Extreme Weather and Agricultural Productivity:
Farm Level Responses

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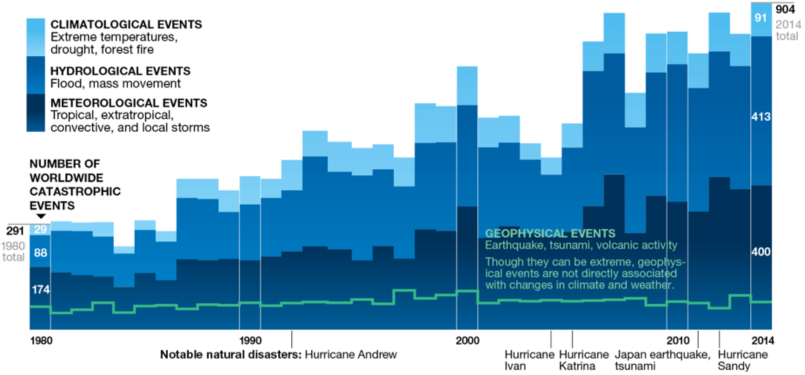
Climate Change and Extreme Weather events



Climate Change in Developing Countries

A rise in average temperatures and an expected increase in extreme weather events:

- Rural poor on the front line
- In many developing countries traditional farming is still the main economic activity and source of livelihood
- Weather shocks are a constant threat to the subsistence of small farming households

Research questions

Focus on developing countries with traditional farming

- How does extreme temperature events affect agricultural productivity?
- What are the margins for mitigation/adaptation available to farmers?
- To what extent the economic and geographic environment play a role in these responses?

What we know

- Non-linear relationship between temperatures and yields
  - After a certain threshold, high temperatures reduce crop yields (Deschenes & Greenstone 2007, 2012, Roberts & Schlenker 2009)
  - Usually explored with aggregate data (district, county, etc), mostly in the US.
- Little evidence of mitigation strategies being at place (Burke & Emerik 2016)
- Little evidence from other developing countries
  - Guiteras (2009) documents non-linearities in yields using district data in India
  - A constrained data-intensive exercise: e.g. no monitoring stations in rural areas; monthly averages temperatures absorb important variation

Our Contribution

1. We propose the use of high frequency satellite data on temperatures and precipitation
   - We geo-match it with information for Peruvian household farms (2007-2015)
2. We use rich agricultural data to unpack the effect of extreme temperature on yields
   - Yields are Y/T: we model the shock as a reduction in TFP that can affect both Y and T
   - A production function approach to identify effects on TFP
3. We highlight the importance of the economic and geographic environment
   - Region-specific analysis: Coast v Highlands
4. We simulate impacts on yields under different standard climate change scenarios using our estimates

Our Results

1. We find strong non-linearities of temperature on yields
   - Thresholds similar to the US, but vary across regions

2. We document negative effects of extreme temperature on TFP

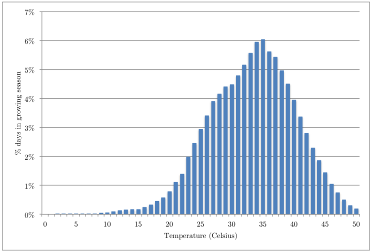
3. Yield decomposition differs by region: in the richer coast $Y \downarrow$, T unchanged; in the highlands $T \uparrow$, Y unchanged
   - Consistent with a model of consumer-producer households with subsistence that face imperfect input markets
   - We find other margins of adjustment in labor and crop mix

4. Our simulation of climate change scenarios suggest strong heterogeneous effects
   - The hotter coast would suffer strong damages on averages, while the cooler highlands would benefit from higher temperatures

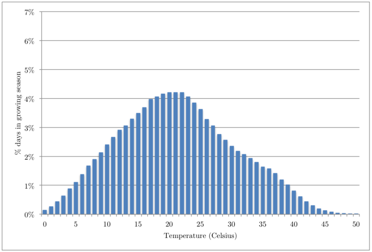
Context: Rural Peru

- Rural poverty rate is $>50\%$
- Mostly households farming small parcels of land (< 3 hs)
- Diverse climatic regions and agricultural practices
  - Coast: sub-tropical, hot, arid (< 1 mm/day)
  - Highlands: high altitude, cool, wet (> 3.5 mm/day)

