How Does Temperature Affect Land Values in the US?

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MARIE CURIE ACTIONS

FONDAZIONE ENI ENRICO MATTEI

Centro Euro-Mediterraneo per i Cambiamenti Climatici

Outline

1. What is the best functional form to describe the relationship between climate and land values?
   - US agriculture east of the 100th meridian
   - Focus on temperatures
2. What are the benefits (and costs) of using degree days?
3. What is the role of seasons?

Ricardian model

- Standard Ricardian model

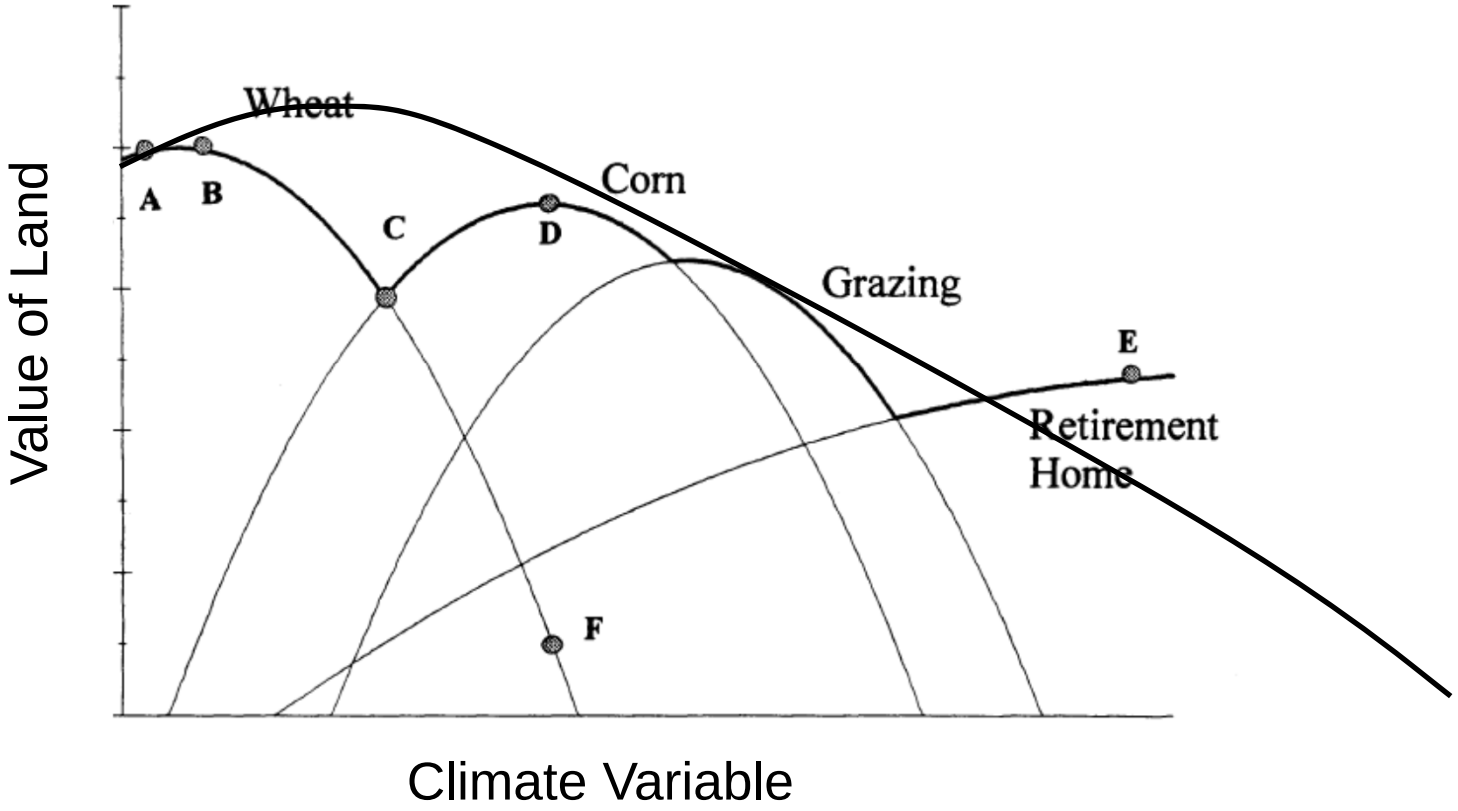
$$Y_{i,t} = \boldsymbol{\beta}\, h(C_i) + \boldsymbol{\gamma} X_{i,t} + \boldsymbol{\theta} Z_i + \epsilon_{i,t}$$

- Mendelsohn, Nordhaus and Shaw (1994) - MNS

$$Y_{i,t} = \beta_0 + \sum_k \beta_{1,k} T_{i,k} + \sum_k \beta_{2,k} T_{i,k}^2 + \sum_k \beta_{3,k} P_{i,k} + \sum_k \beta_{4,k} P_{i,k}^2 + \boldsymbol{\gamma} X_{i,t} + \boldsymbol{\theta} Z_i + \epsilon_{i,t}$$

- Results from a large number of Ricardian studies show that
  - The relationship between climate and land values is quadratic
  - Seasons are significantly different

Land value and climate



Source: Mendelsohn, Nordhaus and Shaw (AER, 1994)

Non-linear relationship

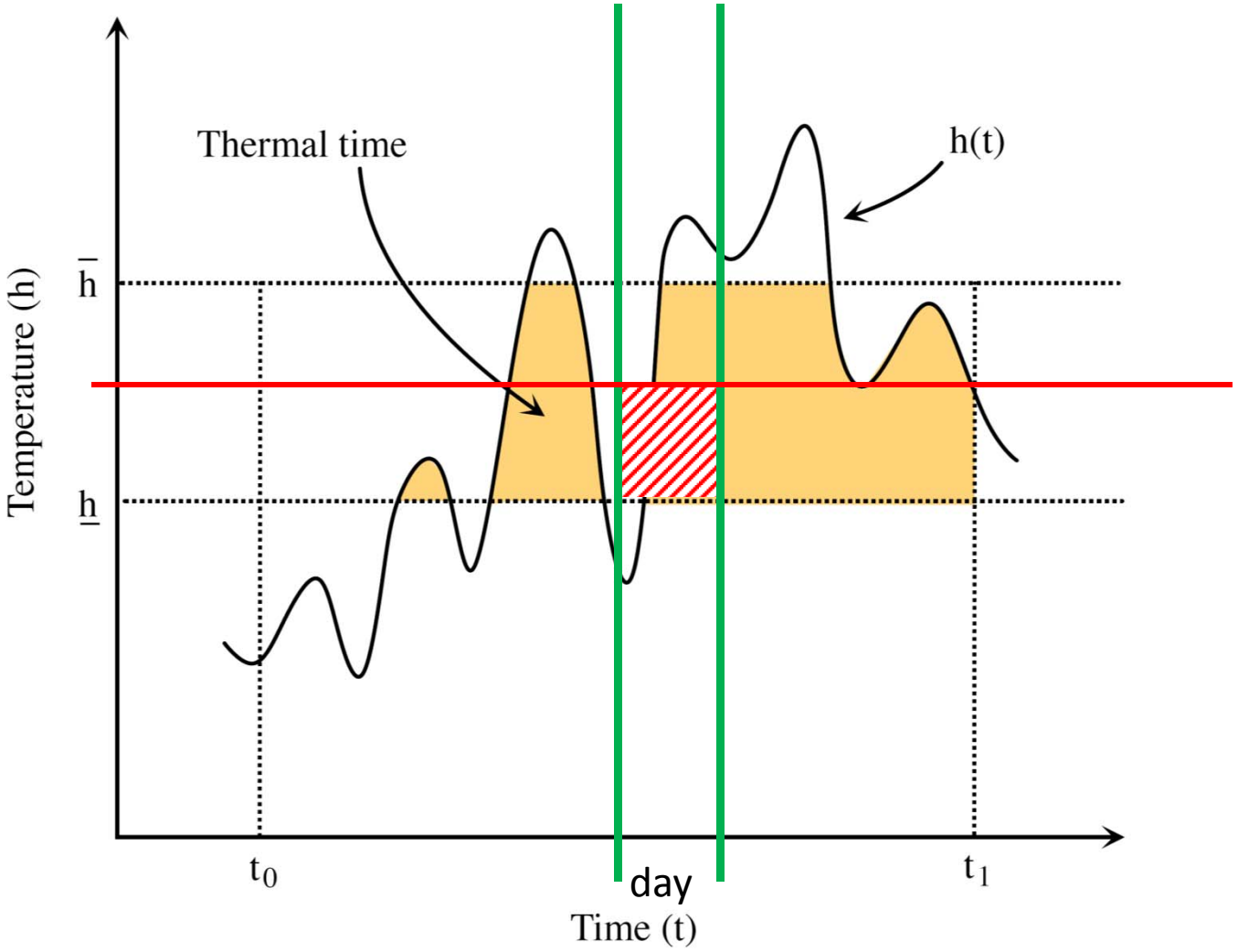
- Schlenker, Hanemann and Fisher (RESstat 2006) - SHF
  - A quadratic, seasonal model does not characterize well the agronomic relationship between heat and crop growth

1. Crops respond to the overall amount of heat they receive during the growing season, no matter when

2. Crops grow well and linearly when temperatures are within a mild range

3. Outside of this mild temperature interval the effect of temperature on crop growth is strongly non-linear.
   - Crops do not grow at all if it is too cold
   - Crops grow much less if it is too hot

Thermal time



Average daily temperature

Picture borrowed from: Ortiz-Bobea, A (2010) "Towards a More Transparent Approach of Assessing Climate Change Impacts on Agriculture" Dissertation Proposal

Degree days

- SHF suggest replacing seasonal temperatures with degree days over the growing season. They use the interval 8-32 °C for beneficial degree days:
  - $dd8\text{–}32_{i,r} = \begin{cases} 0 \text{ if } & t_{i,r} \leq 8 \\ t_{i,r} - 8 \text{ if } & 8 < t_{i,r} \leq 32 \\ 24 \text{ if } & t_{i,r} > 32 \end{cases}$
  - $DD8\text{–}32_i = \sum_{r \in R} dd_{i,r}$
- Degree days above 34 °C to control for extreme heat:
  - $dd34_{i,r} = \begin{cases} 0 & \text{if } t_{i,r} \leq 34 \\ t_{i,r} - 34 & \text{if } t_{i,r} > 34 \end{cases}$
  - $DD34_i = \sum_{r \in R} dd34_{i,r}$
- We also test the impact of cold degree days
  - $cdd8_{i,r} = \begin{cases} 8 - t_i \text{ if } & t_{i,r} \leq 8 \\ 0 \text{ if } & t_{i,r} > 8 \end{cases}$
  - $CDD8_i = \sum_{r \in R} cdd8_{i,r}$

Summary of SHF (2006)

- In summary, SHF argue that:

1. degree days between 8 and 32 °C are better than average temperature;
2. the effect of degree days rises linearly from 8 to 32 °C and then falls precipitously after 34 °C;
3. cold degree days do not matter;
4. seasons (spring summer fall) within the growing season do not matter;
5. all that matters is degree days over a fixed growing season (winter or non-growing season does not matter).

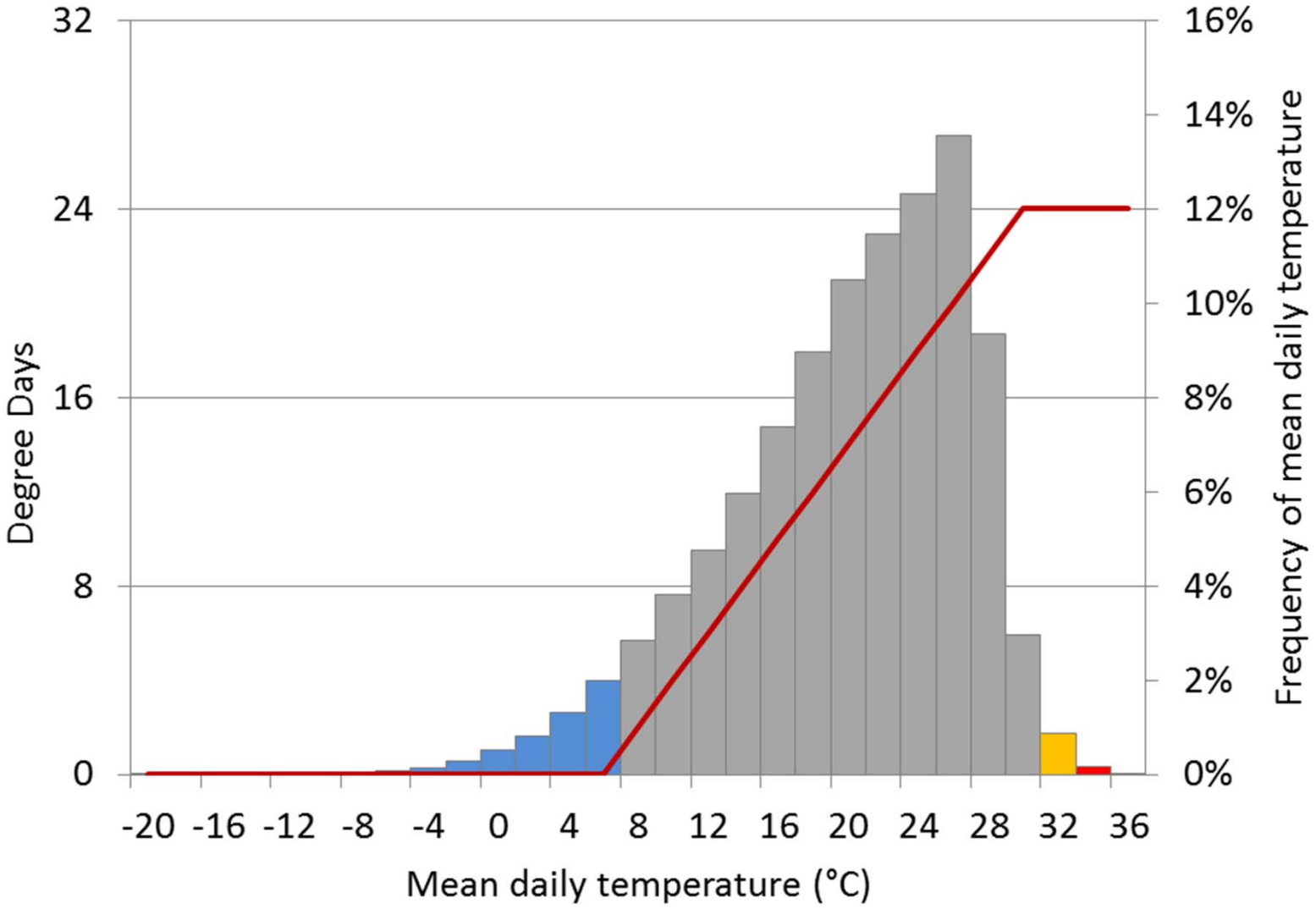
Research questions

- Are degree days better than average temperature?
- Is the effect of temperature on crops positive and largely linear up to 34°C and then precipitously negative?
- Do seasons matter?

