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IMPACT OF CLIMATE CHANGE ON THE INDIAN ECONOMY: EVIDENCE FROM FOOD GRAIN YIELDS

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We analyse the effects of rainfall and temperature on yields of paddy and millets (pearl millet and sorghum) in India for the period 1966–1999, at the district level. Unlike other studies, we control for fertiliser use and irrigation. We find that paddy (India's leading food crop) is sensitive to the climate variables but also to fertiliser use and irrigation. Millets are less affected by climate variables although sorghum shows some sensitivity to temperature. Our results have important implications for how India's agriculture will adapt to climate change.

Keywords: Climate change; agricultural impacts; developing countries.

JEL Codes: O13, Q54, R11

1. Introduction

Meteorological data compiled over the past century suggest the earth is warming. In keeping with this, for India as a whole, mean annual temperature shows a significant warming trend of 0.51°C per 100 years during the period 1901–2007 (Kothawale *et al.*, 2010). Similarly, global projections of temperature and for precipitation augur a warmer and wetter world, on average. Simulations with regional climate models

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(RCM) project similar trends for both variables for India — by 2030s annual mean temperatures and summer monsoon rainfall are both expected to increase on average (GoI, 2010). But for a country of sub-continental proportions there are, as expected, significant regional variations in past and future trends. Both these facts have significant implications for the Indian economy in terms of the impact of climate change and also its regional incidence.

This is particularly true for the agricultural sector where climate is a direct input into production. While the salience of this sector in India has declined over the years, it still remains important in the socio-economic fabric of the country. Though agriculture alone (other than forestry and fisheries) accounts for only about 15% of GDP, it still employs 55% of the workforce. Moreover, according to the 2011 census, 69% of the population (which is growing) remains rural and intimately connected to this sector. There are also important forward and backward linkages to agriculture from the rest of the economy.

Our primary interest in this sector, however, is from the perspective of poverty which remains widespread despite significant progress in reducing it — the country is still estimated to have one-third of the world's poor. According to some estimates, 32.7% of the population is below the international poverty line of US$ 1.25 per day (PPP) while 68.7% live on less than US$ 2 per day (World Bank, 2010).[1] A key aspect of poverty is its incidence which is rural and concentrated among agricultural labor. Thus, according to the Indian Planning Commission, in the year 2009–2010 more than one in three of the rural population was poor (33.8%) whereas the figure for urban areas was about one in five (20.9%). Equally important for our analysis, nearly 50% of agricultural laborers were below the poverty line in rural areas (GoI, 2012).

Within agriculture, we focus on three key food crops, namely, rice and pearl millet (*bajra*) and sorghum (*jowar*). Using district level panel data on annual yields (output per unit hectare), inputs, and climate variables for 1966–1999, we find significant impacts of rainfall and temperature on yields of these crops.

Our methodology is based on estimating an agricultural production function with exogenous climate variables, namely, precipitation, and temperature. Thus, we eschew crop simulation approaches that rely on experimental data.[2] We do not also estimate reduced form relationships between economic variables such as profits or the monetary value of yield and various forms of weather measures.

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[1] The definition and measurement of poverty in India is controversial and politically charged and somewhat of an obsession with Indian economists. We do not enter into this area other than providing illustrative numbers for purposes of our argument.

[2] This approach is interestingly referred to as "production function" approach *a la* Deschênes and Greenstone (2007) and Guiteras (2009). A comprehensive discussion of the pros and cons of this approach is found in Schlenker and Roberts (2009). For examples of the hedonic approach (also known as the Ricardian approach) which focuses on variations in land prices or profits see the seminal paper by Mendelsohn *et al.* (1994). This paper has spawned an extensive literature across several countries. Early applications of the Ricardian approach to India are Dinar *et al.* (1998) and Kumar and Parikh (2001). A recent application to Africa (Ethiopia) is Deressa and Hassan (2009).

