How Large is the Potential Economic Benefit of Agricultural Adaptation to Climate Change?

Huang Kaixing*   Nicholas Sim

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Background knowledge

- **Climate change**
- **Weather fluctuation**
- **Adaptation**

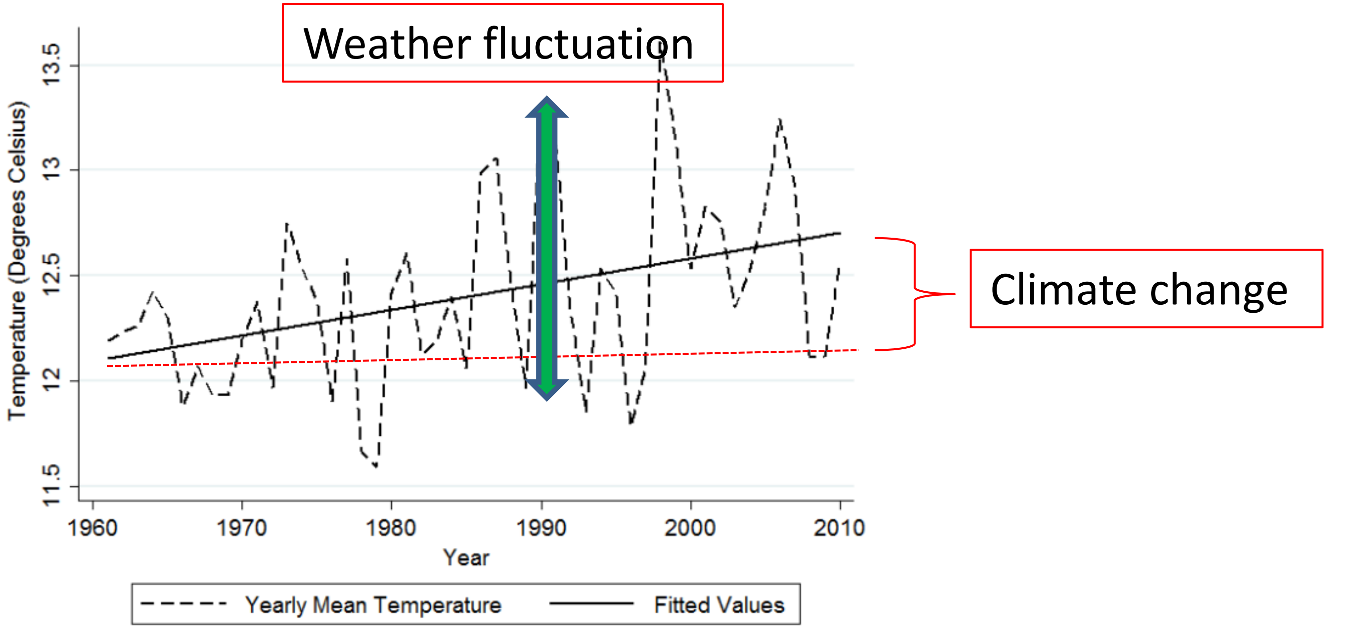

FIGURE 1. YEARLY MEAN TEMPERATURE FLUCTUATIONS IN THE US, 1960–2010

Data source: Physical Sciences Division of National Oceanic and Atmospheric Administration (http://www.esrl.noaa.gov/psd/)