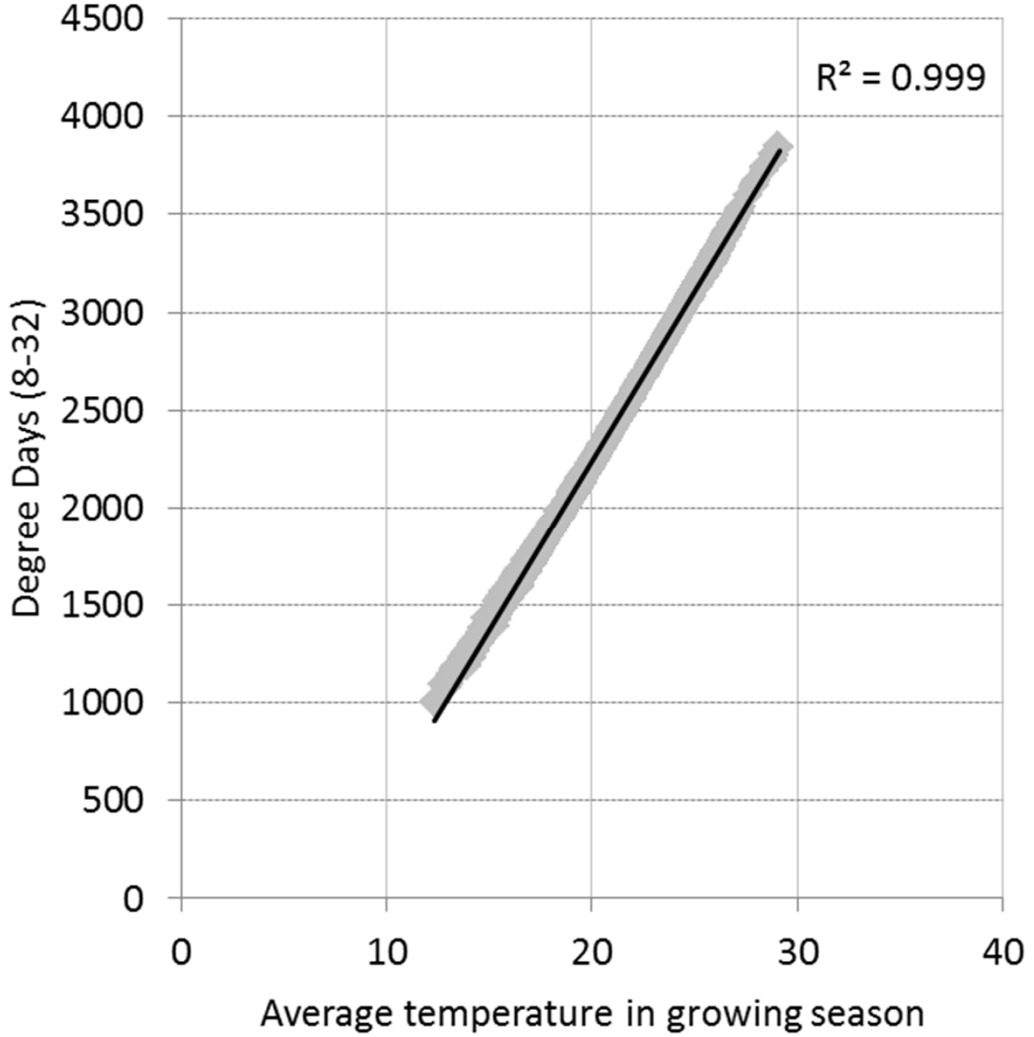
Model and Data

- US Agricultural Census data for 1982, 1987, 1992, 1997, 2002, 2007
- 2,395 out of 2,471 counties east of the 100th meridian
- North American Regional Reanalysis NARR weather dataset 1979-2007
  - 3-hour weather data over a 32x32 km grid from 1978 to present
  - Averages 1979-2007
- Semilog pooled model with year fixed effects, with and without state fixed effects
- Controls for: socio-economic factors, soil, geography

DD8-32 vs average temperature



DD8-32 vs average temperature



Degree Days vs Average Temperature

	DD8-32	AV TEMP	DD8-32	AV TEMP
	(1)	(2)	(1-FE)	(2-FE)
$DD8\text{-}32_{4\text{-}9}$	0.000180***		0.000286***	
	[5.75e-05]		[9.55e-05]	
$DD8\text{-}32_{4\text{-}9}$ sq.	-2.25e-07***		-1.94e-07***	
	[1.31e-08]		[2.09e-08]	
$T_{4\text{-}9}$		0.000222***		0.000304***
		[4.93e-05]		[8.06e-05]
$T_{4\text{-}9}$ sq.		-2.27e-07***		-1.90e-07***
		[1.17e-08]		[1.83e-08]
$P_{4\text{-}9}$	0.162***	0.172***	0.252***	0.257***
	[0.0246]	[0.0245]	[0.0287]	[0.0288]
$P_{4\text{-}9}$ sq	-0.00920***	-0.00966***	-0.0129***	-0.0130***
	[0.00127]	[0.00126]	[0.00148]	[0.00149]
State fixed effects	No	No	Yes	Yes
Adjusted R^2	0.777	0.776	0.830	0.830
Impact of +2°C	-28.1%	-28.3%	-21.4%	-21.0%
	[-30.5% , -25.8%]	[-30.6% , -26%]	[-25% , -17.5%]	[-24.7% , -16.8%]
Impact of +4°C	-49.8%	-51.1%	-39.8%	-40.3%
	[-52.8% , -46.6%]	[-54.5% , -47.8%]	[-45.5% , -33.4%]	[-46% , -33.9%]

Notes: Robust standard errors in brackets; *** p<0.01, ** p<0.05, * p<0.1; 95% bootstrap confidence intervals for climate change impacts in brackets. All climate variables from April to September. DD8-32 in °C. We subtract 8 °C to average seasonal temperature and multiply by 183. Precipitations in cm/month.

Are DD better than av. temperature?

- There are no apparent benefits from using degree days
- There are instead problems:

1. No accounting for days <8 °C within the growing season (30 times more frequent than days with temperatures above 34 °C);
2. Calculating degree days requires many arbitrary choices;
3. Large amount of weather observations needed
   - SHF extrapolate daily mean temperature from mean monthly temperature

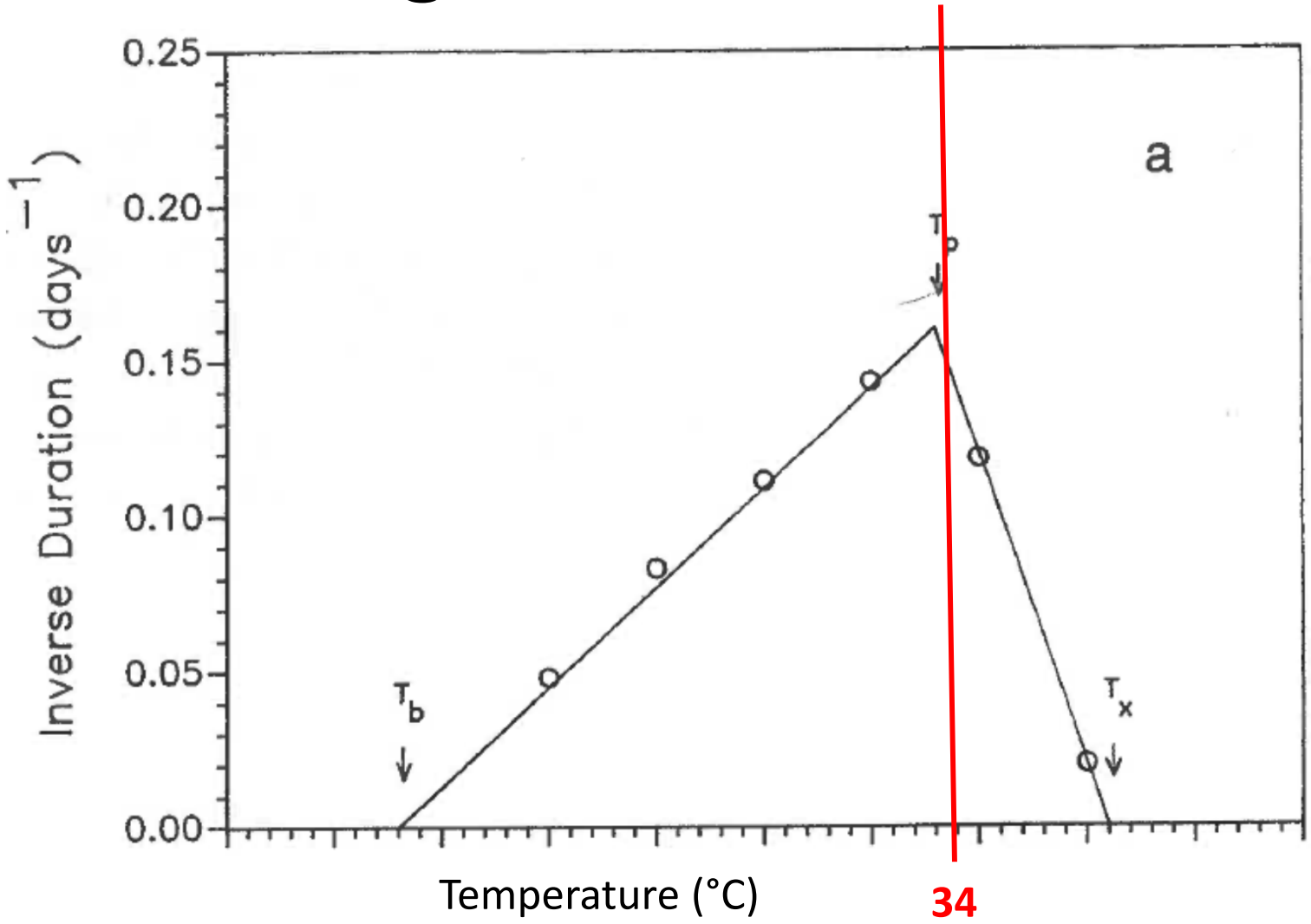
Research questions

- Are degree days better than average temperature and should they be truncated at 32 °C?

- Is the effect of temperature on crops positive and largely linear up to 34°C and then precipitously negative?

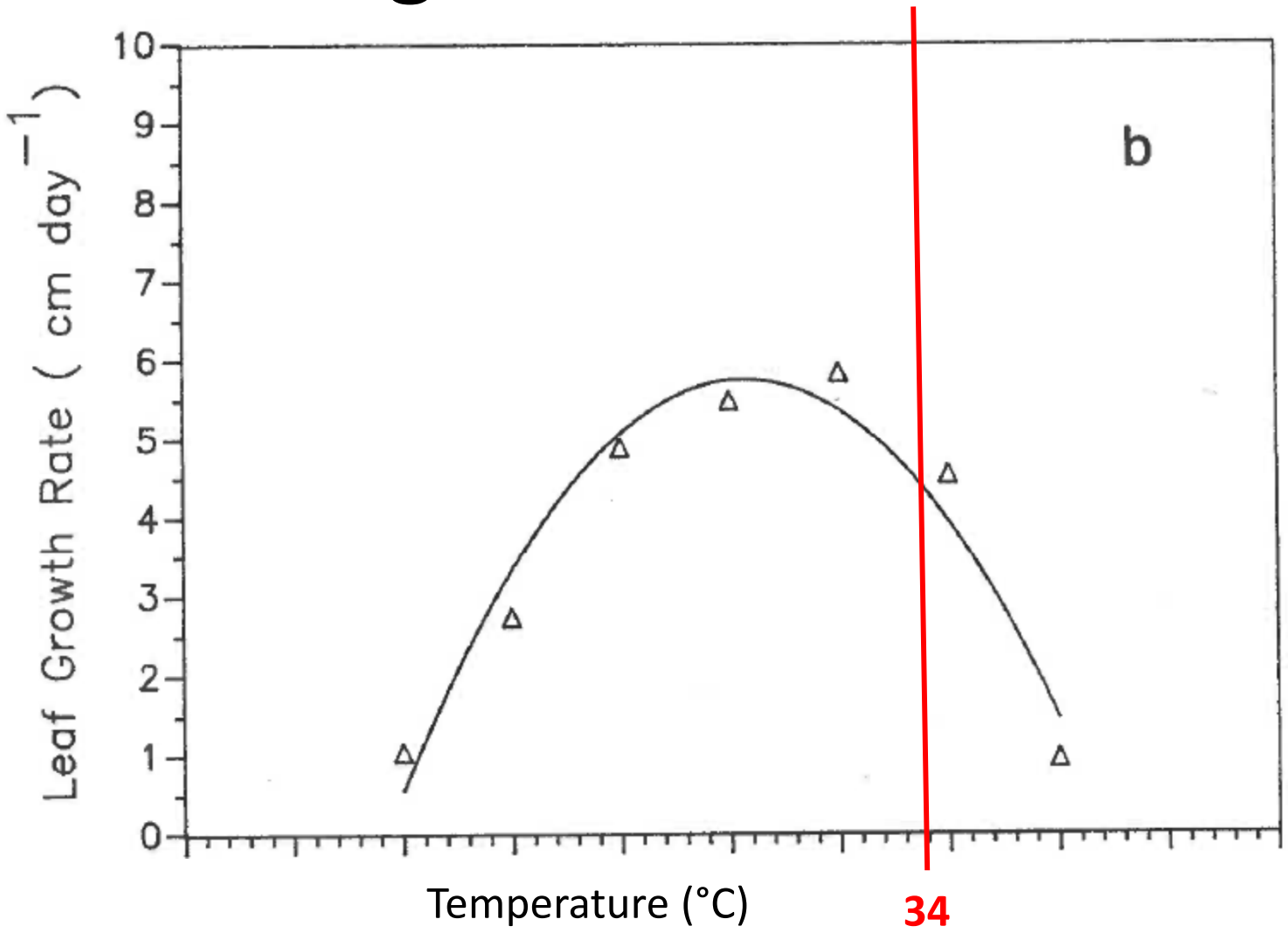
- Do seasons matter?