Our focus on rice and millets is deliberate. The former is the most important cereal food crop in India accounting for 23.3% of gross cropped area and about 43% of total food grain production as well as 46% of cereal production (Singh, 2009). In economic terms, rice (including paddy) was ranked highest by value among all agricultural products in India with a total output of about $38.4 billion in 2010 (FAO, 2011a). India is considered to be one of the original centers of rice cultivation covering 44 million hectares. Its rice harvesting area is the largest in the world. Around 65% of the total population in India eats rice and it provides the main source of income and employment for more than 50 million households (IRRI).

From our perspective of rural poverty in particular, we note rice (actually paddy)[3] as cultivated in most parts of India, is a highly labor-intensive crop. Also, much of this labor especially during sowing and transplanting is provided by women. Thus, there is an important gender dimension as well (FAO, 2004, 2011b).[4]

Millets on the other hand are traditional "coarse cereals" whose importance is more in terms of their role as a staple crop consumed by the poor.[5] In terms of food grain production, millets ranked fourth in India behind rice, wheat and maize (FAO, 2011a)[6] Within millets we concentrate on the two key varieties, namely, pearl millet (*bajra*) and sorghum (*jowar*). Post Green Revolution, millets have lost ground to other food crops, especially wheat and rice — the production of millets has more or less remained constant between 1966–2006, whereas that of rice and wheat has increased by 125% and 285%, respectively (MNI, 2009).

Table A.1 provides normal (averaged over 2005–2006 to 2009–2010) area, production and yield of food crops in India. As the table shows, rice and wheat now account for more than three fourths of food grain output in India with "coarse cereals" contributing only about one sixth (16%). But, as late as 1970, the picture was quite different — the contribution to food grain output of rice, wheat and "coarse cereals" in 1970–1971 was respectively, 39%, 22%, and 28.2%. As we discuss later and anticipating our empirical results, this has important policy implications *vis-à-vis* climate change — we find millets in particular to be much less sensitive to temperature and rainfall than rice and by corollary more climate resilient.

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[3] Paddy (*Oryza sativa*) is the rice grain with husk (which is also known as rice hull). In this paper, rice cultivation actually refers to paddy. Paddy becomes rice after the removal of husk by threshing. In 2010, India produced approx. 143 million tons of paddy and about 95 million tons of rice (FAO, 2012). Rice husk is mainly used as fuel in boilers in rice mills.

[4] Conversely, in Asia (and in sub-Saharan Africa), women who are employed are more likely to be employed in agriculture than in other sectors — almost 70% of employed women in Southern Asia work in agriculture (FAO, 2011b)

[5] In India, "coarse cereals" (a loaded and highly normative term) comprise millets, barley and maize (Table A.1). Millets in turn primarily comprise pearl millet (*bajra*) and sorghum (*jowar*) which dominate in area and production. This is followed by finger millet (*ragi*) and small millets. *Bajra*, *jowar* and maize together account for over 90% each of area and production of 'coarse cereals' in India (Table A.1).

[6] This was a distant fourth rank, however — production of these four crops in 2010 was, respectively, 95, 81, 14.1 and 13.3 million tons (FAO, 2011a). By value too, millet output was about $2.3 billion for the same year (compared to $38.4 billion for rice).

Again, from a poverty perspective both rice and millets are largely grown by small and marginal farmers (i.e., those with holdings less than 2 hectares) and with much less irrigation as compared to wheat which is almost entirely irrigated and cultivated by relatively bigger farmers. Table A.2 shows 57% of area under rice is cultivated by marginal and small farmers compared to 44% for wheat. At the other end of the spectrum, large wheat farmers (holdings of 10 hectares or more) account for more than 10% of the area under their crop compared to similar large rice farmers who account for only about 5.5% of the area under rice. Finally, 90% of area under wheat is irrigated compared to 59% for rice and only 29% for other cereals (coarse cereals).

