How do heat waves, cold waves, droughts, hail and tornadoes affect US agriculture?

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Motivation

- Extreme weather events cited as being major source of agricultural losses from climate change

- But surprisingly few studies

- We systematically study how the most damaging weather extremes affect crop yields and land values
  - Heat waves / cold waves
  - Drought
  - Hail
  - Tornados

Extreme weather

- The definition of weather extremes is quite challenging
- Some studies use fixed thresholds
  - Climate change will certainly modify the frequency of extreme events
  - But do not consider adaptation
- Most of the definitions in climate and weather literature: extreme = rare
  - Tail events
  - Site and season specific
  - Unclear how climate change will alter the tails

Extreme weather

- Climatologists see extreme events as outcome of unusual meteorological conditions
  - Combined abnormal conditions of atmospheric pressure, temperature, humidity, wind
  - Possible correlation with temperature and precipitation

Extreme weather

- Heat waves, cold waves, droughts, and wet spells are the weather extremes that create the largest damages to agriculture (IPCC 2012)

- Many competing definitions but one common thread is that duration matters
  - Heat waves are prolonged periods of extreme temperatures
  - Droughts are prolonged periods with dry conditions

Heat waves and temperature bins

- The underlying hypothesis is that damages are cumulative and not perfectly time separable
- Temperature bin models are not well-suited to study heat waves
  - The temperature bins models assume that the effect of temperature is time-separable
- Extreme temperature bins imprecisely capture some effects of the heat waves

Crop yield model

$$y_{i,t} = \alpha + \sum_{j=-1,0,3,6,\ldots}^{J} \beta_j x_{i,j,t} + \gamma_1 P_{i,t} + \gamma_2 P_{i,t}^2 + \boldsymbol{\eta} X_{i,t} + \boldsymbol{\varphi} E_{i,t} + \eta_i + \epsilon_{i,t}$$

- Adapted from Schlenker and Roberts (2009)
  - $y_{i,t}$ is the log of yield per hectare in county *i* in year *t*
  - $x_{i,t,j}$ is the number of days with mean temperature within a 3 °C interval 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
  - $E_{i,t}$ is a vector of extreme events observed in county *i* in time *t*
  - η_i is a county fixed effect
  - $\varepsilon_{i,t}$ is assumed to be a random component
  - Standard errors corrected for spatial correlation

Ricardian model

$$\mathrm{V_{i,t}} = \beta\,\mathrm{h(C_i)} + \boldsymbol{\varphi} E_i + \gamma \mathrm{X_{i,t}} + \theta \mathrm{Z_i} + \epsilon_{\mathrm{i,t}}$$

- Adapted from Mendelsohn, Nordhaus and Shaw (1994)
  - $V_{i,t}$ is is the log of land value per hectare at time t for observation *i*
  - $h(\cdot)$ is a generic function of the vector of climate variables C
  - E_i is a vector of frequencies of extreme events in county *i*
  - $X_{i,t}$ is a set of socio-economic variables that vary over time
  - Z_i is a set of geographic and soil characteristics fixed over time
  - $\varepsilon_{i,t}$ is assumed to be a random component
  - With and without state fixed effects, farmland weights
  - Standard errors corrected for spatial correlation

Agriculture Data

- Crop yield model
  - Corn and soybeans yields in 1979-2007 from USDA
- Ricardian model
  - Balanced panel using six US Agricultural Census years from 1982 to 2007
  - Controls for socio-economic, geographic, soil characteristics
- Counties East of the 100^{th} meridian in the US

Weather and Climate Data

- NARR 2 meter air temperature and precipitation from 1979
  - Temperature, precipitation
  - Heat waves
  - Variables calculated at grid-cell level and averaged at county level
- NOAA climate divisions database
  - Drought
  - Area weighted average of climate divisions data
- NOAA storm events database
  - Hail and tornados
  - Number of events / 100 sq miles in each county

Heat and cold waves

- SREX IPCC report and NOAA:
  - A *prolonged period* of *abnormally* hot/cold weather
  - At least 3 consecutive days with mean temperature 2 standard deviations above/below climatological mean
  - Count events in each season
  - Robustness tests using 1.5 standard deviations and more consecutive days

Drought

- IPCC SREX report:

  A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term.