The agronomic literature



Reproduced from Ritchie and NeSmith (1991). Calculated from graphical data from Grobellaar (1963). Maize plants were grown in an artificial environment with identical temperature until the appearance of the fourth leaf and then placed in environments with constant temperature ranging from 5 to 40°C.

The agronomic literature



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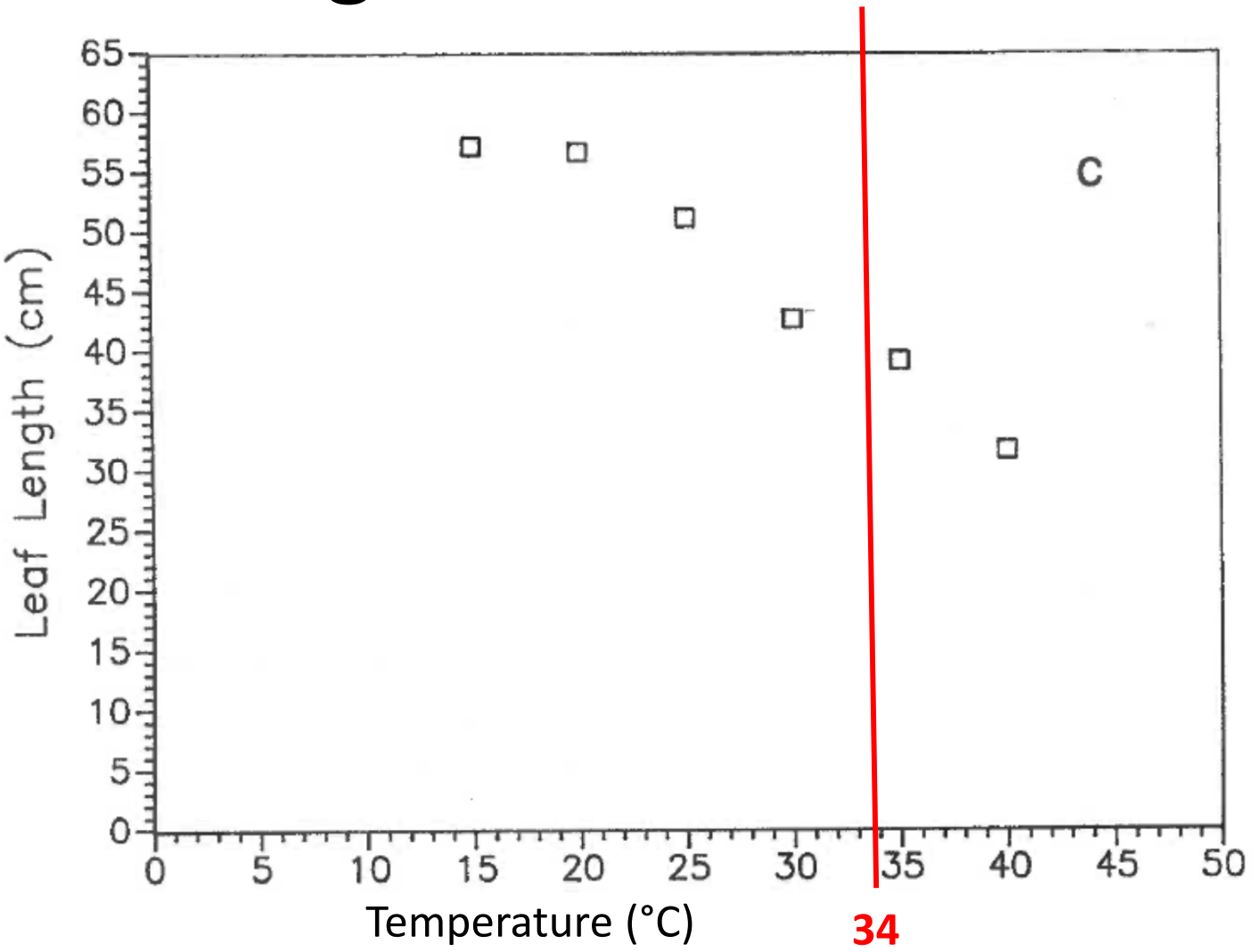

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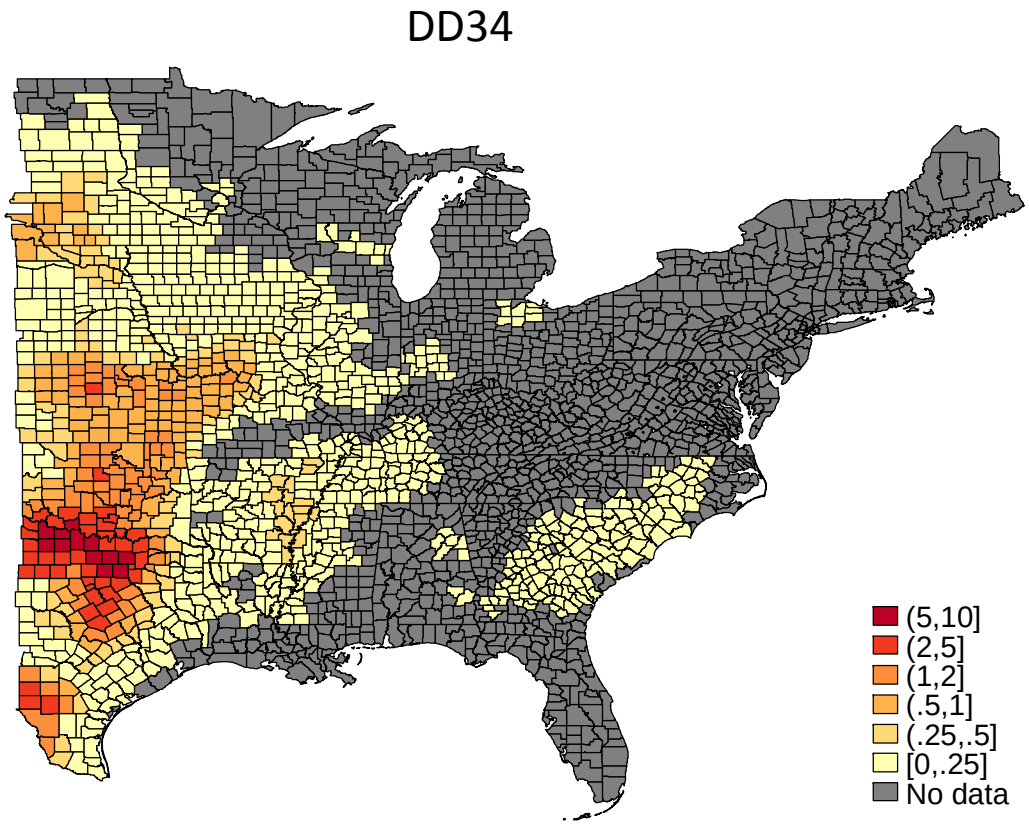
The agronomic literature

- Duration of growth follows the pattern highlighted by SHF
  - Agronomists use degree days to study phenology of plants
  - Farmers use degree days to plan management activities

- Growth rate is quadratic
- Development is jointly determined by the growth rate and the duration
- Development does not show sudden collapse at 34°C
- A quadratic functional form may impose unnecessary restrictions

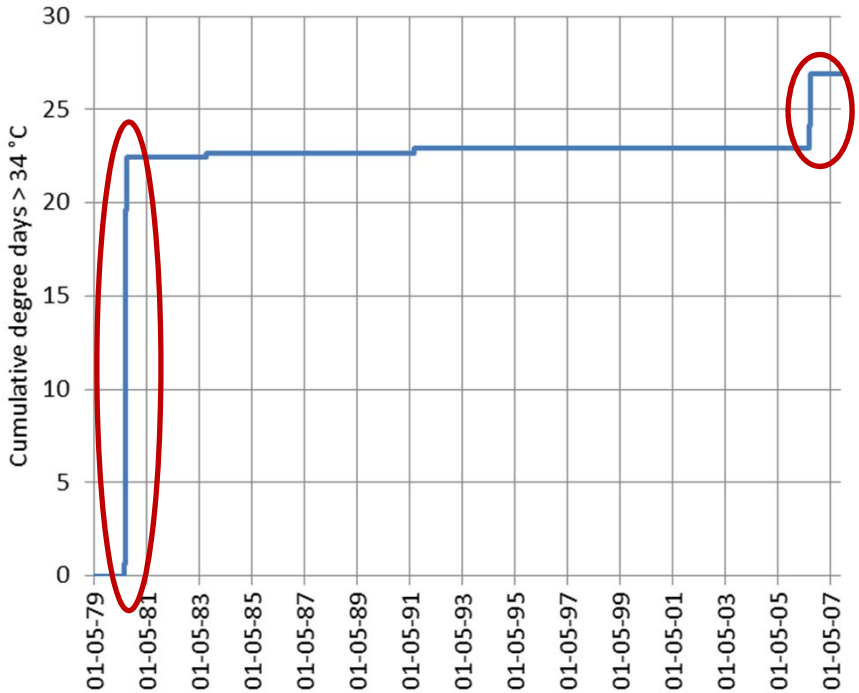
Distribution of DD34 over space



Statistics	NARR	SHF
Average of DD8-32:	2,393	2,290
Average of DD34:	0.19	2.37
Counties in which DD34=0:	55%	0%
90th percentile	0.42	
99th percentile:	3.52	
Maximum:	7.54	5.70

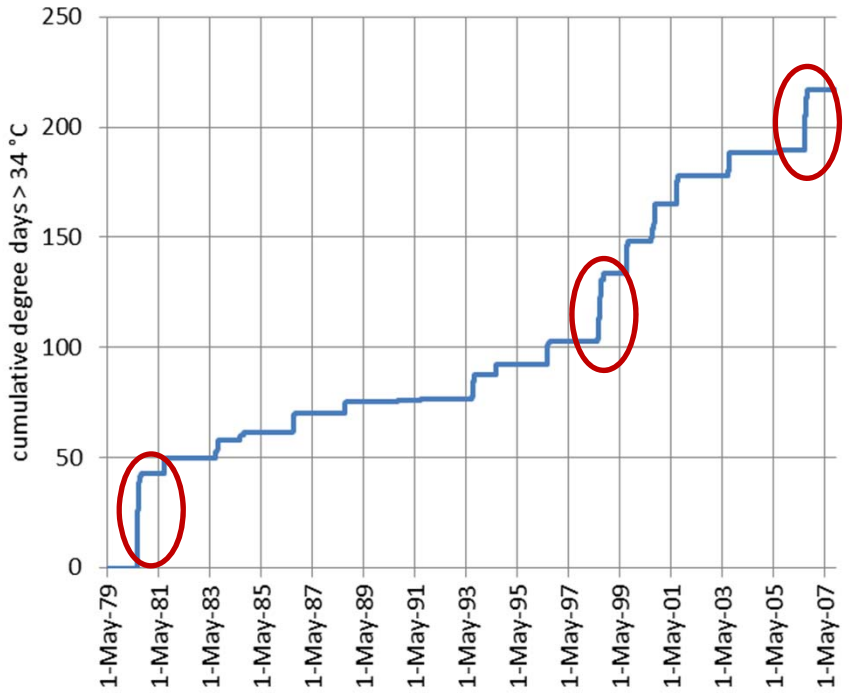
Distribution of DD34 over time

Riley, Kansas (DD34=0.9)