The plan of the paper is as follows. The following section provides the context in terms of projected trends and regional variation in climate variables (rainfall and temperature) for India. It also provides further details on how, when and where our three crops are grown in the country and the potential role of climate variables. Section 3 presents our conceptual framework and situates it in the literature on the impact of climate on agriculture, particularly with regard to India. Section 4 describes the data and econometric methodology. Section 5 presents and interprets the results of our analysis. Section 6 concludes the paper.

2. Climate Change and Agriculture in India

2.1. *Trends and regional variation in climate variables*

India's climate system has unique features. It is dominated by the summer or Southwest monsoon (and to a lesser extent the winter or Northeast monsoon) and by the country's physiological features such as the Western and Eastern Ghats, the central plateau and the Himalayas. The summer monsoon and the rains that it brings are a major weather phenomenon in the Indian subcontinent and deeply influences the lives of its inhabitants. It is a four-month period (June–September) when massive convective thunderstorms dominate India's weather, and is the Earth's most productive wet season (Collier and Webb, 2002). This season provides over 80% of India's rainfall (Bagla, 2006, 2012). Thus the quantity, temporal and spatial distribution of the precipitation (rainfall) accompanying the monsoon is its most monitored component and is particularly important for agriculture. The summer monsoon is also the most economically important weather pattern to the extent that then Indian Finance Minister (Pranab Mukherjee) called it "the real finance minister" (*Hindustan Times*, 2010). More recently, the Governor of India's central bank (Reserve Bank of India or RBI) was also quoted as saying "(A)nd most importantly we also chase monsoon like millions of farmers across the country. So, the monsoon outlook, the monsoon performance is going to be the important factor in determining the RBI policy in the next three months" (Economic Times, 2013). Yet the Indian monsoon is "only partially understood and notoriously difficult to predict" (Wikipedia, 2012).

Though the dependence of agriculture on the summer monsoon has reduced somewhat lately due to increased irrigation and better drought management, Fig. A.1

shows clearly how the two have marched in lockstep. This is not surprising since, out of the total net sown area of 141.0 million hectares (Mha) in India, rain-fed area accounts for 85.0 Mha spreadover 177 districts. This constitutes approximately 60% of the total farming area in the country. Rain-fed agriculture contributes 44% of the total food grain production of the country and produces 75% of pulses and more than 90% of sorghum, millet and groundnut from arid and semi-arid regions. Even after half a century of lopsided policies that have focused on pockets of the country and specific crops, rain-fed regions provide livelihood to nearly 50% of the total rural workforce and sustain 60% of cattle population of the country (MNI *et al.*, 2009).

Keeping in view the peculiarities of India's climate and of the summer monsoon in particular, in a recent exercise a RCM with 50 km resolution, namely, PRECIS was deployed to dynamically downscale global model simulations and superimpose regional details from India (GoI, 2010). This exercise coupled with long instrumental records allows us to capture past trends and also make projections for key climate variables such as temperature and rainfall within the country at a disaggregated level.

As mentioned earlier, for India as a whole, mean annual temperature shows a significant warming trend of 0.51°C per 100 years during the period 1901–2007 (Kothawale *et al.*, 2010). More important, accelerated warming has been observed in the last approximately 40 years (1971–2007), mainly due to intense warming in the recent decade 1998–2007.[7] Increases in the mean have been accompanied by a rise in both maximum and minimum temperatures at the all India level — by 0.71 and 0.27°C, respectively, per 100 years during the period 1901–2007. Also, as with mean temperature, there has been acceleration in trends of both maximum and minimum temperatures during 1971–2007. At the regional level, the homogenous regions[8] of East coast, West coast and the peninsula show an increasing trend in the frequency[9] of hot days but Northern India (North of 22° N) does not. With respect to the frequency of cold days, however, all seven homogenous regions show a decreasing trend (in the frequency of cold days).

With regard to precipitation, Indian monsoon rainfall from 1871–2009 shows only a slight negative trend. But there is significant spatial variation in these trends over this period. Also, there is an increase in extreme rainfall events and their intensities (GoI, 2010; Sen Roy and Balling, 2004).

