Global warming and aerosol pollution have reduced wheat yields in India

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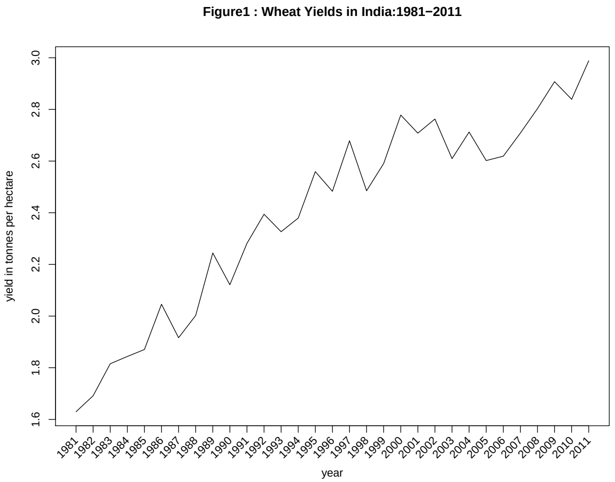
Introduction

- With annual production in 2013 greater than 95 million tonnes, wheat is India's second-largest crop.
- India is the world's second-largest producer of wheat and accounts for 13% of global wheat supply.
- During our study period 1981-2009, the yield of wheat in India approximately doubled.

Figure: All-India wheat yield, 1981-2011



Introduction

- So when we say that global warming and pollution lowered yields, we mean that they lowered yields below what yields *would have been* had warming and pollution not occurred.
- Crop-modeling studies by agricultural scientists indicate that high temperatures are harmful for wheat yield.
- However, these may not give reliable estimates of the size of the effects on farmers' fields where growing conditions are far from optimal.

Introduction

- We use observed yield data from all major wheat-growing districts of India over the period 1981-2009.
- The method used to examine the effect of temperature and aerosol pollution on wheat yields is multiple regression analysis.
- We use a model with district fixed effects and a time trend.

Findings from the Regression Models

- Estimates from models with district fixed effects and time trends indicates that a 1°C increase in average daily maximum and minimum temperature tends to lower yields by 2-3% each.
- Solar radiation has a nearly one-for-one positive effect on yields.

Implications of reducing Aerosol Pollution

- By decreasing aerosol pollution, we can increase the amount of solar radiation reaching the earth's surface.
- Our regression results signal that this pollution reduction may have benefits for wheat productivity.
- However an increase in solar radiation would also lead to an increase in maximum temperature that would lower yield.
- And the reduction in aerosol pollution would also lead to more radiation escaping the ground during the night. This lowers minimum temperature that would raise yield.
- Taking all these indirect influences into account we estimate that a one-standard-deviation decrease in AOD would lead to an increase in yield of about 4-5%.

Further Findings

- The maximum and minimum temperature during the wheat-growing season have increased by 0.7°C and 1°C respectively over the period 1981-2009.
- Applying the results of the regression model we calculate that wheat yields in India would have been higher in 2009 by 4.8% (95% CI: [2.4, 7.4]) if this temperature increase had not occurred.

Study area

- States of Punjab, Haryana, Uttar Pradesh, Uttarakhand, Bihar, Rajasthan, Madhya Pradesh, Maharashtra and Gujarat.
- Merged new districts into their ‘parent’ (1981) districts in order to have a balanced panel so that within-district variation is preserved.
- Variables are area-weighted averages of the new districts comprising a parent district.

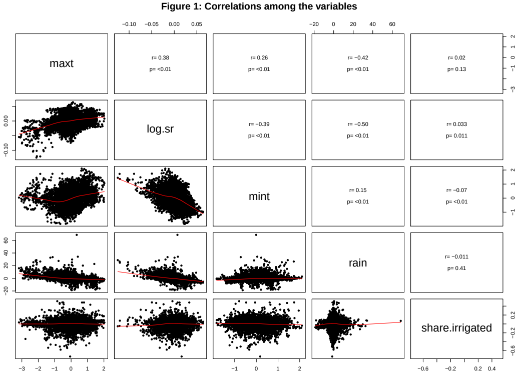
Data

- The original sources for district-level data on agricultural outcomes are state governments' agriculture departments' data. We obtained them mainly from the CMIE database and from the central Ministry of Agriculture.
- Daily gridded ($1^\circ \times 1^\circ$) resolution data on temperature and rainfall were obtained from the Indian Meteorological Department (IMD).
- Daily-level reanalysis data on surface solar radiation are from the MERRA database at the ($2/3^\circ \times 1/2^\circ$) resolution.
- Daily gridded ($1^\circ \times 1^\circ$) resolution data on Aerosol Optical Depth (AOD) was obtained from the GIOVANNI database (for 2000-2013).

