Do Temperature Thresholds Threaten American Farmland?

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Abstract

In this paper we use flexible functional forms to estimate the marginal effect of mean temperatures during 3-hour, daily and longer time intervals on land values. We use US Agricultural Census Data and detailed climate data obtained from the NARR model, a very large dataset that contains climatic data on 3-hour time intervals, at fine spatial resolution, from 1979 to present day. The paper finds no evidence of temperature threshold effects on land values and in the Eastern United States. The flexible functional forms suggest inverted-U shaped or almost constant marginal effects at different levels of temperature whether one is using average temperature over 3-hour, daily, continuous days or the growing season. We find instead evidence that land values in areas that are frequently affected by extreme heat waves reflect large expected productivity losses. Using annual yields and weather data we find evidence that both cold and high temperatures reduce corn, soybeans, and to a lesser extent, cotton yields. The downward sloping section of the relationship that relates temperature and yields is steeper than the upward sloping section but we do not find evidence of sudden discontinuities.

Keywords: agriculture, climate change, weather, crop yields, ricardian, threshold.

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1 Introduction

Most cross-sectional Ricardian models use a quadratic functional form to relate mean seasonal temperature and the value of American farmland (Mendelsohn, Nordhaus, and Shaw 1994; Schlenker, Hanemann, and Fisher 2005; Deschênes and Greenstone 2007; Massetti and Mendelsohn 2011, 2012). These studies consistently find a smooth inverted-U shaped relationship between land value and temperatures. This finding confirms agronomic evidence that crops suffer from both low and high temperatures (Ritchie and NeSmith 1991; Basra 2001).

A different set of studies suggests that the quadratic functional form is not flexible enough to represent sharp non-linearities in the relationship between temperature and land values or between temperature and crop yields. This more recent literature stresses the possibility that high temperatures may be more harmful than a quadratic functional form would suggest. Schlenker, Hanemann, and Fisher (2006) (SHF henceforth) use a quadratic functional form of degree days between 8 and 32°C over the growing season in the Eastern United States and separately control for the number of degree days above 34°C.[1] SHF find that the overall relationship between land values and degree days is quadratic, but days with temperature above 34°C are very harmful, thus revealing a threshold not captured by the quadratic functional form. Schlenker and Roberts (2009) (SR henceforth) focus on annual crop yields and annual temperatures using a flexible functional form to separately identify the impact of one hour spent at narrow temperature intervals during the growing season. SR find that temperatures between 0°C and 29°C, 30°C and 32°C (respectively for corn, soybeans and cotton) do not have a statistically significant effect on crop yields but once temperature crosses the crop-specific thresholds it becomes very harmful. Such thresholds suggest that climate change poses a great threat to humanity because farm production would plummet as daily and hourly temperatures start to exceed this threshold. This threshold research echoes concerns in the environmental community that it is not the change in mean temperature that matters but rather the change in the extremes (in this case, temperature extremes).

In a recent paper we find that the importance of using degree days instead of seasonal mean temperature may have been overstated because degree days between 8 and 32°C are highly correlated in the Eastern United States. We also do not find evidence of a threshold at 34°C (Massetti, Mendelsohn, and Chonabayashi 2013). However, as suggested by SR the identification of a temperature threshold may require a fully flexible model rather than ad-hoc assumptions on specific temperature levels.

In this paper we use a Ricardian model to estimate the impact of temperature on land values using several flexible function forms. As in SHF and SR, we limit our analysis to land values in counties east of the 100th meridian in the United States, where agriculture is mainly rain fed. We rely on flexible functional forms that measure marginal temperature effects within narrow bands across the observed range of temperatures in the sample. We rely on a temporally detailed meteorological data set of temperature and precipitation, the North America Regional Reanalysis (NARR) (National Climate Data

[1] In Schlenker, Hanemann, and Fisher (2006) a day with mean daily temperature t °C contributes with t-8 degree days if $8 < t \leq 32$ and with 24 degree days if $t > 32$. A day in which $t > 34$ has $t - 34$ degree days above 34°C. Degree days are summed over all days from April to September.

Center 2012). This is a monumental data set containing both very small grid cells and also three hour observations of weather from 1979 through present day. Contrary to previous studies in the literature, we are able to precisely measure temperatures over short time intervals instead of deriving them using smoothing methods based on monthly minimum and maximum temperatures (SHF) or on the combination of monthly temperatures and daily observations from a limited number of weather stations (SR).

We conduct these tests using 3-hour and daily temperatures. Our rich dataset makes it also possible to test how mean temperature over 5/7/14 consecutive days affects land values. We finally estimate functional models based on the growing season mean temperatures.

Although the focus of this paper is on the relationship between long-term averages of temperatures and land values, we test whether a threshold exists in the relationship between temperature outcomes in a specific year and corn, soybeans and cotton yields in that year.

The paper finds no evidence of temperature threshold effects on both land values and crop yields in the Eastern United States. The flexible functional forms suggest inverted-U shaped or almost constant marginal effects at different levels of temperature whether one is using hourly, daily, average temperature over continuous days or seasonal temperature. Of course, that does not mean land values and crops are not sensitive to temperature. High temperature (as well as low temperatures) negatively affect both land values and crop yields. However, we do not find sharp discontinuities.

We find that models that identify climate sensitivity using temperatures observed over very short term intervals (hours or days) are more unstable than models that use average conditions over longer time periods. This suggests that temperature observations may be imperfectly time separable.

We observe threshold effects only at extremely high temperatures. However, this is a spurious correlation as those temperatures are observed only during major and very rare heat waves, mainly in the Central Plains of the United States. The threshold disappears once we control for the frequency of observing those abnormal climatic conditions but areas that are frequently affected by extreme heat waves are susceptible to record large productivity losses and thus have lower land values.

Our results are consistent with other studies that estimate the seasonal impact of temperature on land values. If a threshold existed, higher seasonal temperatures should have been more harmful because they would invariably have included more days above the threshold. This would have been especially evident in studies of tropical regions such as Africa and Latin America which span the equator. Although higher temperatures are harmful in these regions (Kurukulasuriya et al. 2006; Seo and Mendelsohn 2008), there is no evidence of dramatic losses at relatively high seasonal temperatures.

The next section of the paper reviews the methodology to measure climate effects. Section 3 examines the climate data in more detail since this data is one important difference between this paper and other studies. Section 4 displays the results. The paper concludes with a discussion of the limitations of the research, the main conclusions, and the policy implications.

2 Methodology

We consider a traditional Ricardian model of the relationship between land value and climate (Mendelsohn, Nordhaus, and Shaw 1994):

$$\mathrm{Y_{i,t}} = \beta\, \mathrm{h(C_i)} + \gamma \mathrm{X_{i,t}} + \theta \mathrm{Z_i} + \epsilon_{\mathrm{i,t}} \tag{1}$$

where Y is land value per hectare at time t for observation i, $h(\cdot)$ is a generic function of the vector of climate variables C, X is a set of socio-economic variables that vary over time, Z is a set of geographic and soil characteristics that are fixed over time, and ε is assumed to be a random component. Several studies found that a loglinear functional form fits agricultural land values more closely than a linear model (Mendelsohn and Dinar 2003, Schlenker, Hanemann and Fisher 2005; 2006; Massetti and Mendelsohn 2011; 2012). This study also uses a loglinear functional form so that $Y_{i,t}$ is the log of land value per hectare.