Projections for climate in the medium-run for India seem to indicate it will be warmer and wetter but with significant regional variation. Overall there will be (i) an increase in average surface temperature by 2–4°C, (ii) changes in the distribution of rainfall (inter-temporal and spatial) during both monsoon and non-monsoon months, (iii) decrease in the number of rainy days by more than 15 days, (iv) an increase in the

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[7] All four major Indian seasons, namely, summer/pre-monsoon, monsoon, post-monsoon and winter contribute to this trend. But the increase in winter and post-monsoon temperatures is most marked — by 0.80°C and 0.82°C, respectively over the last hundred years (GoI, 2010). This has significant implications for rice yields as noted below.

[8] A uniform or homogenous region is an area in which everyone shares in one or more distinctive characteristics, in this case climate.

[9] Defined as days per decade.

intensity of rainfall by 1–4mm/day, and (v) an increase in the frequency and intensity of cyclonic storms (Ranuzzi and Srivastava, 2012).

2.2. *Rice and millets in India: key issues*

Rice is the most important food crop in India.[10] It accounts for 23.3% of gross cropped area and 43% of total food grain production as well as 46% of cereal production (Singh, 2009). In economic terms, rice (including paddy) was ranked highest by value among all agricultural products in India with a total output of about $38.4 billion in 2010 (FAO, 2011a). The production of rice alone has more than quadrupled from around 21 million tons in 1950 to 95 million tons in 2010.

There are three seasons for growing rice in India — autumn (pre-*kharif*), winter (*kharif*) and summer (*rabi*) — named according to the season of harvest (though all crops are not grown in all regions). Winter or *kharif* rice (sown during June–July and harvested in November–December) is the main growing season and accounts for 84% of the country's rice crop.[11] This is followed by summer rice (sown during November–February and harvested in March–June) at 9% and autumn rice (sown during May–August and harvested in September–October) which accounts for 7% of the rice crop.

Among millets, pearl millet (*bajra*) is the most widely grown type of millet followed by sorghum (*jowar*).[12] Because of their tolerance to difficult growing conditions such as drought, low soil fertility and high temperature, they can be grown in areas where other cereal crops, such as maize or wheat would not survive (Basavaraj *et al.*, 2010). Pearl millet in India is grown as a single season crop. Cultivation predominantly takes place on marginal lands and un-irrigated lands. It is also grown in a small area as summer crop under irrigation particularly in the Northwestern states of India mainly as a fodder crop. Area trends of pearl millet in India are constantly declining. Between 1972–1973 and 2004–2005, nearly 3 million hectares has been diverted from pearl millet cultivation to other crops. Pearl millet production is concentrated in Gujarat, Maharashtra, and Rajasthan which account for 70% of production in India. These states also have the highest concentration of pearl millet consumers since bulk of the consumption for food use takes place in the areas where it is grown.

3. Framework and Relevant Literature

Our methodology is based on estimating an agricultural production function with exogenous climate variables, namely, precipitation and temperature. Our analysis is at the district level using a panel dataset for physical yield (output divided by gross cropped area) for rice and pearl millet.

Several studies have looked at the impact of climate-related variables on crop yields specifically for India. Lahiri and Roy (1985) (LR) look at the supply response of rice

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[10] This discussion is based on Singh (2009).

[11] As can be noted, sowing and transplanting of winter rice is during the summer monsoon (June–September).

[12] This discussion is based on Basavaraj *et al.* (2010).

yields at the all-India level and also include monthly rainfall (either in the sowing season or in the growing season). The paper is in the agricultural economics tradition of acreage and yield response to price (and also to "supply shifters" such as rainfall) and models this response in a Nerlovian partial adjustment framework (for which they actually do not find evidence). Lahiri and Roy postulate a gamma distribution for the effect of rainfall on yield (right skewed and bounded at zero), i.e., less rainfall (droughts) is worse than too much (floods). For yield, they find the optimal monthly average rainfall is about 293mm for the months of July and August. They also argue that with the spread of HYVs post-mid 1960s (1965 onwards) Indian agriculture has become more rainfall-dependent, especially since water requirement has gone up and the spread of irrigation has not kept pace with it.