Background knowledge

– **Value of Adaptation**

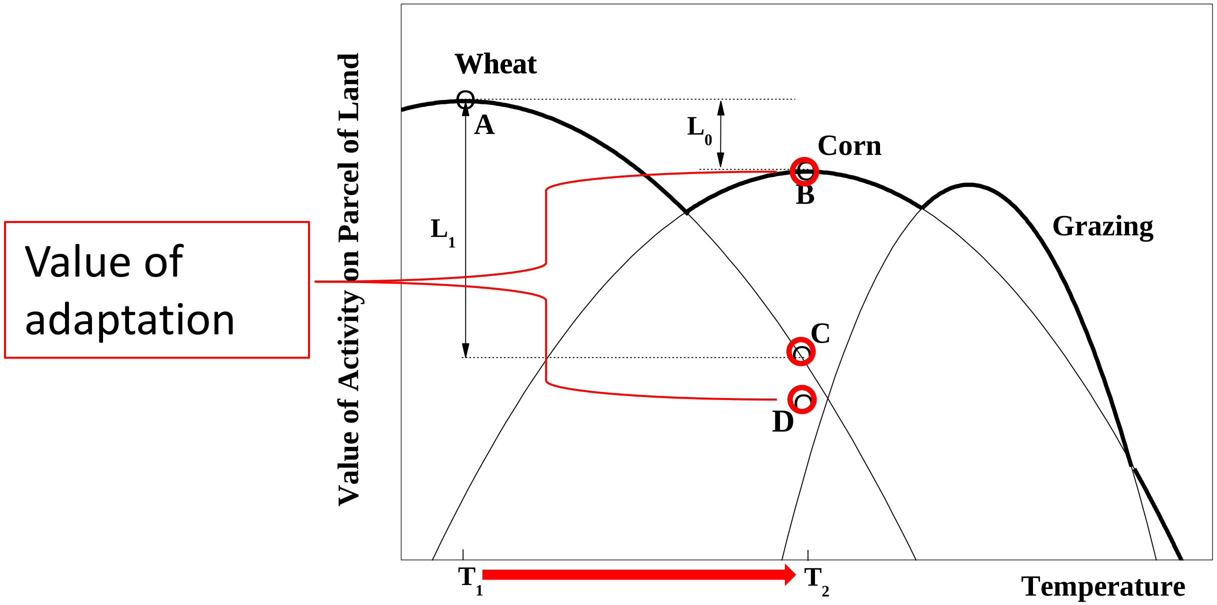

FIGURE 2. VALUE OF LAND AS A FUNCTION OF AVERAGE TEMPERATURE

Adapted from Mendelsohn, Nordhaus, and Shaw (1994) and Kelly, Kolstad, and Mitchell (2005)

Literature

- Estimating damage of climate change: Mendelsohn, Nordhaus, and Shaw (1994 AER), Schlenker, Hanemann, and Fisher (2005 AER), (2006 RES), Deschênes and Greenstone (2007 AER)
- Little is known about the benefits of adaptation
  - Overestimate the damage
  - Policy

Literature

- Micro-level studies: specific adaptation method
  - e.g., Kurukulasuriya and Mendelsohn (2008) Seo and Mendelsohn (2008) Di Falco and Veronesi (2013)
  - Numerous adaptation methods
  - Implemented in isolation or in combination
  - What is the overall benefits?

Literature

- Macro-level studies
  - Burke and Emerick (2016, AEJ): Recent climate trends
  - Not fully adapted (*Bayesian learning simulation*)

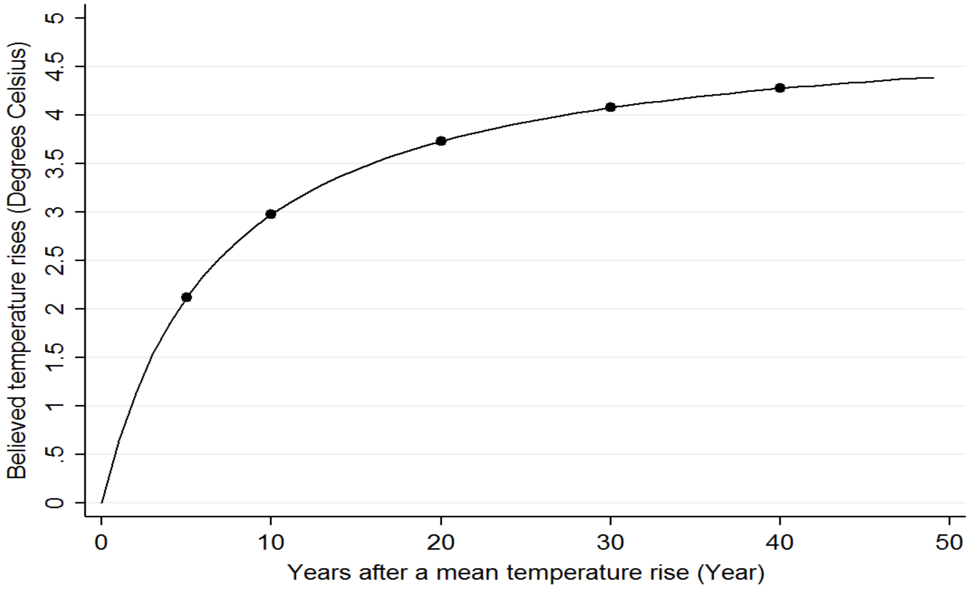

Figure D2. A simulation of farmers' believed "true" temperature rise after an assumed 5 °C temperature increase in the base year