Data

- Constructed the area-weighted average temperature, rainfall and solar radiation of all the grid cells intersecting a 1981 district.
- Daily temperature and solar radiation variables were averaged over the growing season in each year.
- Rainfall summed over the growing season in each year.
- The growing season varies from state to state beginning a little earlier in North-West India.
- Data on dates of growing season was obtained from crop calendars published by IMD.

Figure: Correlations among the variables



Notes: Correlations were calculated using residual variation in the variables after removing the influence of district fixed effects and overall linear time trend. Number of observations = 5920. P values are listed below the correlation coefficients.

	Dependent Var-log of yield of wheat in tonnes/hectare			
	(1)	(2)	(3)	(4)
MaxT	-0.02624***	-0.02262***	-0.02558***	-0.02132***
	(0.009)	(0.008)	(0.009)	(0.008)
log_SR	0.95265**	0.82854**	0.71138*	0.63683
	(0.427)	(0.405)	(0.425)	(0.422)
MinT	-0.02933**	-0.01958	-0.03410***	-0.02081*
	(0.013)	(0.012)	(0.013)	(0.012)
Rain	0.00096	0.00090	0.00005	0.00009
	(0.001)	(0.001)	(0.001)	(0.001)
Share_Irrigated	0.37459***	0.33424***	0.44760***	0.36370***
	(0.055)	(0.053)	(0.056)	(0.054)
Linear Trend	Yes	No	No	No
Quadratic Trend	No	Yes	No	No
Linear Trend by State	No	No	Yes	No
Quadratic Trend by State	No	No	No	Yes
Observations	5,920	5,920	5,920	5,920
R-squared	0.947	0.950	0.949	0.952

	Dependent Var-log of yield of wheat in tonnes per hectare				
	MaxT only	add MinT	add log_SR	add Rain	add Share_Irrigatec
MaxT	-0.02346**	-0.01376	-0.02516***	-0.02332**	-0.02624***
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
MinT		-0.04999***	-0.03480***	-0.03550***	-0.02933**
		(0.013)	(0.013)	(0.013)	(0.013)
log_SR			0.84227*	0.92101**	0.95265**
			(0.433)	(0.444)	(0.427)
Rain				0.00113	0.00096
				(0.001)	(0.001)
Share_Irrigated					0.37459***
					(0.055)
Linear Trend	Yes	Yes	Yes	Yes	Yes
District Fixed Effects	Yes	Yes	Yes	Yes	Yes
Observations	5,920	5,920	5,920	5,920	5,920
R-squared	0.944	0.945	0.945	0.945	0.948

- Omitting Solar radiation halves the coefficient on MaxT.
- Omitting Solar radiation increases the coefficient on MinT.
- Lobell et. al. (2011) used country level data for the period 1980-2008 and found that wheat yields in India declined by 9% in response to a 1° increase in daily maximum temperature.
- The authors' do not control for solar radiation an important confounder.
- Given solar's radiation positive correlation with maximum temperature, the above effect is an underestimate of the true effect of temperature on yields.
- This high estimate of India from the country-level data may be because Indian wheat is largely irrigated and is grown at relatively higher temperatures.

Burney et. al. (2014)

- State-level data from the 9 wheat-growing states were used to examine the effect of weather and pollution variables on wheat yields.
- However, owing to the small number of states, estimates in this study are imprecise.
- Further, the study does not report correcting standard errors for the temporal and spatial correlation.
- This renders the estimates even less precise.

