Adapting to Heat with (in)Secure Land Rights

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joint with Liang Diao (Osaka University) & Huiqian Song (Kyoto University)

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  - **Extensive margin adaptation**: enlarging crop areas

  vs. **Intensive margin adaptation**: increasing other inputs (e.g., irrigation, capital, labor...)

- Very different adaptation responses to heat depending on the context:
  - Aragon et al. (2021, AEJ:EP), He & Chen (2022, JEEM) and Hsiao et al. (2026, NBER) show that **Peruvian**, **Ethiopian** & **Brazilian farmers expand croplands**, while Burke & Emerick (2016, AEJ:EP) and Cui (2020, JAERE) find that **US farmers** (weakly) **reduce theirs**
  - Burke & Emerick (2016, AEJ:EP) and Bareille & Chakir (2024, AJAE) find that **US** & **French farmers increase input use**, while Chen & Cong (2021, JEEM) and Jagnani et al. (2021, EJ) showed that **Chinese** & **Kenyan farmers** (weakly) **reduce theirs**

→ We argue that such contrasting results are actually consistent with the (so-far ignored) **role of land rights** and **institutions** in changing the picture

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This paper: Institutions & Adaptation to climate change

Objective

To **theoretically** and **empirically** assess the impacts of land rights in shaping farmers' adaptation to heat and, ultimately, heat damage on crop yields.

- **Theory:** toy-model showing that **farmers receiving better land rights** shift from **extensive** to **intensive margin adaptation**, ultimately **reducing heat damage on crop yields**
- **Empirics: triple-differences identification strategy** (two treatments) with heat × land registry
  - **Exploratory analysis:** global data on crop yields & cadaster index quality
  - **Causal analysis:** staggered cadastral reform in Greece (roll out reform)
  - We validate empirically all of our theoretical propositions
- In total, better land rights could offset by **at least two thirds** the negative impacts of climate change on agricultural productivity by 2100

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Data

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  - Most comprehensive database on observed crop yields worldwide
  - 6 crops, 12,658 regions, 54 countries, 1900–2020 (unbalanced panel) Figure
  - Covers approximately two-thirds of global crop calories
  - Provides an explicit relationship between daily temperatures and crop yields Table
- Global data on cadasters from D'Arcy et al. (2024, JPE): "Cadasters and Economic Growth: A Long-Run Cross-Country Panel"
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  - Index ranging from 0 to 1, combining three dimensions:
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    - Format: cartographic = 1; narrative = 0.75
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  - 159 countries from 1000 to 2015 (balanced panel)

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Econometrics: triple-difference estimation

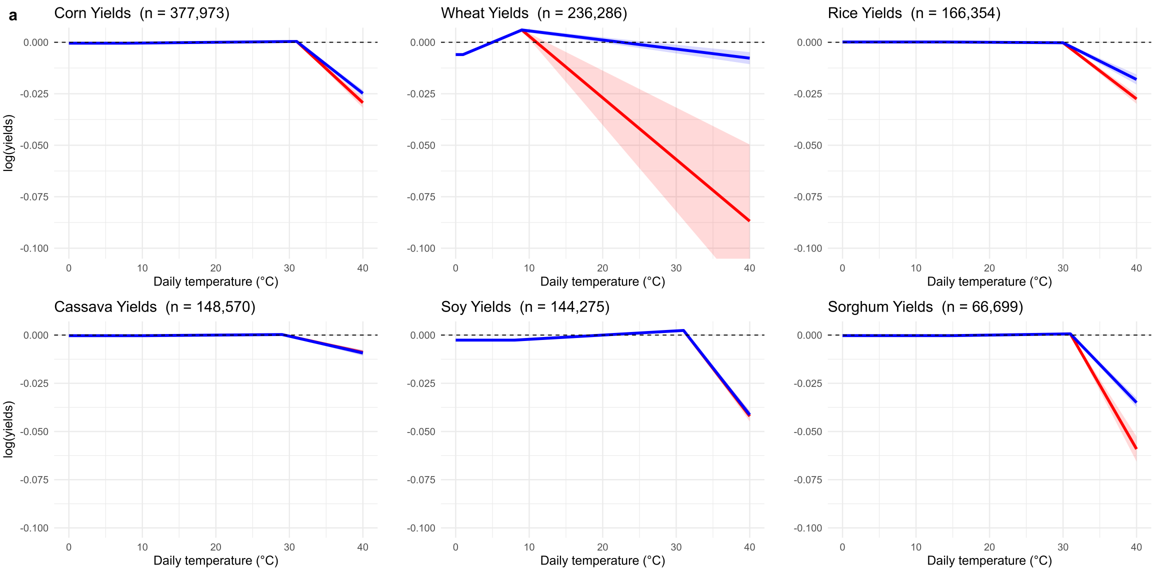
- Our preferred specification for **crop yields** of crop k in region i & year t is:

$$\log(y^k_{i,t}) = \beta^k_0 GDD_{i,t} + \beta^k_1 KDD_{i,t} + \beta^k_2 Cadaster_{i,t} + \beta^k_3 KDD_{i,t} \times Cadaster_{i,t} + \beta^k_4 P_{i,t} + \beta^k_5 P^2_{i,t} + \nu^k_i + \mu^k_t + \varepsilon^k_{i,t}$$

where $y^k_{i,t}$ is the yields of crop k ($k \in \{1,2,3,4,5,6\}$ for **wheat**, **rice**, **maize**, **cassava**, **soy** & **sorghum**)
$BDD_{i,t}$ counts the degree days below a threshold during the growing season
$KDD_{i,t}$ counts the degree days above a threshold during the growing season
$P_{i,t}$ is the amount of precipitation during the growing season
$Cadaster_{i,t}$ equals 1 if the D'Arcy et al. index is above 0.5 (0 otherwise)
ν^k_i is the region fixed effect
μ^k_t is the year fixed effect
$\varepsilon^k_{i,t}$ is the remaining error

- We estimate β^k_0 to β^k_5 for $k \in \{1,2,3\}$ with OLS, clustering the standard errors at the regional level

Results


a
Corn Yields (n = 377,973)
Wheat Yields (n = 236,286)
Rice Yields (n = 166,354)
Cassava Yields (n = 148,570)
Soy Yields (n = 144,275)
Sorghum Yields (n = 66,699)
log(yields)
0.000
-0.025
-0.050
-0.075
-0.100
0
10
20
30
40
Daily temperature (°C)

Insights from the exploratory analysis

→ **Heat damage on crop yields are larger with incomplete vs. complete land rights** (as proxied by cadasters)

- Results robust to potential confounders and data particularities
  - Adding GDP per capita controls Table
  - Alternative cadaster threshold Table
  - Post-1980 sample (1980–2015) Table
- Yet, limitations remain:
  - Theoretically, what could explain this discrepancy between complete vs. incomplete land rights?
    - Shift from *extensive* to *intensive* margin adaptation?
  - Empirically, the cadaster index is likely **endogenous**:
    - **Simultaneous** with outcomes (institutions evolve with productivity; Acemoglu et al., 2001, AER)
    - Affected by **omitted factors** (politics, fiscal capacity, preferences)

→ Global analysis is informative but **not fully causal** (estimates should be read as **correlations**)

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Theory: Land rights and farmers' adaptation to heat

Initial conditions

- A farmer is endowed with one plot of land of size 1
- Initially, the whole plot has **high potential productivity**, equal to y_h

Two treatments

- **Heat** $\alpha \in [0, 1]$: share of land with **low** potential productivity ($y_l < y_h$)
- **Land rights** T: constraints on gross revenues

Two choice variables

- $L = L_h + L_l$: **cultivated land** (*extensive-margin adaptation*)
- $L_{l \to h}$: **land improvement** from y_l to y_h (*intensive-margin adaptation*)

→ Resolution by increasing α for different levels of T Analytics

Proposition 1: insecure land rights

Farmers with insecure land rights react to heat by expanding crop areas (**extensive margin adaptation**), while keeping other inputs unchanged (**no intensive margin adaptation**).

Proposition 2: secure land rights

Farmers with secure land rights react to heat by holding crop areas constant (**no extensive margin adaptation**), but raising other inputs (**intensive margin adaptation**).

Proposition 3: heat damage

For equal heat exposure, heat damage are smaller under secure than insecure land rights.

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Agriculture in Greece

- **Ideal case study:** Greece is classified as either "developed" or "developing," depending on the source
- Few professional farms; many subsistence farmers (Eurostat, 2011)
  - Highest farmer share in Europe
  - Smallest average farm size (4.8 ha)
  - Only 10% of households rely on off-farm jobs
- Farmland covers about half of the territory, and roughly half of it is arable
  - Wheat, barley, and maize account for **more than 80%** of Greek arable land

Figure: Greek agricultural landscapes

Hellenic cadastral reform in Greece (1/2)

- Initially, land rights were organized under a **person-based system** dating back to 1853
  - Land records were maintained in paper form at local mortgage offices
  - Records were sorted by last names
- No clear property boundaries
  - **No cadastral map**
  - Boundaries were defined by written descriptions (e.g. "between the donkey path and the forest")

→ **Numerous land disputes due to multiple claims to the same property**

Figure: Old local mortgage office ("Υποθηκοφυλακεία")

- The reform aims at establishing a **deed-based system**
  - Land records are digitally stored in a database
  - Boundaries are defined by **cadastral maps** at the plot level
- Roll-out at the prefecture level since 2008 (**mostly between 2014 and 2019**)
  - Preparation of preliminary cadastral maps
  - Landowners declare their properties and verify or correct boundaries
  - Land disputes are settled by independent administrative committees
- Typically completed within 18 months per prefecture
- Land registration is mandatory

Figure: New digital Greek cadastre

Land registry: panel data at the prefecture (regional unit) level from 2011 to 2019

- **Treatment:** the starting year t of the land registry (cadaster), from the official website
- A region is treated in year t ($t \in [2014, 2019]$) if at least 85% of its municipalities start in year t
  Figure

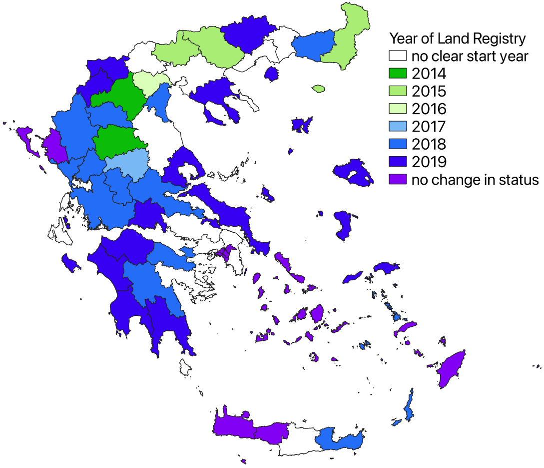

Figure: Year of land registry at the regional unit level

Weather: historical daily weather data from ERA5

- **Treatment:** cumulative exposure above 28°C during the growing season, expressed as KDD
- Based on a reconstructed intra-day temperature distribution *à la* Schlenker & Roberts (2009, PNAS), using a sine interpolation between daily minimum and maximum temperatures Figure
- We aggregate 5-arc-minute gridded measurements at the regional level
- We define growing season from April 1 to August 31
  - Wheat and barley are sowed from early November to late April
  - Maize is sowed from early April to late May