Methodology-Basic idea

- Two models using
  - Cross-sectional climate differences (Mendelsohn, Nordhaus, and Shaw 1994)
  - Inter-annual random weather fluctuations (Massetti and Mendelsohn 2011, Seo 2013, Moore and Lobell 2014)
- Problem: “comparing apples with oranges”

Methodology

- Separate cross-sectional climate differences from inter-annual weather fluctuations

A key fact: weather fluctuations are common across regions

$$w_{it} = T_i + \Delta_t + \varepsilon_{it}$$

- w_{it}: weather outcome of county i in year t
- T_i: climate of county i
- Δ_t: weather fluctuations that are common across counties in year t
- ε_{it}: county-specific weather shocks

Table 1. the consequents of various fixed effects on the climate change impact panel studies

	Year 1	Year 2	Within county mean
A. No fixed effects			
County 1	$x_{11} = T_1 + \Delta_1 + \varepsilon_{11}$	$x_{12} = T_1 + \Delta_2 + \varepsilon_{12}$	$T_1 + \frac{\Delta_1 + \Delta_2}{2} + \frac{\varepsilon_{11} + \varepsilon_{12}}{2}$
County 2	$x_{21} = T_2 + \Delta_1 + \varepsilon_{21}$	$x_{22} = T_2 + \Delta_2 + \varepsilon_{22}$	$T_2 + \frac{\Delta_1 + \Delta_2}{2} + \frac{\varepsilon_{21} + \varepsilon_{22}}{2}$
Within year mean	$\Delta_1 + \frac{T_1 + T_2}{2} + \frac{\varepsilon_{11} + \varepsilon_{21}}{2}$	$\Delta_2 + \frac{T_1 + T_2}{2} + \frac{\varepsilon_{12} + \varepsilon_{22}}{2}$	
B. Year fixed effects: subtracting within year mean from each observation			
County 1	$\frac{T_1 - T_2}{2} + \frac{\varepsilon_{11} - \varepsilon_{21}}{2}$	$\frac{T_1 - T_2}{2} + \frac{\varepsilon_{12} - \varepsilon_{22}}{2}$	
County 2	$\frac{T_2 - T_1}{2} + \frac{\varepsilon_{21} - \varepsilon_{11}}{2}$	$\frac{T_2 - T_1}{2} + \frac{\varepsilon_{22} - \varepsilon_{12}}{2}$	
C. County fixed effects: subtracting within county mean from each observation			
County 1	$\frac{\Delta_1 - \Delta_2}{2} + \frac{\varepsilon_{11} - \varepsilon_{12}}{2}$	$\frac{\Delta_2 - \Delta_1}{2} + \frac{\varepsilon_{12} - \varepsilon_{11}}{2}$	
County 2	$\frac{\Delta_1 - \Delta_2}{2} + \frac{\varepsilon_{21} - \varepsilon_{22}}{2}$	$\frac{\Delta_2 - \Delta_1}{2} + \frac{\varepsilon_{22} - \varepsilon_{21}}{2}$	
D. Two way fixed effects: subtracting within county and within year mean, and plus sample mean			
County 1	$\frac{\varepsilon_{11} - \varepsilon_{12} - \varepsilon_{21} + \varepsilon_{22}}{4}$	$-\frac{\varepsilon_{11} - \varepsilon_{12} - \varepsilon_{21} + \varepsilon_{22}}{4}$	
County 2	$-\frac{\varepsilon_{11} - \varepsilon_{12} - \varepsilon_{21} + \varepsilon_{22}}{4}$	$\frac{\varepsilon_{11} - \varepsilon_{12} - \varepsilon_{21} + \varepsilon_{22}}{4}$	