Kanwar (2006) extends this line of research to several food grains. He looks at supply response using a state-level panel dataset and again finds rainfall matters considerably for supply response (it's a "supply shifter").[13] Also using state-level panel data, Auffhammer *et al.* (2012) extend Auffhammer *et al.* (2006) and explicitly look at the impact of too little/too much rainfall (akin to gamma rainfall) on rice yields. Whereas their earlier work looked at crop output (with area as an explanatory variable) the latter paper looks at yield per hectare. They too find significant climate impacts.

A problem with state- or national-level analysis is the need to aggregate rainfall and other weather data (there are several observation stations in a state) to one value at the state- or national-level. This is problematic since several Indian states are large, often bigger than countries in Europe and elsewhere.[14] Given the variation in rainfall and other weather variables for a state, the resulting measurement error may bias the coefficients on weather variables downward (Auffhammer *et al.*, 2012). Moreover, our paper is more comprehensive in its scope, since it looks at the impact of both temperature and rainfall on yields, at the district-level.

As in this paper, district-level panel data for India has been used in this context by several other studies starting with Dinar *et al.* (1998), Kumar and Parikh (2001), Sanghi and Mendelsohn (2008), Kumar (2009), Guiteras (2009), and recently by Fishman (2011) and Krishnamurthy (2012). The first four are variants of the Ricardian approach in that they estimate the impact of climatic variables on net agricultural revenues per unit area at the district level. For instance, Kumar and Parikh (2001) and Kumar (2009) estimate the impact of climate change on net agricultural revenue per hectare (revenue minus cost of labor and fertilizer, normalized by area).[15] For various reasons, they use

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[13] "In other words, rainfall is the single most important factor determining supply response even today. Despite decades of massive irrigation schemes, the food crops continue to be rainfall-dependent." (Basavaraj *et al.*, 2010, p. 80)

[14] For instance, the five biggest states of India, namely, Rajasthan, Madhya Pradesh (MP), Maharashtra, Andhra Pradesh (AP) and Uttar Pradesh (UP) range from 342,000 sq km to 241,000 sq km. The biggest state, Rajasthan, is almost as big as Germany, whereas the next two (MP and Maharashtra) are almost the size of Poland and bigger than Italy and the Philippines each. Andhra Pradesh and Uttar Pradesh, respectively are bigger than or the same size as United Kingdom.

[15] Kumar (2009), *inter alia*, extends the temporal coverage of the dataset used in the earlier study using the same methodology.

net revenue instead of land prices as is the norm for the Ricardian approach. This is not sufficient to distinguish between the responses of different crops to climate change, which our paper manages to capture. While both papers use district-level data to measure the impact of temperature and rainfall changes, the dependent variable and the controls are different. Our paper controls for fertilizer and irrigation which are critical inputs in the agricultural process. Kumar and Parikh find that a 2°C temperature rise and 7% increase in rainfall would lead to almost 8% loss in farm level net revenue (much lower than what agronomic studies predict since they do not account for adaptation). Using a similar approach to Kumar and Parikh (2001), Sanghi and Mendelsohn (2008) find that agricultural net revenue in India may fall by 12% in (and more broadly within an interval of 4% to 26%). Our paper finds a positive effect of higher rainfall, on all three crops, while the effect of temperature differs from crop to crop. The results may differ due to the difference in approaches adopted.

Among more recent studies, a well cited one by Guiteras (2009) examines the impact of temperature and rainfall on combined yield (in money terms) for five major food and one cash crop, namely, rice, wheat, jowar, bajra, maize, and sugarcane. The precipitation variables have been defined both as total monthly rainfall (for the growing season months of June–September), as well as total growing season rainfall. For defining the temperature variable, he adopts two approaches: the first is "degree-days", where it is acknowledged that crops do not absorb heat below a temperature of 8°C, and then absorb heat linearly till a threshold of 32°C. This captures the cumulative heat exposure of the crop. The second method he adopts is useful in capturing nonlinear temperature effects. He counts the number of growing season days in each 1°C interval, and includes these totals as separate regressors.

