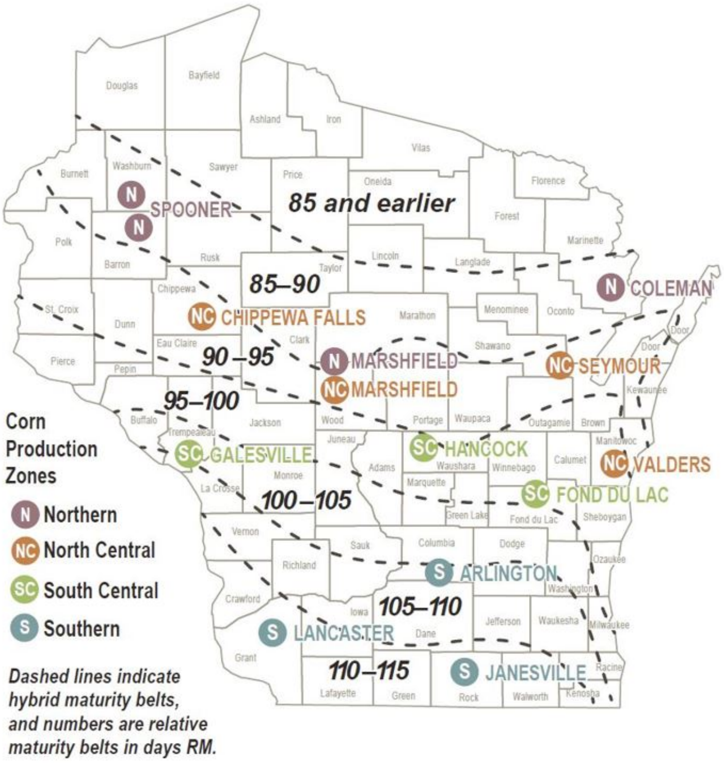

Figure 1: **Map of research locations of Wisconsin field experimental data** Web: http://corn.agronomy.wisc.edu/ HT/images/Map.jpg. Accessed: 4/7/2019

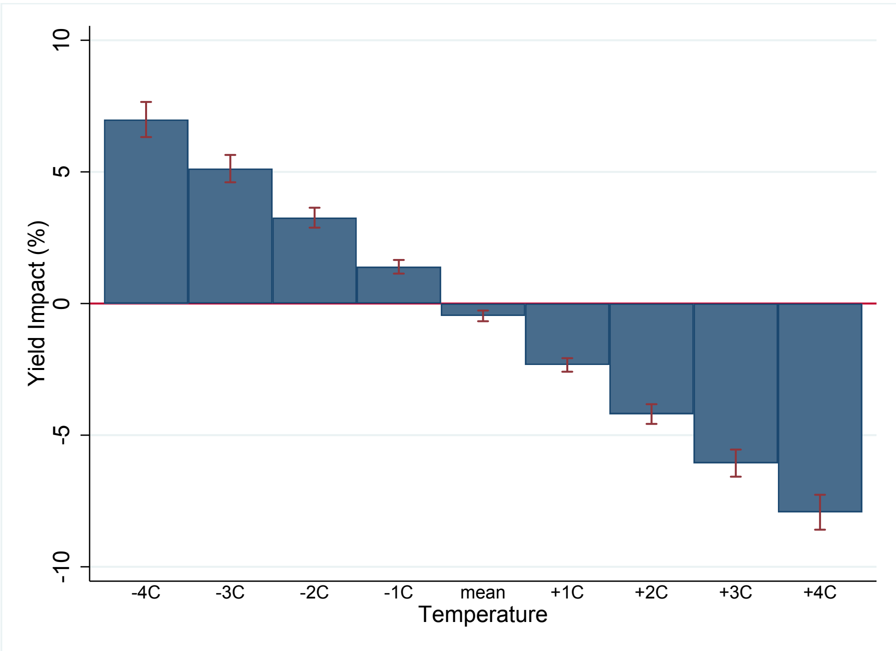

Figure 2: Marginal percentage effect of plant densities as *tmin* and *tmax* of each month deviate from the mean by 1°C increments

Notes: The main specification in equations (1) and (2) is implemented. The Impacts are reported as the percentage change in yield. The vertical solid lines show 90% confidence interval.

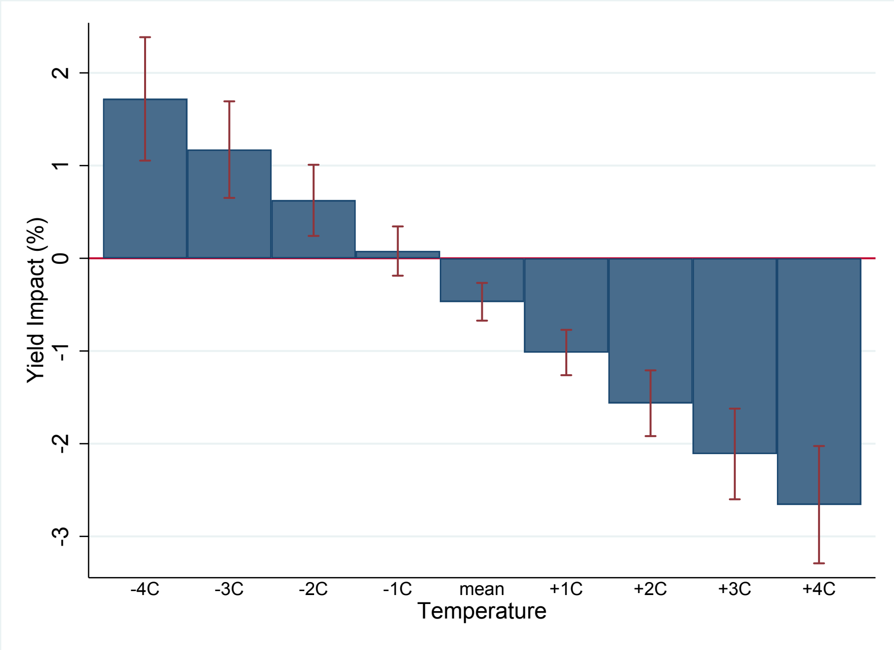

Figure 3: Marginal percentage effect of plant densities as *tmin* and *tmax* of each month from June to August deviate from the mean by 1°C increments

Notes: The main specification in equations (1) and (2) is implemented. Impacts are reported as the percentage change in yield. The vertical solid lines show 90% confidence interval.

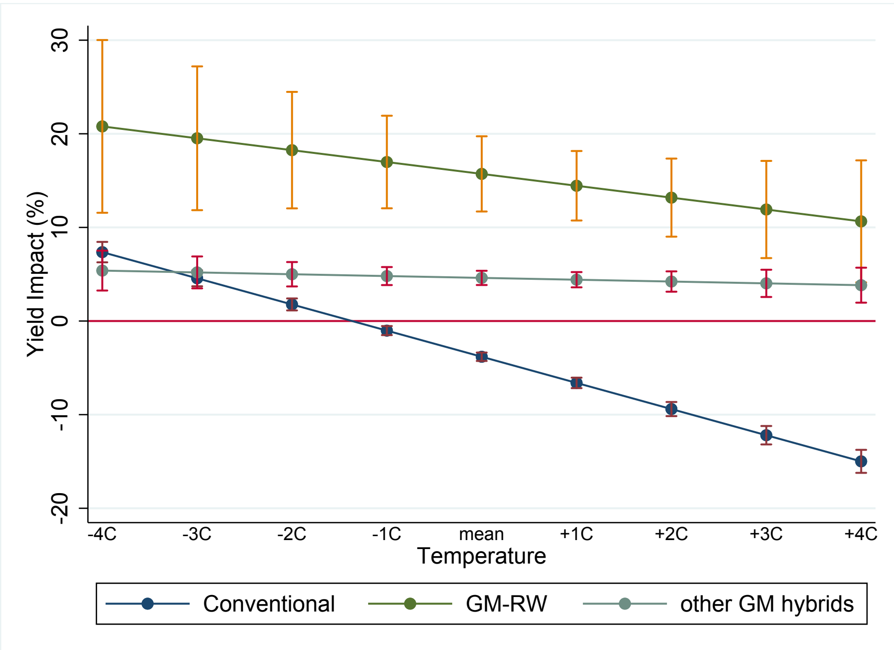

Figure 4: Marginal impacts of plant density for the three varietal groups (1) and (8)

Notes: The figure shows the results of the model specification in equations (models including interaction terms among weather, planting density and GM varietal group dummy variable). Impacts are reported as the percentage change in yield. The vertical solid lines show 90% confidence interval.