In all the Ricardian studies of US agriculture, the relationship between climate and land values is assumed to be nonlinear. This nonlinearity has traditionally been captured using a quadratic model of temperature and precipitation. This assumption has been supported by the data as the squared terms on climate have generally been statistically significant. The previous studies have also all assumed that seasonal effects are important. This assumption has been verified by the data which reveals seasonal effects are significantly different (Mendelsohn, Nordhaus, and Shaw 1994; Massetti, Mendelsohn, and Chonabayashi 2013). However, in this paper we focus on the months from April to September, following the assumption of the literature that uses flexible forms. We also follow the literature in limiting our analysis to counties east of the 100th meridian, where agriculture is mostly rain fed.

We adapt the model proposed by Schlenker and Roberts (2009) and we estimate the following model with a pooled OLS regression:

$$Y_{i,t} = \alpha + \sum_{j=-1,0,3,6,\dots}^{J} \beta_j x_{i,j} + \gamma_1 P_i + \gamma_2 P_i^2 + \boldsymbol{\eta} X_{i,t} + \boldsymbol{\theta} Z_i + \epsilon_{i,t} \tag{2}$$

where $Y_{i,t}$ is the log of average value of land per hectare in county *i* at time *t*, $x_{i,j}$ is long-run average of the number of 3-hour time intervals, days or consecutive days with mean temperature between j and $j + 3$°C, P_i is the long-run average mean precipitations between Apr-Sep, $X_{i,t}$ are time-varying control variables and Z_i are time-invariant control variables. Z_i includes measurements of soil characteristics, of local geographic conditions and in some models, also indicators of the frequency of very high temperature spells in county *i*. All time intervals with temperature below freezing are counted together in the $j = -1$ bin. Temperatures that are very high are also counted together in the $j = J$ bin, where J varies depending on the time interval used (i.e. 3-hour, day, …).

The assumption in the Ricardian literature is that land values are only affected by long-term climatic conditions that affect the expectations of farmers about the productivity of farmland. Land values reflect the long-term productivity of agricultural land after all the economically efficient adaptations have been adopted. Therefore, land values may not exhibit thresholds because farmers can switch crops, change management practices and switch from cropland to rangeland or other land uses. Adaptation makes the long-term relationship between temperature and land values smoother. It is therefore worth examining the effect of weather shocks on major crop yields following the same set-up of Schlenker and Roberts (2009) with our more accurate weather dataset:

$$Y_{i,t} = \sum_{j=-1,0,3,6,\dots}^{J} \beta_j x_{i,t,j} + \gamma_1 P_{i,t} + \gamma_2 P_{i,t}^2 + \boldsymbol{\eta} X_{i,t} + \eta_i + \epsilon_{i,t} \tag{3}$$

where $Y_{i,t}$ is the log of yield per hectare in county *i* in year t, $x_{i,t,j}$ is the number of 3-hour time intervals, days or consecutive days with mean temperature between j and $j+3$ °C in year t, $P_{i,t}$ is the amount of rainfall during April September in year t, $X_{i,t}$ contains a state by year quadratic time trend and η_i is a county fixed effect.

3 Data

3.1 Climate Data

Temperature data in Schlenker and Roberts (2009) was not observed but rather was constructed from a spatially disaggregated dataset of monthly temperatures and a set of daily temperature observations from a limited number of weather stations. Hourly data was estimated using a smoothing sinusoidal function of daily minimum and maximum temperatures.

This paper relies instead on a data set generated by the National Climatic Data Center called the North American Regional Reanalysis (NARR).[2] The NARR dataset provides a high spatial (32 km) and temporal (3 hour) analysis of the historic climate of North America and adjacent oceans from October 1979 to December 2011. Using the NARR data, we compute mean daily temperature from the eight reported measures of 3 hour temperature in each day. We also use the 3 hour values but we do not estimate hourly temperatures as the exercise may be prone to errors. Furthermore, in the agronomic literature there are not clear indications that crops are sensitive to very short temperature changes in the range of temperatures typically observed in the Eastern United States.

For each NARR grid cell we compute the amount of time spent at each 3°C temperature bin during each year from 1979 to 2007. We then compute the average time spent at each 3°C temperature interval in

[2] See http://nomads.ncdc.noaa.gov/docs/ncdc-narrdsi-6175-final.pdf for further information.

the years 1979-2007. Finally, we aggregate data at the county's centroid using the four closest grid cells, with weights inverse to distance.[3]

In the SR exercise measurement errors may emerge in pairing monthly and daily temperatures and in estimating hourly temperatures from daily minimum and maximum temperatures. A comparison of the SR data and the NARR data reveals a similar distribution of daily mean temperature over all counties east of the 100th meridian during the years 1979-2005 but NARR temperatures are on average higher (see Figure A - 1 in the Appendix). The differences are bigger at the tails of the distribution. For example, in the NARR dataset days with mean temperature in the 27-30°C and in the 30-33°C intervals are 30% and 70% more frequent than in the SR data. Furthermore, the NARR dataset reveals that infra-daily temperatures are not normally distributed. Under average conditions the distribution of temperature is right-skewed. In very hot days the distribution of temperature is instead left-skewed. The infra-daily distribution of temperature is not uniform over space and is linked to well-defined geographic conditions. A sinusoidal curve based on daily minimum and maximum observations would introduce measurement error that is correlated with other climatic and geographic conditions (Massetti, Mendelsohn, and Chonabayashi 2013).

The NARR data also reveals that the distribution of temperature is negatively skewed from April to September in the Eastern United States. Extremely high temperatures occur rarely. 90% of the 3-hour time intervals and 96% of daily mean temperatures observed from 1979 to 2007 over the Eastern United States are below 30°C. 97% of prolonged intervals of 5, 7 or 14 days have average temperature below 30°C. For this reason we group very high temperatures in one single bin. We repeat each exercise using 36, 39 and 42°C as the last bins for 3-hour temperatures and 30, 33 and 36°C for other time spans. Also temperatures below freezing are very rare during the growing season and are grouped into a single bin.

It is instructive to note that extremely high temperatures (3-hour intervals above 42°C and mean daily temperatures above 42°C) are very rare, they occur only in the Central Plains of the United States mainly along the Texas-Oklahoma border, and also tend to happen in clusters (Figure A - 2 and Figure A - 3 in the Appendix). That is, they tend to be associated with "heat waves". During these events temperatures remain very high for several days in a row. These higher bins consequently are a poor proxy for an extreme event, "a heat wave", which has its own unique meteorological characteristics in addition to being warm.

3.2 Farmland Value and Control Variables

We build a balanced panel using US Agricultural Census data for 1982, 1987, 1992, 1997, 2002 and 2007. We use the following time varying socio-economic variables: income per capita, population density, population density squared, residential house price index. We also control for a set of geographic, time invariant characteristics at counties centroids: latitude, elevation, and distance from major metropolitan areas. We use USGS data to estimate the average annual surface and ground water use per hectare of

[3] Robustness tests in Massetti, Mendelsohn, and Chonabayashi (2013) show that alternative methods to aggregate grid cells do not generate significant differences in impact estimates.

farmland during 1982-2007. Finally, we control for some important soil characteristics: salinity, percentage of soil subject to flooding, percentage of land with low drainage, soil erodibility, average slope length factor, percentage of sand and of clay, minimum available water capacity, and permeability. We include 2,406 out of the 2,471 counties east of the 100th meridian. Further details on the data used are available in the Appendix.

We obtain data on corn, soybeans and cotton crop yields on harvested acres for counties east of the 100th meridian, for the years 1979-2007, from the USDA National Agricultural Statistical Service.