2 heat waves responsible for all DD34

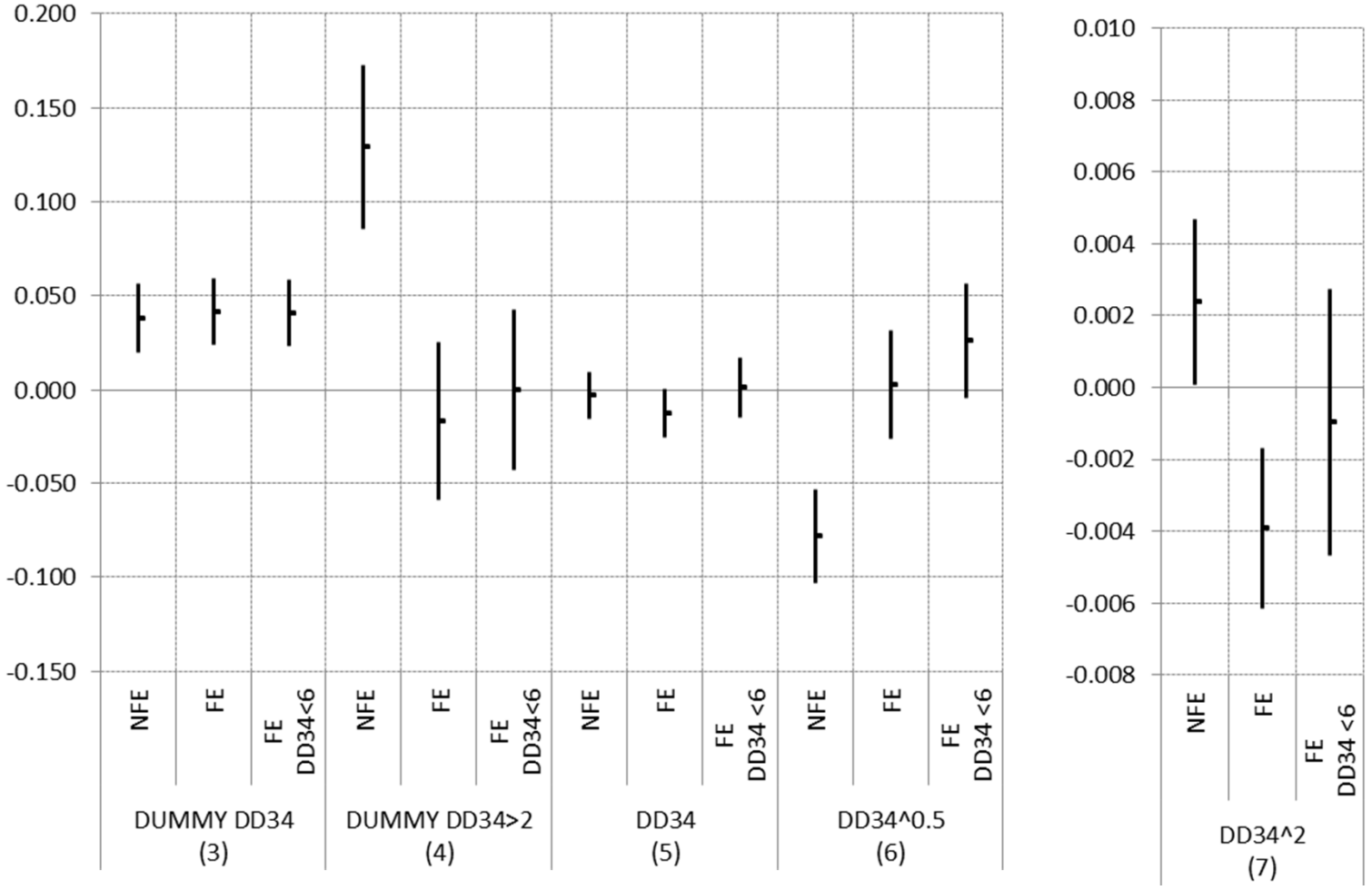
Clay, Texas (DD34=7.2)



3 summers responsible for 50% of DD34

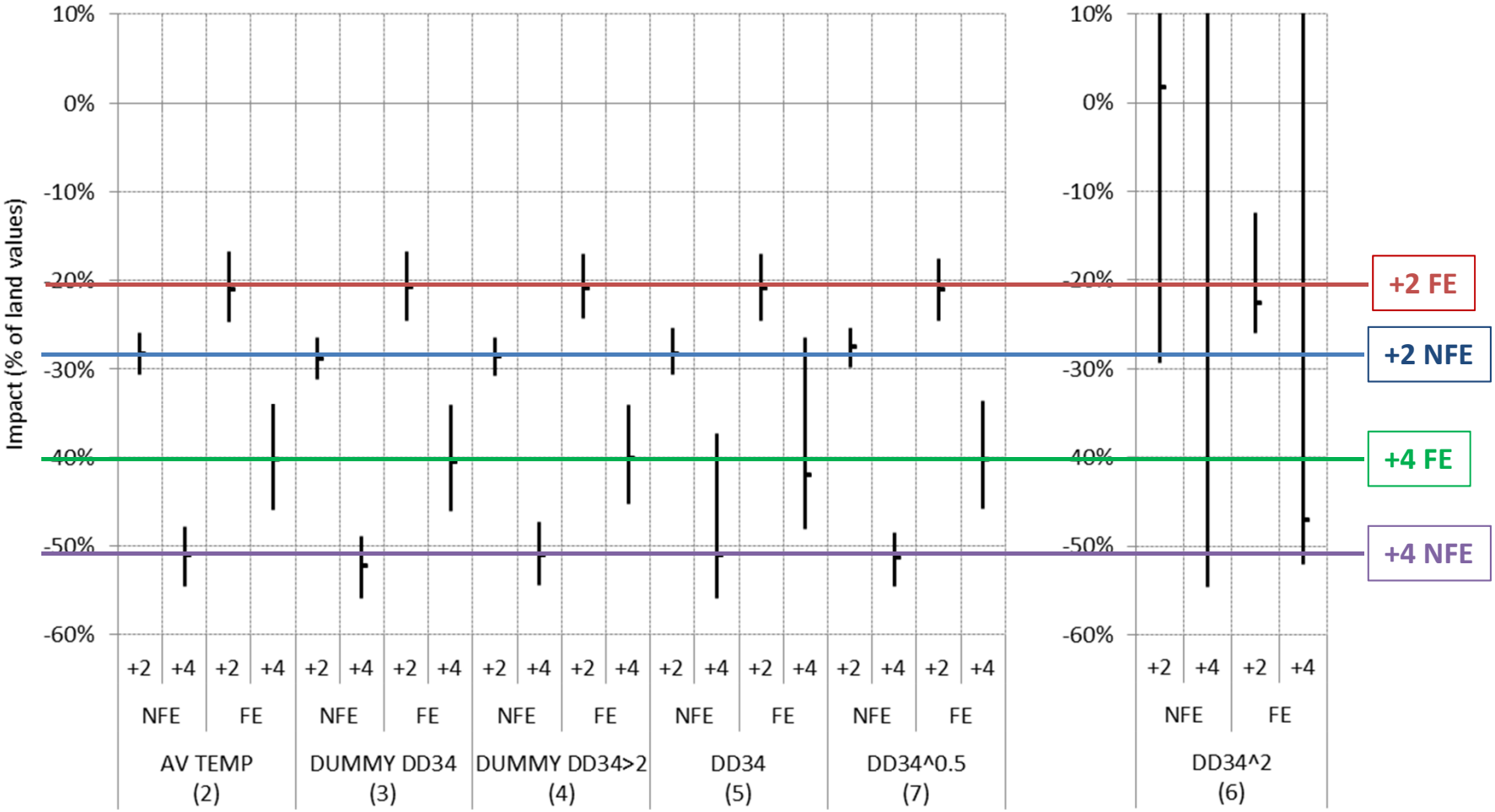
- DD34 poorly proxies heat waves / variance
- More approriate indicators needed

Threshold at 34 °C - Coefficients



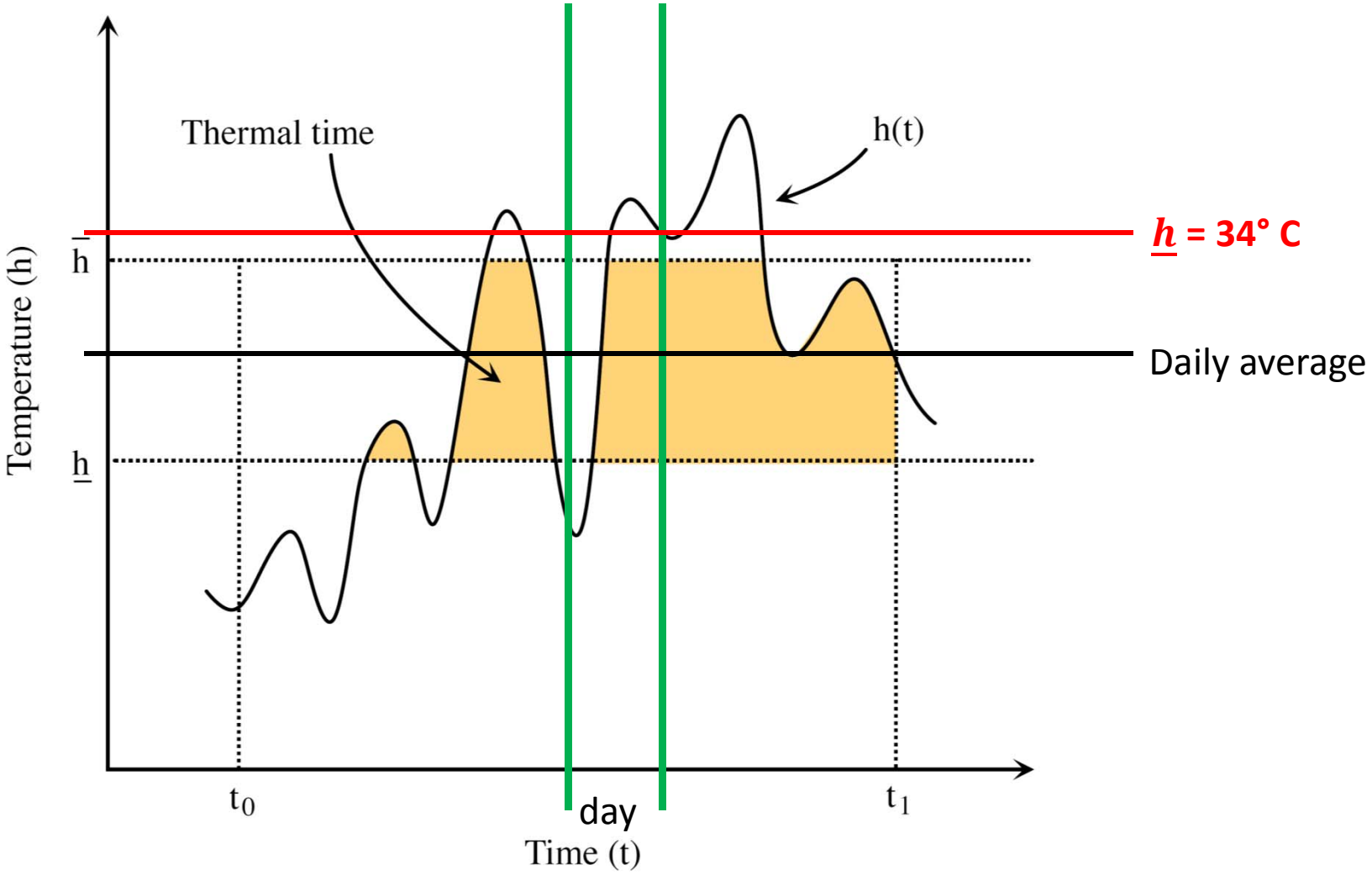
Notes: Central estimates and 95% confidence intervals. NFE: without state fixed effects; FE: with state fixed effects; FE DD34 <6: state fixed effects, only if degree days above 34 °C is lower than 6.

Threshold at 34 °C - Impacts



Notes: Central estimates and 95% bootstrap confidence intervals. NFE: without state fixed effects; FE: with state fixed effects; FE DD34 <6: state fixed effects, only if degree days above 34 °C is lower than 6. Confidence intervals of the model with DD34^2 are truncated.

Thermal time



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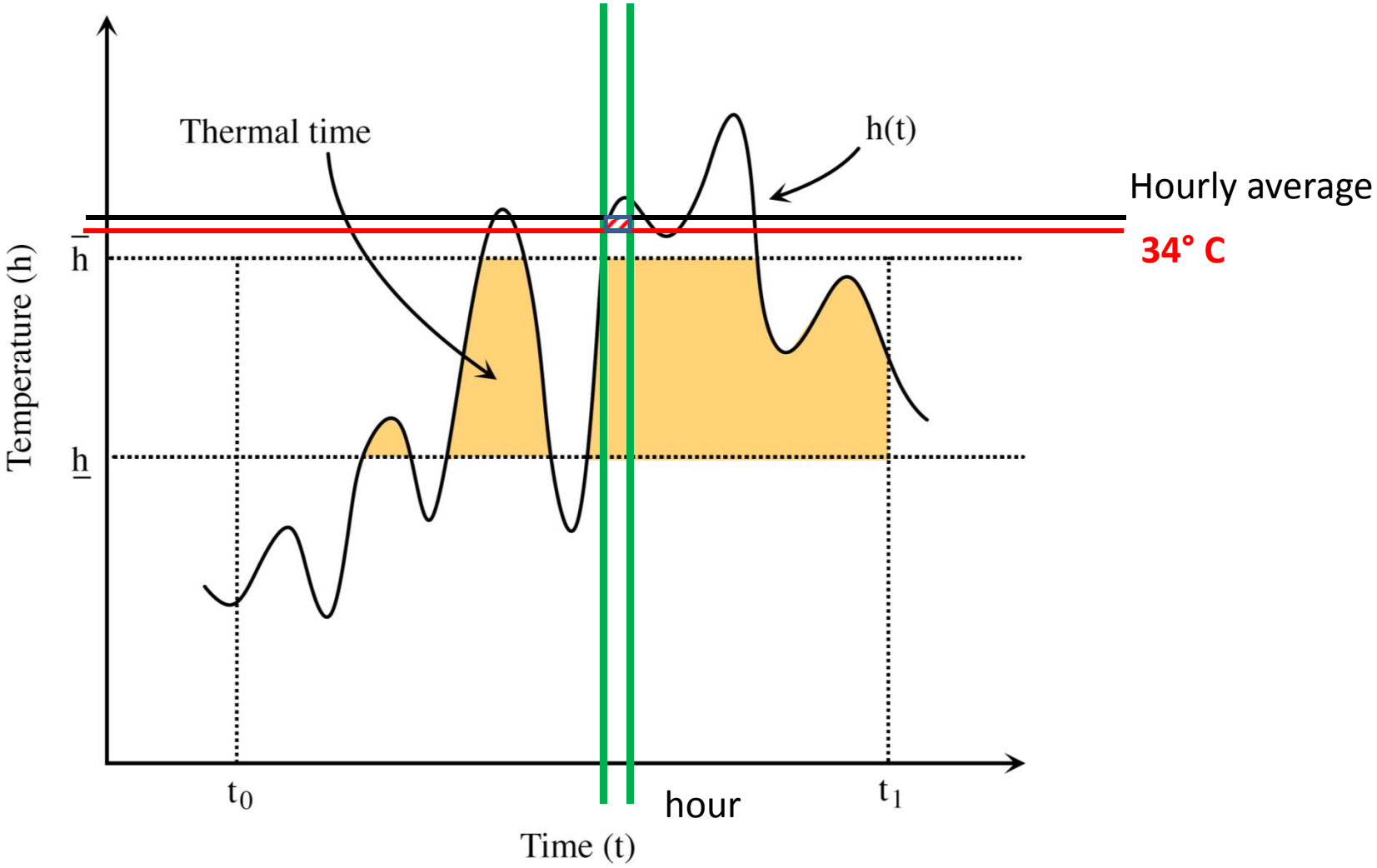
Thermal time