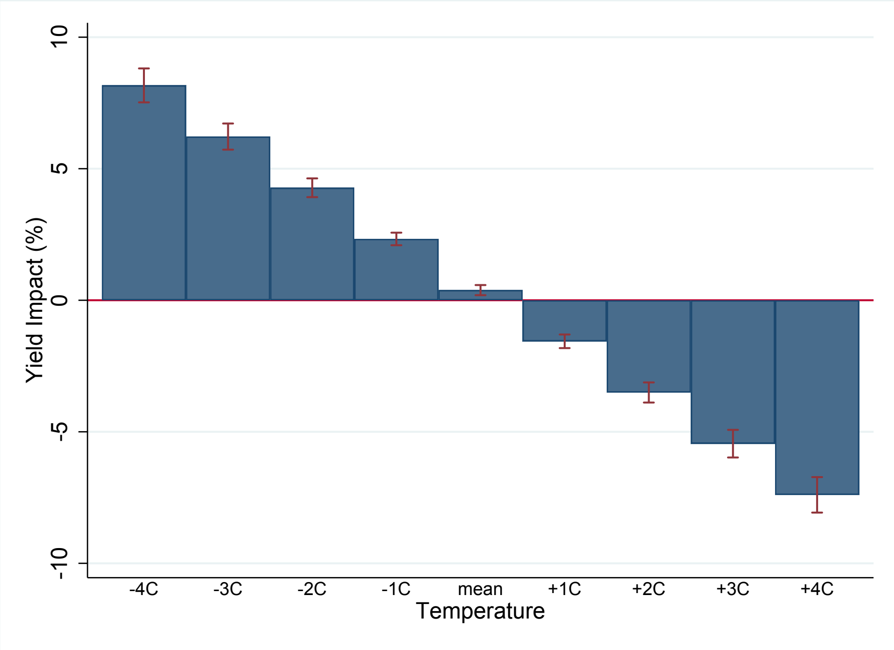

Figure 5: Marginal percentage effect of plant density as *tmin* and *tmax* of each month deviate from the mean by 1°C increments

Notes: The figure shows the results of the model with all variables of the main specification except the managerial inputs and practices. Impacts are reported as the percentage change in yield. The vertical solid lines show 90% confidence interval.

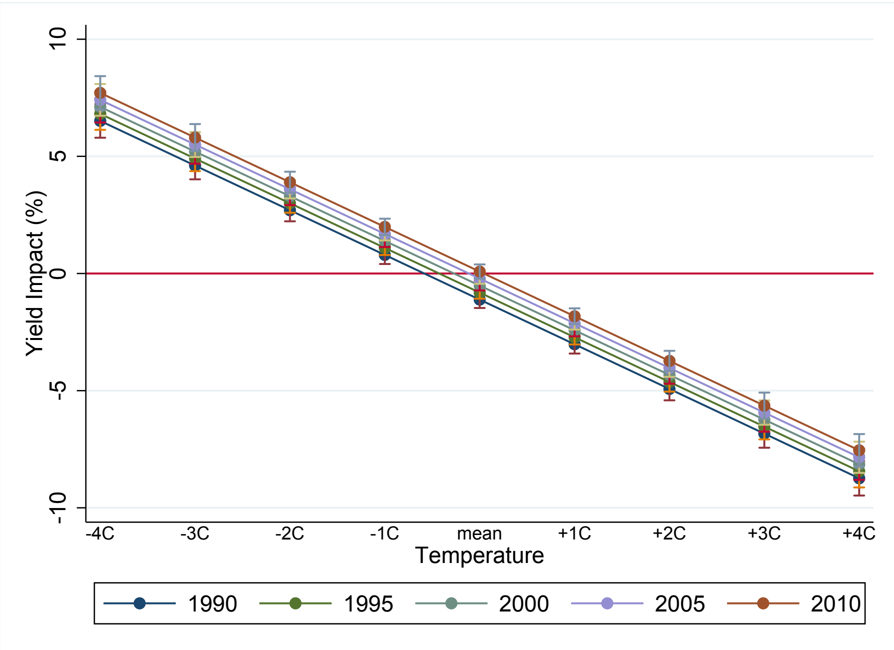

Figure 6: Marginal impact of plant density across years estimated by the model including the interaction term between time trend and plant density

Notes: The figure shows the results of the model with all variables of the main specification and the interaction term between time trend and plant density. Impacts are reported as the percentage change in yield. The vertical solid lines show 90% confidence interval.

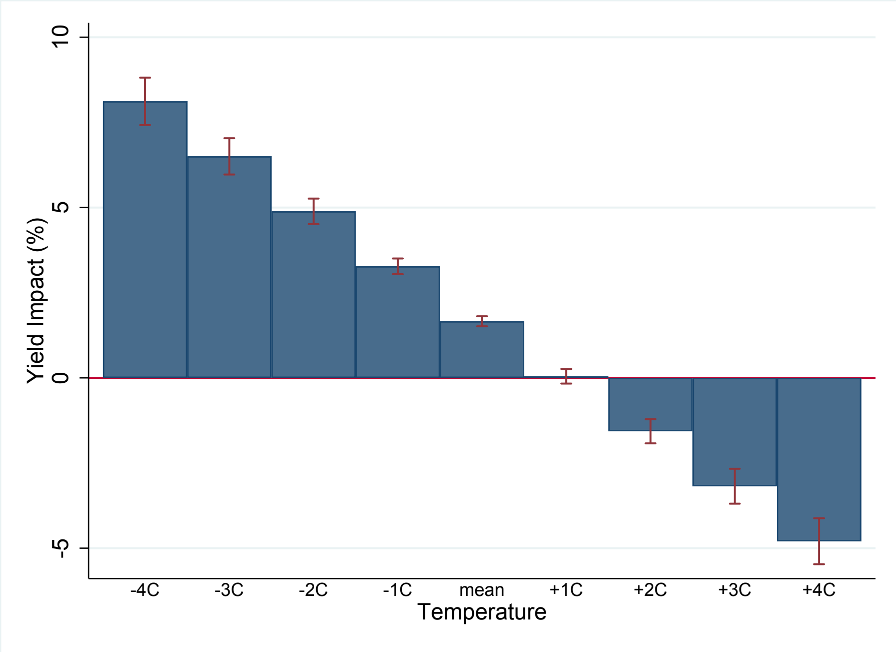

Figure 7: Marginal percentage effect of plant densities as *tmin* and *tmax* of each month deviate from the mean by 1°C increments

Notes: The figure shows the results of the model with the main specification that replaces PDSI as a measure of water availability with a quadratic function of precipitation.

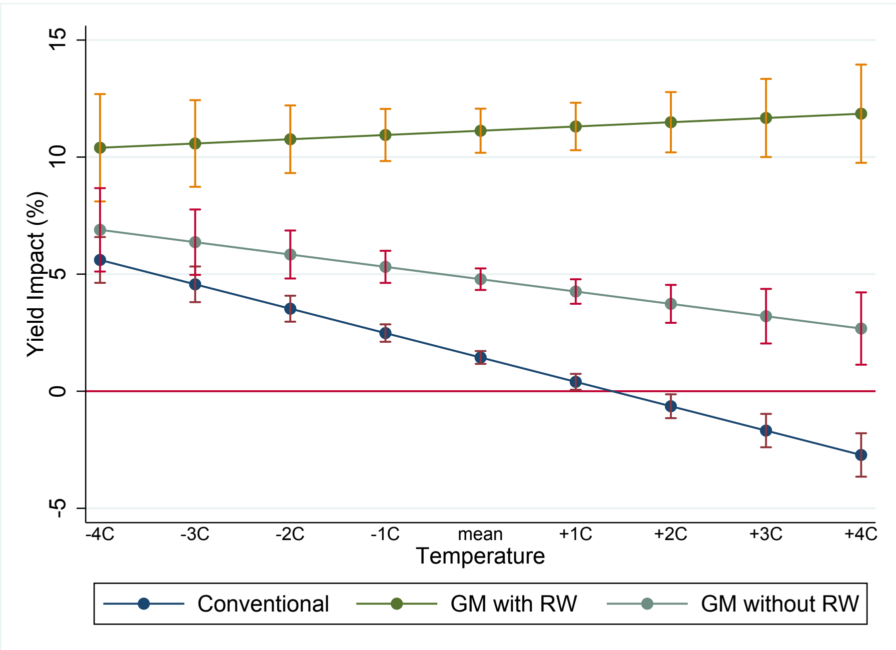

Figure 8: Marginal impacts of plant density for the three varietal groups

Notes: The figure shows the results of the model specification in equations (1) and (8) replacing PDSI as a measure of water availability with a quadratic function of precipitation. Impacts are reported as the percentage change in yield. The vertical solid lines show 90% confidence interval.