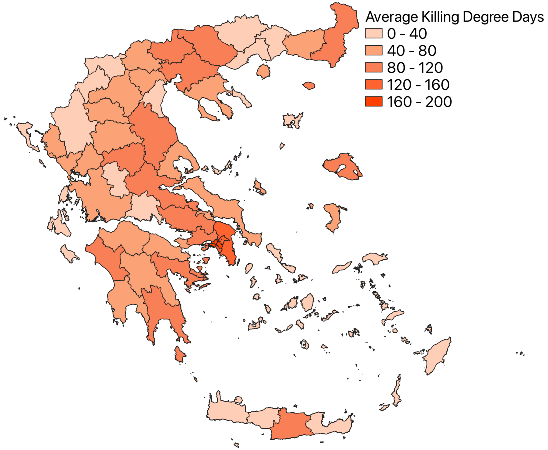

Figure: Long-term average of killing degree days above 28°C, 2011–2019

Data (3/3)

- **Agricultural outcomes:** regional yearly data from the Hellenic Statistical Authority between 2011 and 2019
  - **Crop yields** data from 2011 for (i) **wheat**, (ii) **barley** and (iii) **maize**
  - **Crop areas** data from 2011
  - **Input use** from 2012 (except labor for 2013 and 2016 only)
    - Number of tractors to measure **capital** (machinery)
    - Number of workdays to measure **labor**
    - Number of pumps to measure **irrigation**
- Final panel of **57 regions** measured for **9 years** for **9 outcome variables**

- Our preferred specification for **crop yields** of crop k in region i & year t is:

$$\log(y_{i,t}^k) = \beta_1^k KDD_{i,t} + \beta_2^k Reform_{i,t} + \beta_3^k KDD_{i,t} \times Reform_{i,t} + \beta_4^k P_{i,t} + \beta_5^k P_{i,t}^2 + \nu_i^k + \varepsilon_{i,t}^k$$

where $y_{i,t}^k$ is the yields of crop k ($k \in \{1,2,3\}$ for **wheat**, **barley** & **maize**)
$KDD_{i,t}$ counts the degree days above 28°C during the growing season
$P_{i,t}$ is the amount of precipitation during the growing season
$Reform_{i,t}$ equals 1 if the reform has occurred at least 2 years ago (0 otherwise)
ν_i^k is the region fixed effect
$\varepsilon_{i,t}^k$ is the remaining error

- We estimate β_1^k to β_5^k for $k \in \{1,2,3\}$ with OLS, clustering the standard errors at the regional level

- We estimate the same replacing **crop yields** $y_{i,t}^k$ by **crop areas** $a_{i,t}^k$ or **total inputs** $x_{i,t}^l$ (for $l \in \{1,2,3\}$, resp. quantity of tractors, labor and irrigation per hectare)

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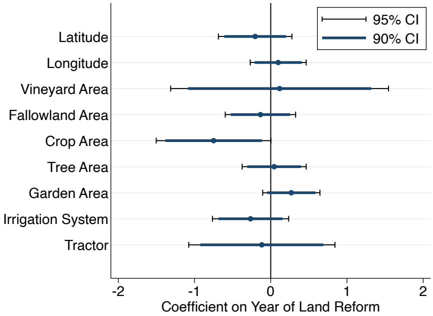
Identification strategy: triple-difference estimation

- Variation comes from two treatments: **heat** and **land reform**
  - We compare the effects of **region-specific abnormal heat** across regions **with** vs. **without** cadastral reform (or not yet treated)
  - Regional fixed effects absorb time-invariant heterogeneity (+ controls; no year FE, cf. Fisher et al., 2012, AER)
- **Key identifying assumption:** abnormal heat and land reform are exogenous to yields, practices, and geography
  - Heat shocks are exogenous by construction
  - Land reform is plausibly exogenous
- Balance tests show no strong relationship between reform timing and pre-treatment observables
  - Except crop area: consistent with CAP management Subsidies
- No differential temperature trend: KDD evolves similarly in early- and late-treated regions Figure

Balance test: predictors of reform timing



Results (1/7): crop yields

Table: Estimated heat impacts on crop yields with and without land reform

	Dependent variable: $\log(y^k_{i,t})$		
	Wheat	**Barley**	**Maize**
KDD^{28}	-0.0014***	-0.0007*	-0.0010**
	(0.0004)	(0.0004)	(0.0005)
$KDD^{28} \times Reform$	0.0018***	0.0015*	0.0022***
	(0.0006)	(0.0008)	(0.0005)
Reform	-0.0945	-0.1118*	-0.1060**
	(0.0574)	(0.0581)	(0.0377)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
Average joint estimate of KDD^{28}	-0.0012***	-0.0006	-0.0008*
	(0.0004)	(0.0004)	(0.0005)
Average joint effect of Reform	-0.0137	-0.0463	-0.0094
	(0.380)	(0.0370)	(0.227)
χ^2 test for $KDD^{28} + KDD^{28} \times Reform$	0.3657	0.6486	3.7956*
Adj. R^2	0.6892	0.7367	0.7051
Observations	436	453	383

NOTE. *, **, *** indicate p-values below 0.1, 0.05, and 0.01.

- **Without the reform:** +1 KDD reduces crop yields by about 0.1% (in line with Hultgren et al., 2025, Nature)
- **With the reform:** +1 KDD has no statistically significant effect

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Results (2/7): crop areas (extensive margin adaptation)

Table: Estimated heat impacts on crop areas with and without land registry

	Dependent variable: $\log(1 + a^k_{i,t})$		
	Wheat	**Barley**	**Maize**
KDD^{28}	0.0040***	0.0035***	0.0038***
	(0.0008)	(0.0010)	(0.0010)
$KDD^{28} \times Reform$	-0.0038***	-0.0024**	-0.0035**
	(0.0009)	(0.0012)	(0.0015)
Reform	-0.0107	0.2054	-0.2184
	(0.1056)	(0.1277)	(0.1703)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
Average joint estimate of KDD^{28}	0.0036***	0.0033***	0.0034***
	(0.0008)	(0.0009)	(0.0009)
Average joint effect of Reform	-0.1836***	0.1001	-0.3739***
	(0.0537)	(0.1029)	(0.1411)
χ^2 test for $KDD^{28} + KDD^{28} \times Reform$	0.0350	1.7196	0.0470
Adj. R^2	0.9450	0.8767	0.9502
Observations	513	513	513

NOTE. *, **, *** indicate p-values below 0.1, 0.05, and 0.01.

- **Without the reform:** +1 KDD increases crop area by about 0.4%
- **With the reform:** +1 KDD has no statistically significant effect

Results (2/7): crop areas (extensive margin adaptation)

Table: Estimated heat impacts on crop areas with and without land registry

	Dependent variable: $\log(1 + a^k_{i,t})$		
	Wheat	**Barley**	**Maize**
KDD^{28}	0.0040***	0.0035***	0.0038***
	(0.0008)	(0.0010)	(0.0010)
$KDD^{28} \times Reform$	-0.0038***	-0.0024**	-0.0035**
	(0.0009)	(0.0012)	(0.0015)
$Reform$	-0.0107	0.2054	-0.2184
	(0.1056)	(0.1277)	(0.1703)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
Average joint estimate of KDD^{28}	0.0036***	0.0033***	0.0034***
	(0.0008)	(0.0009)	(0.0009)
Average joint effect of Reform	-0.1836***	0.1001	-0.3739***
	(0.0537)	(0.1029)	(0.1411)
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Observations	513	513	513

NOTE. *, **, *** indicate p-values below 0.1, 0.05, and 0.01.

- **Without the reform:** +1 KDD increases crop area by about 0.4%
- **With the reform:** +1 KDD has no statistically significant effect

Results (3/7): input use (intensive margin adaptation)

Table: Estimated heat impacts on inputs with and without land registry

	Dependent variable: $log((1 + x^k_{i,t})/A_{i,t})$		
	Machinery	**Labor**	**Irrigation**
KDD^{28}	-0.0022 **	0.0017	0.0002
	(0.0010)	(0.0022)	(0.0007)
KDD^{28} × Reform	0.0026 **	0.0056 ***	0.0017 **
	(0.0010)	(0.0009)	(0.0008)
Reform	-0.1917 **	-0.4960 ***	-0.2441
	(0.0879)	(0.0968)	(0.1603)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
Average joint estimate of KDD^{28}	-0.0019 **	0.0019	0.0004
	(0.0009)	(0.0022)	(0.0006)
Average joint effect of Reform	-0.0773	-0.2229 ***	-0.1668
	(0.0511)	(0.0632)	(0.1401)
χ^2 test for $KDD^{28} + KDD^{28}$ × Reform	0.31933	9.6877 ***	8.4727 ***
R^2	0.6483	0.9297	0.6826
Observations	511	76	454

NOTE. *, **, *** indicate p-values below 0.1, 0.05 and 0.01.