4 Results

4.1 Flexible Form Tests of Any Thresholds on Land Values

As in SR we adopt a flexible functional form in the following analysis to test for thresholds of temperature. Rather than just daily temperature thresholds, we examine a full range of thresholds at different durations. We explore 3 hour and daily temperatures, the average temperature in 3, 7 and 14 consecutive days, and average growing season temperatures. In each case, we group temperature in 3°C bands and then estimate the marginal impact of temperature in each band separately (with an interaction terms between temperature and a dummy for that band). These tests check directly whether there are sharp discontinuities at different temperature and precipitation levels. We make these tests with and without state fixed effects.

Our first set of results is summarized in Figure 1 and Figure 2. The figures report central estimates and 95% robust confidence intervals of the marginal impact of changing one time unit in the 18-21°C interval (omitted in the regression) with the same time unit at a different temperature. Our results reveal that the relationship between land values and mean temperature measured at 3-hour and daily intervals is quite erratic, especially for temperatures below 18°C and when we do not use state fixed effects. The relationship becomes more stable as we move from 3-hour to daily mean temperatures. If we abstract from the lowest temperatures, quite rare in the Eastern United States during April-September, an irregular inverted-U shaped pattern roughly relates temperature and land values. We generally do not find evidence of a threshold at high temperatures. However, in order to be comprehensive, we further examine the possibility that thresholds appear at temperatures higher than 42°C for 3-hour time intervals and higher than 36°C for daily means. We discuss further below this additional set of results.

Before moving to the effect of extremely high temperatures we turn our attention to the optimal time-span over which temperatures should be measured in flexible models. The large, almost erratic, fluctuations that we record, especially at the low temperatures, reflect some problems of the method used. First, as only few counties have very low or very high temperatures, the temperature bins at the tails of the distribution may select some uncontrolled characteristics of those counties. Second, in the 3-hour temperature bins we may observe day/night effects that we are not able to separate.[4] More in

[4] Preliminary results indicate that separating day and nights reduces the sudden reversals of the coefficients.

general we are not separating between different seasons within April-September. This means that we may inadvertently pick some Spring/Summer/Fall effects. Finally, the effect of temperatures over short time periods may not be easily identifiable.

Agronomic experiments have mainly focused on testing the effect of constant conditions and have repeatedly shown that temperatures at night and during the day have markedly different conditions. For example, corn grows well when days are warm and nights are cool. Pooling together cool summer nights and cool spring afternoons may lead to non-significant or erratic impacts of marginal temperature impacts on agricultural productivity.

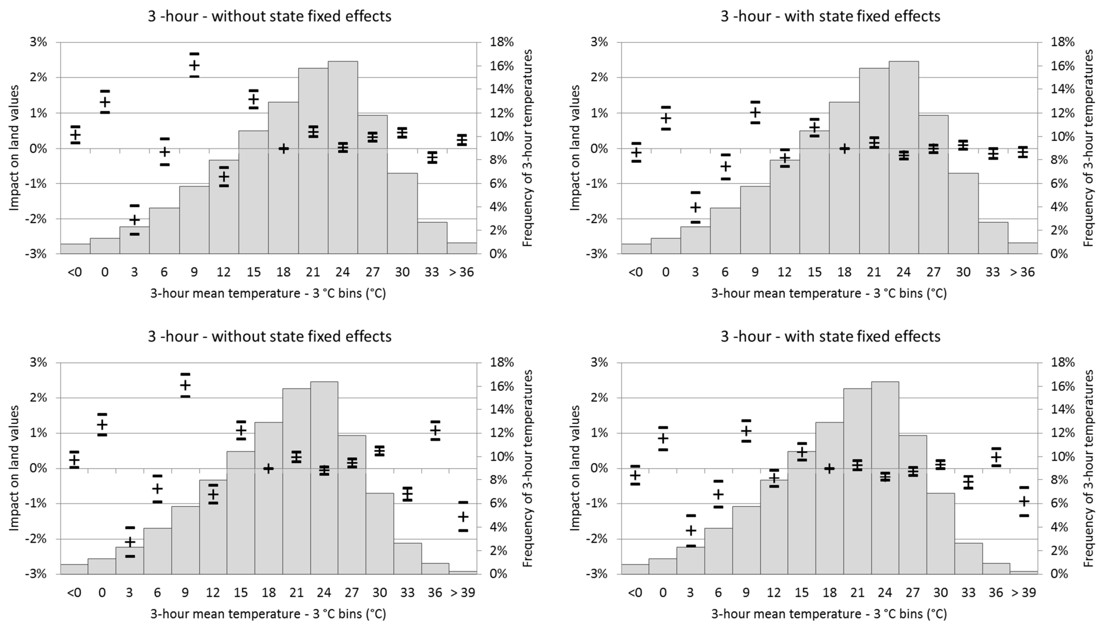
Using average conditions over periods longer than hours or days would attenuate these problems. We start by using average temperature over 3, 7 and 14 consecutive days and we conclude using the mean daily temperature over April-September.[5] As Figure 3 shows, our results indicate that the overall relationship between land values and climate becomes smoother and more regular as we extend the length of the intervals over which average temperature is computed. A rather flat, inverted-U shaped relationship appear as we move from 3 to 7 and to 14 consecutive days. Also in this case, we do not find evidence of a threshold at the high temperatures.

Finally, we interact mean daily temperature in April-September with dummies for each 1°C interval to estimate the marginal impact of uniform warming over the whole growing season. In this case we also include a flexible functional form for mean precipitations over the growing season.[6] The results for average daily temperature and monthly precipitation over the growing season are reported in Figure 4. Whether or not one uses fixed effects, the analysis suggests that warmer temperatures have an almost constant negative marginal impact on land values. The results suggest that the quadratic functional form was too nonlinear and should have been flatter. There is absolutely no evidence of a temperature threshold. Finally, it is interesting to note that the confidence intervals around the marginal estimates are much tighter with the flexible functional form compared to the quadratic model.[7]

[5] For each grid point of the NARR dataset and for each day in April-September we estimate the mean temperature 3, 7 and 14 consecutive days. We then count how many consecutive intervals of 3, 7 and 14 days we record during April-September

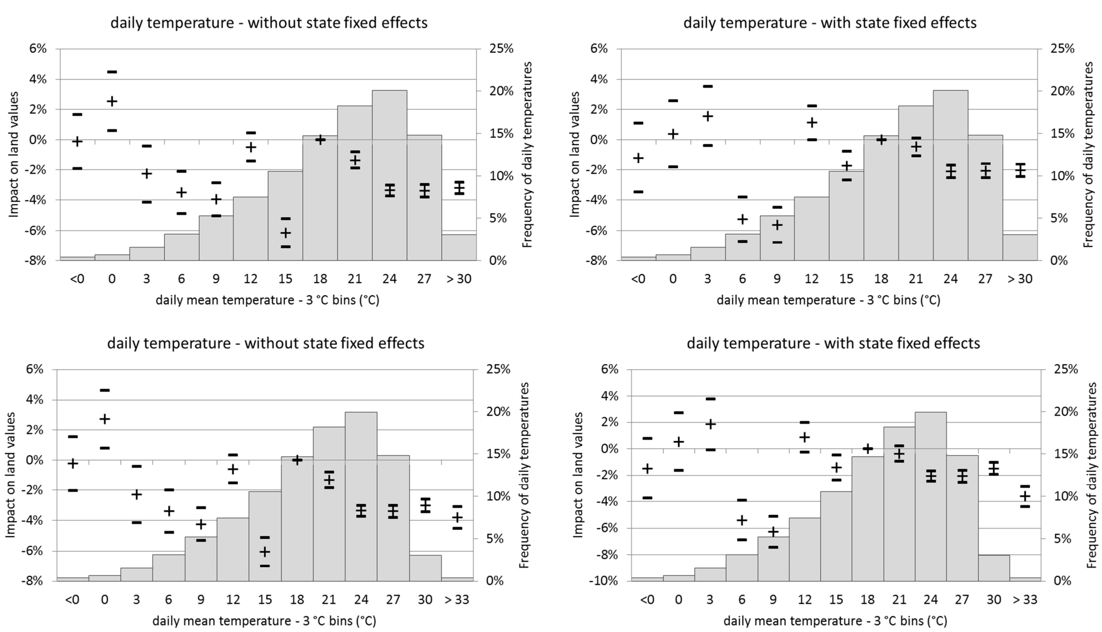
[6] Results show that including a flexible functional form for precipitations increases the forecasting power of the model but does not significantly affect temperature marginals.