Total effect of reducing pollution on yields

- Let y denote log yield

$$\frac{dy}{dAOD} = \frac{\partial y}{\partial log\_SR}\frac{\partial log\_SR}{\partial AOD} + \frac{\partial y}{\partial Maxt}\frac{\partial Maxt}{\partial AOD} + \frac{\partial y}{\partial Mint}\frac{\partial Mint}{\partial AOD}$$

- The partial derivative involving the yield variables are obtained from the regression of yield on log_SR, Maxt and Mint.
- The partial derivative with respect to AOD are obtained from regressions of log_SR, Maxt and Mint on AOD

Regressions with AOD as the independent variable

- Data on daily gridded AOD is available only from the year 2000 onwards so the period of this analysis is 2000-2013.
- We regressed MaxT and MinT and log(SR) on AOD with grid fixed effects and a quadratic day of the season trend and year fixed effects.
- Results imply
- $\frac{\partial log\_SR}{\partial AOD} = -0.17$ [$s.e. = 0.003$]
- $\frac{\partial Maxt}{\partial AOD} = -1.17$ [$s.e. = 0.08$]
- $\frac{\partial Mint}{\partial AOD} = 1.87$ [$s.e. = 0.07$]

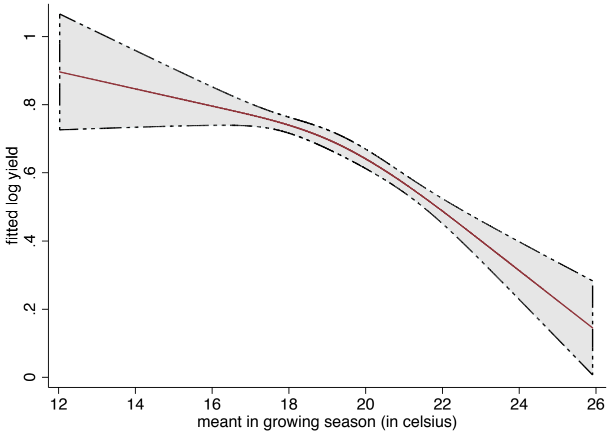
Regressions with AOD as the independent variable

- Combining these effects of AOD on $MaxT$, $MinT$, and $ln(SR)$, with their effects on yield, the total effect of a one-unit change in AOD on ln(yield) was calculated to be -0.18 with a 95% C.I of [-0.31 -0.05].
- Since the standard deviation of AOD in the data is 0.24, this translates into an increase in yields close to 4% for a one S.D decrease in AOD.
- This is a large effect.

Alternative Models

- MeanT was also modelled using restricted cubic splines to allow for a non-linear effect of temperature on yield.

Figure: log yield as a restricted cubic spline of daily mean temperature



- The spline model indicates that the negative impact of temperature on yields is higher at higher temperatures.
- This is consistent with experimental studies that find that temperature increases are more harmful for wheat productivity at higher temperatures.

Table: Results of Weather Variables Effect on Wheat Yields Controlling for Year Fixed Effects

	Dependent Var-log of yield of wheat in tonnes per hectare
	Year Fixed Effect
	(1)
MaxT	-0.04547***
	(0.014)
log_SR	0.61384
	(0.492)
MinT	-0.01105
	(0.014)
Rain	0.00165
	(0.001)
Share_Irrigated	0.34772***
	(0.048)
District Fixed Effects	Yes
Observations	5,920
R-squared	0.953

The impact of past climate change on current yields

- Temperature has trended over the period 1981-2009.
- Question of interest is how wheat growth would have evolved without this trend.
- MinT and MaxT were detrended as follows

- T^*_{it}=predicted temp for district i at year t based on a regression of temp on a linear time trend.
- T^d_{it} = detrended temp=$T_{it} - T^*_{it} + T^*_{i,1980}$

The impact of past climate change on current yields

- By the end of the period the production weighted maximum and minimum temperature in the wheat growing season increased by 0.7°C and 1°C.
- We compute the difference between predicted yields with observed weather and predicted yields with detrended weather.
- Predicted yields were calculated using the parameters from the linear model with district fixed effects and linear time trend.

The impact of past climate change on current yields

- To arrive, at the national effect, a production weighted average of these differences was taken.
- The combined effect of the trend in MaxT and MinT was to reduce wheat yields by 4.8% with a 95% confidence interval of $[-7.2, -2.4]$.

Caveats of the analysis

- Days with maximum temperature exceeding 33°C are not present in the data.
- If days with temperatures exceeding this bound are expected to occur with climate change then the estimated parameter of the impact of Maxt can no longer be applied to infer about the effect of such hot days on wheat yields.

Conclusion

- Global warming over the period 1981-2009 has reduced wheat yields.
- Reductions in aerosol pollution that decrease solar dimming appear to raise yields.
- Finding about the potential gains from pollution has to be qualified by somewhat smaller and noisier estimates that result when the linear trend is replaced by the quadratic trend
- Our preferred specification is the linear model as it preserves the most variation in the data and results indicate that models with quadratic trend are probably not required for identification