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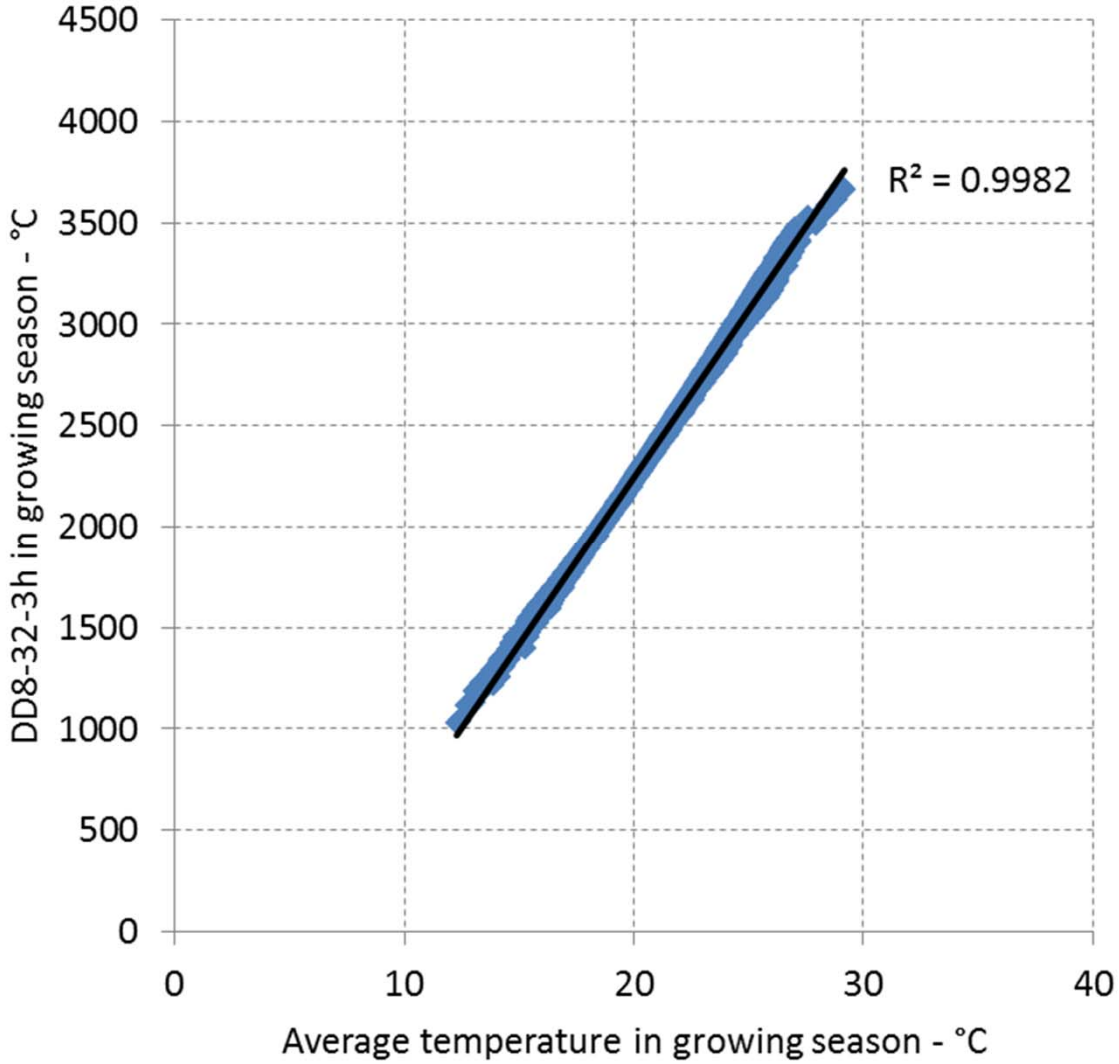
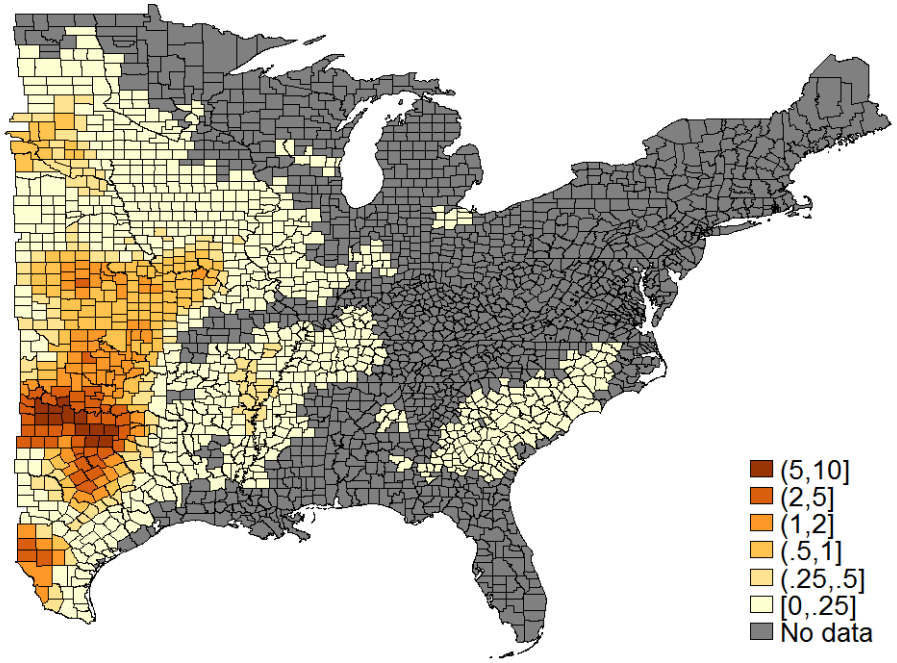
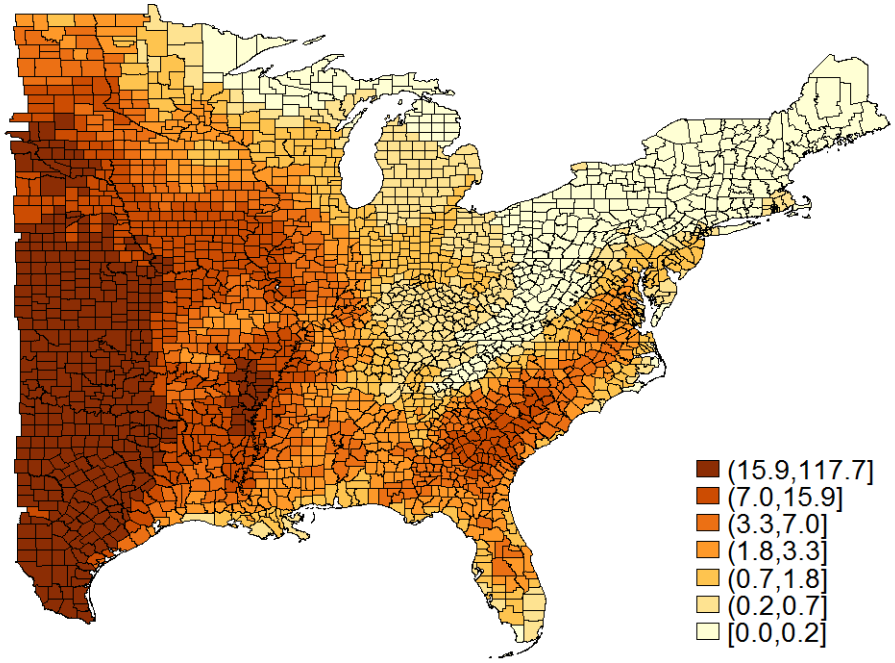
Degree days with 3-hour means



DD34 - NARR



DD34 - NARR - 3h



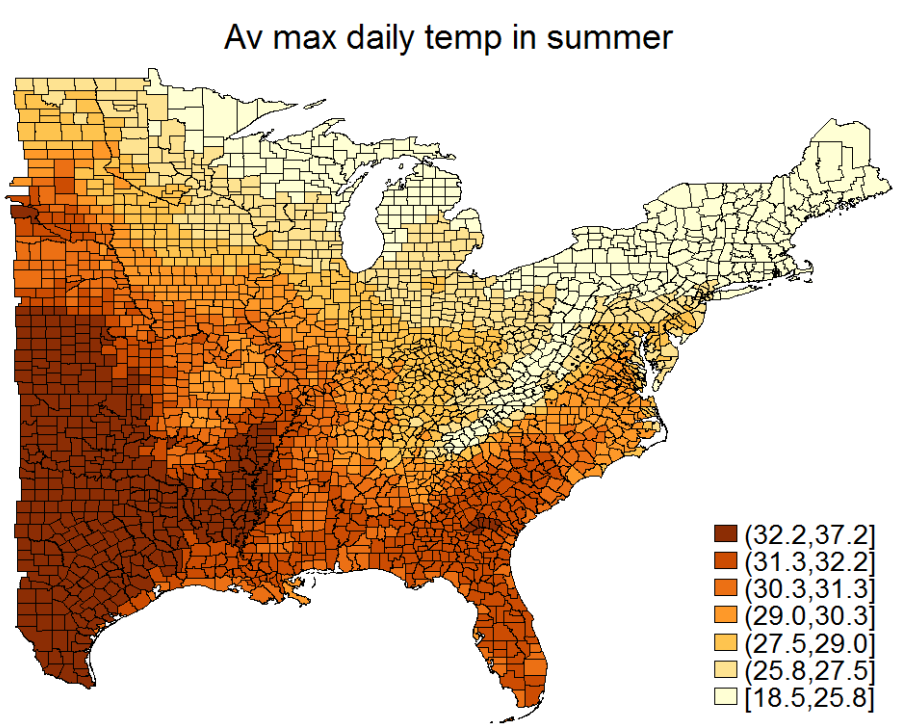
Statistics	NARR	SHF REStat 2006
Mean of DD8-32:	2,393	2,290
Mean of DD34:	0.19	2.37
Counties in which DD34=0:	55%	0%
90th percentile	0.42	
99th percentile:	3.52	
Maximum:	7.54	5.70

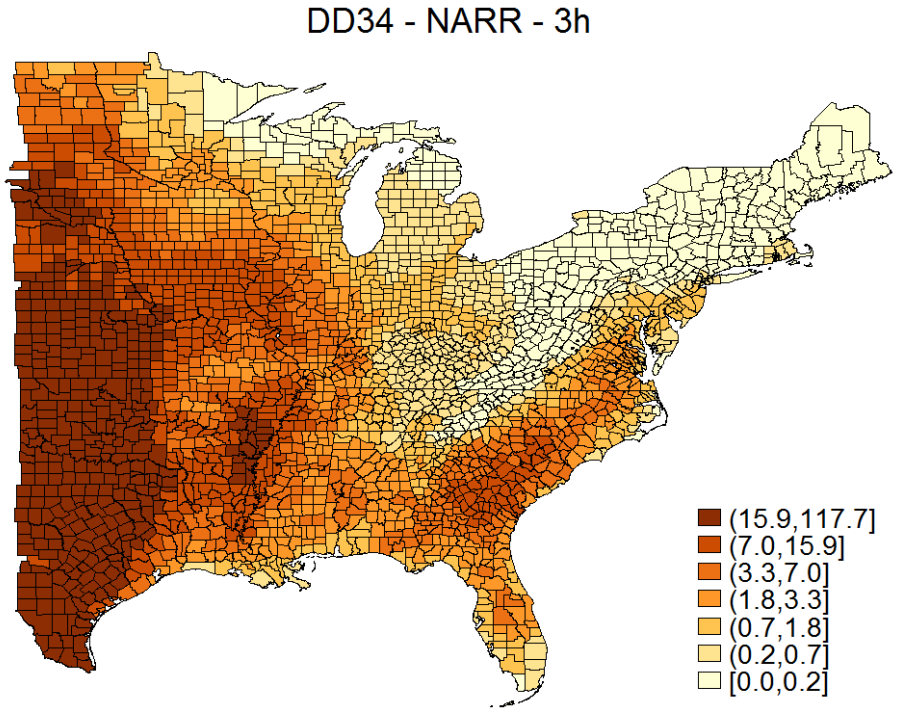
Notes: NARR climatologies 1979-2007 based on daily mean temperatures, 2,409 counties east of the 100° meridian; SHF degree days based on Thom's (1954, 1966) formula, 2,398 counties east of the 100° meridian.