[7] We tested the same model using a flexible functional form also for precipitations. The marginal impact of temperature is largely unaffected. Results suggest a beneficial effect of more rainfall that varies depending on whether a county is relatively dry, normal, or wet. More rainfall is more beneficial in relatively dry counties. Rainfall starts to become harmful, however, in very wet counties.



Notes: distribution of 3-hour mean temperature intervals over all grid points of the NARR dataset east of the 100th meridian in the United States from 1979 to 2007. The figure reports the marginal impact and the 95% confidence interval of adding one 3-hour time interval, compared to a time interval at 18°C.

Figure 1. Flexible models of 3-hour temperature intervals.



Notes: distribution of daily mean temperature over all grid points of the NARR dataset east of the 100th meridian in the United States from 1979 to 2007. The figure reports the marginal impact and the 95% confidence interval of adding one 3-hour time interval, compared to a time interval at 18°C.

Figure 2. Flexible models of daily temperature intervals.

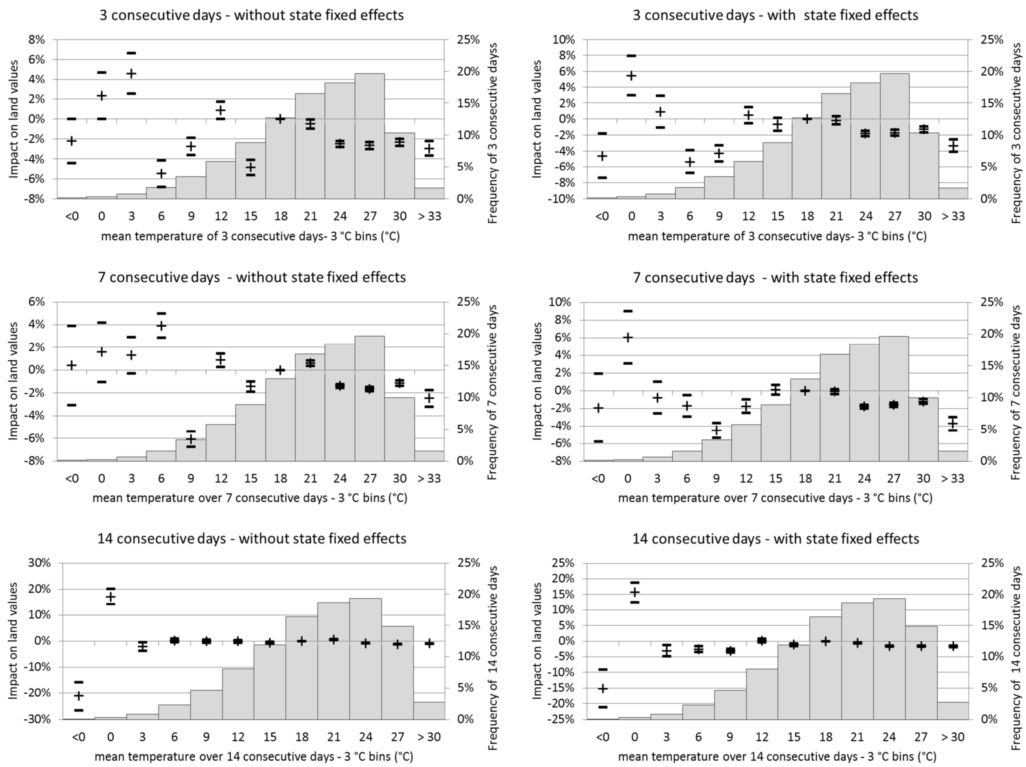
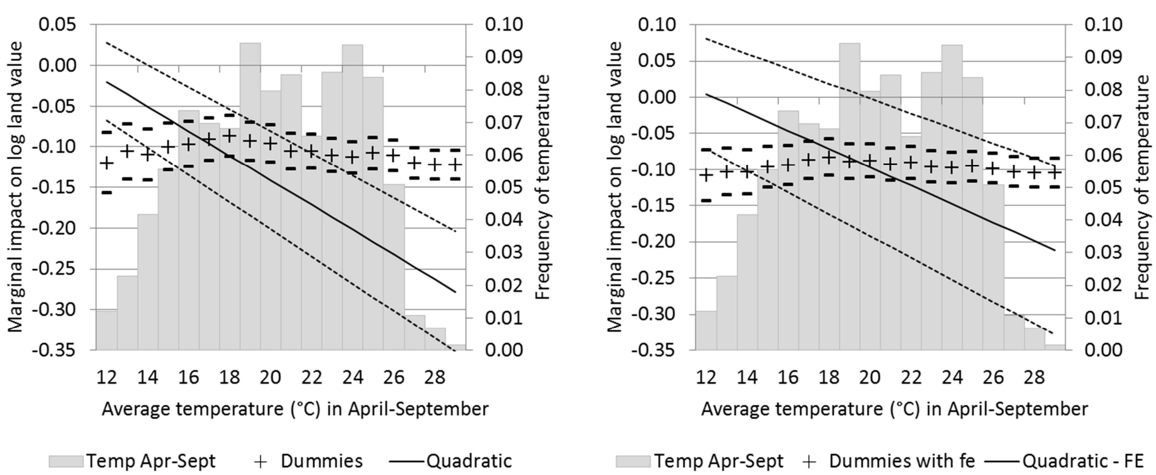
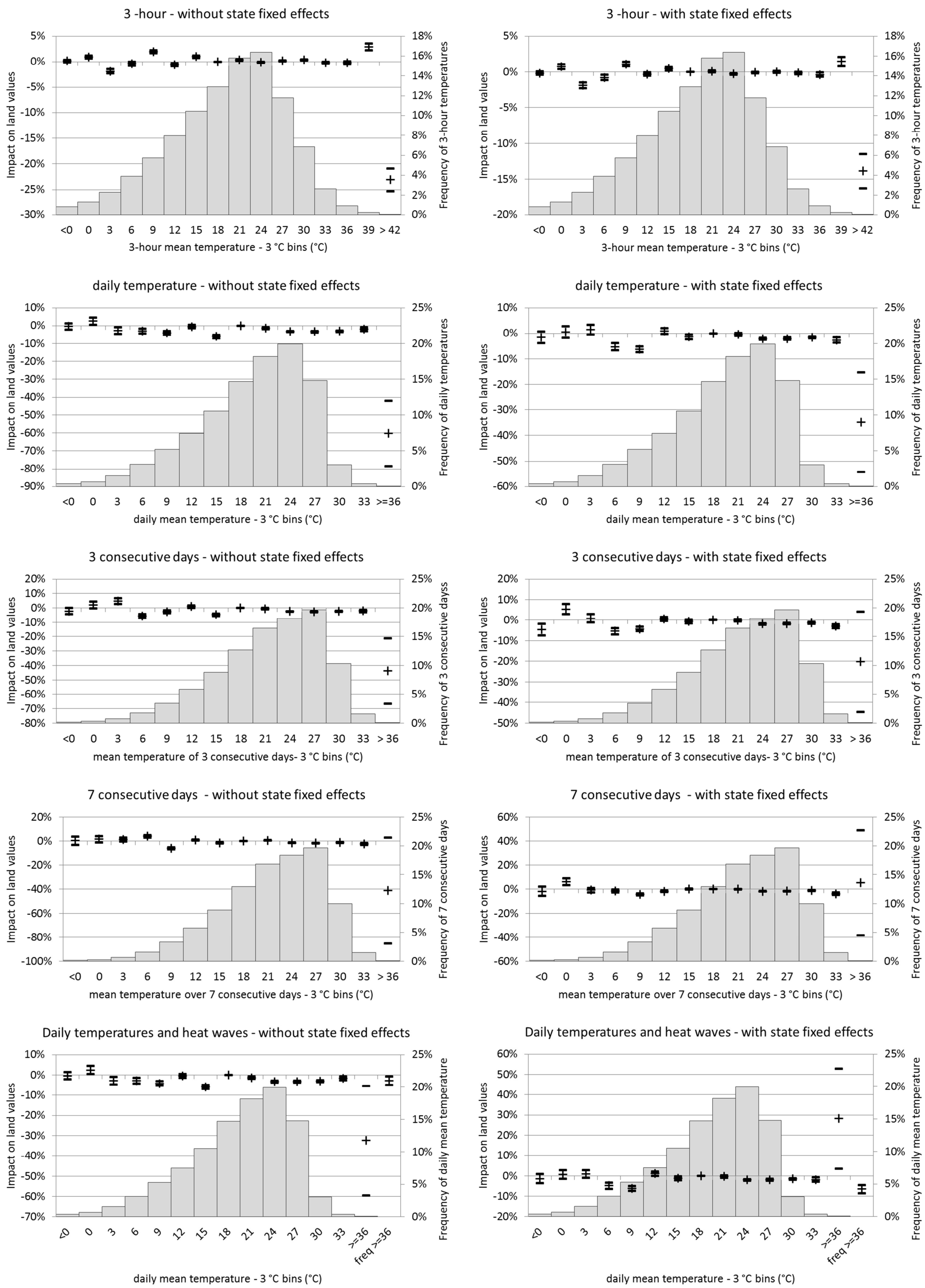