Figure: Distribution of daily average temperature by climatic region



: Coast



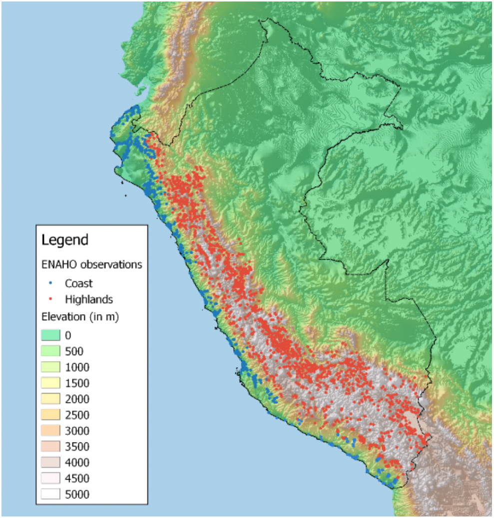
: Highlands

Data

- ENAHO 2007-2015: HH survey with sample of 55K farmers in the coast and highlands of Peru.
- Daily average daytime land surface temperatures (LSTs) from NASA at 5.6km x 5.6km squares (MODIS)
- Monthly precipitation rates from reanalysis at 5.6km x 5.6km squares (CHIRPS)
- Soil quality data at a 9km x 9km grid (IIASA - FAO)

Rural Peru: households

Figure: Agricultural survey observations by region



Summary Statistics

Variable	Coast (1)	Highlands (2)	p-value (1)=(2) (3)
A. Household characteristics			
Daily per capita expenditure	4.040	2.347	0.000
Poor (%)	0.261	0.550	0.000
Extreme poor (%)	0.045	0.209	0.000
Has at least 1 unmet need (%)	0.295	0.382	0.000
Child labor (%)	0.132	0.390	0.000
Household size	4.406	4.312	0.001
HoH completed primary educ. (%)	0.590	0.498	0.000
B. Agricultural characteristics			
Value of agric. output	3052.7	682.0	0.000
Output per hectarea	2323.8	1077.3	0.000
Land used (ha)	2.381	1.906	0.000
Hire workers (%)	0.558	0.471	0.000
Nr. HH members work in agric.	2.197	2.315	0.000
Fruits (% total output)	0.318	0.035	0.000
Tubers (% total output)	0.056	0.356	0.000
Cereals (% total output)	0.302	0.314	0.010
Use tractor (%)	0.541	0.164	0.000
Use fertilizer (%)	0.768	0.744	0.000
Use pesticides (%)	0.651	0.412	0.000
Uncultivated land (% of land holding)	0.121	0.448	0.000
Irrigated land (% land holding)	0.823	0.287	0.000
Observations	7,969	47,026	

Notes: Sample restricted to farming households in Coast and Highlands. Columns 1 and 2 display mean values. Columns 3 shows the p-value of a mean comparison test between both regions. Expenditure and agricultural output are measured in 2007 USD. HoH=household head, HH=household, HDD=harmful degree days

Climatic regions have different agricultural practices:

- Coast: richer, more modern, market- oriented
- Highlands: poorer, subsistence farming
- We study short run responses to weather shocks in these two different models, both prevalent in developing countries

Analytical framework

- The botanical literature has established long ago that very high temperatures are harmful for plant growth.
- That would mean that, conditional on inputs (land T and labor L), output Y decreases with extreme temperature: this is a TFP shock.
- Most of the literature focuses on how extreme temperature affects yields Y/T in the US.
- However, we need to be explicit about constraints farmers face to rationalize a drop in yields, e.g. is land fixed in the short run?
- How is the farming environment different for small household farmers in developing countries?