A Appendix

Table S1: Regression results of the main model specification

	lnyld
plant density	0.329***
	(0.019)
tmin5	0.168***
	(0.031)
tmin6	-0.153***
	(0.042)
tmin7	0.211***
	(0.038)
tmin8	-0.446***
	(0.033)
tmin9	0.451***
	(0.029)
tmax5	-0.031
	(0.026)
tmax6	0.071*
	(0.038)
tmax7	0.170***
	(0.031)
tmax8	0.306***
	(0.031)
tmax9	-0.135***
	(0.027)
tmin5 × plant density	-0.004***
	(0.001)
tmin6 × plant density	0.003**
	(0.001)
tmin7 × plant density	-0.007***
	(0.001)
tmin8 × plant density	0.015***
	(0.001)
tmin9 × plant density	-0.014***
	(0.001)
tmax5 × plant density	0.000
	(0.001)
tmax6 × plant density	-0.001
	(0.001)
tmax7 × plant density	-0.005***
	(0.001)
tmax8 × plant density	-0.011***
	(0.001)
tmax9 × plant density	0.005***
	(0.001)

Continued

PDSI5(wet)	-0.077**
	(0.033)
PDSI6(wet)	-0.148***
	(0.039)
PDSI7(wet)	0.146***
	(0.029)
PDSI8(wet)	-0.466***
	(0.037)
PDSI9(wet)	0.021
	(0.035)
PDSI5(dry)	-1.479***
	(0.067)
PDSI6(dry)	1.885***
	(0.121)
PDSI7(dry)	0.000
	(0.087)
PDSI8(dry)	-1.363***
	(0.088)
PDSI9(dry)	-0.652***
	(0.077)
PDSI5(wet) × plant density	0.001
	(0.001)
PDSI6(wet) × plant density	0.006***
	(0.001)
PDSI7(wet) × plant density	-0.005***
	(0.001)
PDSI8(wet) × plant density	0.016***
	(0.001)
PDSI9(wet) × plant density	-0.000
	(0.001)
PDSI5(dry) × plant density	0.051***
	(0.002)
PDSI6(dry) × plant density	-0.065***
	(0.004)
PDSI7(dry) × plant density	-0.003
	(0.003)
PDSI8(dry) × plant density	0.046***
	(0.003)
PDSI9(dry) × plant density	0.023***
	(0.003)

Continued

year	0.009***
	(0.000)
RW	0.039***
	(0.005)
other GM	0.040***
	(0.003)
1 if previous crop is corn	0.080***
	(0.027)
1 if previous crop is wheat	0.120***
	(0.027)
1 if previous crop is alfalfa or alfalfa/hay	0.185***
	(0.026)
1 if previous crop is soybean	0.095***
	(0.026)
1 if previous crop is lupine	-0.175***
	(0.035)
fall tillage, 1 if yes, 0 if no	0.000
	(0.002)
spring tillage, 1 if yes, 0 if no	-0.037***
	(0.004)
apply insecticide, 1 if yes, 0 if no	-0.062***
	(0.004)
fertilizer N	0.000***
	(0.000)
Observations	28521
R-squared	0.662

Notes: Table regresses plot-level log of yield on plant density, weather variables(monthly average of daily minimum and maximum temperature(**tmin** and **tmax**), and monthly PDSI from May to September), the interactions between plant density and weather variables, and the managerial inputs and practices described in Table 1. The model also includes linear time trend and production zone fixed effect model. Units for **tmin** and **tmax** are °C. Unit for plant density is 1000 acre^{-1}. In consideration of the possible heteroskedasticity, Huber-White's robust standard errors are calculated and shown in parentheses. ***Significant at 1% level. **Significant at 5% level. *Significant at 10% level.

Table S2: Regression results of the model specification in equations (1) and (8)

	(1)
	lnyld
planting density	0.267***
	(0.045)
RW × planting density	-2.025***
	(0.132)
other GM × planting density	-0.126*
	(0.072)
tmin5	0.282***
	(0.056)
tmin6	0.504***
	(0.087)
tmin7	-0.244***
	(0.077)
tmin8	-0.650***
	(0.059)
tmin9	0.702***
	(0.054)
tmax5	0.068
	(0.044)
tmax6	-0.155**
	(0.071)
tmax7	0.380***
	(0.048)
tmax8	0.364***
	(0.056)
tmax9	-0.372***
	(0.047)
tmin5 × planting density	-0.008***
	(0.002)
tmin6 × planting density	-0.020***
	(0.003)
tmin7 × planting density	0.009***
	(0.003)
tmin8 × planting density	0.022***
	(0.002)
tmin9 × planting density	-0.023***
	(0.002)
tmax5 × planting density	-0.003*
	(0.002)
tmax6 × planting density	0.007***
	(0.003)
tmax7 × planting density	-0.012***
	(0.002)
tmax8 × planting density	-0.013***
	(0.002)
tmax9 × planting density	0.013***
	(0.002)

Continued

RW × tmin5	3.550***
	(0.559)
RW × tmin6	4.771***
	(0.556)
RW × tmin7	-4.341***
	(0.617)
RW × tmin8	-1.386***
	(0.374)
RW × tmin9	1.354***
	(0.342)
other GM × tmin5	-0.389***
	(0.140)
other GM × tmin6	-0.646***
	(0.144)
other GM × tmin7	0.546***
	(0.141)
other GM × tmin8	1.269***
	(0.157)
other GM × tmin9	-1.293***
	(0.127)
RW × tmax5	-2.967***
	(0.395)
RW × tmax6	-2.851***
	(0.558)
RW × tmax7	1.108***
	(0.373)
RW × tmax8	2.100***
	(0.535)
RW × tmax9	-1.829***
	(0.414)
other GM × tmax5	-0.004
	(0.114)
other GM × tmax6	-0.544***
	(0.138)
other GM × tmax7	-0.091
	(0.108)
other GM × tmax8	-0.705***
	(0.125)
other GM × tmax9	1.038***
	(0.108)

Continued

PDSI5(wet)	-0.594***
	(0.070)
PDSI6(wet)	0.149
	(0.091)
PDSI7(wet)	-0.397***
	(0.064)
PDSI8(wet)	-0.583***
	(0.070)
PDSI9(wet)	-0.166***
	(0.063)
PDSI5(dry)	-4.155***
	(0.462)
PDSI6(dry)	2.785***
	(0.294)
PDSI7(dry)	0.386*
	(0.210)
PDSI8(dry)	-2.973***
	(0.251)
PDSI9(dry)	-0.447**
	(0.183)
PDSI5(wet) × planting density	0.020***
	(0.002)
PDSI6(wet) × planting density	-0.005
	(0.003)
PDSI7(wet) × planting density	0.014***
	(0.002)
PDSI8(wet) × planting density	0.021***
	(0.003)
PDSI9(wet) × planting density	0.006***
	(0.002)
PDSI5(dry) × planting density	0.147***
	(0.017)
PDSI6(dry) × planting density	-0.097***
	(0.011)
PDSI7(dry) × planting density	-0.018**
	(0.008)
PDSI8(dry) × planting density	0.103***
	(0.009)
PDSI9(dry) × planting density	0.016**
	(0.007)

Continued

RW × PDSI5(wet)	2.185***
	(0.381)
RW × PDSI6(wet)	-2.111***
	(0.438)
RW × PDSI7(wet)	0.998***
	(0.236)
RW × PDSI8(wet)	-0.148
	(0.479)
RW × PDSI9(wet)	1.175***
	(0.295)
other GM × PDSI5(wet)	0.609***
	(0.115)
other GM × PDSI6(wet)	-0.156
	(0.128)
other GM × PDSI7(wet)	0.681***
	(0.089)
other GM × PDSI8(wet)	0.904***
	(0.132)
other GM × PDSI9(wet)	-0.364***
	(0.133)
RW × PDSI5(dry)	5.027***
	(0.618)
RW × PDSI6(dry)	3.669***
	(1.292)
RW × PDSI7(dry)	-3.996***
	(0.473)
RW × PDSI8(dry)	2.584**
	(1.062)
RW × PDSI9(dry)	-0.459
	(0.881)
other GM × PDSI5(dry)	3.768***
	(0.503)
other GM × PDSI6(dry)	-3.970***
	(0.433)
other GM × PDSI7(dry)	0.189
	(0.272)
other GM × PDSI8(dry)	4.147***
	(0.386)
other GM × PDSI9(dry)	-0.420
	(0.275)

Continued

RW × tmin5 × planting density	-0.116***
	(0.018)
RW × tmin6 × planting density	-0.162***
	(0.018)
RW × tmin7 × planting density	0.145***
	(0.021)
RW × tmin8 × planting density	0.051***
	(0.012)
RW × tmin9 × planting density	-0.046***
	(0.011)
RW × tmax5 × planting density	0.095***
	(0.013)
RW × tmax6 × planting density	0.096***
	(0.018)
RW × tmax7 × planting density	-0.039***
	(0.012)
RW × tmax8 × planting density	-0.071***
	(0.018)
RW × tmax9 × planting density	0.064***
	(0.014)
other GM × tmin5 × planting density	0.012**
	(0.005)
other GM × tmin6 × planting density	0.023***
	(0.005)
other GM × tmin7 × planting density	-0.018***
	(0.005)
other GM × tmin8 × planting density	-0.040***
	(0.005)
other GM × tmin9 × planting density	0.042***
	(0.004)
other GM × tmax5 × planting density	0.000
	(0.004)
other GM × tmax6 × planting density	0.017***
	(0.005)
other GM × tmax7 × planting density	0.003
	(0.004)
other GM × tmax8 × planting density	0.022***
	(0.004)
other GM × tmax9 × planting density	-0.034***
	(0.004)