- Soil moisture (agricultural) drought
  - Imbalance between supply and demand of water
  - Palmer Drought Severity Index (PDSI)
- Meteorological drought
  - Lack of precipitation
  - Standardized Precipitation Index (SPI)
    - Number of standard deviations from average precipitation during X months before the month under consideration
    - 12 months periods in order not to capture seasonal effects

Hail and Tornados

- Hail has sever negative effects on crops
  - Short, localized but potentially destructive
  - Hail insurance since early 19th century
  - Number of events/100 sq miles
  - Control for hail size in robustness tests

- Tornados have destructive impact but rare and spatial extent very limited
  - Mild and sever storms
  - Number of events/100 sq miles

	Corn				Soybeans			
	Mean	St. Dev.	Min	Max	Mean	St. Dev.	Min	Max
Cold wave (count, Apr-Sep)	0.99	1.29	0	10.0				
Heat wave (count, Apr-Sep)	0.12	0.37	0	4.00				
Drought - PDSI Moderate (count, Apr-Sep)	0.66	0.68	0	2.0				
Drought - PDSI Extreme (count, Apr-Sep)	0.04	0.10	0	0.50				
Hail (count Apr-Sep / 100 sq. miles)	0.31	0.55	0	10.9				
Tornado (Cat < 3) count, Apr-Sep / 100 sq. miles)	0.05	0.14	0	3.1				
Tornado (Cat ≥ 3) (count, Apr-Sep / 100 sq. miles)	0.004	0.031	0	1.1				

	Corn				Soybeans			
	Mean	St. Dev.	Min	Max	Mean	St. Dev.	Min	Max
Cold wave (count, Apr-Sep)	0.99	1.29	0	10.0	1.00	1.30	0	10.0
Heat wave (count, Apr-Sep)	0.12	0.37	0	4.00	0.12	0.39	0	4.00
Drought - PDSI Moderate (count, Apr-Sep)	0.66	0.68	0	2.0	0.65	0.68	0	2.0
Drought - PDSI Extreme (count, Apr-Sep)	0.04	0.10	0	0.50	0.03	0.10	0	0.50
Hail (count Apr-Sep / 100 sq. miles)	0.31	0.55	0	10.9	0.34	0.58	0	11.4
Tornado (Cat < 3) count, Apr-Sep / 100 sq. miles)	0.05	0.14	0	3.1	0.06	0.14	0	3.1
Tornado (Cat ≥ 3) (count, Apr-Sep / 100 sq. miles)	0.004	0.031	0	1.1	0.004	0.033	0	1.1

	Separately		All extreme events	
	Corn	Soybeans	Corn	Soybeans
Cold Wave (count, Apr-Sep)				
Heat Wave (count, Apr-Sep)				
Drought - PDSI Moderate (count, Apr-Sep)				
Drought - PDSI Extreme (count, Apr-Sep)				
Hail (count/100 sq. miles, Apr-Sep)				
Tornado (Cat < 3) (count/100 sq. miles, Apr-Sep)				
Tornado (Cat ≥ 3) (count/100 sq. miles, Apr-Sep)				

Notes: Notes: all coefficients have been multiplied by 100. A total of 55,030 county-year observations is used to estimate the corn yield model. 46,658 county-year observations are used to estimate the soybeans yield model. Unbalanced panels used for both corn and soybeans models. All standard errors corrected for spatial correlation.