Analytical framework

A Simple Model of Producer-Consumer Households

- Utility: non-homothetic over consumption c: $U(c - s, l)$
- Production subject to productivity shocks A: $F(A, L, T)$
- Weather w affects productivity $A(w)$, both directly (i.e. health of crops) and indirectly (via quality of L and T).
- Additionally:
  - Inter-temporal use of land (fallow or crop rotation), optimal to have uncultivated land
  - Outside opportunities are restricted, households rely on their endowments.

Implications for the empirical analysis

- Extreme temperatures should reduce TFP
  - Endowments should be a good predictor of input use
- Response to extreme heat (drop in TFP) depends of how close the HH is to minimum consumption level s

Table 2: Main empirical predictions

Effect of extreme temperature on	Non-subsistence farmers $c > s$	Subsistence farmers $c = s$
Yields (Y/T)	-	-
Agricultural output (Y)	-	0
Hired labor (L^h)	-	-
Domestic labor (L^d)	?	+
Land (T)	?	+

Empirical Approach

- Starting from a Cobb-Douglas production function, estimate:

$$\ln Y_{ivt} = \alpha \ln T_{it} + \beta \ln L_{it} + \underbrace{g(\gamma, \omega_{it}) + \phi Z_i + \rho_j + \psi_t}_{\ln \text{TFP}} + \xi_{ivt}$$

- Y: annual agricultural output (in constant prices)
- T: land used
- L: labor (hours, wage bill)
- $g(\gamma, \omega_{it})$: Non linear function of the weather
- $\phi Z_i + \rho_j + \psi_t$: District and growing season FE + controls (soil, HH charact.)

Empirical Approach

We model $g(\gamma, \omega_{it})$ following recent literature (Schlenkler & Roberts 2006, Deschenes & Greenstone 2007):

- Temperature:
  - Cumulative exposure to heat has a non-linear effect
  - Degree days (DD): 8 - τ_{High}
  - Harmful degree days (HDD): above τ_{High}
  - In our case, estimate τ_{High} by region
  - Average: 32 C (Previous US studies: 29-32 C). Coast: 27 C , Highlands: 35 C

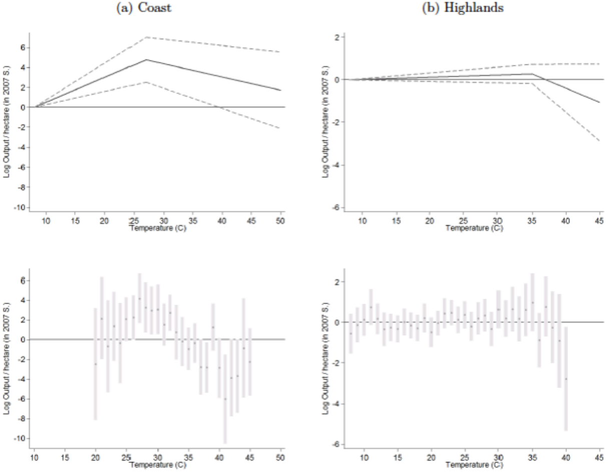
Degree Days

- g enters our estimation as

$$g(\gamma, \omega_{it}) = \underbrace{\gamma_0 DD_{it} + \gamma_1 HDD_{it}}_{\text{temperature}} + \underbrace{\gamma_2 PP_{it} + \gamma_3 PP_{it}^2}_{\text{precipitation}}$$

Results: Temperature and yields

Figure 3: Non-linear relationship between temperature and agricultural yields



Notes: Top panels depict piece-wise function for temperature, including degree-days and harmful degree days at each region's respective thresholds. Bottom panel shows coefficients of individual regressions of model 3 using 1°C bins that measure the fraction of the growing season spent in that temperature. Bars indicate 95% confidence intervals.