Continued

RW × PDSI5(wet) × planting density	-0.073***
	(0.012)
RW × PDSI6(wet) × planting density	0.072***
	(0.015)
RW × PDSI7(wet) × planting density	-0.035***
	(0.008)
RW × PDSI8(wet) × planting density	0.003
	(0.016)
RW × PDSI9(wet) × planting density	-0.038***
	(0.010)
RW × PDSI5(dry) × planting density	-0.172***
	(0.022)
RW × PDSI6(dry) × planting density	-0.129***
	(0.044)
RW × PDSI7(dry) × planting density	0.146***
	(0.017)
RW × PDSI8(dry) × planting density	-0.089**
	(0.035)
RW × PDSI9(dry) × planting density	0.012
	(0.029)
other GM × PDSI5(wet) × planting density	-0.020***
	(0.004)
other GM × PDSI6(wet) × planting density	0.005
	(0.004)
other GM × PDSI7(wet) × planting density	-0.024***
	(0.003)
other GM × PDSI8(wet) × planting density	-0.030***
	(0.005)
other GM × PDSI9(wet) × planting density	0.012***
	(0.005)
other GM × PDSI5(dry) × planting density	-0.133***
	(0.018)
other GM × PDSI6(dry) × planting density	0.142***
	(0.015)
other GM × PDSI7(dry) × planting density	-0.008
	(0.010)
other GM × PDSI8(dry) × planting density	-0.142***
	(0.013)
other GM × PDSI9(dry) × planting density	0.013
	(0.009)

Continued

1 if previous crop is corn	-0.006
	(0.032)
1 if previous crop is wheat	0.038
	(0.032)
1 if previous crop is alfalfa or alfalfa/hay	0.090***
	(0.031)
1 if previous crop is soybean	0.001
	(0.031)
1 if previous crop is lupine	-0.092***
	(0.033)
fall tillage, 1 if yes, 0 if no	-0.001
	(0.003)
spring tillage, 1 if yes, 0 if no	-0.048***
	(0.005)
apply insecticide, 1 if yes, 0 if no	-0.076***
	(0.005)
fertilizer N	0.000***
	(0.000)
Observations	28521
R-squared	0.705

Notes: Table regresses plot-level log of yield on plant density, weather variables(monthly average of daily minimum and maximum temperature(**tmin** and **tmax**), and monthly PDSI from May to September), GM variety dummies, and managerial inputs and practices. The specification also includes linear time trend, production fixed effect and the interactions among plant density, weather variables, and GM variety dummies. Units for **tmin** and **tmax** are °C. Unit for plant density is 1000 acre^{-1}. In consideration of the possible heteroskedasticity, Huber-White's robust standard errors are calculated and shown in parentheses. ***Significant at 1% level. **Significant at 5% level. *Significant at 10% level.

Table S3: Regression results of the main model specification without including the managerial inputs and practices as control variables

	lnyld
planting density	0.396***
	(0.020)
year	0.012***
	(0.000)
tmin5	0.142***
	(0.029)
tmin6	-0.310***
	(0.041)
tmin7	0.061
	(0.042)
tmin8	-0.237***
	(0.033)
tmin9	0.498***
	(0.033)
tmax5	-0.070***
	(0.025)
tmax6	0.195***
	(0.037)
tmax7	0.237***
	(0.034)
tmax8	0.210***
	(0.031)
tmax9	-0.100***
	(0.027)
tmin5 × planting density	-0.003***
	(0.001)
tmin6 × planting density	0.009***
	(0.001)
tmin7 × planting density	-0.001
	(0.002)
tmin8 × planting density	0.007***
	(0.001)
tmin9 × planting density	-0.016***
	(0.001)
tmax5 × planting density	0.002*
	(0.001)
tmax6 × planting density	-0.006***
	(0.001)
tmax7 × planting density	-0.008***
	(0.001)
tmax8 × planting density	-0.008***
	(0.001)
tmax9 × planting density	0.004***
	(0.001)

Continued

PDSI5(wet)	-0.046
	(0.033)
PDSI6(wet)	-0.168***
	(0.042)
PDSI7(wet)	0.212***
	(0.029)
PDSI8(wet)	-0.363***
	(0.038)
PDSI9(wet)	0.011
	(0.037)
PDSI5(dry)	-1.738***
	(0.068)
PDSI6(dry)	1.443***
	(0.110)
PDSI7(dry)	0.220***
	(0.074)
PDSI8(dry)	-1.538***
	(0.096)
PDSI9(dry)	-0.134
	(0.082)
PDSI5(wet) × planting density	0.001
	(0.001)
PDSI6(wet) × planting density	0.006***
	(0.001)
PDSI7(wet) × planting density	-0.007***
	(0.001)
PDSI8(wet) × planting density	0.013***
	(0.001)
PDSI9(wet) × planting density	-0.000
	(0.001)
PDSI5(dry) × planting density	0.060***
	(0.002)
PDSI6(dry) × planting density	-0.048***
	(0.004)
PDSI7(dry) × planting density	-0.010***
	(0.003)
PDSI8(dry) × planting density	0.052***
	(0.003)
PDSI9(dry) × planting density	0.004
	(0.003)
Observations	28521
R-squared	0.641

Notes: Table regresses plot-level log of yield on plant density, weather variables(monthly average of daily minimum and maximum temperature(**tmin** and **tmax**), and monthly PDSI from May to September), and the interactions between plant density and weather variables. The model also includes linear time trend and production zone fixed effect model. Units for **tmin** and **tmax** are °C. Unit for plant density is 1000 acre^{-1}. In consideration of the possible heteroskedasticity, Huber-White's robust standard errors are calculated and shown in parentheses. ***Significant at 1% level. **Significant at 5% level. *Significant at 10% level.

Table S4: Regression results of the second robustness check

	(1) lnyld
plant density	0.328***
	(0.019)
t	-0.007
	(0.005)
t × plant density	0.001***
	(0.000)
tmin5	0.173***
	(0.031)
tmin6	-0.112**
	(0.044)
tmin7	0.200***
	(0.039)
tmin8	-0.462***
	(0.033)
tmin9	0.441***
	(0.029)
tmax5	-0.025
	(0.026)
tmax6	0.018
	(0.042)
tmax7	0.194***
	(0.032)
tmax8	0.315***
	(0.031)
tmax9	-0.118***
	(0.028)
tmin5 × plant density	-0.004***
	(0.001)
tmin6 × plant density	0.002
	(0.002)
tmin7 × plant density	-0.007***
	(0.001)
tmin8 × plant density	0.016***
	(0.001)
tmin9 × plant density	-0.014***
	(0.001)
tmax5 × plant density	-0.000
	(0.001)
tmax6 × plant density	0.001
	(0.001)
tmax7 × plant density	-0.006***
	(0.001)
tmax8 × plant density	-0.012***
	(0.001)
tmax9 × plant density	0.004***
	(0.001)

Continued

PDSI5(wet)	-0.030
	(0.036)
PDSI6(wet)	-0.199***
	(0.042)
PDSI7(wet)	0.170***
	(0.030)
PDSI8(wet)	-0.467***
	(0.037)
PDSI9(wet)	0.014
	(0.036)
PDSI5(dry)	-1.475***
	(0.067)
PDSI6(dry)	1.946***
	(0.120)
PDSI7(dry)	-0.005
	(0.086)
PDSI8(dry)	-1.414***
	(0.086)
PDSI9(dry)	-0.624***
	(0.076)
PDSI5(wet) × plant density	-0.000
	(0.001)
PDSI6(wet) × plant density	0.007***
	(0.001)
PDSI7(wet) × plant density	-0.006***
	(0.001)
PDSI8(wet) × plant density	0.016***
	(0.001)
PDSI9(wet) × plant density	-0.000
	(0.001)
PDSI5(dry) × plant density	0.051***
	(0.002)
PDSI6(dry) × plant density	-0.067***
	(0.004)
PDSI7(dry) × plant density	-0.003
	(0.003)
PDSI8(dry) × plant density	0.048***
	(0.003)
PDSI9(dry) × plant density	0.022***
	(0.003)

Continued

1 if previous crop is corn	0.089***
	(0.026)
RW	0.036***
	(0.004)
other GM	0.039***
	(0.003)
1 if previous crop is wheat	0.128***
	(0.027)
1 if previous crop is alfalfa or alfalfa/hay	0.193***
	(0.026)
1 if previous crop is soybean	0.102***
	(0.026)
1 if previous crop is lupine	-0.175***
	(0.035)
fall tillage, 1 if yes, 0 if no	0.000
	(0.002)
spring tillage, 1 if yes, 0 if no	-0.038***
	(0.004)
apply insecticide, 1 if yes, 0 if no	-0.063***
	(0.004)
fertilizer N	0.000***
	(0.000)
Observations	28521
R-squared	0.662

Notes: Table regresses plot-level log of yield on plant density, weather variables(monthly average of daily minimum and maximum temperature(**tmin** and **tmax**), and monthly PDSI from May to September), the interactions between plant density and weather variables, and the managerial inputs and practices described in Table 1. The model also includes linear time trend, and production zone fixed effect model. The density effect is allowed to vary across years by including the interaction between plant density and time trend. Units for **tmin** and **tmax** are °C. Unit for plant density is 1000 acre^{-1}. In consideration of the possible heteroskedasticity, Huber-White's robust standard errors are calculated and shown in parentheses. ***Significant at 1% level. **Significant at 5% level. *Significant at 10% level.