- **Without the reform:** +1 KDD leads to -0.2% tractors, not significant otherwise
- **With the reform:** +1 KDD leads to +0.1 to 0.7% in inputs

Table: Estimated heat impacts on inputs with and without land registry

	Dependent variable: $log((1+x^k_{i,t})/A_{i,t})$		
	Machinery	**Labor**	**Irrigation**
KDD^{28}	-0.0022 **	0.0017	0.0002
	(0.0010)	(0.0022)	(0.0007)
KDD^{28} × Reform	0.0026 **	0.0056 ***	0.0017 **
	(0.0010)	(0.0009)	(0.0008)
Reform	-0.1917 **	-0.4960 ***	-0.2441
	(0.0879)	(0.0968)	(0.1603)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
Average joint estimate of KDD^{28}	-0.0019 **	0.0019	0.0004
	(0.0009)	(0.0022)	(0.0006)
Average joint effect of Reform	-0.0773	-0.2229 ***	-0.1668
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Results (4/7): summary

- Overall, **more secure land rights** encourage farmers to switch from **extensive-margin adaptation** (area adjustment) to **intensive-margin adaptation** (higher input use), ultimately **reducing heat damage on crop yields**

- **Robustness checks:** the main interaction estimates remain qualitatively unchanged under
  - alternative outcome transformations Table
  - alternative heat definitions Table
  - alternative time structures of the error term Table
  - staggered DiD in hot years (Callaway & Sant'Anna, 2021, JoE) Table
  - additional control interactions Figure
  - corrections for spatial correlation Table
  - randomization inference Figure
  - placebo tests on pre-treatment timing Figure

Results (4/7): summary

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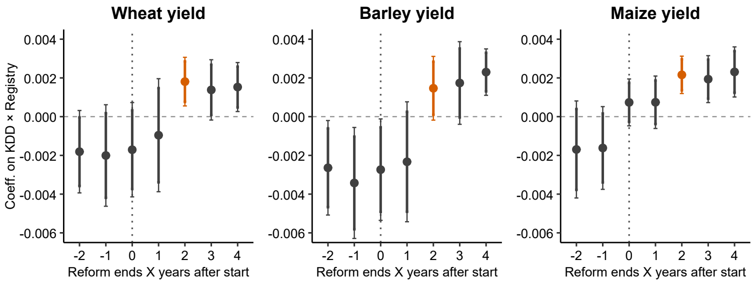
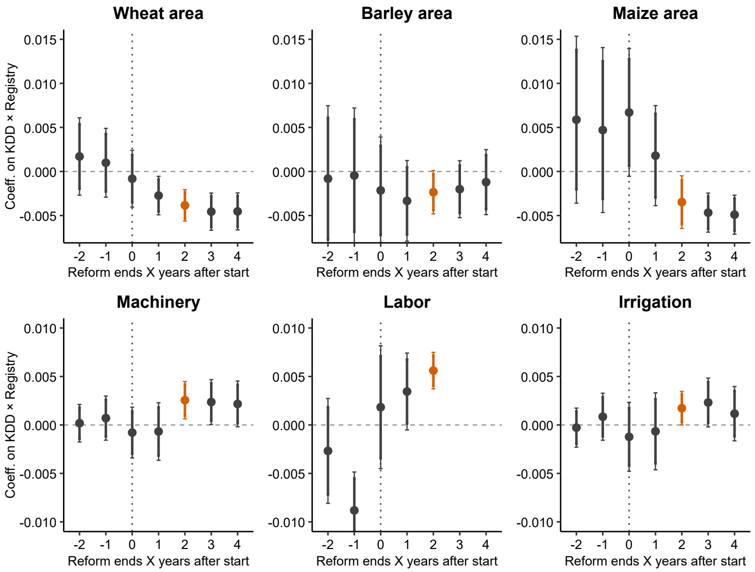
Results (5/7): dynamic effects

- The land registry reform is a **multi-year process** (18 months to be completed), so its effects on tenure security are unlikely to appear immediately
  - Our **baseline** assumes that reform exposure starts **two years after initiation**
  - Consistent with Diao et al. (2024, JEEM), who find a similar delay for forest-fire effects
- We test this timing by re-estimating the interaction between **KDD** & **land reform** after shifting the treatment date backward and forward
  - Negative values: placebo / anticipation tests
  - 0–1 years: implementation still ongoing
  - 2–4 years: post-completion effects
- For **crop yields**, effects emerge clearly only once treatment is assigned with a delay of about **two years**



Results (6/7): dynamic effects



Results (7/7): ruling out other mechanisms

- Theory predicts that extensive margin adaptation takes place from cropland (wheat, barley & maize areas) extending on marginal lands...
- ... but not on other land types

Table: Estimated heat impacts on other areas with and without land registry

	Dependent variable: $\log(1 + a^k_{i,t})$			
	Arable lands	**Non-arable lands**	**Permanent crops**	**Fallows**
KDD^{28}	0.0019***	0.0006	0.0005	0.0035*
	(0.0004)	(0.0006)	(0.0003)	(0.0020)
$KDD^{28} \times Reform$	-0.0018***	-0.0004	-0.0034	0.0022
	(0.0005)	(0.0013)	(0.0022)	(0.0034)
Reform	0.1554***	0.2285**	0.3146*	0.2457
	(0.0459)	(0.0999)	(0.1611)	(0.2670)
Precipitation controls	Yes	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes	Yes
Average joint estimate of KDD^{28}	0.0017***	0.0006	0.0002	0.0038**
	(0.0004)	(0.0005)	(0.0004)	(0.0019)
Average joint effect of Reform	0.0744***	0.2118***	0.1645**	0.3447**
	(0.0254)	(0.0674)	(0.0709)	(0.1413)
χ^2 test for $KDD^{28} + KDD^{28} \times Reform$	0.0942	0.0603	1.6218	3.0195*
Adj. R^2	0.9770	0.9580	0.9864	0.7862
Observations	495	495	513	513

- **Other sectoral land uses** Table
- **Fire frequency** Table
- **Credit accessibility** (livestock; see Fafchamps et al., 1998, JDE)
- **Takeaway:** the results are unlikely to reflect alternative channels unrelated to our theory

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Climate change impacts with & without the cadaster (1/2)

- Our preferred specification was:

$$\log(y_{i,t}^k) = \beta_1^k KDD_{i,t} + \beta_2^k Reform_{i,t} + \beta_3^k KDD_{i,t} \times Reform_{i,t} + \beta_4^k P_{i,t} + \beta_5^k P_{i,t}^2 + \nu_i^k + \varepsilon_{i,t}^k$$

- So far we reason comparing $\hat{\beta}_1$ to $\hat{\beta}_3$... but what will be the total impacts of the reform by the end of the century?
- We couple our results with CMIP6 projections for 2095-2099
- Spatially-detailed projections on all grid cells of Greece with agriculture (in comparison to 2015-2019)
  - Average values and bootstrapped standard errors over 1,000 replicates

Climate change impacts with & without the cadaster (2/2)

- The new cadaster offsets most (if not all) climate change damage on crop yields:
  - 80% ($0.8 \approx |0.110/-0.139|$) for wheat yields Figure
  - 68% for barley yields Figure
  - 173% for maize yields! Figure

Table: Projected impacts of climate change on crop yields with and without the reform

	With Cadaster	**Without Cadaster**	**Difference**
Wheat Yield	-0.029	-0.139	0.110
	(0.123)	(0.086)	(0.090)
Barley Yield	-0.024	-0.075	0.051
	(0.141)	(0.096)	(0.107)
Maize Yield	0.058	-0.079	0.137
	(0.225)	(0.216)	(0.063)

NOTE. The table presents the future impacts of the predicted heat and precipitation conditions on wheat, barley and maize yields with land reform in column 1, without land reform in column 2, and their difference in column 3. The average values reflect the average impacts of a RCP4.5 scenario on all Greek regions, as predicted by CMIP6. Displayed within brackets, the standard deviations surrounding the average estimate are obtained by bootstrap over 1,000 replications.

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Conclusion

- Land rights plays a crucial role in determining heat damage to agriculture
- Exploiting the recent "Hellenic Cadastre" roll-out program, we show that **land rights affect both farmers' adaptation strategies** at the intensive & extensive margins and **heat damage on crop yields**
- With the new land registry, one additional degree days leads to:
  - Expending crop areas by -0.1 to 0.1% (vs. 0.4% without the reform)
  - Using additional inputs by 0.1 to 0.7% (vs. -0.2 to 0% without the reform)
  - Zero losses in crop yields (vs. -0.1% for the three main crops without the reform)
- Results confirmed by a global analysis and supported by a theory
- In total, the reform could offset by **at least two thirds** the negative impacts of climate change on Greek agricultural productivity by 2100

→ **Key role of institutions in encouraging our societies to adapt to climate change!**

Thanks

francois.bareille@inrae.fr

Nonlinear relation between temperature and yields

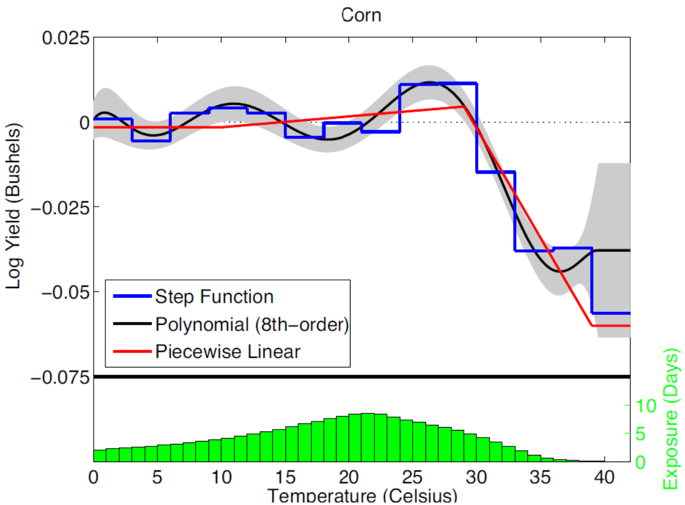


Figure: Relation between temperature & corn yields (Schlenker & Roberts, 2009, PNAS) Back

Analytical expressions

- Case 1: **insecure land rights**

$$L^*_{l\to h} = 0 \ , \ L^* = max\left\{\frac{T}{py_h}, \frac{T-(1-\alpha)py_h}{py_l} + 1 - \alpha\right\}, \qquad (1)$$
$$L^*_h = min\left\{\frac{T}{py_h}, 1-\alpha\right\} \ , \ L^*_l = max\left\{0, \frac{T-(1-\alpha)py_h}{py_l}\right\}.$$

- Case 2: **intermediate land rights**

$$L^*_{l\to h} = min\left\{0, \frac{T-(1-\alpha)py_h - \alpha py_l}{py_h - py_l}\right\} \ , \ L^* = 1 \ , \ L^*_h = 1-\alpha \ , \ L^*_l = \alpha. \qquad (2)$$

- Case 3: **secured land rights** Back

$$L^*_{l\to h} = \alpha \ , \ L^* = 1 \ , \ L^*_h = 1-\alpha \ , \ L^*_l = \alpha. \qquad (3)$$

Crop yields & temperature in Hultgren et al. (2025, Nature)

Crop	Growing degree days (GDD)	"Killing" degree days (KDD)
Corn	8 - 31	≥31
Soy	8 - 31	≥31
Rice	14 - 30	≥30
Sorghum	15 - 31	≥31
Cassava	10 - 29	≥29
Wheat	1 - 9	≥9

Figure: Data-driven relationship between crops yields & daily temperature from Hultgren et al. (2025, Nature) Back