Climate differences

Specific Weather shocks

Common weather fluctuations

Specific Weather shocks

Note: T_i *is the mean climate in county* $i \in (1,2)$, *it is constant across time in the short time period (such as 30 year);* Δ_t *is the inter-annual weather fluctuations that is at the same magnitude across counties in year* $t \in (1,2)$; ε_{it} *is the county specific inter-annual weather fluctuations, we call it weather fluctuation abnormity.*

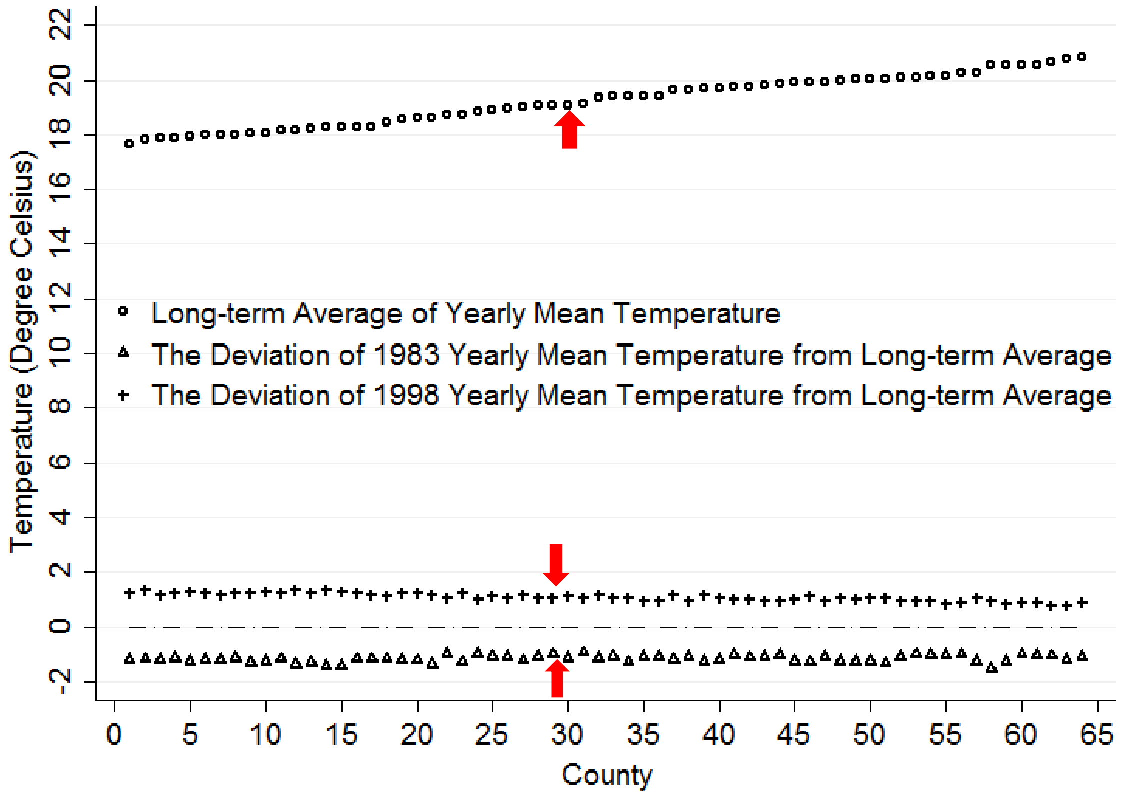

FIGURE 2. COUNTY-LEVEL LONG-TERM AVERAGE OF YEARLY MEAN TEMPERATURE AND DEVIATIONS OF GIVEN YEARS YEARLY MEAN TEMPERATURE FROM THE LONG-TERM AVERAGES FOR COUNTIES WITHIN THE US STATE OF LOUISIANA

Notes: This figure depicts long-term (1981–2000) county-level average of yearly mean temperature and two sample years' (1983 and 1998) yearly mean temperature deviations from long-term county-level averages for all of the 64 counties (parishes) within the US state of Louisiana. The x-axis denotes counties sorted by yearly mean temperature. See section II for the data source and descriptions.