Figure 3. Flexible models of mean temperature over 3, 7 and 14 consecutive days with and without fixed effects.



Notes. Average April-September temperatures (°C) interacted with dummies for 1°C intervals, without (left) and with (right) state fixed effects. Temperature distribution of grid-points east of the 100th meridian from the NARR Merge model. Tick dashed lines limit the 95% confidence interval. The figures also display the marginal impact of 1°C warming using a quadratic model of seasonal mean temperature and precipitations.

Figure 4. Flexible models of daily temperature and precipitation over the growing season with and without fixed effects.



Notes. Models as in Figure 2, with the inclusion of a higher temperature band. In the bottom row we introduce a control variable for the number of years with which days with mean temperature at or above 36°C are observed.

Figure 5. The effect of heat waves on land values.

4.2 Heat Waves

A sharp reduction of land values is associated only to extremely high mean temperatures of 42°C and 36°C, for 3-hour and daily intervals respectively (Figure 5). However the conditions under which these extreme temperatures are observed are very rare. Those temperatures were never observed in the greatest majority of the counties in the east of the United States in 1979-2007. In the small fraction of counties where those temperatures have been observed, they have occurred only under extremely strong heat waves. These heat waves occur rarely and are mainly explained by exceptional climatic circumstances. Days above 36°C are observed every three years between 1979 and 2007 across the border of Texas and Oklahoma. In most counties that ever recorded such temperatures, only one or at most two events from 1979 to 2007 have pushed mean daily temperatures above 36°C (or 3-hour time periods above 42°C). For example, the large 1980 heat wave that brought havoc to the South of the United States accounts for a large fraction of the extreme temperature observations. The heat wave of 2006 is another example. Heat waves are also associated to drought conditions, making it hard to separate the effect of temperature and of water shortage. For these reasons we argue that extremely high temperatures above 36°C or 42°C should not be used to control for average climatic conditions. These temperatures are a poor proxy for the probability of recording heat waves. The sudden drop of land values that we observe in Figure 5 is the result of a spurious correlation.

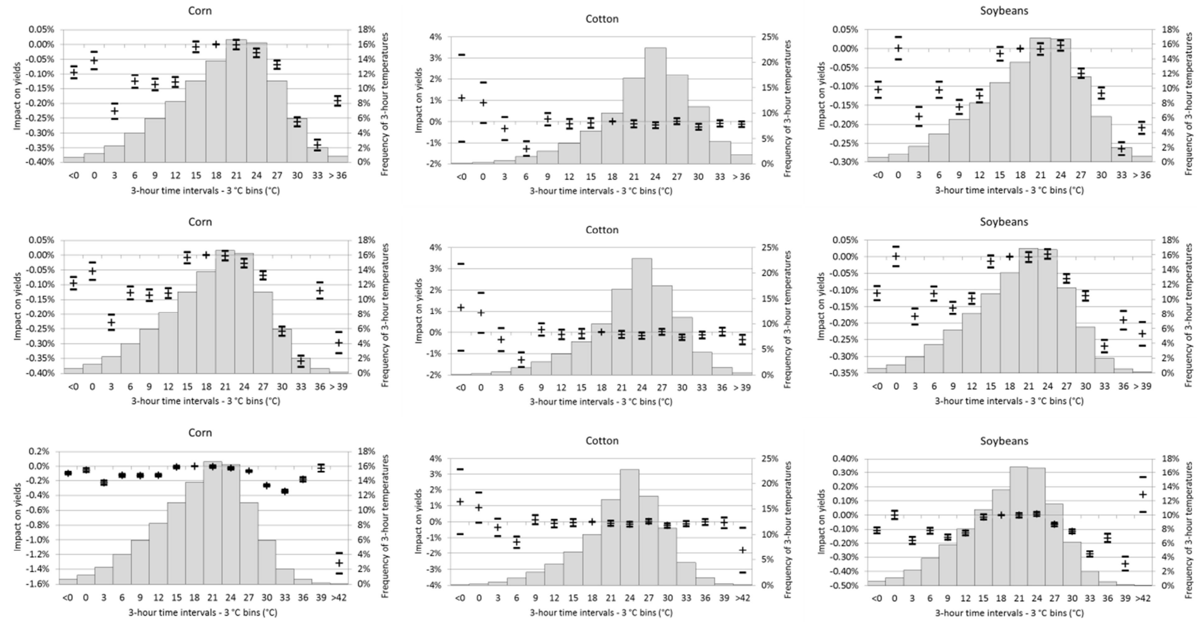
With NARR data we can control for the number of years during 1979-2007 under which days with mean temperature above 36°C were observed. Counties that are more frequently exposed to heat waves should incorporate this into land values. In particular, one single, totally isolated event should have little impact on land values.