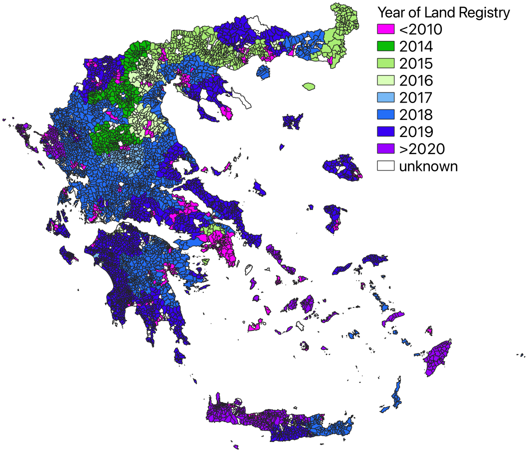


Figure: Year of Land Registry at the Municipality Unit Level Back

Computation of killing degree days

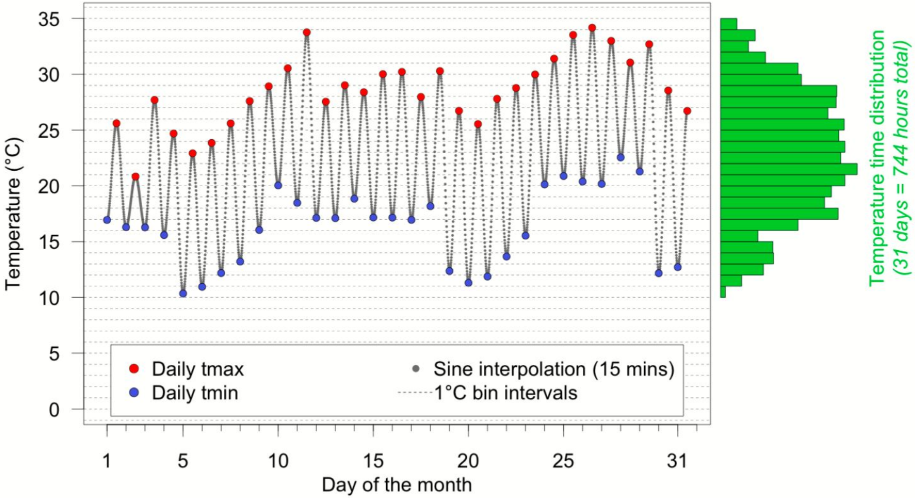


Figure: Reconstruction of temperature distribution (Source: Ortiz-Bobea, 2021, Handbook) Back

Summary Statistics

Table: Summary statistics at the regional level ($N \times T = 513$).

	Mean	S.D.	Min	Median	Max
Wheat yields (tons/ha)	2.49	0.77	0.38	2.59	4.68
Barley yields (tons/ha)	2.23	0.80	0.40	2.30	4.99
Maize yields (tons/ha)	8.95	4.06	0.72	9.82	50.00
Wheat area (ha)	6,314.05	12,626.52	0.00	164.50	64,715.20
Barley area (ha)	1,479.51	2,363.56	0.00	220.50	18,753.90
Maize area (ha)	1,837.91	3,827.09	0.00	60.90	23,862.60
Agricultural area (ha)	42,731.13	42,263.95	0.01	28,688.20	132,153.20
Arable area (ha)	22,403.71	31,904.47	0.00	5327.90	90,305.10
Regional area (ha)	164,435.29	138,392.68	4,845.34	154,056.69	484,834.61
Tractors (nb.ha)	1.82	12.47	0.00	0.32	220.00
Irrigation pumps (nb. equiments/ha)	0.19	0.29	0.00	0.10	1.68
Labor (nb. days/ha)	221.37	1,089.81	12.07	47.09	8,8865.39
Killing degree days (nb. above 28°C)	48.49	51.06	0.00	35.65	283.94
Beneficial degree days (nb. days in 0°C-28°C)	2,730.01	393,58	1,879.81	2,627.65	3,557.59
Rainfall (centimeters)	19.28	13.06	1.03	18.42	61.94
Hellenic Cadastre (0/1)	0.24	0.43	0.00	0.00	1.00

NOTE. The table presents the summary statistics for our sample at the regional level between 2011 and 2019. Our outcome variables are respectively the crop yields and areas, as well as the agricultural inputs. Our two treatment variables are respectively the killing degree days (expressed in numbers of days above 28°C during the growing season – April 1 to August 31) and Hellenic Cadastre (binary variable taking the value one when the region has received the cadastral reform, and zero otherwise). The statistics for labor are computed on another dataset, with data available for 2013 and 2016 only. See the text for a full description of the variables and their corresponding sources.

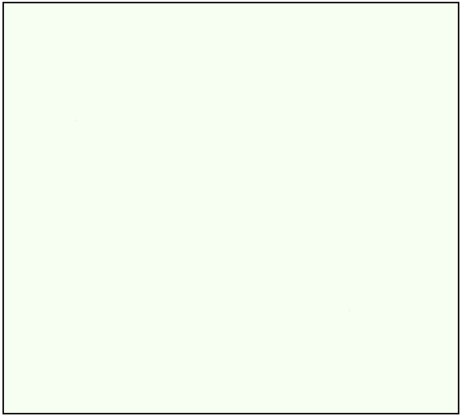


Figure: The unit of uncultivated land with high potential yields

NOTE. The figure represents the farm structure before climate change. Back

Theory

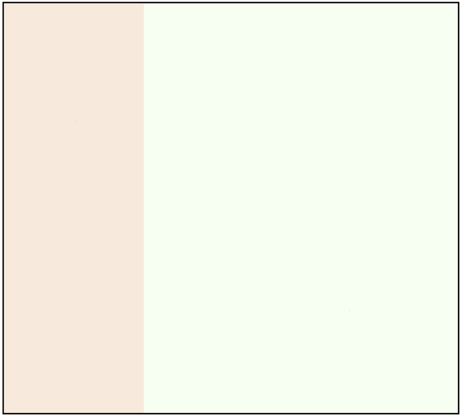


Figure: The unit of uncultivated land with both low & high potential yields
NOTE. The figure represents the farm structure with limited climate change.

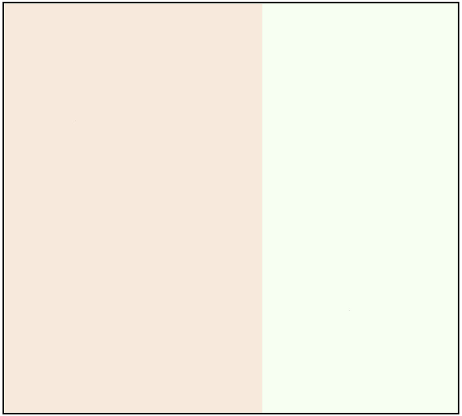


Figure: The unit of uncultivated land with both low & high potential yields
NOTE. The figure represents the farm structure with amplified climate change. Back

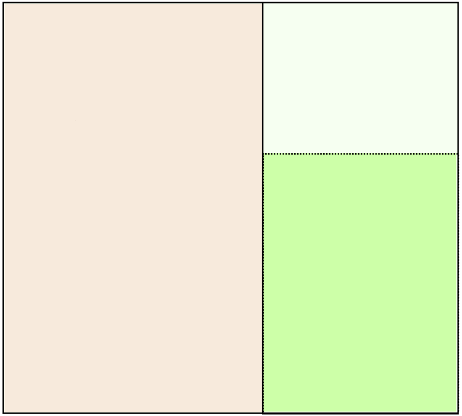
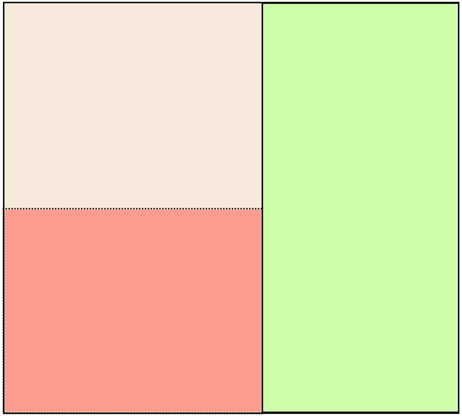


Figure: Extensive margin decisions

NOTE. The figure represents a farm hypothetical acreage decision with amplified climate change.



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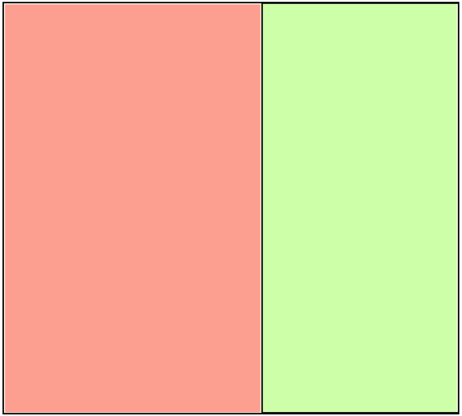


Figure: Extensive margin decisions

NOTE. The figure represents a farm hypothetical acreage decision with amplified climate change. Back

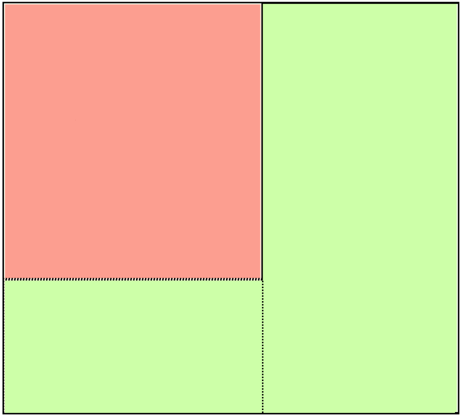


Figure: Intensive margin decisions

NOTE. The figure represents a farm hypothetical irrigation decision with amplified climate change. Back

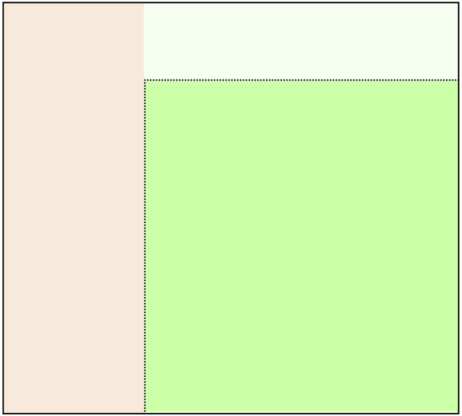


Figure: Extensive margin decisions for low heat exposure

NOTE. The figure represents a farm hypothetical acreage decision with limited climate change.