Table B1. Climatic variations after using different fixed effects

Panel A. Percentage of counties with remaining temperature variation below/above (℃):

	±0.4	±0.6	±0.8	±1.0
(A1). State-by-year fixed effects and county fixed effects	4.8	0.7	0.2	0.0
(A2). State-by-year fixed effects only	68.5	53.9	40.6	29.2
(A3). County fixed effects only	79.4	64.5	48.8	34.6

Panel B. Percentage of counties with remaining precipitation variation below/above (Inches):

	±4	±6	±8	±10
(B1). State-by-year fixed effects and county fixed effects	10.3	2.4	0.6	0.2
(B2). State-by-year fixed effects only	20.4	8.0	3.6	1.4
(B3). County fixed effects only	32.5	14.2	5.1	1.5

Econometric model (SAR): with adaptation

$$(1) \qquad y_{it} = \rho \sum_{j=1}^{n} w_{ij} y_{jt} + \sum_{k=1}^{K} c_{itk} \alpha_k + \sum_{g=1}^{G} l_{itg} \beta_g + \gamma_{st} + \epsilon_s + \mu_{it}$$

$$i = 1, \dots, n; \quad t = 1, \dots, T$$

- y_{it}: agricultural profits
- w_{ij}: inverse-distance spatial-weighting matrix
- c_{itk}: climatic variable k
- l_{itg}: soil and other controls g
- γ_{st}: state-by-year fixed effects
- ϵ_s: state-fixed effects

• Why SAR

Econometric model (SAR): no adaptation

$$(2) \qquad y_{it} = \rho \sum_{j=1}^{n} w_{ij} y_{jt} + \sum_{k=1}^{K} c_{itk} \alpha_k + \sum_{g=1}^{G} l_{itg} \beta_g + \tau_i + \theta q_t + \varepsilon_{it}$$

$$i = 1, \ldots, n; \quad t = 1, \ldots, T$$

- τ_i: county-fixed effects
- q_t: time trend

Data

- Historical agricultural profits & climate
  - 2155 US counties east of the 100 °meridian
  - 1982-2012
- Climate predictions
  - RCP4.5
  - Four CMIP5 models: CCSM4, CESM1-BGC, CanESM2, and NorESM1-M

Table C2. Summary Statistics of Climate Normal and Climate Predictions

	Growing Season:			
	Average temperature (℃)	GDD (℃)	GHDD (℃)	GTP (Inches)
Climate Normal				
	20.23	2272	0.11	23.50
	(3.25)	(558)	(0.43)	(3.60)
Predicted climatic changes by the end of this century under scenario RCP4.5:				
CCSM4	1.95	379	0.38	1.90
	(0.61)	(55)	(0.66)	(2.17)
CESM1-BGC	2.04	384	0.49	2.63
	(0.99)	(65)	(1.55)	(2.97)
CanESM2	2.27	583	1.47	0.41
	(0.50)	(74)	(3.01)	(1.61)
NorESM1-M	2.79	547	3.13	1.35
	(0.80)	(89)	(4.92)	(1.80)

Notes: All entries are simple averages over the 2155 sample counties. See the text for how the climate normal and climate predictions are calculated. Standard deviations are reported in parentheses.

TABLE 5—REGRESSION RESULTS OF THE EFFECTS OF CLIMATIC VARIABLES ON AGRICULTURAL PROFITS AND FARMLAND VALUES

Independent Variables	Profits: With adaptation		Profits: No adaptation		Farmland values: With adaptation	
	(1a)	(1b)	(2a)	(2b)	(3a)	(3b)
100 GDD (℃)	7.80	7.34	12.3	12.3	255.6	277.8
	(2.35)	(2.37)	(1.10)	(1.10)	(21.3)	(21.5)
10000 GDD square	-0.17	-0.16	-0.29	-0.29	-5.37	-5.85
	(0.05)	(0.05)	(0.03)	(0.03)	(0.45)	(0.45)
GTP (inches)	2.06	2.10	0.38	0.36	19.9	24.9
	(0.69)	(0.69)	(0.61)	(0.61)	(10.8)	(10.8)
GTP square	-0.03	-0.04	-0.03	-0.03	-0.05	-0.08
	(0.01)	(0.01)	(0.01)	(0.01)	(0.22)	(0.22)
GHDD square root	-3.94	-4.14	-10.05	-10.11	-180.2	-179.1
	(1.46)	(1.47)	(0.95)	(0.95)	(30.4)	(30.2)
Control for spatial dependence	Yes	Yes	Yes	Yes	Yes	Yes
State-by-year fixed effects	Yes	Yes	No	No	Yes	Yes
State-fixed effects	Yes	Yes	No	No	Yes	Yes
County-fixed effects	No	No	Yes	Yes	No	No
Time trend	No	No	Yes	Yes	No	No
10 land quality indicators	Yes	No	Yes	No	Yes	No