The bottom row of Figure 5 displays results of the model that uses daily mean temperature and a control variable that counts the number of years in which those temperatures were observed. The inclusion of a more accurate proxy for the occurrence of heat waves reduces the significance of the last temperature bin or it completely reverses its impact. The model in which the last temperature bin is omitted (not shown in Figure 5) finds that augmenting by one year the frequency with which days with temperature higher than 36°C are observed reduces land values by approximately 5%, both with or without state fixed effects.

4.3 The Impact of Temperatures on Yields

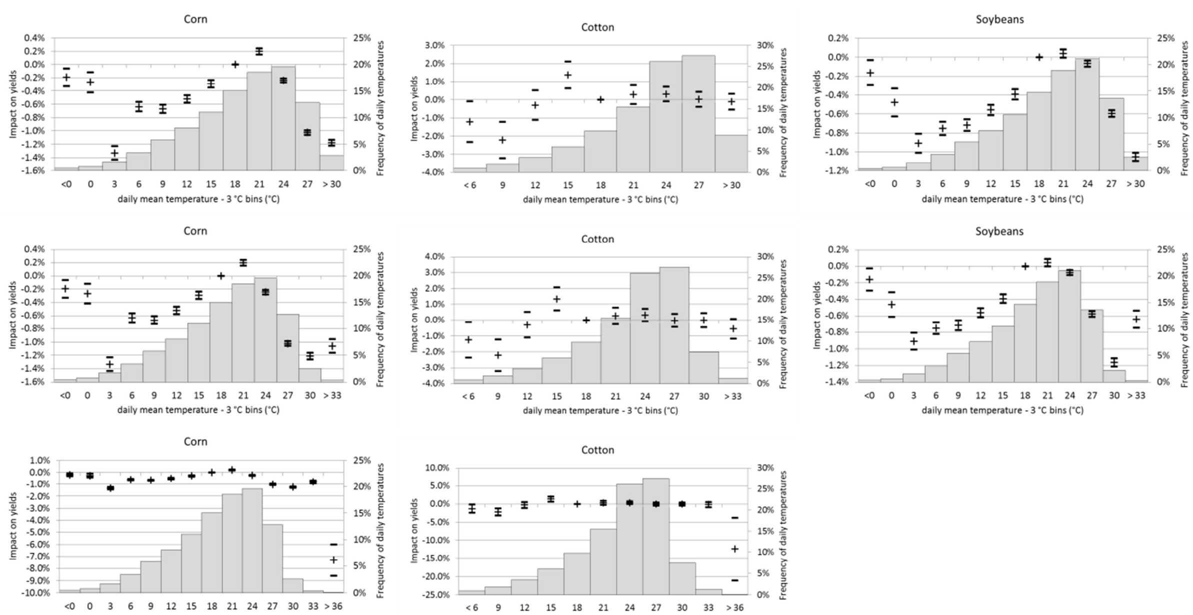
Although the main focus of this paper is to search for thresholds in the long-run relationship between land values and temperatures, we also test if there are tipping points in the relationship between yields and temperatures, as in SR.

We assess the effect of exposure to each 3°C temperature bin during April-September, for 3-hour time periods and days, on corn, cotton and soybeans yields. We use crop yields in all counties east of the 100^{th} meridian that report production, for all years from 1979 to 2007. As in SR we include a state quadratic time trend. The identification strategy relies on county-specific annual deviations of the distribution of temperatures from the county average observed distribution, after controlling for the effect of a state-wide time trend. We are therefore identifying the impact of weather shocks rather than the impact of climate change. The yield/weather relationship is thus expected to be steeper than the land value/climate relationship.



Notes: The underlying distribution of temperature is from NARR data and is restricted to counties in which the crop is produced.

Figure 6. The impact of 3-hour temperature intervals on corn, cotton and soybeans yields.



Notes: The underlying distribution of temperature is from NARR data and is restricted to counties in which the crop is produced.

Figure 7. The impact of daily temperature intervals on corn, cotton and soybeans yields.

Our results reveal an inverted-U relationship between temperature and corn and soybeans yields. When we use 3-hour time intervals the relationship is noisier than when we use daily intervals. The response functions of crops are quite erratic at low temperatures, as for land values. This is probably because exposure at the low temperature intervals is limited as farmers typically wait for the end of frost days before planting field crops. At temperatures greater than 3°C a clear inverted-U relationship emerges from our results. The most beneficial temperatures are around 18-24°C for both corn and soybeans. Both lower and higher temperatures are harmful for corn and soybeans. These findings are in line with agronomic evidence, which shows that corn and soybeans suffer from both high and cold temperatures.

Our results suggest that the downward sloping part of the relationship between yields and temperatures is steeper than the upward sloping part. For corn, we find an acceleration of the harmful effect of temperature at about 30°C (3-hour) and 27°C (daily mean) for corn. The harmful effect for soybeans is instead more gradual. Overall, our results clearly indicate that high temperatures are harmful for crops, but do not provide evidence of the existence of a threshold, of a sudden discontinuity. Our results also indicate that temperatures solidly above 3°C are highly positive for corn and that temperatures below 15/18 °C are clearly harmful for soybeans.

Cotton is quite different from corn and soybeans. It is planted in warm climates and it is highly irrigated. The exposure to high temperatures is mitigated by means of irrigation. One would thus expect that the overall relationship between yields and temperatures is flatter for cotton than for corn and soybeans. This is indeed what we find in our analysis. When we use 3-hour time intervals the marginal effects are hardly distinguishable from zero. However, when we use daily mean temperatures we find a significant inverted-U shaped relationship between yields and temperatures. Cold days are very harmful for cotton. The optimal temperature is at about 15°C and then yields decline smoothly, almost linearly, without the evidence of any threshold.

As for land values, we observe a sudden drop of yields only when we separately control for very high temperatures. Once again, these are very rare, unexpected, events that are clearly harmful for crops. Also in this case the large losses observed at the high temperatures should be interpreted as the combined effect of many exceptionally warm days and with other peculiar climatic conditions rather than the effect of a single day or a single 3-hour time interval at that temperature. Further research is clearly needed to separate all different characteristics of these exceptional events.

Our results partially confirm what found by SR. High temperatures are found to be harmful by both studies. The marginal impact of high temperatures is also similar, even if they cannot be easily compared as we use time intervals with different lengths. However, contrary to SR, we find that cold temperatures negatively affect yields, a solid result in many agronomic studies. We suspect that SR miss the upward sloping part of the relationship between temperatures and yields. The marginal effect of temperatures below 27°C on crop yields is quite erratic and hardly distinguishable from zero in their study. This result is at odds with evidence from agronomic research. At 27/30°C the marginal impact of temperature becomes significantly negative in the SR study. The threshold effect may thus emerges due to the lack of the benefit associated to cold temperatures.

5 Conclusion

The traditional empirical studies of farmland values tested quadratic seasonal temperature and precipitation effects and failed to look for threshold effects. Recent literature using degree days over the growing season, has begun to address this shortcoming (Schlenker, Hanemann, and Fisher 2006; Schlenker and Roberts 2009). These studies suggest that there is an important threshold at 34°C for land values and that yields fall precipitously at about 29/30°C. The threshold findings suggest that climate change would be far more harmful to crops than previously thought.

In a recent study we do not find that degree days affect land values in a significantly different way than mean temperatures and we not find evidence of a threshold for land values at 34°C (Massetti, Mendelsohn, and Chonabayashi 2013). However the method used is not sufficiently flexible to study the existence of temperature thresholds.