Results: Yields and TFP by region

Table 3: Effect of temperature on agricultural productivity

	Coast			Highlands		
	Y/T	TFP	TFP	Y/T	TFP	TFP
	(1)	(2)	(3)	(4)	(5)	(6)
Average DD	0.149**	0.093*	0.104*	0.011	0.013	0.021**
	(0.059)	(0.054)	(0.056)	(0.010)	(0.008)	(0.009)
Average HDD	-0.195***	-0.157***	-0.179***	-0.118*	-0.103*	-0.127*
	(0.065)	(0.054)	(0.054)	(0.068)	(0.061)	(0.064)
Input controls	No	Yes	Yes	No	Yes	Yes
Method	OLS	OLS	2SLS	OLS	OLS	2SLS
Obs.	7,962	7,961	7,961	47,020	47,019	47,019
R-squared	0.195	0.349	0.334	0.267	0.446	0.409
F-stat. (first stage)			311.3			1789.5

Notes: Robust standard errors in parentheses. Standard errors are clustered at district level. * denotes significant at 10%, ** significant at 5% and *** significant at 1%. All regressions include as controls: district and growing season fixed effects household head's demographics (age, age^2, gender, and educational attainment), indicators of soil characteristics, average precipitation, and its square. Columns 1 and 4 use log of output per hectare as outcome, while the rest of columns use log of total output. Columns 2-3 and 5-6 include log of inputs as additional controls. Inputs include land used, household members' hours worked in agriculture , and farms' expenditure on hired workers. Columns 3 and 6 use endowments (land owned and household size) as instruments for quantities of land and domestic labor.

Results - Output

Table 4: Effect of temperature on total output and input use

	ln(output)	ln(land used)	Hired workers=1	ln(expend. in hired workers)
	Y	T	L^h	L^h
	(1)	(2)	(3)	(4)
A. Coast				
Average DD	0.146**	-0.004	0.029***	0.094
	(0.062)	(0.013)	(0.010)	(0.085)
Average HDD	$\boxed{-0.174^{**}}$	0.021	-0.028***	0.002
	$\boxed{(0.071)}$	(0.013)	(0.009)	(0.052)
Observations	7,962	7,962	7,962	4,436
R-squared	0.189	0.222	0.185	0.277
B. Highlands				
Average DD	0.005	-0.006	-0.000	0.028***
	(0.010)	(0.007)	(0.003)	(0.010)
Average HDD	$\boxed{-0.046}$	0.073**	0.018	-0.135*
	$\boxed{(0.070)}$	(0.036)	(0.021)	(0.080)
Observations	47,020	47,020	47,020	22,126
R-squared	0.266	0.325	0.155	0.290

Notes: Robust standard errors in parentheses. Standard errors are clustered at district level. * denotes significant at 10%, ** significant at 5% and *** significant at 1%. All regressions include district and growing season fixed effects, average precipitation and its square, and same household and soil controls as column 1 in Table 3.

Results - Land use

Table 4: Effect of temperature on total output and input use

	ln(output)	ln(land used)	Hired workers=1	ln(expend. in hired workers)
	Y	T	L^h	L^h
	(1)	(2)	(3)	(4)
A. Coast				
Average DD	0.146**	-0.004	0.029***	0.094
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Results - Hired labour

Table 4: Effect of temperature on total output and input use

	ln(output)	ln(land used)	Hired workers=1	ln(expend. in hired workers)
	Y	T	L^h	L^h
	(1)	(2)	(3)	(4)
A. Coast				
Average DD	0.146**	-0.004	0.029***	0.094
	(0.062)	(0.013)	(0.010)	(0.085)
Average HDD	-0.174**	0.021	$\boxed{-0.028^{***}}$	$\boxed{0.002}$
	(0.071)	(0.013)	$\boxed{(0.009)}$	$\boxed{(0.052)}$
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	(0.010)	(0.007)	(0.003)	(0.010)
Average HDD	-0.046	0.073**	$\boxed{0.018}$	$\boxed{-0.135^{*}}$
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Notes: Robust standard errors in parentheses. Standard errors are clustered at district level. * denotes significant at 10%, ** significant at 5% and *** significant at 1%. All regressions include district and growing season fixed effects, average precipitation and its square, and same household and soil controls as column 1 in Table 3.