Notes: This table show the estimated climatic coefficients from SAR panel models. Columns 1a and 1b report estimates from model (1) with agricultural profits as the dependent variable; column 2a and 2b report estimates from model (2) with agricultural profits as the dependent variable; columns 3a and 3b report estimates from a variation of model (1) that use the farmland value as the dependent variable. The only difference between models a and b is that model b excludes the soil controls. The Huber-White heteroskedastic consistent standard errors are reported in parentheses.

TABLE 6—PREDICTED IMPACTS OF CLIMATE CHANGE ON U.S. AGRICULTURAL PROFITS AND FARMLAND RENTS BY THE END OF THIS CENTURY (BILLIONS OF 2012 CONSTANT DOLLARS/YEAR)

	Impact on profits: With adaptation		Impact on profits: No adaptation		Impact on land rents: With adaptation		Benefits of adaptation	
Climate model	(1a)	(1b)	(2a)	(2b)	(3a)	(3b)	Value	Percent
CCSM4	-1.27	-0.95	-5.96	-5.99	-0.69	-0.74	4.69	78.70%
	(1.21)	(1.22)	(0.59)	(0.59)	(0.31)	(0.31)		
CESM1-BGC	-1.57	-1.27	-7.21	-7.24	-0.73	-0.82	5.64	78.20%
	(1.21)	(1.21)	(0.64)	(0.64)	(0.34)	(0.34)		
CanESM2	-4.36	-3.78	-12.92	-12.97	-3.90	-4.04	8.56	66.30%
	(2.02)	(2.02)	(1.06)	(1.06)	(0.59)	(0.59)		
NorESM1-M	-5.52	-5.01	-16.14	-16.21	-5.57	-5.68	10.62	65.80%
	(2.23)	(2.22)	(1.22)	(1.22)	(0.82)	(0.82)		
Average	-3.18	-2.75	-10.56	-10.60	-2.72	-2.82	7.38	72.20%

Notes: This table reports the predicted overall climate change impacts of four most frequently used climate models under scenario RCP4.5. All entries are calculated for the 2155 rain-fed non-urban sample counties. Columns 1a and 1b report the impact on profits estimated from model (1) with agricultural profits as the dependent variable; columns 2a and 2b report the impact on profits estimated from model (2) with agricultural profits as the dependent variable; columns 3a and 3b report the impact on farmland rents estimated from a variation of model (1) that use the farmland value as the dependent variable. The only difference between model a and model b is that model b excludes the soil controls. The last two columns report the benefit of adaptation which is the difference between column 2a and 1a. Total impacts are calculated by summing impacts across all sample counties. The historical average total annual profits for these sample counties are $35.3 billion. The Huber-White heteroskedastic consistent standard errors of the impacts are reported in parentheses. See the text for further details.