Table S5: Regression results of the model using a quadratic form of precipitation as measure of water availability

	(1) lnyld
plant density	0.352***
	(0.020)
tmin5	0.135***
	(0.031)
tmin6	-0.501***
	(0.042)
tmin7	0.055
	(0.034)
tmin8	-0.133***
	(0.030)
tmin9	0.615***
	(0.034)
tmax5	-0.043*
	(0.023)
tmax6	0.405***
	(0.029)
tmax7	0.210***
	(0.032)
tmax8	0.058**
	(0.028)
tmax9	-0.272***
	(0.026)
tmin5 × plant density	-0.003***
	(0.001)
tmin6 × plant density	0.016***
	(0.001)
tmin7 × plant density	-0.001
	(0.001)
tmin8 × plant density	0.004***
	(0.001)
tmin9 × plant density	-0.021***
	(0.001)
tmax5 × plant density	0.001
	(0.001)
tmax6 × plant density	-0.012***
	(0.001)
tmax7 × plant density	-0.008***
	(0.001)
tmax8 × plant density	-0.002**
	(0.001)
tmax9 × plant density	0.010***
	(0.001)
prec	0.030***
	(0.007)
prec × plant density	-0.001***
	(0.000)
prec × prec × plant density	0.000***
	(0.000)

Continued

year	0.011***
	(0.000)
RW	0.034***
	(0.005)
other GM	0.026***
	(0.003)
1 if previous crop is corn	0.023
	(0.025)
1 if previous crop is wheat	0.094***
	(0.025)
1 if previous crop is alfalfa or alfalfa/hay	0.125***
	(0.024)
1 if previous crop is soybean	0.004
	(0.024)
1 if previous crop is lupine	-0.177***
	(0.040)
fall tillage, 1 if yes, 0 if no	-0.027***
	(0.003)
spring tillage, 1 if yes, 0 if no	-0.005
	(0.003)
apply insecticide, 1 if yes, 0 if no	-0.057***
	(0.003)
fertilizer N	0.000***
	(0.000)
Observations	28521
R-squared	0.627

Notes: Table regresses plot-level log of yield on plant density, weather variables(monthly average of daily minimum and maximum temperature(**tmin** and **tmax**), and a quadratic form of the mean of monthly cumulative precipitation for the whole growing season, the interactions between plant density and weather variables, and the managerial inputs and practices described in Table 1. The model also includes linear time trend and production zone fixed effect model. Units for **tmin** and **tmax** are °C. Unit for plant density is 1000 acre^{-1}. In consideration of the possible heteroskedasticity, Huber-White's robust standard errors are calculated and shown in parentheses. ***Significant at 1% level. **Significant at 5% level. *Significant at 10% level.

Table S6: Regression results of the model specification measuring water availability with a quadratic form of precipitation

	(1) lnyld
planting density	0.516***
	(0.047)
RW × planting density	-1.617***
	(0.091)
other GM × planting density	-0.322***
	(0.070)
tmin5	0.255***
	(0.057)
tmin6	-0.575***
	(0.091)
tmin7	-0.610***
	(0.061)
tmin8	0.359***
	(0.049)
tmin9	0.362***
	(0.042)
tmax5	-0.180***
	(0.048)
tmax6	0.493***
	(0.070)
tmax7	0.448***
	(0.043)
tmax8	-0.339***
	(0.048)
tmax9	0.161***
	(0.036)
tmin5 × planting density	-0.008***
	(0.002)
tmin6 × planting density	0.019***
	(0.003)
tmin7 × planting density	0.023***
	(0.002)
tmin8 × planting density	-0.014***
	(0.002)
tmin9 × planting density	-0.012***
	(0.002)
tmax5 × planting density	0.006***
	(0.002)
tmax6 × planting density	-0.016***
	(0.002)
tmax7 × planting density	-0.016***
	(0.002)
tmax8 × planting density	0.013***
	(0.002)
tmax9 × planting density	-0.005***
	(0.001)

Continued

RW × tmin5	-0.524***
	(0.141)
RW × tmin6	1.353***
	(0.182)
RW × tmin7	-0.146
	(0.236)
RW × tmin8	0.277
	(0.208)
RW × tmin9	0.057
	(0.210)
other GM × tmin5	-0.567***
	(0.108)
other GM × tmin6	0.629***
	(0.128)
other GM × tmin7	1.385***
	(0.096)
other GM × tmin8	0.214**
	(0.103)
other GM × tmin9	-0.920***
	(0.111)
RW × tmax5	0.586***
	(0.147)
RW × tmax6	-0.430**
	(0.184)
RW × tmax7	0.155
	(0.153)
RW × tmax8	-1.131***
	(0.185)
RW × tmax9	-0.667***
	(0.171)
other GM × tmax5	0.397***
	(0.088)
other GM × tmax6	-1.274***
	(0.119)
other GM × tmax7	-0.464***
	(0.077)
other GM × tmax8	0.216**
	(0.089)
other GM × tmax9	0.171*
	(0.089)

Continued

RW × tmin5 × planting density	0.018***
	(0.005)
RW × tmin6 × planting density	-0.050***
	(0.006)
RW × tmin7 × planting density	0.002
	(0.008)
RW × tmin8 × planting density	-0.002
	(0.007)
RW × tmin9 × planting density	-0.004
	(0.007)
RW × tmax5 × planting density	-0.023***
	(0.005)
RW × tmax6 × planting density	0.015**
	(0.006)
RW × tmax7 × planting density	-0.004
	(0.005)
RW × tmax8 × planting density	0.036***
	(0.006)
RW × tmax9 × planting density	0.025***
	(0.006)
other GM × tmin5 × planting density	0.018***
	(0.004)
other GM × tmin6 × planting density	-0.023***
	(0.004)
other GM × tmin7 × planting density	-0.049***
	(0.003)
other GM × tmin8 × planting density	-0.002
	(0.004)
other GM × tmin9 × planting density	0.029***
	(0.004)
other GM × tmax5 × planting density	-0.014***
	(0.003)
other GM × tmax6 × planting density	0.043***
	(0.004)
other GM × tmax7 × planting density	0.017***
	(0.003)
other GM × tmax8 × planting density	-0.010***
	(0.003)
other GM × tmax9 × planting density	-0.004
	(0.003)

Continued

prec	0.124***
	(0.017)
prec × prec	-0.001***
	(0.000)
prec × planting density	-0.004***
	(0.001)
prec × prec × planting density	0.000***
	(0.000)
RW × prec	-0.517***
	(0.029)
other GM × prec	-0.042*
	(0.023)
RW × prec × prec	0.002***
	(0.000)
other GM × prec × prec	0.000*
	(0.000)
RW × prec × prec × planting density	-0.000***
	(0.000)
other GM × prec × prec × planting density	-0.000**
	(0.000)
pcorn	0.047*
	(0.027)
1 if previous crop is wheat	0.113***
	(0.027)
1 if previous crop is alfalfa or alfalfa/hay	0.166***
	(0.026)
1 if previous crop is soybean	0.044*
	(0.026)
1 if previous crop is lupine	-0.067*
	(0.038)
fall tillage, 1 if yes, 0 if no	-0.037***
	(0.003)
spring tillage, 1 if yes, 0 if no	0.006
	(0.003)
apply insecticide, 1 if yes, 0 if no	-0.055***
	(0.004)
fertilizern N	0.000***
	(0.000)
Observations	28521
R-squared	0.665

Notes: Table regresses plot-level log of yield on plant density, weather variables(monthly average of daily minimum and maximum temperature(**tmin** and **tmax**), and a quadratic form of the mean of monthly cumulative precipitation for the whole growing season), GM variety dummies, and managerial inputs and practices. The specification also includes linear time trend, production fixed effect and the interactions among plant density, weather variables, and GM variety dummies. Units for **tmin** and **tmax** are °C. Unit for plant density is 1000 acre^{-1}. In consideration of the possible heteroskedasticity, Huber-White's robust standard errors are calculated and shown in parentheses. ***Significant at 1% level. **Significant at 5% level. *Significant at 10% level.