Statistics	NARR	SR PNAS 2009
Mean of DD3h8-32:	2,386	2,262
Mean of DD3h34:	8.71	7.42
Counties in which DD3h34=0:	3.7%	0%
90th percentile	23.6	13.8
99th percentile:	72.3	20.5
Maximum:	117.7	35.7

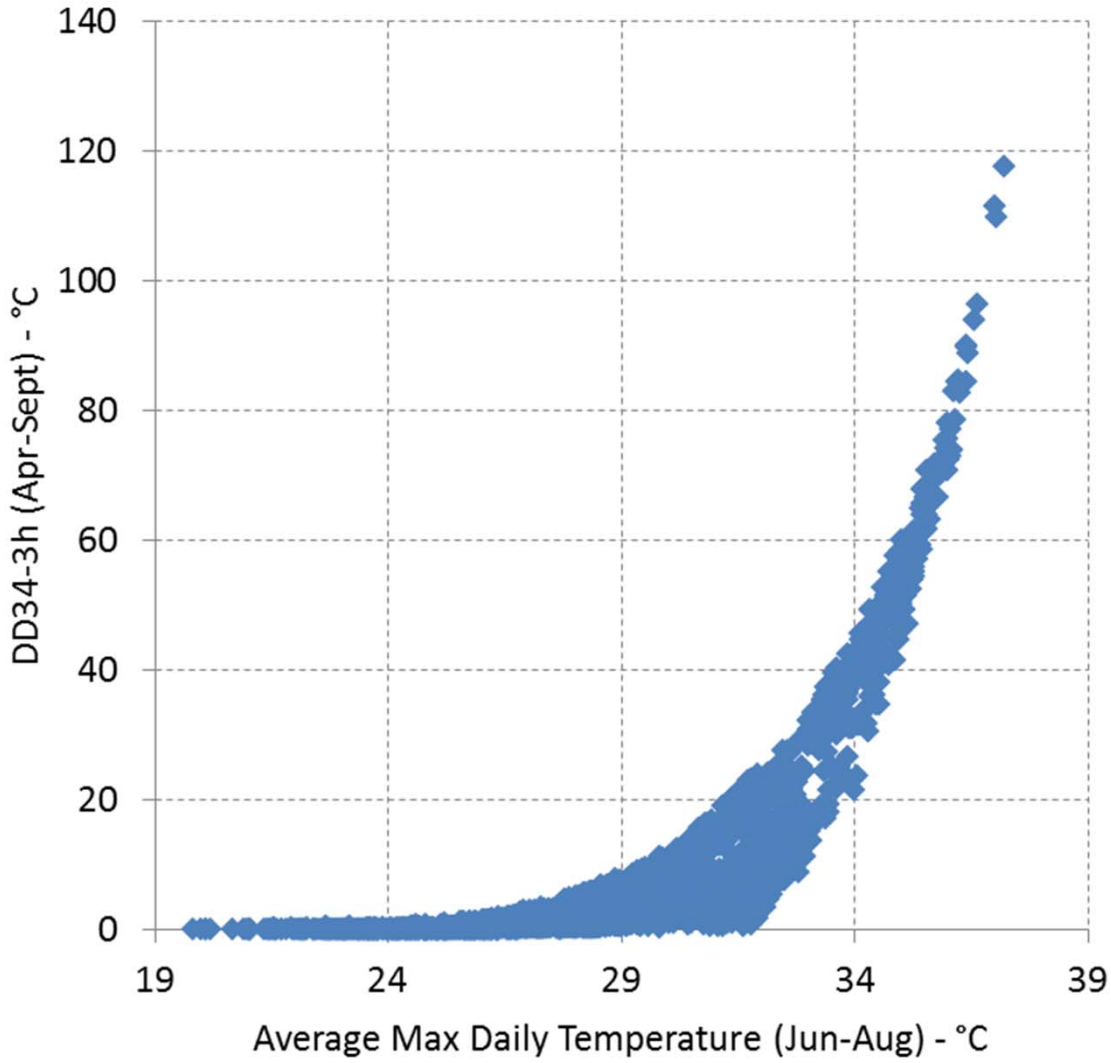
Notes: NARR climatologies 1979-2007 based on 3-hour mean temperatures, 2,395 counties east of the 100° meridian; SR degree days based on 1-hour mean temperatures, 1973-2002.

Max summer temperatures





- 3h degree days above 34 °C capture summer max daily temperatures



- High correlation with max summer temperature (ρ=0.69)
- Thesis: poor proxy of summer max temperatures

	WITHOUT STATE FIXED EFFECTS														
	Growing season												Spring & Summer		
	DD8-32 3h	DD8-32 3h	DD8-32 3h	AV. TEMP	AV. TEMP	AV. TEMP	DD8-32 3h	DD8-32 3h	DD8-32 3h	AV. TEMP	AV. TEMP	AV. TEMP	AV. TEMP	AV. TEMP	AV. TEMP
DD34 3h	— ***			+											
DD34 3h SQ		+ **			+ ***										
DD34 3h SQRT			— ***			— ***				+ ***	+ ***	+ ***			
TSMAX							— ***			— ***			— *		
TSMAX SQ								— ***			— ***			— ***	
TSMAX SQRT									— ***			— ***			— ***
	STATE FIXED EFFECTS														
	Growing season												Spring & Summer		
	DD8-32 3h	DD8-32 3h	DD8-32 3h	AV. TEMP	AV. TEMP	AV. TEMP	DD8-32 3h	DD8-32 3h	DD8-32 3h	AV. TEMP	AV. TEMP	AV. TEMP	AV. TEMP	AV. TEMP	AV. TEMP
DD34 3h	+ **			+ ***											
DD34 3h SQ		+			+ ***										
DD34 3h SQRT			+ **			+ ***				+ ***	+ ***	+ ***			
TSMAX							— **			— ***			+		
TSMAX SQ								—			— ***			+	
TSMAX SQRT									+			— ***			+

Threshold at 8 °C

	AV TEMP & CDD8 (8)	AV TEMP & CDD8 (8-FE)
$T_{4\text{-}9}$	-0.00109***	-0.000460**
	[0.000141]	[0.000180]
$T_{4\text{-}9}$ sq.	1.19e-08	-6.40e-08*
	[2.73e-08]	[3.39e-08]
$CDD8_{4\text{-}9}$	-0.00653***	-0.00367***
	[0.000637]	[0.000742]
$P_{4\text{-}9}$	0.135***	0.238***
	[0.0248]	[0.0293]
$P_{4\text{-}9}$ sq	-0.00756***	-0.0122***
	[0.00128]	[0.00151]
State fixed effects	No	Yes
Adjusted R^2	0.779	0.830
Impact of +2°C	-25.0%	-20.9%
	[-27.7% , -22.1%]	[-24.6% , -16.9%]
Impact of +4°C	-45.5%	-39.6%
	[-50.1% , -41.1%]	[-45.8% , -32.5%]

Notes: Robust standard errors in brackets; *** p<0.01, ** p<0.05, * p<0.1; 95% bootstrap confidence intervals for climate change impacts in brackets. All climate variables from April to September. We subtract 8 °C to average seasonal temperature and multiply by 183. Precipitations in cm/month.

Is there a threshold at 34 °C?

- Improper interpretation of agronomic literature
  - Smooth effect of temperatures on yields
  - The optimal temperature is lower than 32°C
  - Experiment cited uses constant temperature for weeks

- Data shows that degree days 8-32 are highly correlated to average seasonal temperature
- Many problems in measuring DD34
- Cold degree days are significantly harmful

Flexible functional form

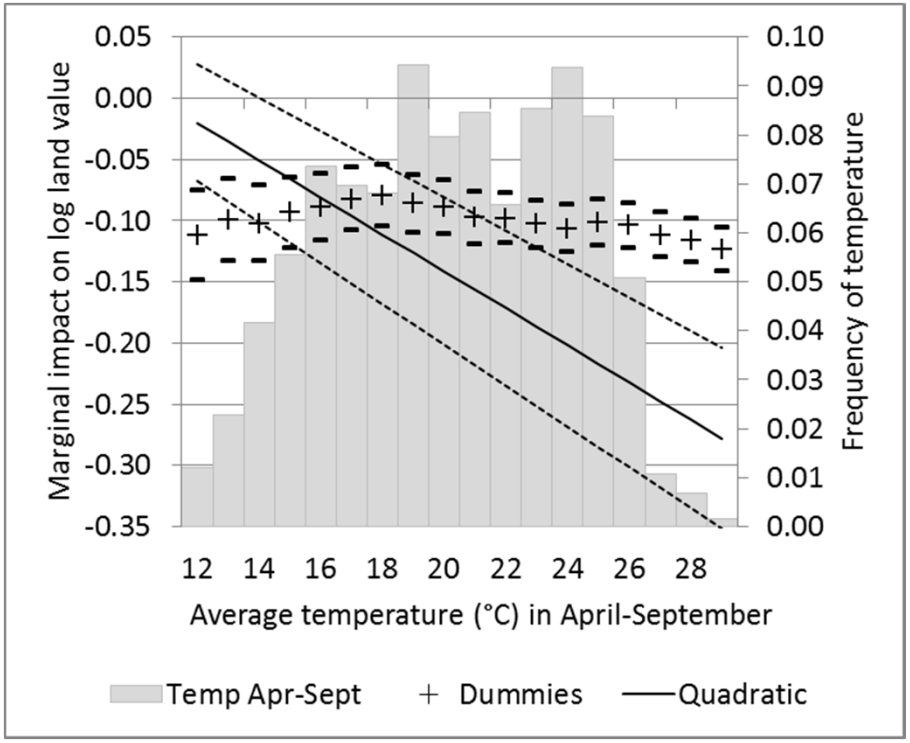
- The quadratic model might be too restrictive
- We interact dummies with temperatures and precipitations
  - 1 °C temperature intervals for growing season
  - 1 cm precipitation intervals

$$y_{i,t} = \beta_0 + \sum_k \beta_k dt_{k,i} T_i + \sum_j \beta_j dp_{j,i} P_i + \boldsymbol{\gamma} X_{i,t} + \boldsymbol{\theta} Z_i + \lambda_t + \epsilon_{i,t}$$

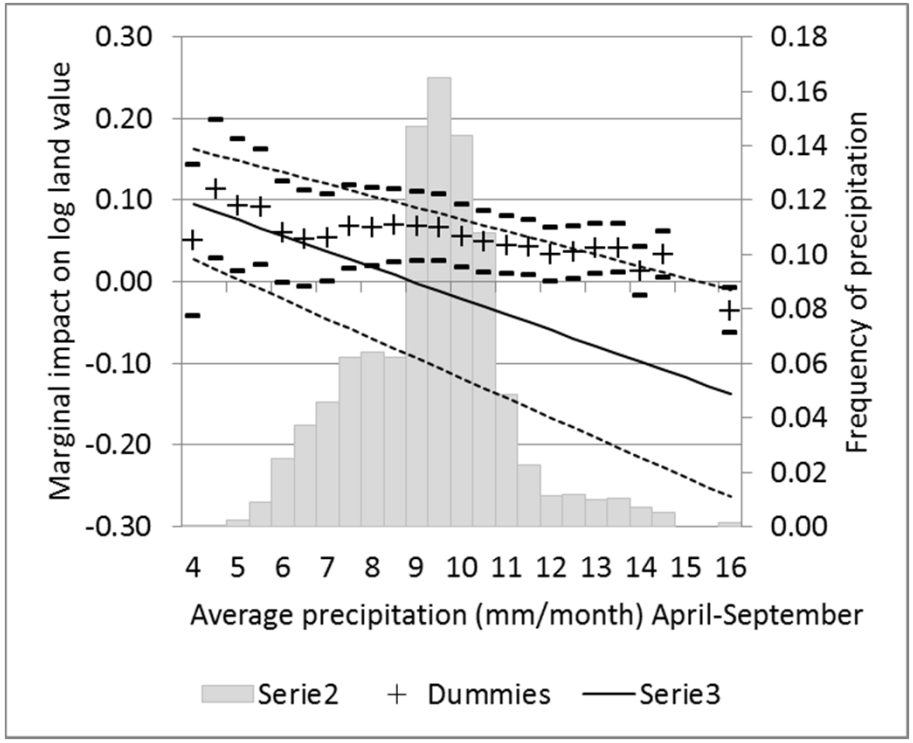
- where $dt_{k,i} = 1$ if $T_k \leq T_i < T_{k+1}$, otherwise $dt_{k,i} = 0$, with $k = 1, \dots, K$ (the same holds for precipitations)

Flexible temperature and precip.

Temperature



Precipitations



- Same holds with and without state fixed effects
- Impacts: -15% (+2 °C), -30% (+4 °C)

Research questions

- Are degree days better than average temperature and should they be truncated at 32 °C?
- Is the effect of temperature on crops positive and largely linear up to 34°C and then precipitously negative?
- Do seasons matter?