	Separately		All extreme events	
	Corn	Soybeans	Corn	Soybeans
Cold Wave (count, Apr-Sep)	-2.16***	-0.82*		
	[0.45]	[0.43]		
Heat Wave (count, Apr-Sep)	-3.48**	-2.11*		
	[1.44]	[1.18]		
Drought - PDSI Moderate (count, Apr-Sep)				
Drought - PDSI Extreme (count, Apr-Sep)				
Hail (count/100 sq. miles, Apr-Sep)				
Tornado (Cat < 3) (count/100 sq. miles, Apr-Sep)				
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Heat Wave (count, Apr-Sep)	-3.48**	-2.11*		
	[1.44]	[1.18]		
Drought - PDSI Moderate (count, Apr-Sep)	-3.23***	-1.86***		
	[0.72]	[0.64]		
Drought - PDSI Extreme (count, Apr-Sep)	-36.4***	-21.2***		
	[6.17]	[5.46]		
Hail (count/100 sq. miles, Apr-Sep)				
Tornado (Cat < 3) (count/100 sq. miles, Apr-Sep)				
Tornado (Cat ≥ 3) (count/100 sq. miles, Apr-Sep)				

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Drought - PDSI Extreme (count, Apr-Sep)	-36.4***	-21.2***		
	[6.17]	[5.46]		
Hail (count/100 sq. miles, Apr-Sep)	-0.91*	-0.85*		
	[0.54]	[0.52]		
Tornado (Cat < 3) (count/100 sq. miles, Apr-Sep)				
Tornado (Cat ≥ 3) (count/100 sq. miles, Apr-Sep)				

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Heat Wave (count, Apr-Sep)	-3.48**	-2.11*		
	[1.44]	[1.18]		
Drought - PDSI Moderate (count, Apr-Sep)	-3.23***	-1.86***		
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Hail (count/100 sq. miles, Apr-Sep)	-0.91*	-0.85*		
	[0.54]	[0.52]		
Tornado (Cat < 3) (count/100 sq. miles, Apr-Sep)	-1.3	-1.74		
	[1.22]	[1.42]		
Tornado (Cat ≥ 3) (count/100 sq. miles, Apr-Sep)	-1.59	-4.7		
	[4.31]	[4.03]		

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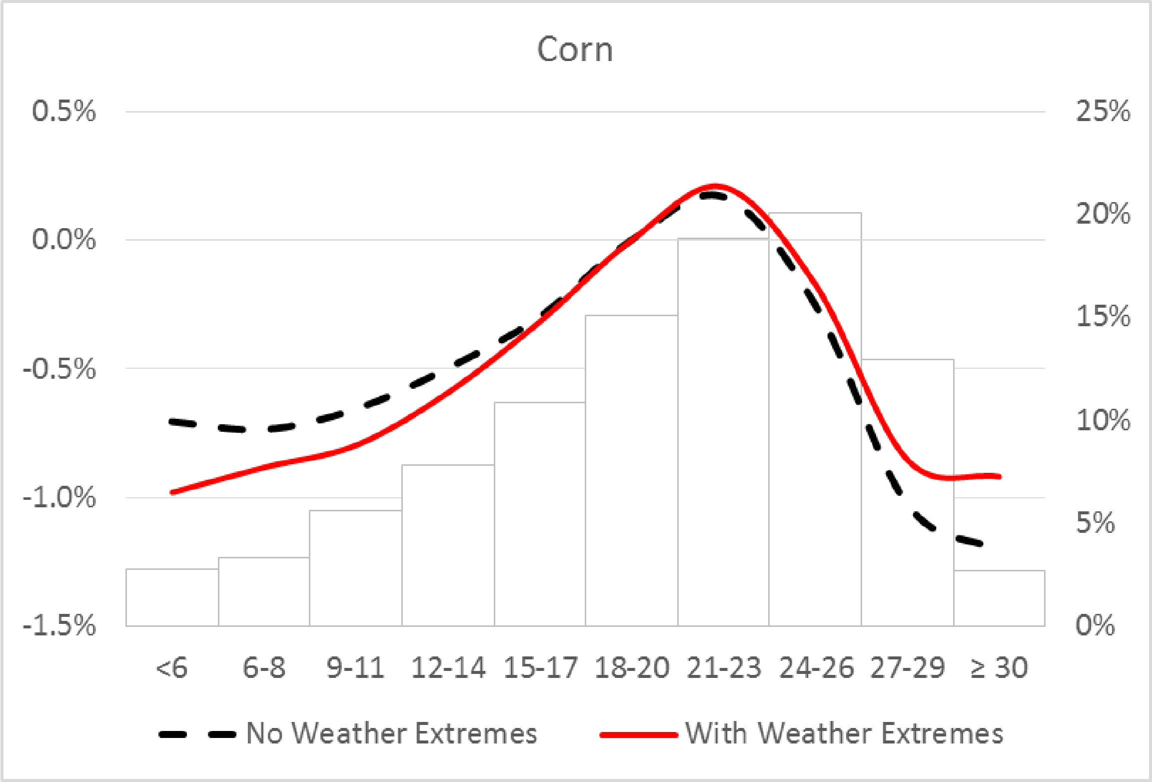
	Separately		All extreme events	
	Corn	Soybeans	Corn	Soybeans
Cold Wave (count, Apr-Sep)	-2.16***	-0.82*	-1.73***	-0.53
	[0.45]	[0.43]	[0.45]	[0.43]
Heat Wave (count, Apr-Sep)	-3.48**	-2.11*	-2.83**	-1.73
	[1.44]	[1.18]	[1.44]	[1.13]
Drought - PDSI Moderate (count, Apr-Sep)	-3.23***	-1.86***	-3.29***	-1.93***
	[0.72]	[0.64]	[0.71]	[0.64]
Drought - PDSI Extreme (count, Apr-Sep)	-36.4***	-21.2***	-29.8***	-18.3***
	[6.17]	[5.46]	[6.07]	[5.23]
Hail (count/100 sq. miles, Apr-Sep)	-0.91*	-0.85*	-0.88*	-0.75
	[0.54]	[0.52]	[0.71]	[0.64]
Tornado (Cat < 3) (count/100 sq. miles, Apr-Sep)	-1.3	-1.74	-1.41	-3.41***
	[1.22]	[1.42]	[1.13]	[1.02]
Tornado (Cat ≥ 3) (count/100 sq. miles, Apr-Sep)	-1.59	-4.7	-0.83	-4.1
	[4.31]	[4.03]	[4.22]	[3.96]