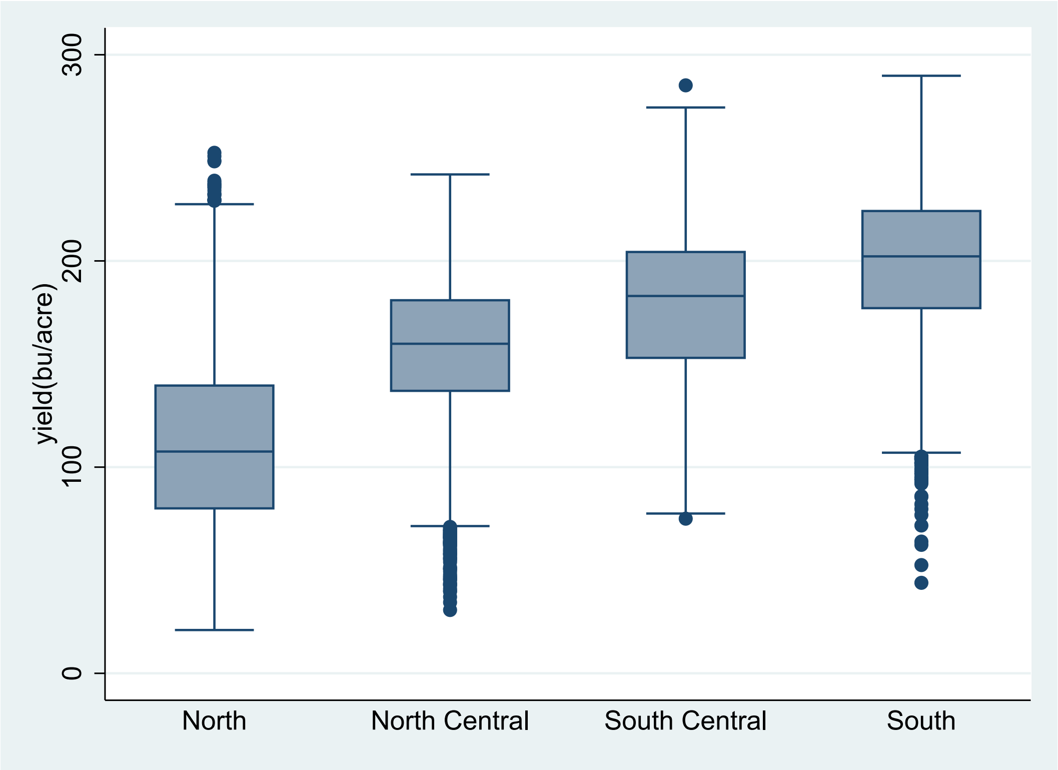

Figure S1: Distribution of yield for four production zones

Notes: Each box plot corresponds to the yield of plots in a production zone. The solid line in each distribution is the median. The upper hinge and the lower hinge are the 75^{th} and the $25th$ percentile values of yield separately. The upper adjacent line represents 75^{th} $percentile\ value + 1.5 \times interquantile\ range$ and the lower adjacent line represents 25^{th} $percentile\ value - 1.5 \times interquantile\ range$.

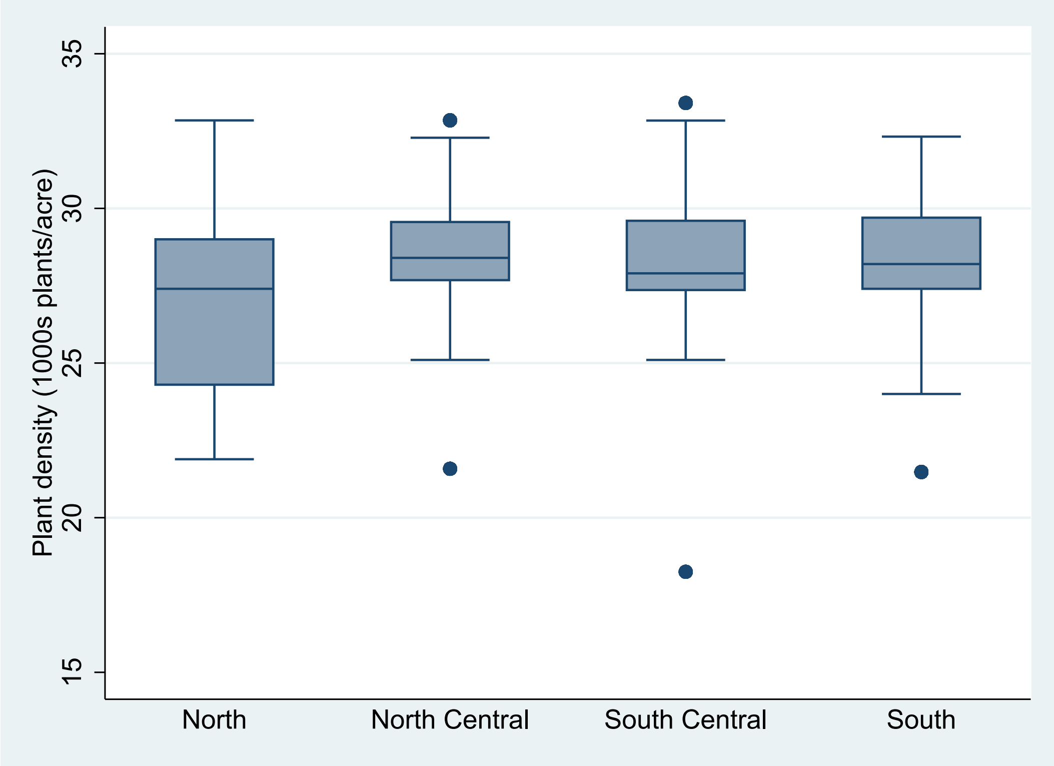

Figure S2: Distribution of plant density for four production zones

Notes: Each box plot corresponds to the plant density of plots in a production zone. The solid line in each distribution is the median. The upper hinge and the lower hinge are the 75^{th} and the $25th$ percentile values of plant density separately. The upper adjacent line represents 75^{th} $percentile\ value + 1.5 \times interquantile\ range$ and the lower adjacent line represents 25^{th} $percentile\ value - 1.5 \times interquantile\ range$.

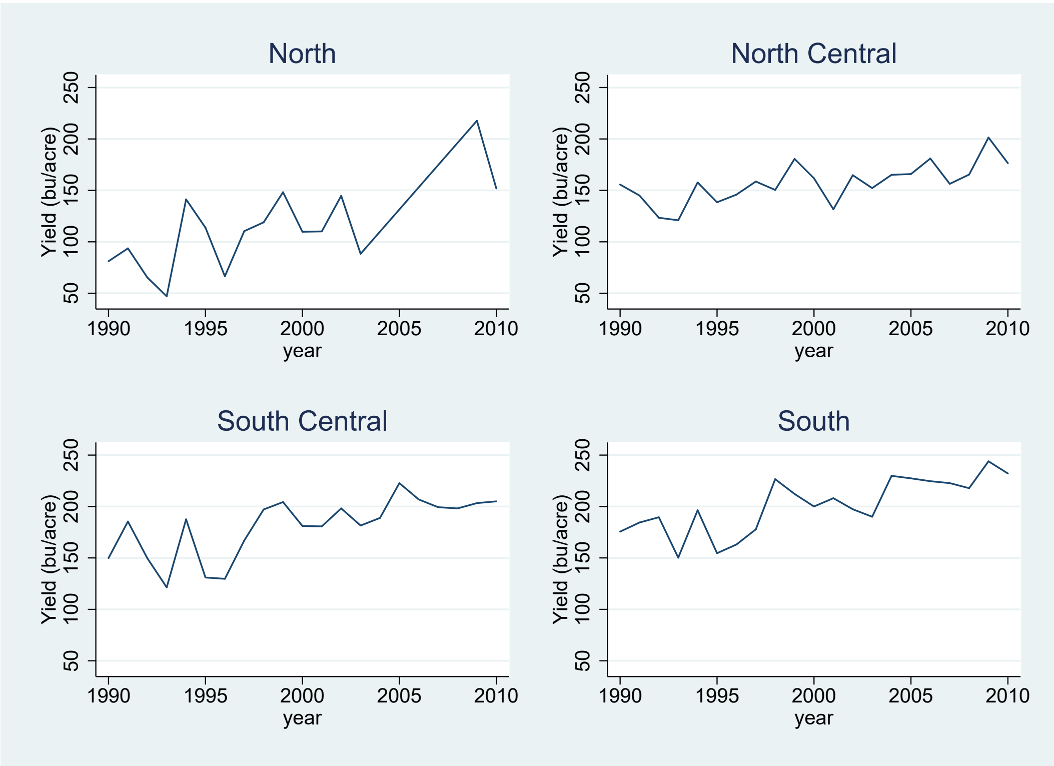

Figure S3: The change in the average corn yields in four production zones over years