4 Seasons vs one growing season

			Usual Planting dates			Usual Harvesting dates		
Crop	State	% of total harvest acres	Begin	Peak	End	Begin	Peak	End
Corn	Iowa	17%	19-Apr	Apr 25 - May 18	26-May	21-Sep	Oct 5 - Nov 9	21-Nov
	Illinois	15%	14-Apr	Apr 21 - May 23	5-Jun	14-Sep	Sep 23 - Nov 5	20-Nov
Cotton	Texas	47%	22-Mar	Apr 8 - Jun 7	20-Jun	10-Aug	Sep 13 - Dec 21	11-Jan
	Georgia	13%	23-Apr	May 2 - May 31	11-Jun	23-Sep	Oct 10 - Dec 2	18-Dec
Sorghum	Kansas	46%	22-Mar	Apr 8 - Jun 7	20-Jun	10-Aug	Sep 13 - Dec 21	11-Jan
	Texas	37%	23-Apr	May 2 - May 31	11-Jun	23-Sep	Oct 10 - Dec 2	18-Dec
Soybeans	Iowa	12%	2-May	May 8 - Jun 2	16-Jun	21-Sep	Sep 28 - Oct 20	31-Oct
	Illinois	12%	2-May	May 8 - Jun 12	24-Jun	19-Sep	Sep 26 - Oct 26	7-Nov
Spring Wheat	North Dakota	49%	16-Apr	Apr 24 - May 25	3-Jun	1-Aug	Aug 8 - Sep 13	25-Sep
	Montana	18%	6-Apr	Apr 14 - May 12	18-May	30-Jul	Aug 7 - Sep 6	13-Sep
Winter Wheat	Kansas	26%	10-Sep	Sep 15 - Oct 20	1-Nov	15-Jun	Jun 20 - Jul 5	15-Jul
	Oklahoma	10%	3-Sep	Sep 15 - Oct 22	6-Nov	1-Jun	Jun 6 - Jun 27	3-Jul

- Growing season is not April-September
- Growing season is endogenous

Winter Wheat

- In 2009 winter wheat comprises 69% of all wheat produced

- Winter wheat is planted in the fall, goes into dormancy during the winter, and is harvested for grain the following spring

When weather conditions are favorable for early fall growth, much of the winter wheat in the southern Great Plains is grazed in the fall prior to going into dormancy and again in the late winter and early spring when new growth starts.

Source: USDA 2010. Field Crops Usual Planting and Harvesting Dates. USDA, National Agricultural Statistics Service, October 2010, p. 32.

Winter precipitations

“DENVER — After enduring last summer’s destructive drought, farmers, ranchers and officials across the country’s parched heartland had hoped that plentiful winter snows would replenish the ground and refill their rivers, breaking the grip of one of the worst dry spells in American history. No such luck.”

Healy, Jack (2013). “In Drought-Stricken Heartland, Snow is No Savior.” The New York Times, February 23, 2013.

	DD 2 SEAS. T	DD 2 SEAS. T&P	DD 2 SEAS. T	DD 2 SEAS. T&P
	(9)	(10)	(9-FE)	(10-FE)
$DD8\text{-}32_{4\text{-}6}$	0.00682***	0.00599***	0.00665***	0.00578***
	[0.000292]	[0.000282]	[0.000398]	[0.000405]
$DD8\text{-}32_{4\text{-}6}$ sq.	-2.54e-06***	-1.99e-06***	-2.66e-06***	-2.13e-06***
	[1.25e-07]	[1.17e-07]	[1.57e-07]	[1.63e-07]
$DD8\text{-}32_{7\text{-}9}$	-0.00559***	-0.00372***	-0.00643***	-0.00511***
	[0.000381]	[0.000360]	[0.000479]	[0.000485]
$DD8\text{-}32_{7\text{-}9}$ sq.	7.87e-07***	7.28e-09	1.28e-06***	7.10e-07***
	[1.24e-07]	[1.16e-07]	[1.51e-07]	[1.57e-07]
$P_{4\text{-}9}$	-0.0219		0.00823	
	[0.0294]		[0.0338]	
$P_{4\text{-}9}$ sq	-0.000908		-0.00236	
	[0.00149]		[0.00169]	
$P_{4\text{-}6}$		0.413***		0.198***
		[0.0275]		[0.0342]
$P_{4\text{-}6}$ sq.		-0.0198***		-0.00900***
		[0.00129]		[0.00157]
$P_{7\text{-}9}$		-0.210***		-0.145***
		[0.0156]		[0.0213]
$P_{7\text{-}9}$ sq.		0.00775***		0.00457***
		[0.000735]		[0.000982]
State fixed effects	No	No	Yes	Yes
Adjusted R^2	0.799	0.811	0.837	0.839
Impact of +2°C	-26.1%	-28.4%	-22.6%	-25.2%
	[-28.3% , -23.8%]	[-30.4% , -26.3%]	[-26.1% , -19.2%]	[-28.4% , -21.6%]
Impact of +4°C	-46.8%	-50.2%	-41.4%	-45.1%
	[-50.3% , -43.4%]	[-53.2% , -47%]	[-47% , -35.3%]	[-50.5% , -39.6%]

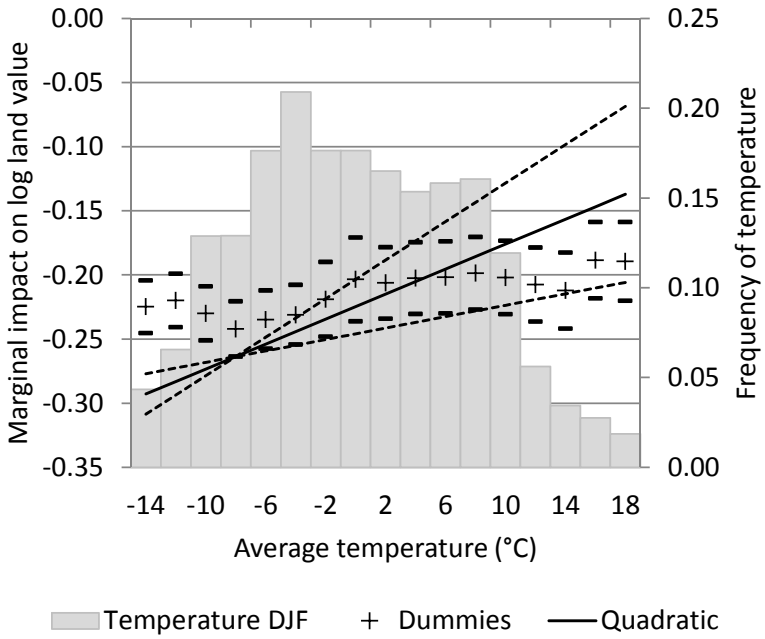
	AV TEMP 2 SEAS. T (11)	AV TEMP 2 SEAS. T&P (12)	AV TEMP 2 SEAS. T (11-FE)	AV TEMP 2 SEAS. T&P (12-FE)
T_{4-6}	0.00755***	0.00645***	0.00625***	0.00553***
	[0.000266]	[0.000267]	[0.000338]	[0.000366]
T_{4-6} sq.	-2.93e-06***	-2.31e-06***	-2.62e-06***	-2.16e-06***
	[1.15e-07]	[1.13e-07]	[1.38e-07]	[1.55e-07]
T_{7-9}	-0.00995***	-0.00753***	-0.00885***	-0.00753***
	[0.000447]	[0.000441]	[0.000551]	[0.000591]
T_{7-9} sq.	2.20e-06***	1.28e-06***	2.10e-06***	1.54e-06***
	[1.45e-07]	[1.42e-07]	[1.73e-07]	[1.90e-07]
P_{4-9}	-0.135***		-0.0521	
	[0.0300]		[0.0353]	
P_{4-9} sq	0.00476***		0.000506	
	[0.00153]		[0.00176]	
P_{4-6}		0.289***		0.128***
		[0.0288]		[0.0366]
P_{4-6} sq.		-0.0140***		-0.00570***
		[0.00135]		[0.00167]
P_{7-9}		-0.211***		-0.148***
		[0.0152]		[0.0215]
P_{7-9} sq.		0.00811***		0.00478***
		[0.000717]		[0.000993]
State fixed effects	No	No	Yes	Yes
Adjusted R^2	0.805	0.813	0.838	0.840
Impact of +2°C	-24.9%	-27.3%	-23.5%	-25.5%
	[-27.3% , -22.5%]	[-29.4% , -24.9%]	[-27% , -20%]	[-29% , -21.8%]
Impact of +4°C	-45.2%	-49.4%	-42.6%	-46.1%
	[-48.7% , -41.6%]	[-52.7% , -46%]	[-47.7% , -36.8%]	[-51.4% , -40.6%]

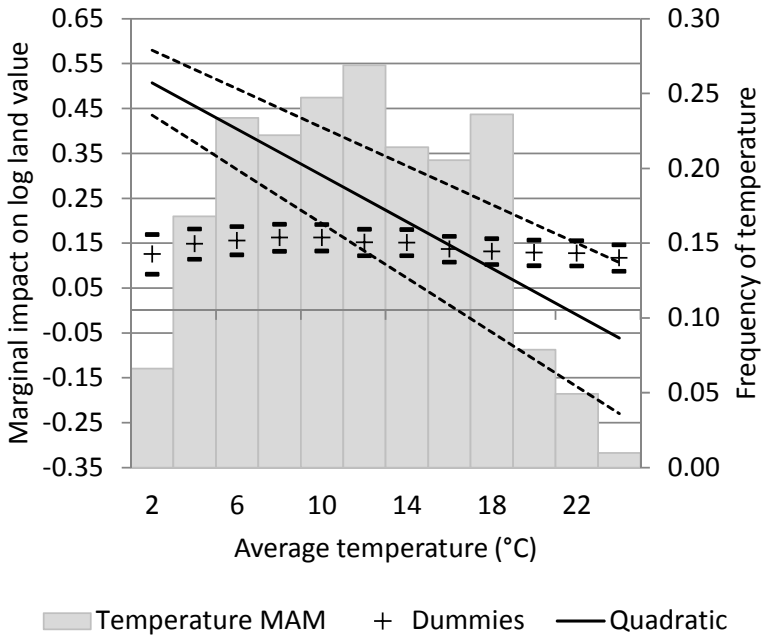
4 seasons - temperatures

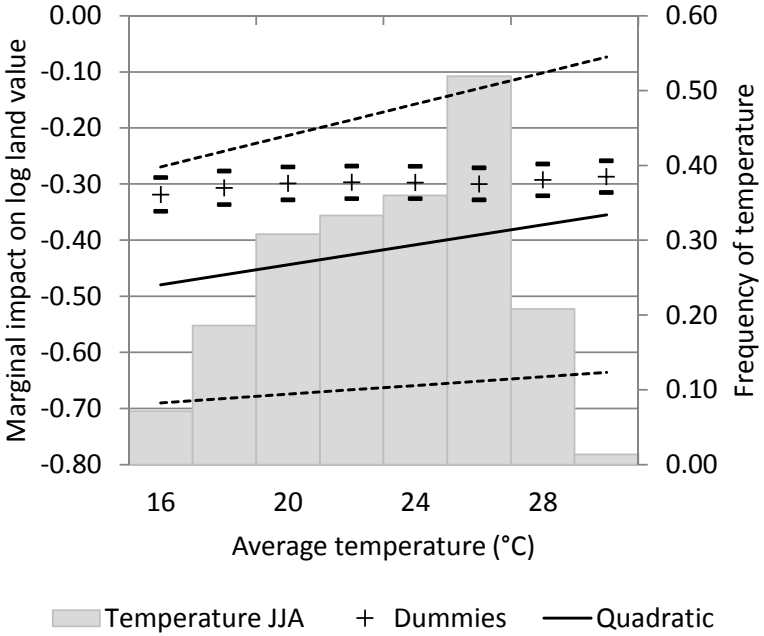
	AV TEMP 4 SEAS. T (13)	AV TEMP 4 SEAS. T&P (14)	AV TEMP 4 SEAS. T (13-FE)	AV TEMP 4 SEAS. T&P (13-FE)		AV TEMP 4 SEAS. DJF (15)	AV TEMP 4 SEAS. DJF (15-FE)
T1-3	-0.00331***	-0.00304***	-0.00191***	-0.00248***	T12-2	-0.00206***	-0.00174***
	[0.000223]	[0.000257]	[0.000273]	[0.000275]		[0.000209]	[0.000249]
T1-3 sq.	-1.24e-07	1.13e-07	7.17e-07***	7.08e-07***	T12-2 sq.	3.00e-07***	5.74e-07***
	[1.03e-07]	[1.22e-07]	[1.30e-07]	[1.32e-07]		[8.31e-08]	[9.00e-08]
T4-6	0.00698***	0.00585***	0.00583***	0.00507***	T3-5	0.00391***	0.00205***
	[0.000285]	[0.000313]	[0.000360]	[0.000373]		[0.000197]	[0.000222]
T4-6 sq.	-2.46e-06***	-1.90e-06***	-2.49e-06***	-1.99e-06***	T3-5 sq.	-1.60e-06***	-1.03e-06***
	[1.39e-07]	[1.51e-07]	[1.67e-07]	[1.75e-07]		[1.37e-07]	[1.47e-07]
T7-9	-0.00763***	-0.00531***	-0.00732***	-0.00556***	T6-8	-0.00612***	-0.00621***
	[0.000489]	[0.000531]	[0.000582]	[0.000602]		[0.000509]	[0.000606]
T7-9 sq.	1.51e-06***	6.11e-07***	1.73e-06***	1.02e-06***	T6-8 sq.	5.51e-07***	8.89e-07***
	[1.56e-07]	[1.64e-07]	[1.80e-07]	[1.89e-07]		[1.59e-07]	[1.95e-07]
T10-12	0.00309***	0.00334***	0.00269***	0.00349***	T9-11	0.00365***	0.00514***
	[0.000171]	[0.000180]	[0.000191]	[0.000198]		[0.000271]	[0.000268]
T10-12 sq.	1.42e-08	-2.66e-07*	-1.04e-06***	-8.74e-07***	T9-11 sq.	-2.09e-07	-1.00e-06***
	[1.38e-07]	[1.61e-07]	[1.73e-07]	[1.76e-07]		[2.33e-07]	[2.55e-07]
p. Apr-Sept	-0.121***		-0.000381				
	[0.0326]		[0.0350]				
P. Apr-Sept sq	0.00513***		-0.00133				
	[0.00165]		[0.00175]				
State FE	No	No	Yes	Yes	State FE	No	Yes
Adjusted R2	0.814	0.822	0.844	0.849	Adjusted R2	0.825	0.852
Impact of +2°C	-17.6%	-18.4%	-18.7%	-16.6%	Impact of +2°C	-17.2%	-15.3%
	[-22.4% , -12.6%]	[-23.8% , -13.1%]	[-22.7% , -14.1%]	[-21.3% , -10.6%]		[-22.5% , -11.5%]	[-20.2% , -10%]
Impact of +4°C	-34.9%	-37.4%	-37.1%	-34.2%	Impact of +4°C	-34.1%	-30.3%
	[-42.1% , -26.8%]	[-45.1% , -28.6%]	[-43.9% , -28.6%]	[-41.2% , -25.1%]		[-42.1% , -25.5%]	[-38.3% , -20.7%]