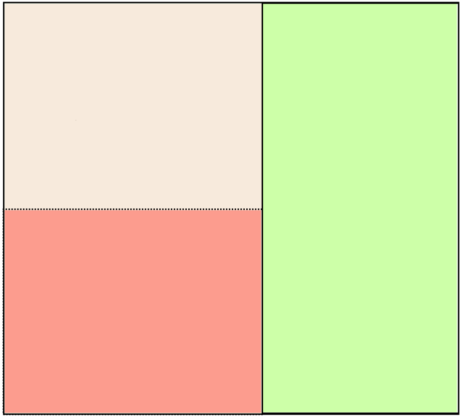


Figure: Extensive margin decisions for higher heat exposure

NOTE. The figure represents a farm hypothetical acreage decision with amplified climate change. Back

Table: Balance in Weather before Cadastral Reform

Dependent Variable:	Probability of Land Reform in Year					
	2014	2015	2016	2017	2018	2019
KDD^{28}	-.000276	.000612	.000115	.000341	-.00151	-.00317
	(.000571)	(.000613)	(.000504)	(.00038)	(.00128)	(.00215)
Precipitation	.152	.00865	.0474	.062	.418*	.288
	(.137)	(.0735)	(.0604)	(.0671)	(.225)	(.195)
Precipitation^2	-.0358	.0081	-.00867	-.0142	-.0643	-.0256
	(.0428)	(.0138)	(.0138)	(.018)	(.0582)	(.0393)
Adj. R^2	-0.00	0.07	-0.03	-0.00	0.13	0.25
Observations	59	57	54	53	52	37

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

NOTE. Samples are all regional units without cadastral reform by 2014 in column 1; 2015 in column 2; 2016 in column 3; 2017 in column 4; 2018 in column 5; and 2019 in column 6. For each column, the sample covers all regions that has not received the land registry by that year. The dependent variable is a dummy indicator that equals one if the regional units start the cadastral reform in that year. Back

Table: Balance in Agriculture Outcomes before Cadastral Reform

Dependent Variable:	Probability of Land Reform in Year					
	2014	2015	2016	2017	2018	2019
Wheat Yield	.736	.227	.0295	.18	1.95	5.12*
	(.922)	(.687)	(.7)	(.815)	(2.22)	(2.57)
Maize Yield	.0416	-.177	-.257*	-.000861	.0269	1.15*
	(.174)	(.128)	(.14)	(.173)	(.47)	(.579)
Barley Yield	.248	-.364	1.78*	.133	1.61	-8.26*
	(1.13)	(.829)	(.938)	(1.16)	(3.17)	(3.96)
Wheat Area	3.08e-07	1.38e-06***	-2.88e-07	5.83e-07	1.37e-06	1.85e-06
	(3.75e-07)	(2.82e-07)	(3.74e-07)	(4.40e-07)	(1.24e-06)	(1.64e-06)
Barley Area	7.26e-07	-1.81e-06	-8.28e-07	-1.41e-06	-4.51e-06	4.69e-06
	(1.78e-06)	(1.34e-06)	(1.29e-06)	(1.51e-06)	(4.19e-06)	(4.03e-06)
Maize Area	9.12e-07	1.15e-06	8.86e-07	5.07e-07	8.75e-07	-5.64e-06*
	(9.10e-07)	(6.90e-07)	(8.27e-07)	(9.83e-07)	(2.69e-06)	(3.14e-06)
Non Fallow Agri. Area	-1.48e-07	9.42e-08	-1.03e-07	-9.60e-08	-9.62e-07	-8.81e-07
	(2.50e-07)	(1.84e-07)	(1.77e-07)	(2.08e-07)	(5.68e-07)	(1.00e-06)
Machinery	-.0000103	5.88e-06	.0000278**	-9.09e-06	.0000269	.0000358
	(.0000153)	(.0000113)	(.0000105)	(.0000138)	(.0000379)	(.0000541)
Irrigation	-1.79e-06	-.0000191*	-.0000276**	.0000186	.0000265	.0000923
	(.0000146)	(.0000107)	(.0000106)	(.0000138)	(.0000389)	(.0000631)
Adj. R^2	-0.02	0.64	0.22	-0.03	0.08	0.26
Observations	41	39	36	35	34	22

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

NOTE. The sample consists of regional units without cadastral reform by 2014 in column 1; 2015 in column 2; 2016 in column 3; 2017 in column 4; 2018 in column 5; and 2019 in column 6. For each column, the sample covers all regions that has not received the land registry by that year. The dependent variable is a dummy indicator that equals one if the regional units start the cadastral reform in that year.

Back

Identification strategy

Table: Balance in Geography before Cadastral Reform

Dependent Variable:	Probability of Land Reform in Year					
	2014	2015	2016	2017	2018	2019
Latitude	-.0113	.0233	.00917	.00722	-.1	.239***
	(.0303)	(.0335)	(.0217)	(.0237)	(.0694)	(.0746)
Longitude	-.00384	.022	.00605	-.00233	.00897	.0478
	(.0155)	(.0171)	(.0113)	(.0124)	(.0363)	(.0393)
Elevation	.000183	-.000314*	-.000245**	-.000147	-.000299	-.000328
	(.000147)	(.000167)	(.000111)	(.000127)	(.000377)	(.000555)
Terrain Ruggedness	-.000182	.000213	.000547***	.000375	.00116	.00275***
	(.000268)	(.000307)	(.0002)	(.000234)	(.000704)	(.000988)
Land Fertility	.0000388	.0000875*	.000025	3.37e-06	.000277**	-.0000565
	(.0000452)	(.0000503)	(.0000334)	(.0000365)	(.000107)	(.00012)
Adj. R^2	0.02	0.22	0.12	-0.03	0.21	0.42
Observations	59	57	54	53	52	37

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

NOTE. The sample consists of regional units without cadastral reform by 2014 in column 1; 2015 in column 2; 2016 in column 3; 2017 in column 4; 2018 in column 5; and 2019 in column 6. For each column, the sample covers all regions that has not received the land registry by that year. The dependent variable is a dummy indicator that equals one if the regional units start the cadastral reform in that year. Back

Identification strategy

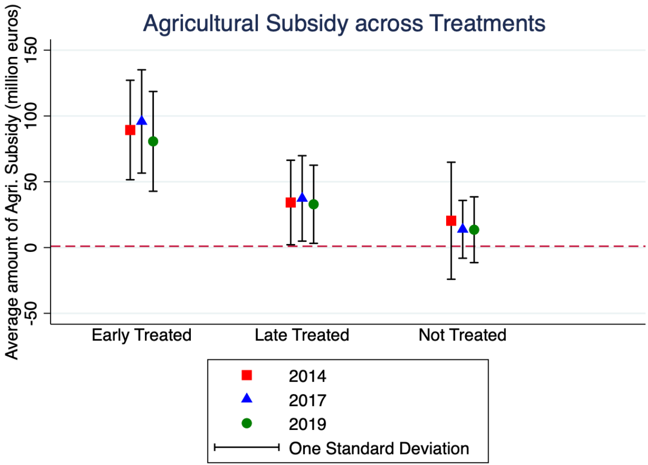


Figure: Agricultural Subsidy across Treatments

NOTE. Early treated are regional units that receive the land registry in and before 2016. Late treated are regional units that receive the land registry in and after 2017. Not treated are regional units that do not receive the land registry between 2014 and 2019.

Back

Table: Estimated interactions of heat with land registry with alternative outcome transformations

	Wheat	Barley	Maize
	Panel A. Crop yields		
Benchmark	0.0018 ***	0.0015 *	0.0022 ***
	(0.0006)	(0.0008)	(0.0005)
arcsinh($y^k_{i,t}$)	0.0004 ***	0.0003	0.0015 ***
	(0.0001)	(0.0002)	(0.0003)
CR($y^k_{i,t}$)	0.0018 ***	0.0014	0.0023 ***
	(0.0007)	(0.0009)	(0.0007)
	Panel B. Crop areas		
Benchmark	-0.0038 ***	-0.0024 *	-0.0035 **
	(0.0009)	(0.0012)	(0.0015)
arcsinh($a^k_{i,t}$)	-0.0040 ***	-0.0024 *	-0.0035 ***
	(0.0010)	(0.0012)	(0.0015)
CR($a^k_{i,t}$)	-0.0069 *	-0.0037	-0.0016
	(0.0040)	(0.0036)	(0.0025)
	Machinery	**Labor**	**Irrigation**
	Panel C. Agricultural Inputs		
Benchmark	0.0026 **	0.0056 ***	0.0017 **
	(0.0010)	(0.0009)	(0.0008)
arcsinh($x^k_{i,t}/A_{i,t}$)	0.00002 *	0.0052 ***	0.00002 *
	(0.00001)	(0.0009)	(0.00002)
CR($x^k_{i,t}/A_{i,t}$)	0.0009 *	0.0037 **	0.0014 ***
	(0.0005)	(0.0014)	(0.0015)

Note. This table presents the estimates of the effects of heat on regional (i) crop yields (Panel A), (ii) crop areas (Panel B) and (iii) agricultural inputs (Panel C), depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to the crop or input considered. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before, and zero otherwise. Regionnally-clustered standard errors are reported in brackets. *, **, *** indicate p-values lower than 0.1, 0.05 and 0.01.

Results: changes in heat definition Back

Table: Estimated interactions of heat with land registry with alternative heat measurements

	Wheat	Barley	Maize
	PANEL A. CROP YIELDS		
Benchmark	0.0018 ***	0.0015 *	0.0022 ***
	(0.0006)	(0.0008)	(0.0005)
Benchmark with KDD^{30} over the growing season	0.0031 ***	0.0020	0.0036 ***
	(0.0010)	(0.0015)	(0.0008)
Benchmark with KDD^{32} over the growing season	0.0062 ***	0.0034	0.0068 ***
	(0.0021)	(0.0033)	(0.0019)
Benchmark with KDD^{34} over the growing season	0.0163 ***	0.0073	0.0167 ***
	(0.0060)	(0.0103)	(0.0061)
Benchmark with KDD^{28} over the whole year	0.0016 ***	0.0014 *	0.0020 ***
	(0.0006)	(0.0008)	(0.0004)
	PANEL B. CROP AREAS		
Benchmark	-0.0038	-0.0024 *	-0.0035 **
	(0.0009)	(0.0012)	(0.0015)
Benchmark with KDD^{30} over the growing season	-0.0056 ***	-0.0041 **	-0.0060 **
	(0.0013)	(0.0019)	(0.0023)
Benchmark with KDD^{32} over the growing season	-0.0100 ***	-0.0059 *	-0.0102 **
	(0.0029)	(0.0034)	(0.0041)
Benchmark with KDD^{34} over the growing season	-0.01780 **	-0.0058	-0.0171 *
	(0.0069)	(0.0055)	(0.0089)
Benchmark with KDD^{28} over the whole year	-0.0036 ***	-0.0023 *	-0.0033 **
	(0.0009)	(0.00012)	(0.0015)
	Machinery	**Labor**	**Irrigation**
	PANEL C. AGRICULTURAL INPUTS		
Benchmark	0.0026 **	0.0056 ***	0.0017 **
	(0.0010)	(0.0009)	(0.0008)
Benchmark with KDD^{30} over the growing season	0.0051 ***	0.0085 ***	0.0024 *
	(0.0018)	(0.0016)	(0.0124)
Benchmark with KDD^{32} over the growing season	0.0118 ***	0.0177 ***	0.0042 *
	(0.0028)	(0.0036)	(0.0026)
Benchmark with KDD^{34} over the growing season	0.0328 ***	0.0515 ***	0.0112
	(0.0823)	(0.0105)	(0.0068)
Benchmark with KDD^{28} over the whole year	0.0027 **	0.0057 ***	0.0018 **
	(0.0011)	(0.0008)	(0.0008)