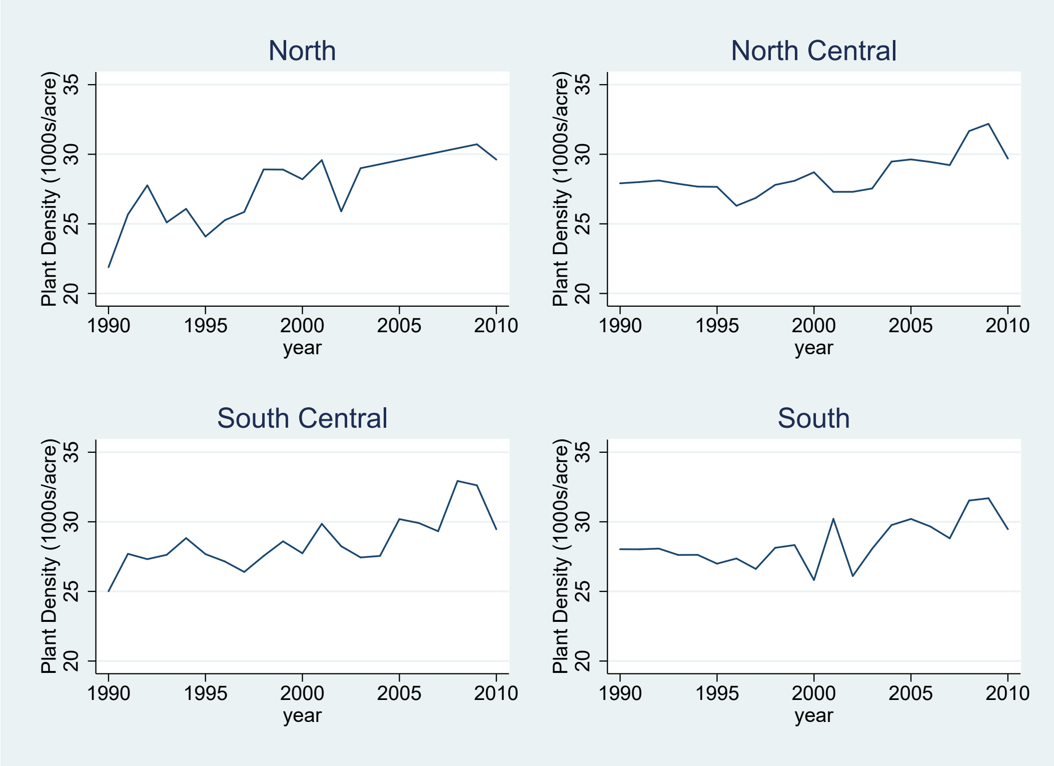

Figure S4: The change in the average of plant density in four production zones over years

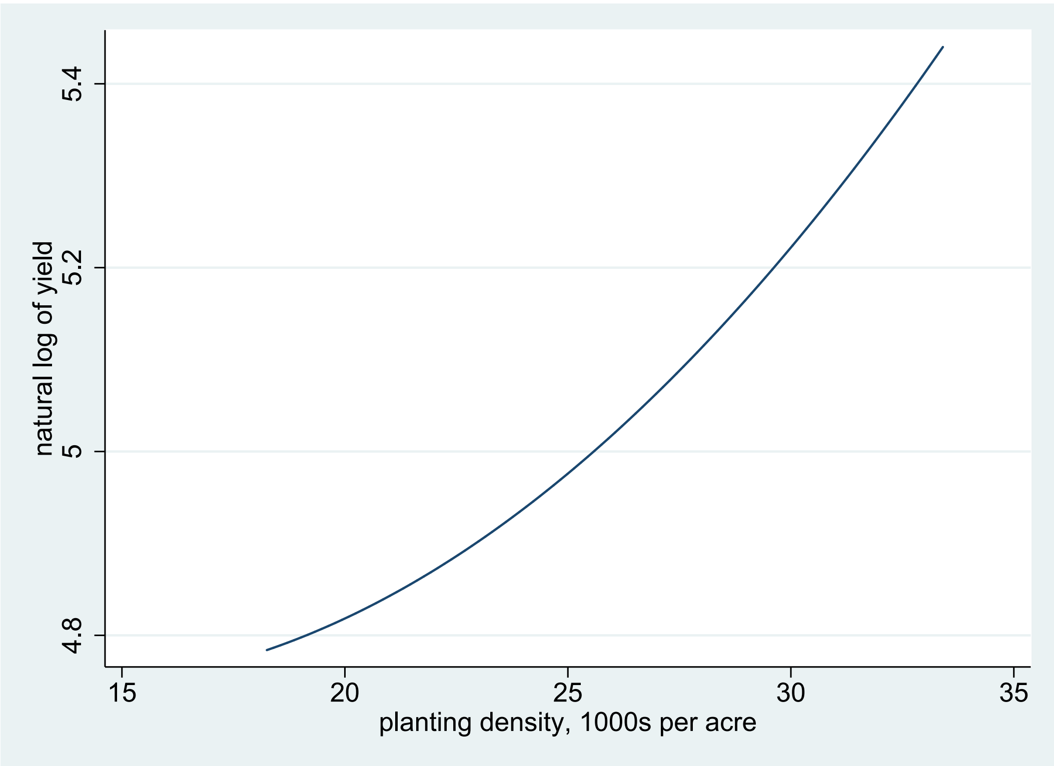

Figure S5: Regression of the natural log of yield on a quadratic form of plant density

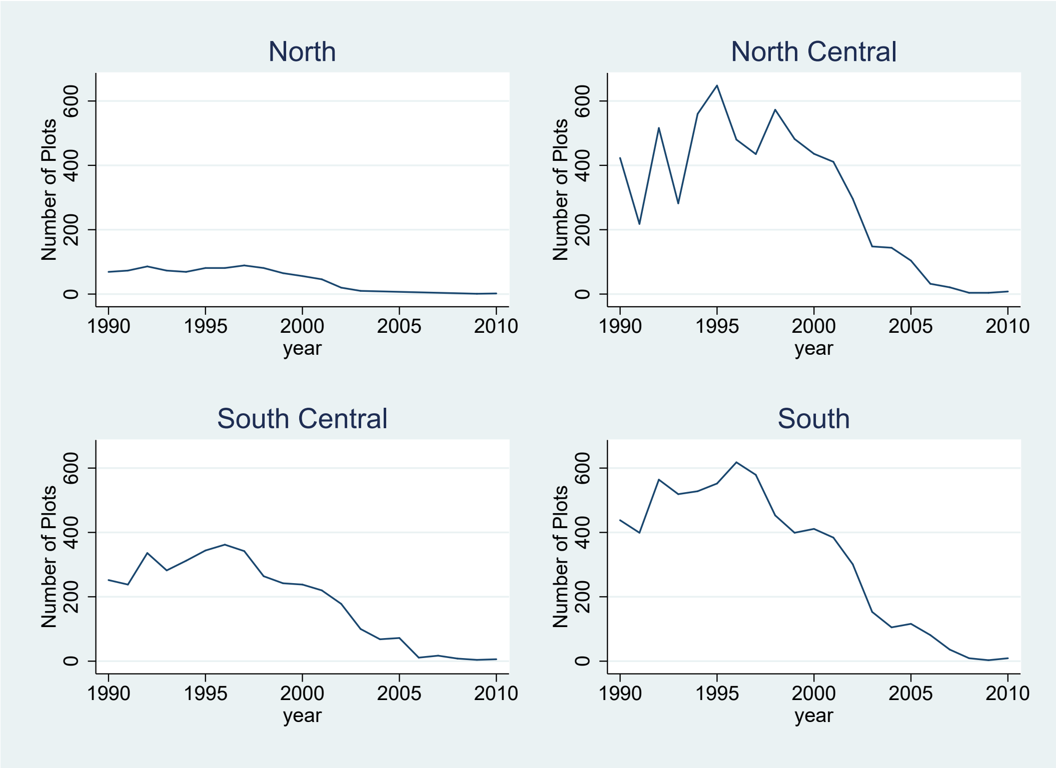

Figure S6: The change in number of plots planting conventional corn over years

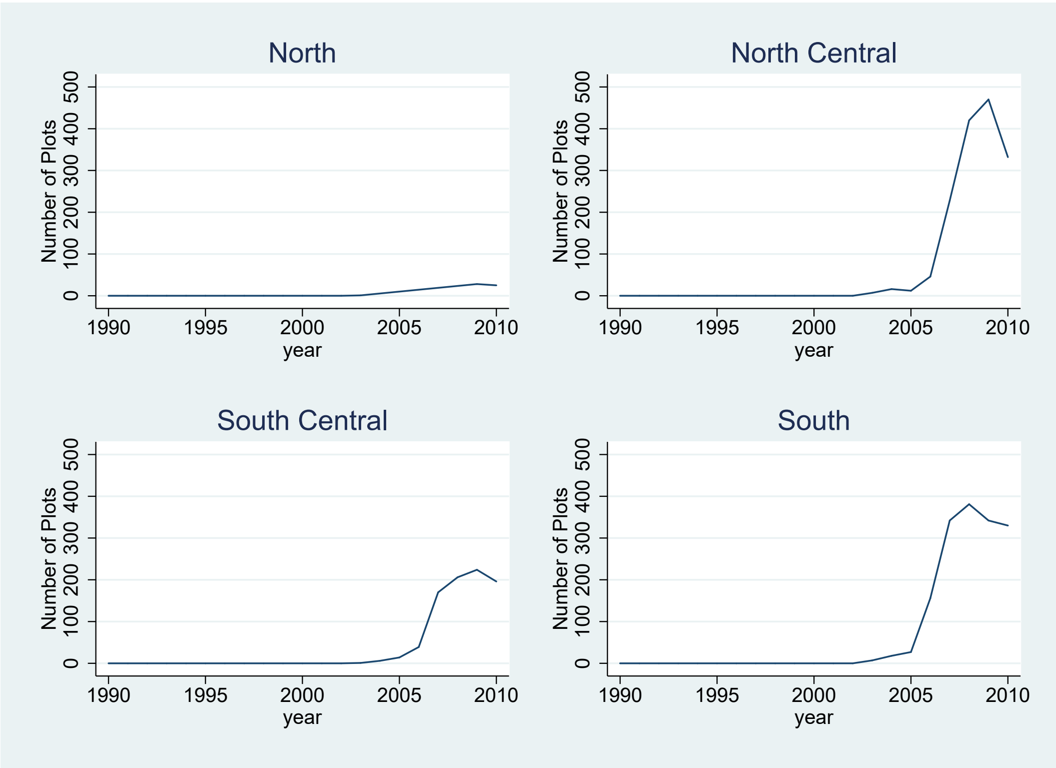

Figure S7: The change in number of plots planting GM corn with Bt trait for corn rootworm.