Guiteras finds climate change could reduce yields by 4.5% to 9% in the medium-run (2010–2039) and by as much as 25% in the long-run (2070–2099) in the absence of long-run adaptation. The main drawback of Guiteras as highlighted by Sarker *et al.* (2012) and by Krishnamurthy (2012) is combining different crops which are impacted differently by climate change. The dependent variable is akin to district income (from six crops)[16] normalizedby area to arrive at gross revenue per hectare, and is difficult to interpret.

Fishman (2011) also uses a district-level panel and shows the impact of intra-seasonal variability of rainfall on yields. By using daily-level data on weather, irrigation and crop yields for some of the main crops (rice, wheat, maize, barley, groundnuts, sorghum, pearl millet, pigeon pea, chickpea, cotton and sugarcane) from districts over four decades, the paper aims to capture the adaptation, by means of expansion of irrigation, to climate change. Precipitation is incorporated into the model in different ways — total monsoon rainfall (in the months of June–September), monthly rainfall for each of the four months, frequency of rainy days (precipitation over 0.1 mm), duration of the longest dry spell, and the shape parameter of the gamma distribution fitted to the

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[16] As stated by Guiteras (2009) "these comprise roughly 75% of total revenues." (p. 9 footnote 6).

distribution of daily rainfall. Temperature has been introduced in the form of "growing season degree-days", which is a measure of heat exposure used to predict crop yield.

Fishman finds that irrigated yields tend to be higher than purely rain-fed yields, and that irrigation acts as an effective buffer against the irregularities of rainfall, especially for the rainy-season crops. Irrigation, however, is not useful in protecting yields against higher temperatures which limits its efficacy as an adaptation mechanism.[17] Fishman only uses irrigation as a control, whereas we also control for fertilizer consumption.

Krishnamurthy (2012) also uses a panel data quantile regression methodology to estimate the impact of climate change on yields of rice and wheat. He suggests that both the Ricardian and panel data approaches used to study the impact of climate change on agriculture are inadequate, because they assume that the covariates (weather variables, agricultural controls, etc.) only affect the mean yield, and not the conditional distribution of the yield, i.e., only the mean agricultural outcomes changes, with no changes in the underlying relationship between the outcomes and the climatic variables. In the paper, he regresses yield on temperature (measured in growing season degree-days *a la* Guiteras) and seasonal and monthly rainfall, for every quantile of the population (like Fishman, only a control for irrigation is used). This methodology is useful to estimate other features of the conditional distribution, other than the mean. The results reveal a significant decline in the yield of wheat across quantiles, while for rice, a moderate decline is seen in the most productive areas, and in the other areas the effects of warming lead to a slight increase in yield.

4. Data and Methodology

4.1. *Data sources*

4.1.1. *Agricultural data*

The data on the agricultural variables span the time period 1966–1999, and have been collected from the ICRISAT VDSA (Village Dynamics in South Asia) Apportioned Meso database. This is a district-level database that includes information on cultivated area, production and area irrigated for different crops, land use, farm harvest prices, rainfall, livestock and agricultural implements, operational holdings, and population census data for 19 states of the country. The boundaries of the districts included in this database are defined as of 1966, i.e., any data on districts that were created after 1966 are given "back" to the parent districts from which the newer districts were created. The final database thus includes data on the parent districts only, which is inclusive of the data "apportioned" amongst the districts created later.