In this paper we use flexible functional forms to estimate the marginal effect of mean temperatures during 3-hour, daily and longer time intervals on land values. We span the whole range of temperatures and we group them in 3°C bands. These flexible models would reveal the existence of abrupt changes in the relationship between temperature and land values. In this first set of models we consider the effect of long-term climate normals on land values. These models account for all the adaptations that farmers have taken to maximize profits from land operations. We focus on US counties east of the 100th meridian and we cover years of the US Agricultural Census from 1982 to 2007. We use weather data from the NARR Merge dataset which provides 3-hour temperature intervals over Northern America with high spatial resolution from 1979 to present day. This data represent a significant improvement over previous analysis of

Using flexible functional forms, we look for thresholds at every temperature. Using degree days, degree hours, and seasonal temperature, we find that marginal temperature effects are surprisingly stable at every temperature level. The marginal impact of seasonal temperature is also quite stable. There is no evidence of a temperature threshold effect. Flexible functional forms were also used to test for a threshold with respect to precipitation. Marginal precipitation effects are more beneficial for relatively dry compared to relatively wet counties. But the marginal effects are less nonlinear than the quadratic model.

Abnormally high temperature intervals have a marked negative impact on land values; however, these temperature intervals are poor proxies for the frequency of heat waves; once a more accurate measurement of the frequency of heat waves is introduced, the threshold effect disappears in the model that uses state fixed effects.

Our results also reveal that identifying the impact of temperatures over very short time intervals is problematic. We obtain a noisy relationship between temperatures and land values when we use 3-hour time intervals and days. Temperatures over longer time periods – e.g. consecutive days, or over the entire growing season – provide a better characterization of the relationship between climate and land values.

We repeat our analysis using annual yields of corn, cotton and soybeans over counties east of the 100th meridian. We estimate the same model as the one used by Schlenker and Roberts (2009), with both 3-hour and daily mean temperature bins. We find a statistically significant inverted-U shaped relationship between temperatures and corn and soybeans yields. The relationship between land values and temperature is however flatter, evidence of adaptation across different climatic zones.

Schlenker and Roberts (2009) may find evidence of a threshold effect at about 30°C because they do not find that cold temperatures are harmful for crops, a well-known fact in agronomy. One problem with the Schlenker and Roberts (2009) study is that it estimated hourly temperatures using monthly average temperatures and sparse weather station daily observations. The method used, although quite accurate, may introduce unwanted noise that we do not have in the more sophisticated NARR dataset. One other problem with the Schlenker and Roberts (2009) study is the focus on very short time intervals (hours). Temperatures over these very brief time intervals may have a non-distinguishable effect on crop yields. Agronomic research provides scarce evidence on the effect of temperatures over extremely short time intervals on yields. Agronomic studies indeed mostly use constant temperatures over controlled environments. All temperatures between 0 and 27/30 °C have an erratic pattern in their study, when agronomic research clearly indicates that moderate temperatures are optimal for crop growth. The effect of higher temperatures may become distinguishable because linked to special circumstances, such as extreme heat spells. These effects may be inadvertently interpreted as a threshold effect.

What are the implications of our results for climate change policy? Climate change is likely to have only gradual effects on American agriculture. Some regions within the country may well be damaged but other regions will gain. Heat waves, defined as unexpected periods with exceptionally high temperatures are harmful for agriculture. If climate change will increase the frequency of these exceptional events land values will decline if new seeds varieties or higher irrigation will not mitigate the effect of exceptionally high temperatures.

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Appendix – Data

We have constructed a balanced panel with observations for 2,406 out of the 2,471 counties east of the 100th meridian, covering 99% of agricultural land, over the years 1982, 1987, 1992, 1997, 2002 and 2007. Units of measurement are in the metric system; economic variables are converted to constant 2005 United States Dollars ($) using the Implicit Price Deflators for Gross Domestic Product (Bureau of Economic Analysis Table 1.1.9). If not otherwise stated, variables measure data of interest in years 1982, 1987, 1992, 1997, 2002 and 2007.

Climate data

Temperature and precipitations – Temperature and precipitation data is obtained processing the North American Regional Reanalysis (NARR) dataset. Temperature at 2 meters above ground. Normals over the period 1979-2007. For further information on the NARR dataset see http://nomads.ncdc.noaa.gov/docs/ncdc-narrdsi-6175-final.pdf .

Agriculture data

Farmland value – Estimated value of land and buildings, average per hectare of farmland. Data source is the Agricultural Census.

Farmland – Land in farms as in the Census of Agriculture from 1982 to 2007, hectares. The Census of Agriculture defines ‘Land in farms’ as agricultural land used for crops, pasture or grazing. It also includes woodland and wasteland not actually under cultivation or used for pasture or grazing, provided it was part of the farm operator’s total operation. Large acreages of woodland or wasteland held for non-agricultural purposes were deleted from individual reports. Land in farms includes acres in the Conservation Reserve and Wetlands Reserve Programs. Land in farms is an operating unit concept and includes land owned and operated as well as land rented from others.

Surface or ground water withdrawals – Thousands of liters per day, per hectare, of surface or ground water for irrigation purposes. The ‘Estimated use of water in the United States’, published every five years by the United States Geological Survey, supplies data on water use at county level starting from 1985. We divided the amount of water used at county level for years 1985, 1990, 1995, 2000, 2005 by the amount of farmland in that county in census years 1987, 1992, 1997, 2002 and 2007, respectively, and we computed the time average of surface water use per hectare of land. We used this variable as a proxy for surface and ground water availability at county level for all time observations of our panel.

Socio-economic data

Income per capita – Per capita personal income, measured in thousands of $; Bureau of Economic Analysis, Regional Economic Accounts, table CA1-3.

Population density – Population from the Bureau of Economic Analysis, Regional Economic Accounts, table CA1-3, measured in hundred persons per squared kilometer. Area estimated from current division of counties boundaries.

Value of owner occupied homes – Median value of owner occupied homes, measured in thousands of $. We use data on the median value of owner occupied homes (SF3 H085) at county level from the 2000 United States Census. Data for other years is obtained using the Home Price Index (HPI) for metropolitan areas or at state level estimated by the Office of Federal Housing Enterprise Oversight (OFHEO). The HPI measures the movement of single-family house prices. It is a repeat-sales index that measures average price changes in repeat sales or refinancing on the same properties (www.fhfa.gov/webfiles/896/hpi_tech.pdf). The HPI was adjusted to reflect inflation using the Implicit Price Deflator of GDP.

Geographic data

Latitude – Latitude of county's centroid, measured in decimal degrees.

Elevation – Elevation of county's centroid, measured in thousands of meters.

Distance from cities – Distance between county's centroid and metropolitan areas with more than 200,000 inhabitants in 2000, measured in kilometers.

Soil characteristics – NRI dataset

Soil data is from the National Resources Inventory (NRI), developed by the United States Department of Agriculture, years 1992 and 1997 (Nusser and Goebel 1997; NRI 2000). The NRI is a longitudinal sample survey of natural resource conditions and trends on non-Federal land in the United States based upon scientific statistical principles and procedures. It is conducted by the U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS). We consider soil samples classified as: cultivated cropland, noncultivated cropland, pastureland and rangeland. We calculate a sample area weighted average of soil characteristics from all samples that fall within a county. In some cases we reclassify qualitative soil characteristics into numeric indicators, as detailed below.

Salinity – Percentage of agricultural land that has salinity–sodium problems.

Flooding – Percentage of agricultural land occasionally or frequently prone to flooding.

Wet factor – Percentage of agricultural land that has very low drainage (poor and very poor).

k factor – Average soil erodibility factor. It is the average soil loss, measured in tons/hectare. the k factor is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff.