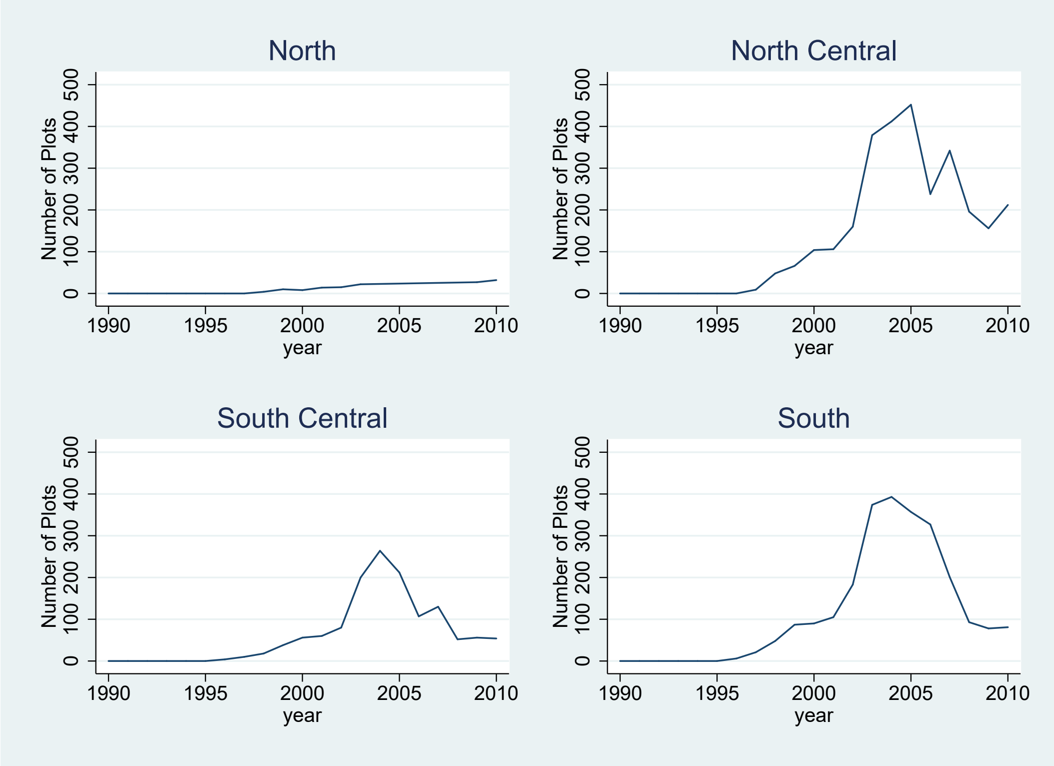

Figure S8: The change in number of plots planting GM corn without Bt trait for corn rootworm

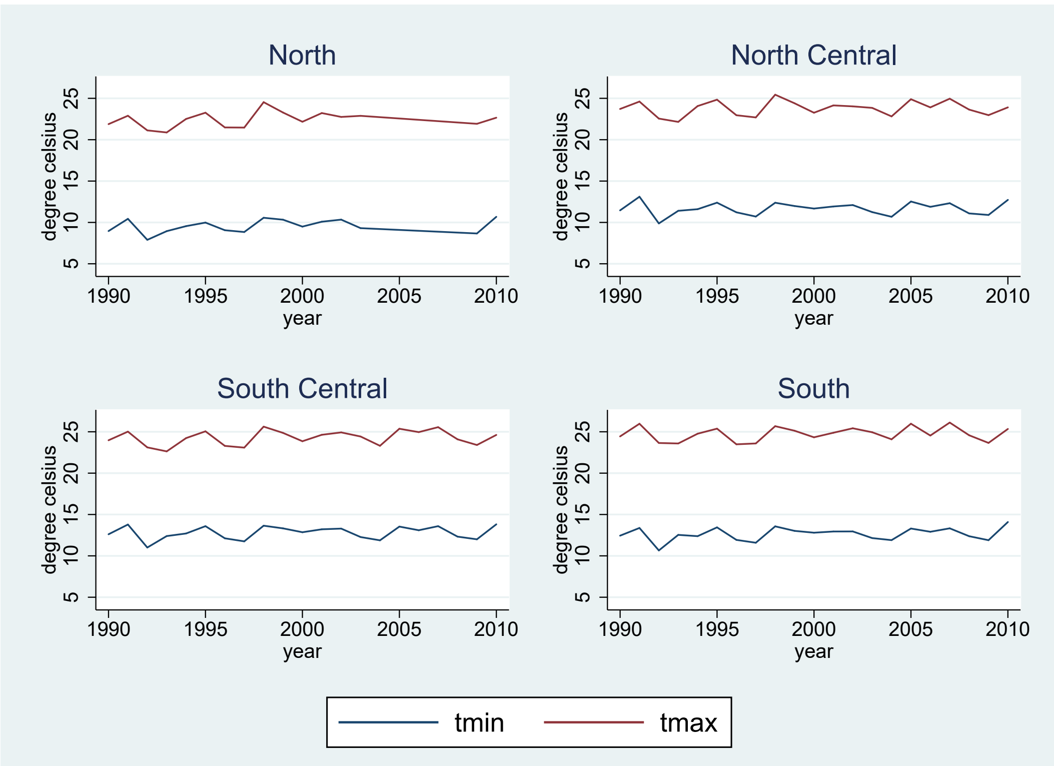

Figure S9: The change in **tmin** and **tmax** across years

Notes: **tmin** and **tmax** are the average of monthly minimum and maximum temperature during the May-September growing season

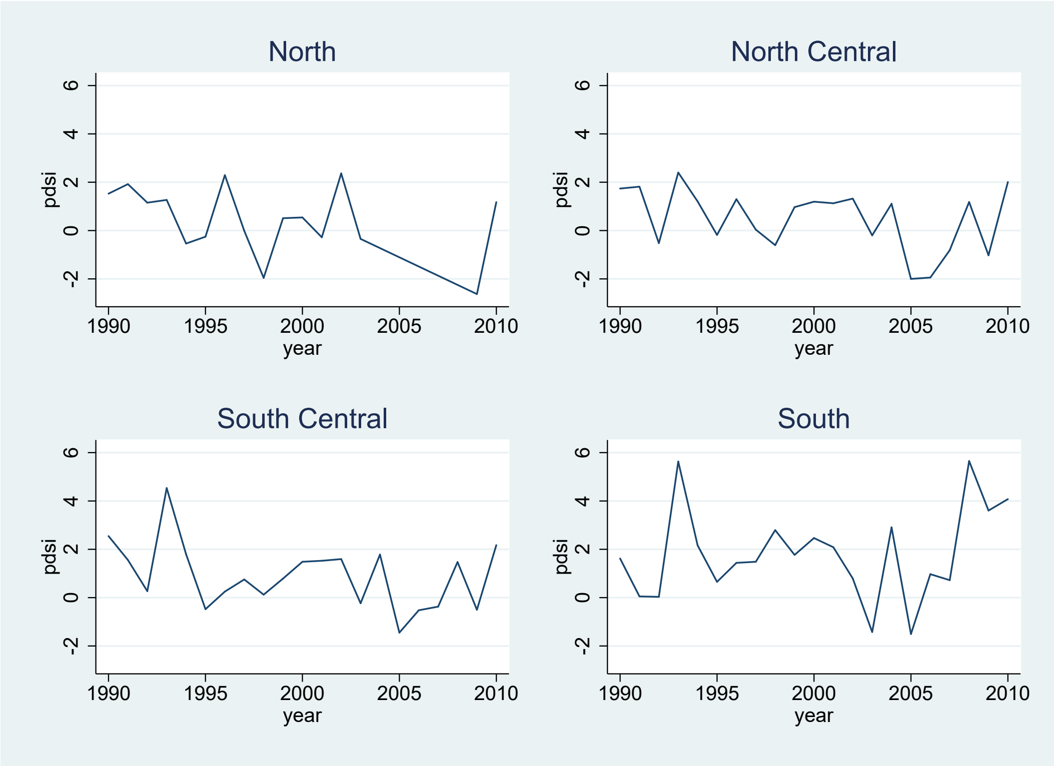

Figure S10: The change in PDSI across years

Notes: PDSI here are the average of monthly PDSI during the May-September growing season