Notes: Notes: all coefficients have been multiplied by 100. A total of 55,030 county-year observations is used to estimate the corn yield model. 46,658 county-year observations are used to estimate the soybeans yield model. Unbalanced panels used for both corn and soybeans models. All standard errors corrected for spatial correlation.

Expected impacts of extreme events

Extreme Event	Corn	Soybeans
Cold Wave	-2.1%/year	-0.8%/year
Heat Wave	-0.4%/year	-0.2%/year
Drought	-3.3%/year	-1.9%/year
Hail	-0.3%/year	-0.3%/year
Tornado	-0.07%/year	-0.12%/year
TOTAL	**-6.2%/year**	**-3.3%/year**

Temperature-yield functions



- Omitting the extreme weather variables biases the estimates of temperature coefficients
- Similar changes for soybeans

Impact of 3 °C warming

	Corn	Soybeans
No extreme events		
With extreme events		

Impact of 3 °C warming

	Corn	Soybeans
No extreme events	-31.9% [-37.6% ; -26.1%]	-30.7% [-36.2% ; -25.2%]
With extreme events		

Impact of 3 °C warming

	Corn	Soybeans
No extreme events	-31.9% [-37.6% ; -26.1%]	-30.7% [-36.2% ; -25.2%]
With extreme events	-20.6% [-26.9% ; -14.2%]	-24.8% [-31.0% ; -18.7%]

- The inclusion of extreme events reduces by 35% crop yield impacts and by 19% soybeans impacts from warming

Land Values

- We do not find that extreme weather events significantly affect land values

- The result does not change if we use a four seasons model, a growing season model or temperature bins

- We suspect subsidized public crop insurance protects land values

Conclusions

- Extreme events reduce corn yields by 6% and soybean yields by 3% per year

- Despite these large damages from extreme events, we find that extreme events do not affect farmland values

- The omission of extreme events bias the coefficients of temperature bin models
- This suggests that most existing weather panel models may be biased because they omit extreme events

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