Slope length – Average slope length factor, measured in meters. Slope length is the distance from the point of origin of overland flow to the point where either the slope gradient decreases enough that deposition begins, or the runoff water enters a well-defined channel that may be part of a drainage network or a constructed channel. For the NRI, length of slope is taken through the sample point.

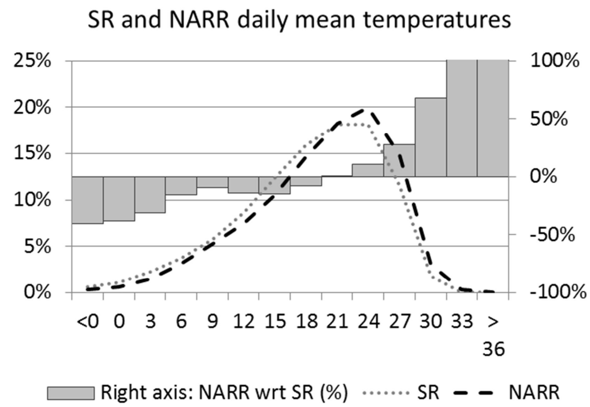
Sand – Percentage of agricultural land classified as sand or coarse- textured soils.

Clay – Percentage of agricultural land that is classified as clay.

Moisture level – Minimum value for the range of available water capacity for the soil layer or horizon. Available water capacity is the volume of water retained in 1 cm3 of whole soil between 1/3-bar and 15-bar tension. It is reported as cm of water per centimeters of soil.

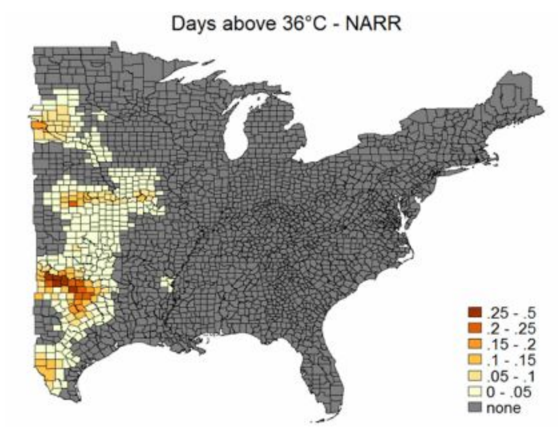
Permeability – The minimum value for the range in permeability rate for the soil layer or horizon, expressed as centimeters/hour.

Appendix – Additional Material



Notes. Distribution of mean daily temperatures during the months April-September, from 1979 to 2005, over counties east of the 100th meridian, all grid points east of the 100th meridian. The 33°C and the >36°C bars truncated. Untruncated values equal to 833% and 7433%, respectively. NARR data has more observations at the high temperatures and less at the low temperatures, with respect to the SR data.

Figure A - 1. NARR and Schlenker and Roberts (2009) data.



Notes. Average number of days with mean temperature at or above 36°C, during 1979-2007, east of the 100th meridian, NARR dataset.

Figure A - 2. Geographic distribution of climatologies of days with temperature at or above 36°C.

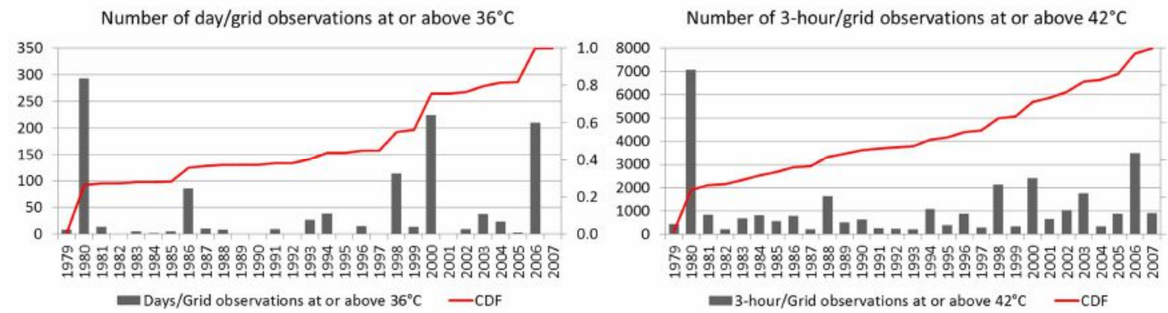
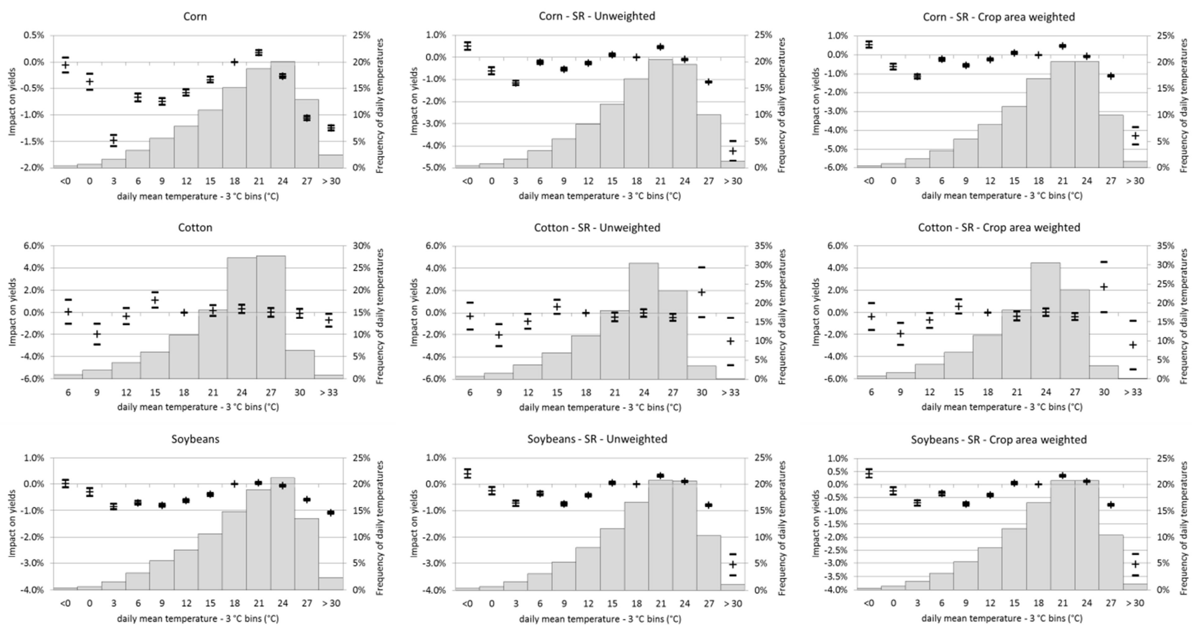


Figure A - 3. Distribution over time of extreme temperature events in the Eastern United States.



Notes. The first column uses temperature data at counties' centroid, derived from NARR. Sample restricted to all counties for which we have weather data from the Schlenker and Roberts (2006) dataset. The second and third columns uses SR data. In the second column temperatures and precipitations at county-level are the average of all grid points that fall within a county. In the third column temperatures and precipitations at county level are the average of grid points that fall within a county, with weights equal to the share of total cropland that falls within the grid area. Histograms depict the frequency with which daily mean temperatures are observed in all counties that report production for that specific crop, over April-September, in the years 1979-2007. United States counties east of the 100th meridian.

Figure A - 4. Impact of temperatures on corn, cotton and soybeans yields: comparing NARR and Schlenker and Roberts (2009) data.