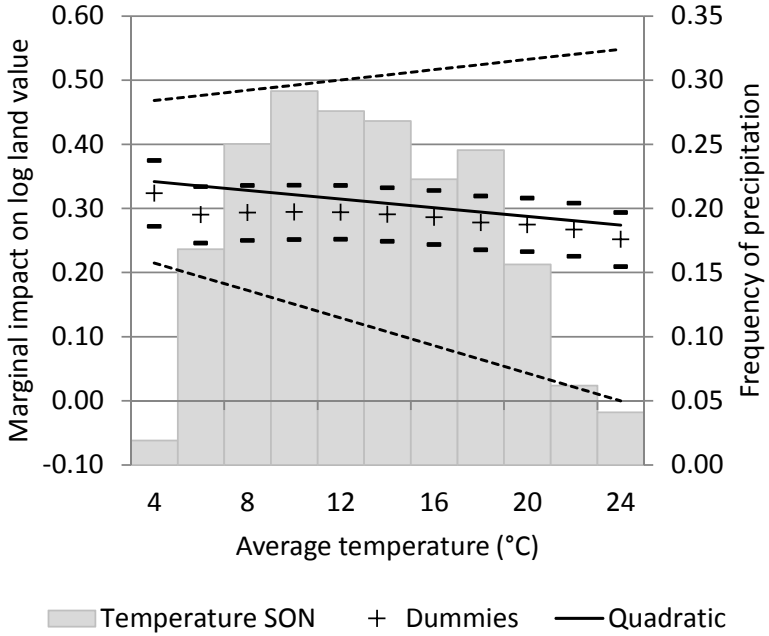
4 seasons - precipitations

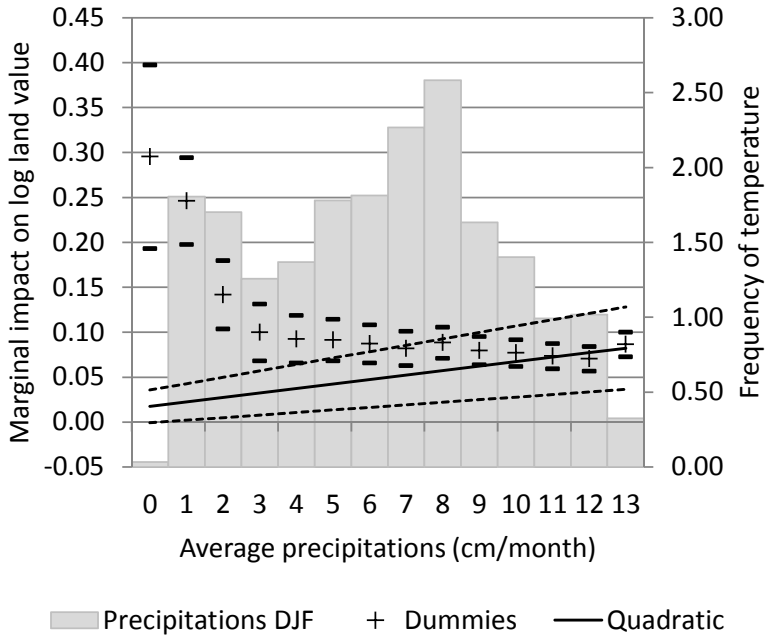
	AV TEMP 4 SEAS. T	AV TEMP 4 SEAS. T&P	AV TEMP 4 SEAS. T	AV TEMP 4 SEAS. T&P		AV TEMP 4 SEAS. DJF	AV TEMP 4 SEAS. DJF
	(13)	(14)	(13-FE)	(13-FE)		(15)	(15-FE)
p1-3		0.00151		0.102***	P12-2	0.0175*	0.00424
		[0.0157]		[0.0196]		[0.00929]	[0.0138]
P1-3 sq.		0.00130		-0.00306***	P12-2 sq.	0.00249***	0.00184**
		[0.000788]		[0.000960]		[0.000543]	[0.000797]
P4-6		0.298***		0.189***	P3-5	0.311***	0.332***
		[0.0344]		[0.0410]		[0.0284]	[0.0335]
P4-6 sq.		-0.0125***		-0.00665***	P3-5 sq.	-0.0167***	-0.0149***
		[0.00159]		[0.00186]		[0.00141]	[0.00166]
P7-9		-0.207***		-0.143***	P6-8	-0.286***	-0.198***
		[0.0159]		[0.0214]		[0.0184]	[0.0257]
P7-9 sq.		0.00762***		0.00404***	P6-8 sq.	0.0115***	0.00720***
		[0.000780]		[0.00101]		[0.000841]	[0.00115]
P10-12		-0.00151		-0.101***	P9-11	0.137***	-0.0301
		[0.0172]		[0.0220]		[0.0223]	[0.0249]
P10-12 sq.		-0.00199**		0.00293***	P9-11 sq.	-0.0106***	-0.000495
		[0.000927]		[0.00111]		[0.00128]	[0.00143]
State FE	No	No	Yes	Yes	State FE	No	Yes
Adjusted R2	0.814	0.822	0.844	0.849	Adjusted R2	0.825	0.852
Impact of +2°C	-17.6%	-18.4%	-18.7%	-16.6%	Impact of +2°C	-17.2%	-15.3%
	[-22.4% , -12.6%]	[-23.8% , -13.1%]	[-22.7% , -14.1%]	[-21.3% , -10.6%]		[-22.5% , -11.5%]	[-20.2% , -10%]
Impact of +4°C	-34.9%	-37.4%	-37.1%	-34.2%	Impact of +4°C	-34.1%	-30.3%
	[-42.1% , -26.8%]	[-45.1% , -28.6%]	[-43.9% , -28.6%]	[-41.2% , -25.1%]		[-42.1% , -25.5%]	[-38.3% , -20.7%]

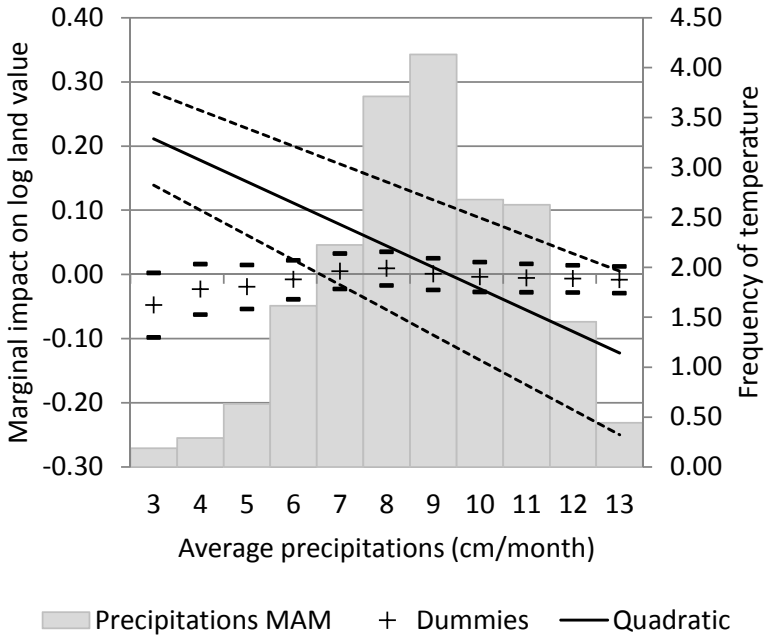

Marginal impact on log land value
Frequency of temperature
Average temperature (°C)
Temperature DJF
Dummies
Quadratic

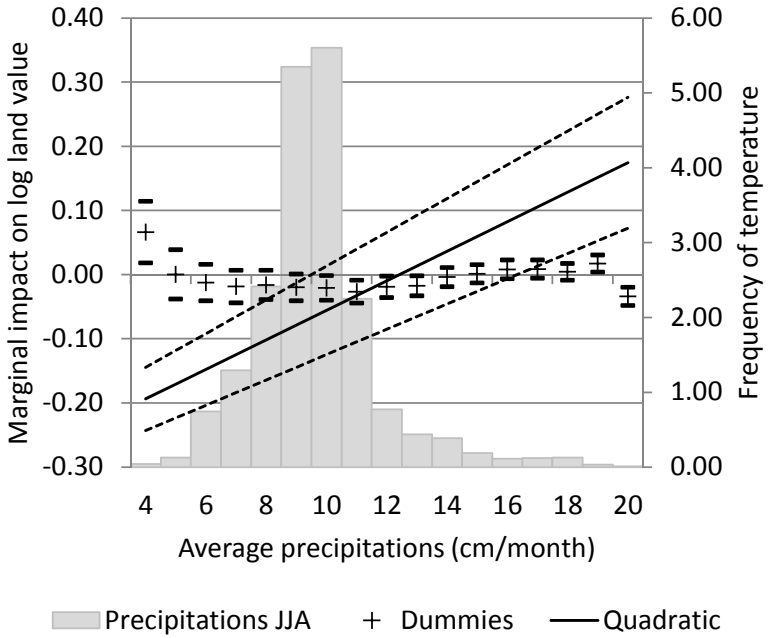

Marginal impact on log land value
Frequency of temperature
Average temperature (°C)
Temperature MAM
Dummies
Quadratic

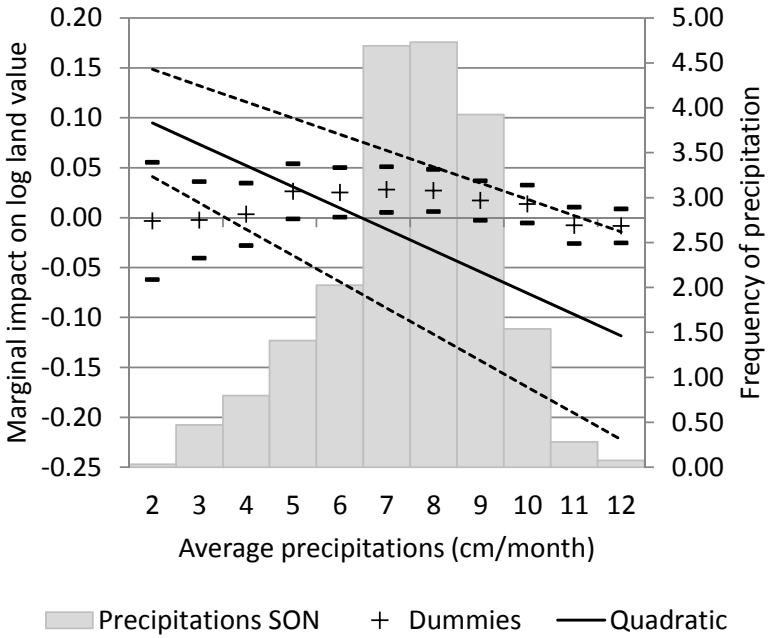

Marginal impact on log land value
Frequency of temperature
Average temperature (°C)
Temperature JJA
Dummies
Quadratic


Marginal impact on log land value
Frequency of precipitation
Average temperature (°C)
Temperature SON
Dummies
Quadratic


Marginal impact on log land value
Frequency of temperature
Average precipitations (cm/month)
Precipitations DJF
Dummies
Quadratic


Marginal impact on log land value
Frequency of temperature
Average precipitations (cm/month)
Precipitations MAM
Dummies
Quadratic


Marginal impact on log land value
Frequency of temperature
Average precipitations (cm/month)
Precipitations JJA
Dummies
Quadratic


Marginal impact on log land value
Frequency of precipitation
Average precipitations (cm/month)
Precipitations SON
Dummies
Quadratic

Impacts of flexible models

	No state fixed effects		State fixed effects	
	+2°C	+4°C	+2°C	+4°C
April-September				
Temperature only	-20.6% [-25.1% , -16.2%]	-41.9% [-50.5% , -33.4%]	-18.6% [-23.2% , -14%]	-37.4% [-46.3% , -28.5%]
Temp. and precip.	-19.1% [-23.5% , -14.7%]	-38.9% [-47.3% , -30.4%]	-15.6% [-20.2% , -11%]	-31.5% [-40.4% , -22.7%]
4 seasons (DJF)				
Temp. and precip.	-7.2% [-9.8% , -4.5%]	-15.0% [-20.1% , -9.9%]	-6.1% [-8.6% , -3.7%]	-13.1% [-18% , -8.3%]

Performance & robustness tests

- Prediction power test:
  - Forecast 25% of warmest counties using 75% coldest counties
  - Perform F-test to check what model has lowest prediction error (Morgan-Granger-Newbold)
  - Confirms that seasonal model with average temperatures has highest accuracy

- Robustness tests
  - Aggregation of climate data at centroid or weighted area average of grid-points
  - Mean daily temperature from daily min and max
  - Repeated cross-section

Conclusions

- Average seasonal temp. better than DD8-32
- No evidence of a threshold at DD34
  - Both using daily mean and 3-hour intervals
- Evidence of a threshold at 8 °C
- Flexible functional forms tend to perform better than the quadratic
  - Flatter marginal impacts
- Seasons matter
  - Lower negative impacts

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