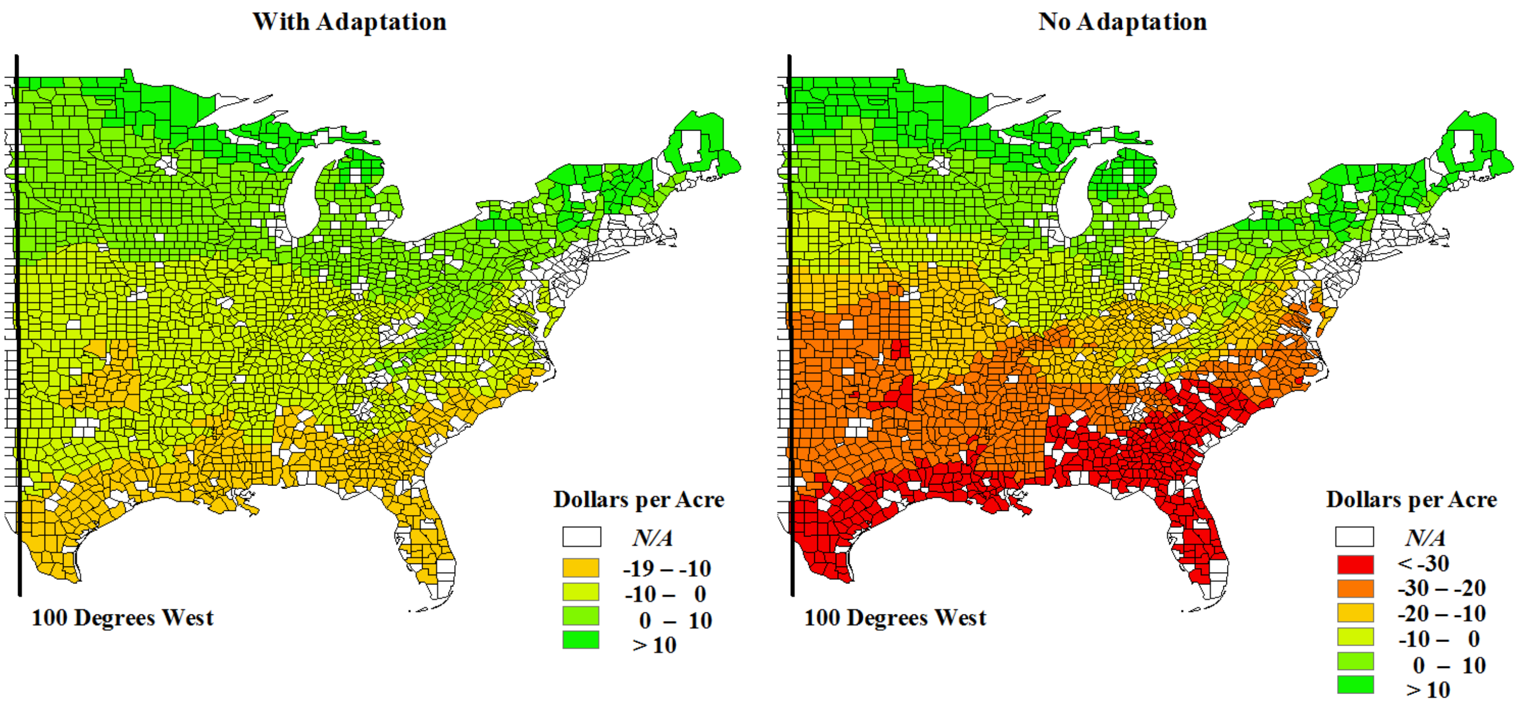

FIGURE 5. GEOGRAPHIC DISTRIBUTION OF COUNTY-LEVEL EFFECTS OF CLIMATE CHANGE BY THE END OF THIS CENTURY UNDER SCENARIO CCSM4 RCP4.5

Notes: the left figure presents the effects that include adaptations and the right figure presents the effects without adaptations. The county-level effects are calculated by combining the estimated climate coefficients from model (1) and (2) with the predicted county-level climate changes. Here we take the predictions from climate model CCSM4 as an example; the geographic distributions of effects predicted from other climate models are quite similar. The sample includes 2155 rain-fed non-urban counties east of the 100' meridian. All values are expressed in 2012 constant dollars.

Sensitivity analysis

- Unobserved county heterogeneity
- The influence of yearly storage and inventory adjustments