NOTE. This table presents the estimates of the effects of heat on regional (i) crop yields (Panel A), (ii) crop areas (Panel B) and (iii) agricultural inputs (Panel C), depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to the crop or input considered. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before,

Results: changes in the time structure of the error terms

Back

Table: Estimated interactions of heat with land registry with alternative specifications

	Wheat	Barley	Maize
	Panel A. Crop yields		
Benchmark + future international prices	0.0020 ***	0.0016 **	0.0024 ***
	(0.0005)	(0.0008)	(0.0005)
Benchmark + quadratic time trend	0.0007	0.0008	0.0011 *
	(0.0006)	(0.0008)	(0.0006)
Benchmark + year fixed effects	0.0008	0.0008	0.0021 ***
	(0.0006)	(0.0008)	(0.0006)
	Panel B. Crop areas		
Benchmark	-0.0038 ***	-0.0024 *	-0.0035 **
	(0.0009)	(0.0012)	(0.0015)
Benchmark + future international prices	-0.0043 ***	-0.0031 **	-0.0041 ***
	(0.0009)	(0.0014)	(0.014)
Benchmark + quadratic time trend	-0.0026 **	0.0004	-0.0013
	(0.0011)	(0.0016)	(0.0019)
Benchmark + year fixed effects	-0.0014	-0.0001	-0.0018
	(0.0014)	(0.0016)	(0.0019)
	Machinery	**Labor**	**Irrigation**
	Panel C. Agricultural Inputs		
Benchmark	0.0026 **	0.0056 ***	0.0017 **
	(0.0010)	(0.0009)	(0.0008)
Benchmark + future international prices	0.0027 ***	0.0059 ***	0.0016 *
	(0.0010)	(0.0009)	(0.0008)
Benchmark + quadratic time trend	0.0023 **	0.0059 ***	0.0027 ***
	(0.0010)	(0.0009)	(0.0008)
Benchmark + year fixed effects	0.0018 *	0.0059 ***	0.0029 **
	(0.0010)	(0.0009)	(0.0011)

Note. This table presents the estimates of the effects of heat on regional (i) crop yields (Panel A), (ii) crop areas (Panel B) and (iii) agricultural inputs (Panel C), depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to the crop or input considered. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before, and zero otherwise. Regionally-clustered standard errors are reported in brackets. *, **, *** indicate p-values lower than 0.1, 0.05 and 0.01.

Table: Estimated interactions of heat with land registry with Conley (1999)'s correction

	Wheat	Barley	Maize
	Panel A. Crop yields		
Benchmark	0.0018 ***	0.0015 *	0.0022 ***
	(0.0006)	(0.0008)	(0.0005)
Benchmark + spatial correlation within 50 km	0.0018 ***	0.0015 *	0.0022 ***
	(0.0006)	(0.0008)	(0.0005)
Benchmark + spatial correlation within 100 km	0.0018 ***	0.0015 *	0.0022 ***
	(0.0006)	(0.0009)	(0.0005)
Benchmark + spatial correlation within 200 km	0.0018 ***	0.0015 *	0.0022 ***
	(0.0005)	(0.0008)	(0.0004)
Benchmark + spatial correlation within 500 km	0.0018 ***	0.0015 *	0.0022 ***
	(0.0003)	(0.0005)	(0.0003)
	Panel B. Crop areas		
Benchmark	-0.0038 ***	-0.0024 **	-0.0035 **
	(0.0009)	(0.0012)	(0.0015)
Benchmark + spatial correlation within 50 km	-0.0038 ***	-0.0024 **	-0.0035 ***
	(0.0013)	(0.0012)	(0.0014)
Benchmark + spatial correlation within 100 km	-0.0038 ***	-0.0024 *	-0.0035 ***
	(0.0011)	(0.0013)	(0.0011)
Benchmark + spatial correlation within 200 km	-0.0038 ***	-0.0024 *	-0.0035 ***
	(0.0013)	(0.0013)	(0.0009)
Benchmark + spatial correlation within 500 km	-0.0038 ***	-0.0024 **	-0.0035 ***
	(0.0010)	(0.0012)	(0.0006)
	Machinery	**Labor**	**Irrigation**
	Panel C. Agricultural Inputs		
Benchmark	0.0026 **	0.0056 ***	0.0017 **
	(0.0010)	(0.0009)	(0.0008)
Benchmark + spatial correlation within 50 km	0.0026 **	0.0056 ***	0.0017 **
	(0.0012)	(0.0009)	(0.0009)
Benchmark + spatial correlation within 100 km	0.0026 **	0.0056 ***	0.0017 **
	(0.0012)	(0.0008)	(0.0010)
Benchmark + spatial correlation within 200 km	0.0026 **	0.0056 ***	0.0017 **
	(0.0012)	(0.0008)	(0.0011)
Benchmark + spatial correlation within 500 km	0.0026 **	0.0056 ***	0.0017 **
	(0.0009)	(0.0008)	(0.0009)

Note. This table presents the estimates of the effects of heat on regional (i) crop yields (Panel A), (ii) crop areas (Panel B) and (iii) agricultural inputs (Panel C), depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to the crop or input considered. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two

- Data comes from Corine Land Cover (2012 and 2018)

Table: Estimated impacts of heat on other sectors according to the presence of land registry

	Dependent variable: $log(1 + a^k_{i,t})$		
	Forests	Urban	Shrubs
KDD^{28}	0.0003	-0.0002	-0.0004
	(0.0003)	(0.0001)	(0.0005)
KDD^{28} × Registry reform	0.0000	0.0001	0.0001
	(0.0000)	(0.0001)	(0.0001)
Registry reform	0.0192	-0.0174	-0.0403
	(0.0219)	(0.0141)	(0.0675)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
χ^2 joint Student test for KDD^{28}	0.1238	1.0639	0.1133
χ^2 joint Wald test for registry	0.7580	1.5507	0.3225
Adj. R^2	0.7206	0.7201	0.8658
Observations	114	114	114

NOTE. This table presents the estimates of the effects of heat on regional areas, depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to area considered. Killing degree days are measured as the cumulative days spent above 28°C between April 1st to August 31th. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before, and zero otherwise. Regionally-clustered standard errors are reported in brackets. *, **, *** indicate p-values lower than 0.1, 0.05 and 0.01.

Results: effects on fire occurrence

Table: Estimated impacts of heat on burnt areas according to the presence of land registry Back

	Dependent variable: $log(1 + a^k_{i,t})$		
	Burnt agricultural areas	**Burnt forest areas**	**Burnt urban areas**
KDD^{28}	0.0057	0.0057 *	0.0008
	(0.0052)	(0.0029)	(0.0023)
$KDD^{28} \times$ Registry reform	0.0041	-0.0049	0.0047
	(0.0151)	(0.0051)	(0.0054)
Registry reform	-2.5160 *	0.4377	-0.7438
	(1.5302)	(0.4185)	(0.5887)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
χ^2 joint Student test for KDD^{28}	0.4288	0.0310	1.0398
χ^2 joint Wald test for registry	6.2241 ***	1.1219	3.3068 *
Adj. R^2	0.3994	0.2552	0.2930
Observations	513	513	513

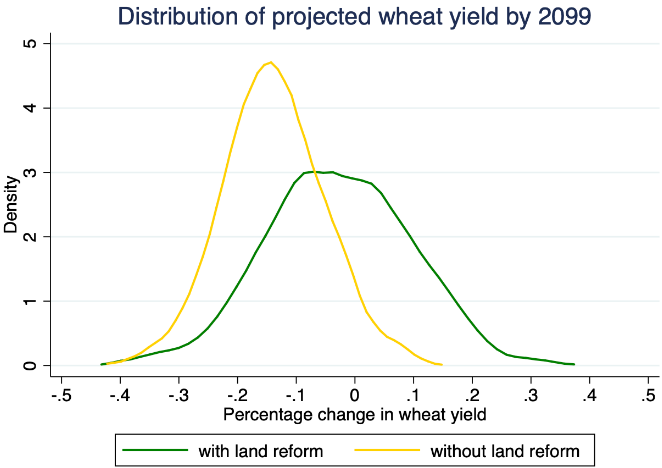
NOTE. This table presents the estimates of the effects of heat on regional areas, depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to crop considered. Killing degree days are measured as the cumulative days spent above 28°C between April 1st to August 31th. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before, and zero otherwise. Regionnally-clustered standard errors are reported in brackets. *, **, *** indicate p-values lower than 0.1, 0.05 and 0.01.

Table: Estimated impacts of heat on animal density according to the presence of land registry Back

	Dependent variable: $log((1+z^k_{i,t})/A_{i,t})$			
	Pigs	**Sheeps**	**Goats**	**Cows**
KDD^{28}	0.0015	-0.0010	0.0003	-0.0004
	(0.0011)	(0.0012)	(0.0004)	(0.0008)
KDD^{28} × Registry reform	-0.0025	0.0050	-0.0001	-0.0056
	(0.0036)	(0.0040)	(0.0007)	(0.0034)
Registry reform	0.684	-0.4364	-0.0595	0.8248
	(0.5299)	(0.3310)	(0.0908)	(0.5717)
Precipitation controls	Yes	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes	Yes
χ^2 joint Student test for KDD^{28}	0.1238	1.0639	0.1133	4.5072 *
χ^2 joint Wald test for registry	0.7580	1.5507	0.3225	1.7066
Adj. R^2	0.7206	0.7201	0.9317	0.8658
Observations	511	511	511	511

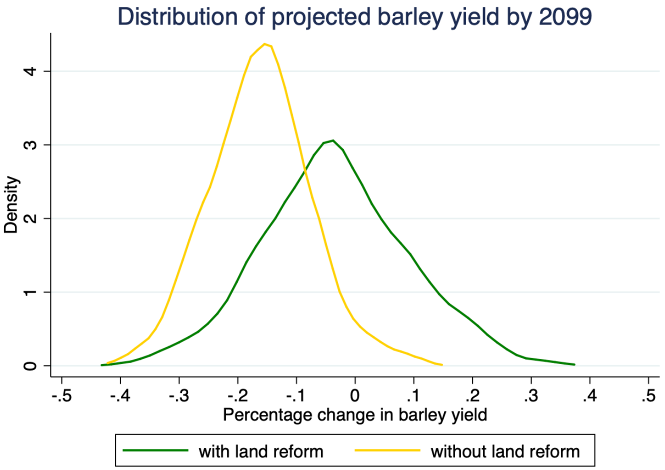
NOTE. This table presents the estimates of the effects of heat on the density of animals in head per hectare per hectare of the whole regional agricultural area (minus fallows), depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to animal considered. Killing degree days are measured as the cumulative days spent above 28°C between April 1st to August 31th. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before, and zero otherwise. Regionnally-clustered standard errors are reported in brackets. *, **, *** indicate p-values lower than 0.1, 0.05 and 0.01.