Results - Explained by subsistence farmers

Table 5: Effect of temperature on land and domestic labor, by subsistence level

	Using extreme poverty			Using basic unmet needs		
	ln(land used)	ln(hours agric. work)	Child labor=1	ln(land used)	ln(hours agric. work)	Child labor=1
	T	L^d	L^d	T	L^d	L^d
	(1)	(2)	(3)	(4)	(5)	(6)
A. Subsistence farmers						
Average DD	-0.010	-0.004	-0.020*	-0.008	-0.016*	-0.020**
	(0.009)	(0.009)	(0.012)	(0.008)	(0.008)	(0.009)
Average HDD	0.150*	0.120	0.197*	0.097*	0.067	0.063
	(0.080)	(0.077)	(0.101)	(0.050)	(0.052)	(0.056)
Observations	9,783	9,783	9,783	17,946	17,946	17,946
R-squared	0.382	0.251	0.235	0.377	0.225	0.208
B. Non-subsistence farmers						
Average DD	-0.006	-0.024***	-0.014***	-0.009	-0.027***	-0.018***
	(0.007)	(0.007)	(0.005)	(0.006)	(0.007)	(0.006)
Average HDD	0.056	0.011	0.016	0.032	-0.002	0.043
	(0.036)	(0.042)	(0.029)	(0.039)	(0.051)	(0.036)
Observations	37,173	37,173	37,173	29,023	29,023	29,023
R-squared	0.331	0.220	0.184	0.326	0.240	0.209

Other Results

- Household in the highlands expand production into woods (areas covered in bushes, etc)
- Production of cereals is replaced by tubers
- Evidence of botanical impact rather than input productivity (analysis by month)

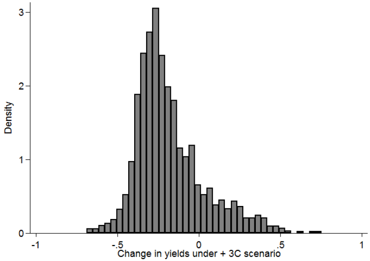
Climate Change Simulations

- Climate change scenarios are contingent on assumptions about behavioral change (e.g. fossil fuel emissions).
- While economic theory suggests that farming technologies are more flexible in the long run, allowing for adaptation, researchers failed to find evidence, e.g. Burke and Emerick (2016), Guiteras (2009)
- Using different emission scenarios from The Intergovernmental Panel on Climate Change, it is estimated that Peru's average temperatures would increase between 1.5 and 3 $^{\circ}$C

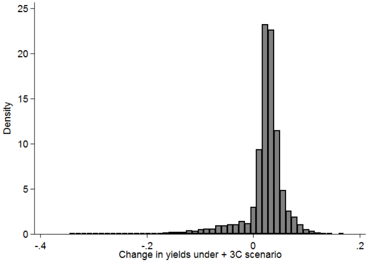
We distribute additional degrees uniformly and use our estimations to compute differences in yields

Distribution of Impacts - 3°C scenario

: Coast



: Highlands



Substantial damages in the coast, while highlands would benefit from higher temperatures

Conclusion

- We confirm the non-linear relationship between temperature and agricultural yields in a sample of Peruvian farmers.
- The threshold at which temperatures become detrimental is different by region
- Effect via agricultural TFP and regions react differently to it
- Subsistence farmers (mostly in the Highlands) increase land use to compensate for lower productivity and domestic labour, and manage to avoid a drop in output.
- Heterogeneous results by region of climate change scenarios highlight strong redistributional effects

Temperature Function: Degree-Days

Piecewise linear function of daily temperature τ_t

$$DD_t = \begin{cases} 0 & \text{if } \tau_t < 8^\circ\mathrm{C} \\ \tau_t - 8 & \text{if } 8 < \tau_t \leq \tau_{High} \\ \tau_{High} - 8 & \text{if } \tau_{High} < \tau_t \end{cases}$$

And:

$$HDD_t = \begin{cases} 0 & \text{if } \tau_t \leq \tau_{High} \\ \tau_t - \tau_{High} & \text{if } \tau_{High} < \tau_t < 40 \\ 40 - \tau_{High} & \text{if } 40 < \tau_t \end{cases}$$

- Threshold temperature τ_{High} will be estimated from data

Back