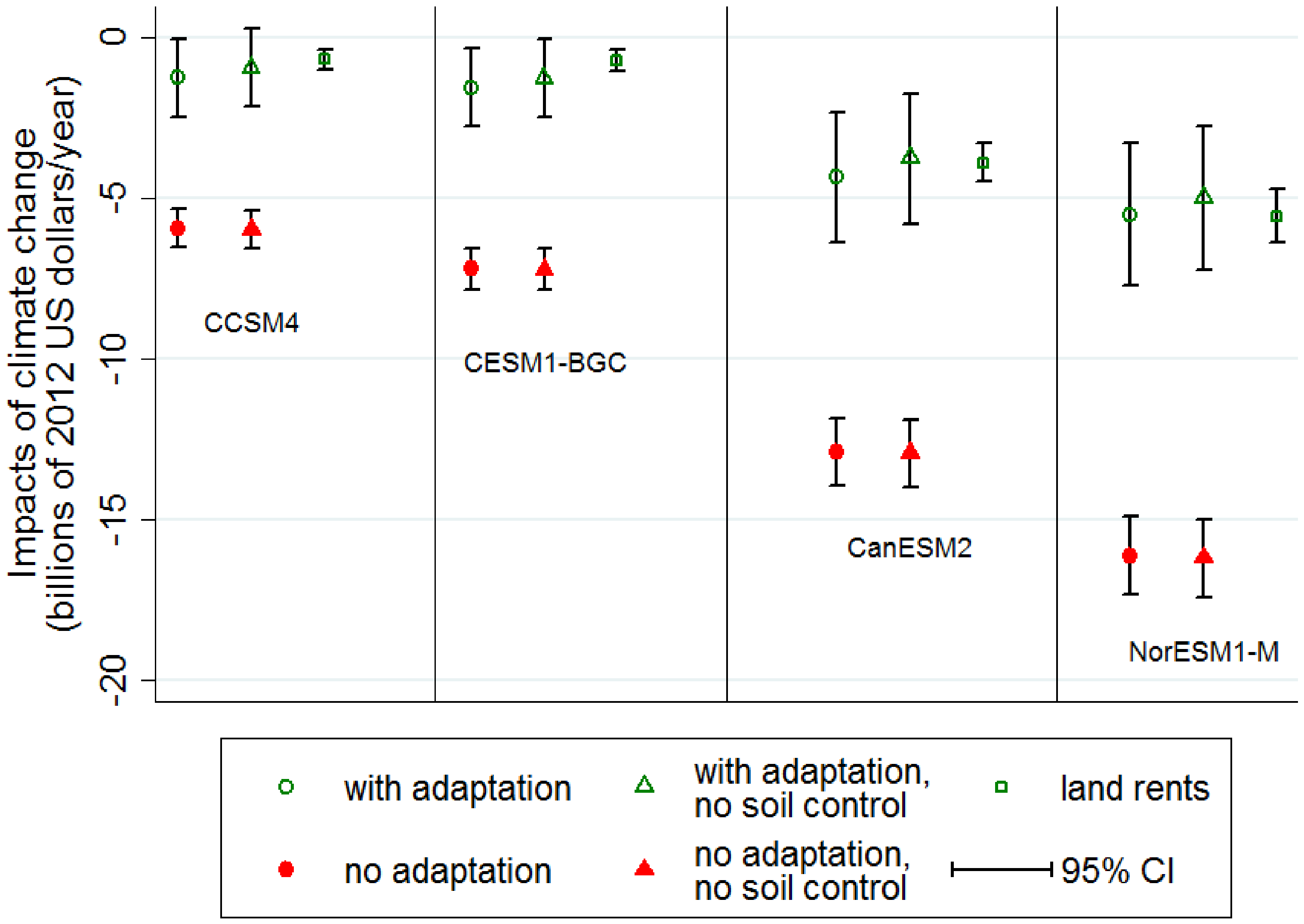

Figure 1. Predicted end-of-this-century impact of climate change on agricultural profits and farmland rents (Billions of 2012 US dollars per year)

Table 4. Robustness checks for the estimated impacts of climate change and the benefits of adaptation (billions of 2012 constant dollars/year)

	(1) Impact on profits: With adaptation	(2) Impact on profits: No adaptation	Benefits of adaptation	
			Value	Percent
[1] Assume $\rho = 0$ in the regressions but address the spatial correlation by clustering the error term at the state level	-3.71	-14.53	10.83	78.23%
[2] Include additional controls for population density, per capita income, and altitude	-4.61	-12.85	8.24	65.88%
[3] Exclude irrigated counties east of the 100 º meridian from the sample	-3.80	-12.00	8.20	70.29%
[4] Calculate degree-day by the minimum and maximum daily temperatures	-3.73	-15.21	11.48	79.07%
[5] Use the highest climate change scenario (RCP8.5)	-9.53	-28.54	19.01	67.32%

Thank you