Simulations on wheat yields



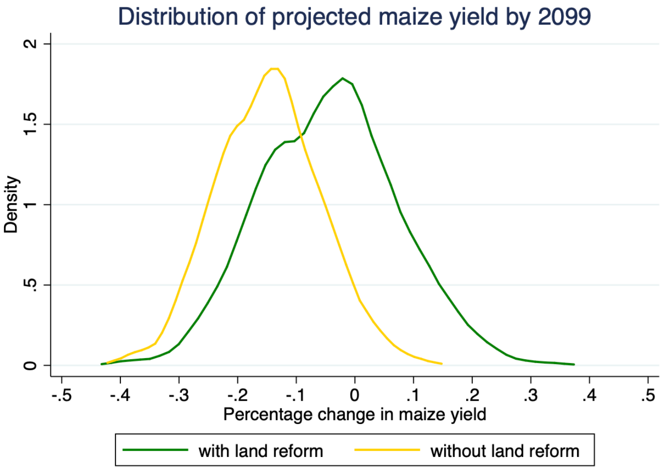
Percentage change in wheat yield contributed by land reform by 2099 Back

Simulations on barley yields



Percentage change in barley yield contributed by land reform by 2099 Back

Simulations on maize yields



Percentage change in maize yields contributed by land reform by 2099 Back

Robustness: adding GDP per capita controls

Table: Heat impacts on crop yields by land tenure security worldwide: GDP controls

	Dependent variable: crop yields					
	Corn	**Wheat**	**Rice**	**Cassava**	**Soy**	**Sorghum**
	Panel A. Baseline specification					
GDD	0.0000***	0.0015***	-0.0000	0.0000**	0.0002***	0.0001*
	(0.0000)	(0.0001)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
KDD $\times$ 1{Cadaster $<$ 0.5}	-0.0033***	-0.0030***	-0.0027***	-0.0008***	-0.0049***	-0.0066***
	(0.0002)	(0.0007)	(0.0001)	(0.0001)	(0.0002)	(0.0004)
KDD $\times$ 1{Cadaster $\geq$ 0.5}	-0.0028***	-0.0004***	-0.0018***	-0.0009***	-0.0049***	-0.0040***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)
R^2	0.828	0.556	0.794	0.671	0.740	0.773
	Panel B. Adding GDP per capita controls					
GDD	-0.0000	0.0015***	0.0000	0.0000**	0.0002***	0.0001*
	(0.0000)	(0.0001)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
KDD $\times$ 1{Cadaster $<$ 0.5}	-0.0026***	-0.0033***	-0.0027***	-0.0008***	-0.0050***	-0.0068***
	(0.0002)	(0.0007)	(0.0001)	(0.0001)	(0.0002)	(0.0004)
KDD $\times$ 1{Cadaster $\geq$ 0.5}	-0.0023***	-0.0003***	-0.0019***	-0.0009***	-0.0049***	-0.0040***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)
R^2	0.830	0.542	0.793	0.671	0.734	0.763

Note. This table presents estimates of the effects of extreme heat exposure on regional crop yields, depending on whether the region is located in a country with secure land rights. The column headings refer to crops considered. Beneficial (BDD) and killing degree days (KDD) are measured as the cumulative number of days spent below vs. above a crop-specific threshold. Standard errors, robust to heteroskedasticity and serial correlation at the country level, are reported in brackets. *, **, *** indicate p-values below 0.1, 0.05 and 0.01. Back

Robustness: alternative cadaster threshold

Table: Heat impacts on crop yields by land tenure security worldwide: alternative threshold

	Dependent variable: crop yields					
	Corn	**Wheat**	**Rice**	**Cassava**	**Soy**	**Sorghum**
	PANEL A. BASELINE SPECIFICATION					
GDD	0.0000***	0.0015***	-0.0000	0.0000**	0.0002***	0.0001*
	(0.0000)	(0.0001)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
KDD $\times$ $1\{\text{Cadaster} < 0.5\}$	-0.0033***	-0.0030***	-0.0027***	-0.0008***	-0.0049***	-0.0066***
	(0.0002)	(0.0007)	(0.0001)	(0.0001)	(0.0002)	(0.0004)
KDD $\times$ $1\{\text{Cadaster} \geq 0.5\}$	-0.0028***	-0.0004***	-0.0018***	-0.0009***	-0.0049***	-0.0040***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)
R^2	0.828	0.556	0.794	0.671	0.740	0.773
	PANEL B. ALTERNATIVE CADASTER THRESHOLD (0.35)					
GDD	0.0000***	0.0015***	0.0000	0.0000**	0.0002***	0.0000
	(0.0000)	(0.0001)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
KDD $\times$ $1\{\text{Cadaster} < 0.35\}$	-0.0027***	-0.0030***	-0.0029***	-0.0009***	-0.0074***	-0.0047***
	(0.0002)	(0.0007)	(0.0002)	(0.0001)	(0.0002)	(0.0007)
KDD $\times$ $1\{\text{Cadaster} \geq 0.35\}$	-0.0028***	-0.0004***	-0.0024***	-0.0009***	-0.0049***	-0.0040***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)
R^2	0.828	0.556	0.794	0.671	0.741	0.773

NOTE. This table presents estimates of the effects of extreme heat exposure on regional crop yields, depending on whether the region is located in a country with secure land rights. The column headings refer to crops considered. Beneficial (BDD) and killing degree days (KDD) are measured as the cumulative number of days spent below vs. above a crop-specific threshold. Standard errors, robust to heteroskedasticity and serial correlation at the country level, are reported in brackets. *, **, *** indicate p-values below 0.1, 0.05 and 0.01. Back

Robustness: post-1980 sample

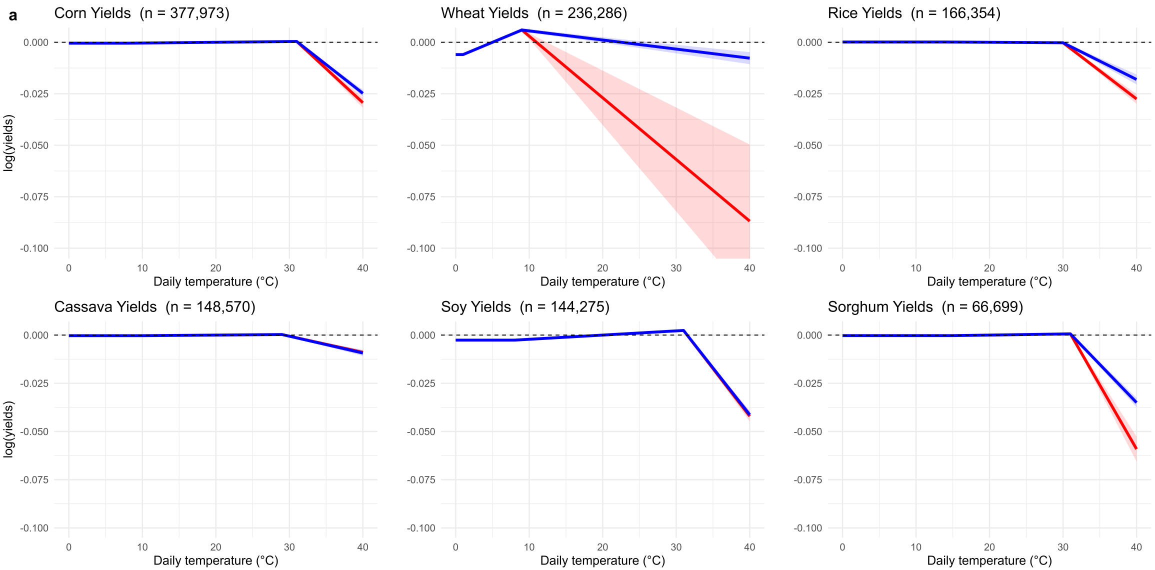
Table: Heat impacts on crop yields by land tenure security worldwide: post-1980 sample

	Dependent variable: crop yields					
	Corn	**Wheat**	**Rice**	**Cassava**	**Soy**	**Sorghum**
	PANEL A. BASELINE SPECIFICATION					
GDD	0.0000***	0.0015***	-0.0000	0.0000**	0.0002***	0.0001*
	(0.0000)	(0.0001)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
KDD × 1{Cadaster < 0.5}	-0.0033***	-0.0030***	-0.0027***	-0.0008***	-0.0049***	-0.0066***
	(0.0002)	(0.0007)	(0.0001)	(0.0001)	(0.0002)	(0.0004)
KDD × 1{Cadaster ≥ 0.5}	-0.0028***	-0.0004***	-0.0018***	-0.0009***	-0.0049***	-0.0040***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)
R^2	0.828	0.556	0.794	0.671	0.740	0.773
	PANEL B. POST-1980 SAMPLE (1980–2015)					
GDD	-0.0001***	0.0016***	0.0000	0.0000	0.0003***	0.0001***
	(0.0000)	(0.0001)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
KDD × 1{Cadaster < 0.5}	-0.0019***	-0.0036***	-0.0024***	-0.0009***	-0.0047***	-0.0055***
	(0.0002)	(0.0008)	(0.0001)	(0.0001)	(0.0002)	(0.0004)
KDD × 1{Cadaster ≥ 0.5}	-0.0017***	-0.0005***	-0.0017***	-0.0009***	-0.0048***	-0.0035***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)
R^2	0.839	0.517	0.803	0.697	0.759	0.805

NOTE. This table presents estimates of the effects of extreme heat exposure on regional crop yields, depending on whether the region is located in a country with secure land rights. The column headings refer to crops considered. Beneficial (BDD) and killing degree days (KDD) are measured as the cumulative number of days spent below vs. above a crop-specific threshold. Standard errors, robust to heteroskedasticity and serial correlation at the country level, are reported in brackets. *, **, *** indicate p-values below 0.1, 0.05 and 0.01. Back

Results

Back



- One concern is that the registry was first implemented in major agricultural regions to improve the administration of CAP payments (as suggested by the balance tests on crop area)
- This could bias the interpretation if reform timing also changed agricultural subsidies, and hence farmers' adaptation capacity
- We do not find strong evidence of differential subsidy trends by reform timing
  - Early-treated and late-treated regions follow broadly similar CAP subsidy dynamics over the sample period
- This supports the view that our results are not primarily driven by subsidy reallocation

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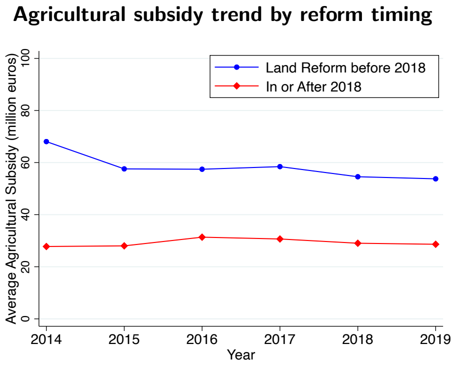

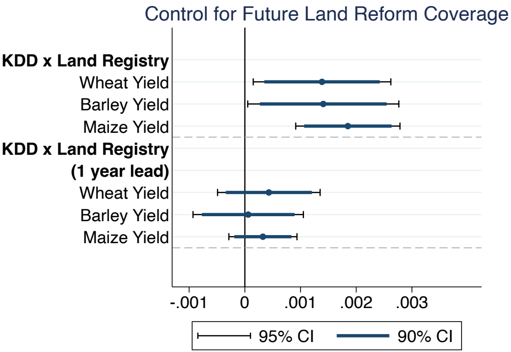

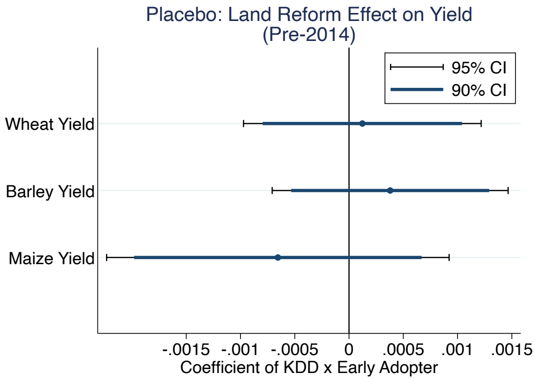

Panel A. Lead coefficients of $KDD\times$ land registry

Panel B. Pre-2014 placebo test: $KDD\times$ early land reform

NOTE. Panel A plots coefficients from a joint regression including the interaction between extreme heat exposure and one-year lead land reform coverage, for wheat, barley, and maize yields. Panel B plots estimated coefficients on $KDD \times EarlyAdopter$ from the main specification on the pre-2014 subsample. *KDD* is the number of killing degree days during the growing season. *EarlyAdopter* equals 1 if the region receives land reform before 2018, and 0 otherwise.

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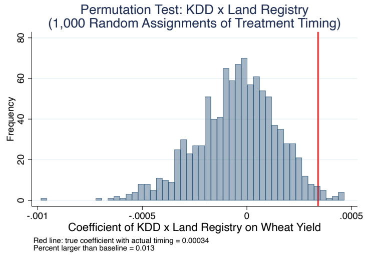
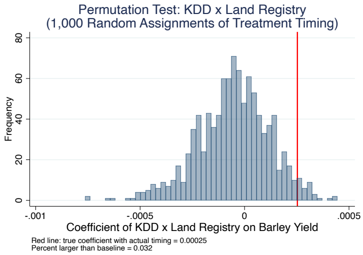
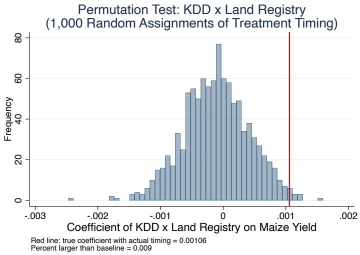


Panel A. Wheat yields



Panel B. Barley yields



Panel C. Maize yields

Note. The figure reports the distribution of the interaction term between extreme heat exposure and land reform based on 1,000 randomized reform assignments across rollout clusters. The vertical line denotes the estimate obtained from the observational data. The p-value is the share of randomized estimates equal to or above the observational estimate.

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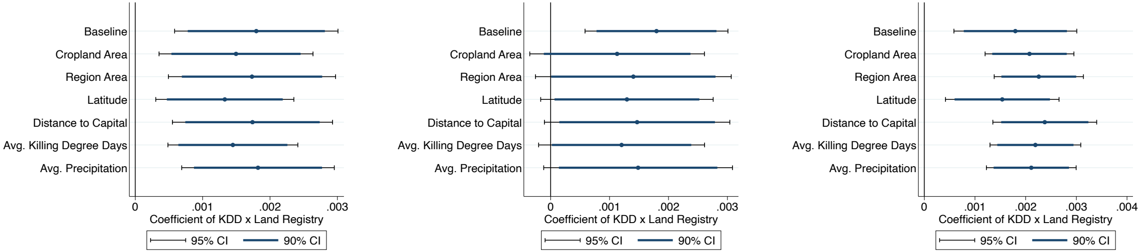

Panel A. Wheat yield **Panel B.** Barley yield **Panel C.** Maize yield

NOTE. All coefficients reported are β_3, the interaction between heat exposure and land reform coverage. The first row replicates the results from Table 1. The other rows add regional controls identified as potentially correlated with land reform coverage and interact them with heat exposure.

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Results: staggered DiD in hot years

Table: Staggered DiD in hot years: yields only

	Placebo (Pre-treatment)		Post-treatment ATT	
	ATT	95% CI	ATT	95% CI
Wheat yield	0.025	[-0.071 ; 0.121]	0.102***	[0.033 ; 0.171]
Barley yield	0.103	[-0.029 ; 0.235]	0.209***	[0.160 ; 0.259]
Maize yield	0.046	[-0.023 ; 0.116]	0.092***	[0.040 ; 0.143]

NOTE. Estimates are computed using the group-time ATT estimator of Callaway & Sant'Anna (2021) with doubly robust estimation. The sample is restricted to hot-year observations (above-median KDD). Treatment is defined as exposure to the land registry reform for at least two years. Placebo estimates average pre-treatment event times; post-treatment estimates average post-treatment event times. 95% confidence intervals are based on standard errors clustered at the regional-unit level. *, **, *** indicate p-values below 0.1, 0.05, and 0.01.

- **No evidence of pre-trends** in hot years before treatment
- **Positive post-treatment effects** on wheat, barley, and maize yields

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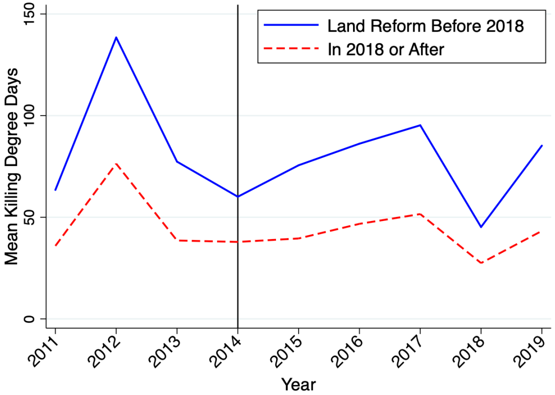
Identification strategy: heat exposure trends



- KDD follows a very similar evolution in regions that received the reform early and in those that received it later
- This supports the idea that abnormal heat exposure is not systematically related to reform timing

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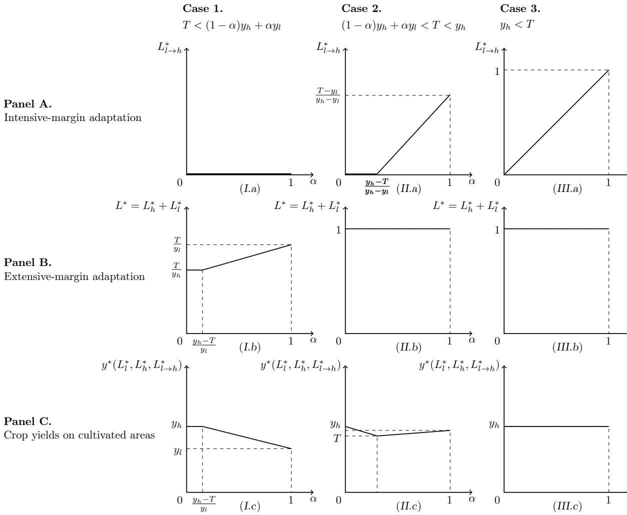
- **Two treatments**
  - $\alpha \in [0,1]$: share of land with **low yields** ($y_l < y_h$, representing *heat exposure*)
  - T: **land dispute constraint** (representing *insecure land rights*)
- **Two choice variables**
  - $L = L_h + L_l$: **cultivated land** with $L < 1$ (*extensive-margin adaptation*)
  - $L_{l\to h}$: **land improvement** from y_l to y_h (*intensive-margin adaptation*)
- Assuming $p = 1$ and $c < r$, the farmer's program is

$$\max_{L, L_{l\to h}} \quad \pi = y_h(L_h + L_{l\to h}) + y_l(L_l - L_{l\to h}) - cL - rL_{l\to h}$$

$$\text{s.t. } 0 \le L_{l\to h} \le L_l \le \alpha, \quad 0 \le L_h \le 1-\alpha,$$
$$y_h(L_h + L_{l\to h}) + y_l(L_l - L_{l\to h}) \le T$$

- Clear analytical solutions Formula



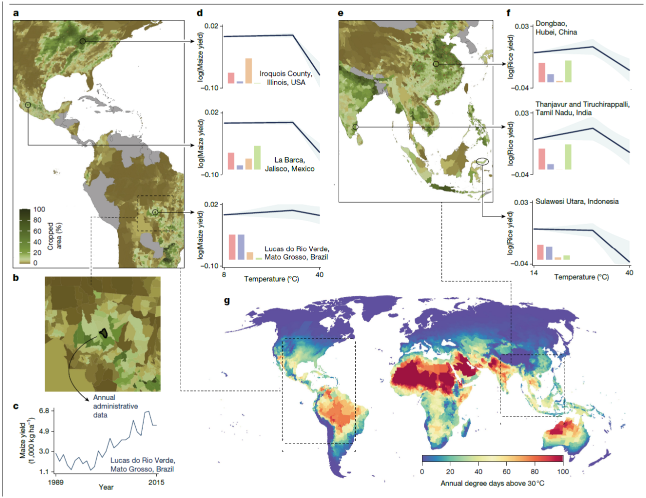


Figure: Global analysis from Hultgren et al. (2025, Nature)

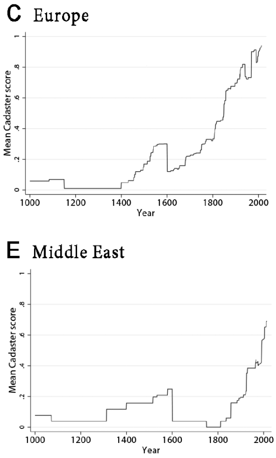


Figure: Evolution of the cadaster index from D'Arcy et al. (2024, JPE)