The variables of interest in this database include the area under, and production of, rice, pearl millet and sorghum (measured in hectares and tons respectively),

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[17] *Inter alia*, he uses a quadratic time trend $f_s(t)$ which is state specific — it reflects technological progress and productivity gains, which are allowed to differ from state to state because of the large variance in agricultural performance across India.

district-wise consumption of fertilizers (tons of nitrogen, phosphate and potash fertilizers used), total gross cropped area in each district (measured in hectares, and accounting for multiple cropping), and gross irrigated area under each of the three crops (measured in hectares, again accounting for multiple cropping). While the data on the area and production have been compiled into the ICRISAT database from the Statistical Abstracts of India, State Statistical Abstracts and the State Season and Crop reports, the data on fertilizer consumption has been obtained from the Fertilizer Statistics for India. Barring data gaps for a few variables in some districts, the area, input and output-related data is available at an annual frequency for all three crops.

The dependent variable considered is the logarithm of yield (tons of output per hectare), for each of the three crops. The two independent variables created from the list of ICRISAT variables are fertilizer consumption and irrigation. The fertilizer variable was created by dividing district-level fertilizer consumption by the gross cropped area of land devoted to all the crops grown in that district. In the absence of data on crop-specific fertilizer consumption this variable is identical for all three crops. The irrigation variable has been defined as the area irrigated for a particular crop in a district, divided by the gross cropped area (for that particular crop). This variable is useful in capturing the intensity of irrigation in determining the yield of a crop.

4.1.2. *Climate data*

The climatic data has been taken from the India Water Portal (www.indiawaterportal.org) which contains 102 years of district-level data on rainfall, temperature, cloud cover, humidity, ground frost frequency and other variables. The database that is used to compile this meteorological dataset is the publicly available Climate Research Unit (CRU) TS2.1 dataset, out of the Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia in Norwich, UK. This dataset consists of interpolated (on 0.5° latitude-longitude grid) global monthly data on variables such as rainfall and temperature from 1901 to 2002. The CRU data was transformed to the district level by simple linear averaging from the gridded data of the CRU dataset.

Two independent variables have been created using this database, i.e., rainfall and temperature. For all three crops, the rainfall variable has been defined as the natural log of annual rainfall (to account for the fact that the distribution of the annual rainfall variable is positively skewed for all crops).[18] The temperature variable has been defined as the 12-month average of the monthly average temperatures. A quadratic term for temperature has also been included to examine the incremental impact of temperature on the yield of all three crops. Table A.3 provides summary statistics of the main variables used in the analysis.

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[18] Since growing season rainfall accounts for roughly 70% of total annual rainfall in the districts we have considered for rice (the proportion is 73% for pearl millet and 75% for sorghum), we find that the results are not significantly different if growing season rainfall (total rainfall in the months of June, July, August, and September) was used instead of total annual rainfall.

4.2. *Methodology*

The numbers of districts selected for each of the crops are 153 for rice, 80 for pearl millet and 88 for sorghum. These districts cut across the agriculturally-important states of the country (rather than being selected from certain states). For the criteria used in selection of districts, refer to the data appendix. Table A.4 lists the districts considered in each state, for every crop. As previously mentioned, the districts included in the ICRISAT database are those that existed as of 1966. However, the climatic dataset has been created taking into account the district boundaries as of 2002, which are remarkably different from those of 1966. The districts that comprise the panel-sample have been selected on the basis of the districts that existed in the ICRISAT database, and the climatic variables for these districts have been approximated from the district to which the largest area of the parent district was allocated[19] (provided that it is more than 50% of the total area of the parent district) (Kumar and Somanathan, 2009).

In the presence of AR cross-sectional dependence (the outcomes are correlated across districts in a given year), along with heteroscedasticity, FGLS (feasible generalized least squares) with fixed effects was found to be an appropriate method of estimation. However, one of the drawbacks of FGLS estimation is that it produces overly optimistic standard error estimates. Moreover, the estimates are only feasible if $N < T$, i.e., the number of observations are less than the number of time period, which is not the case for any of the three crops. To correct this, panel-corrected standard error (PCSE) estimates are obtained, where the parameters are estimated using a Prais–Winsten (or OLS) regression. Equations have been estimated with district and year fixed effects, district fixed effects and district-by-year fixed effects.

For each of the crops, it was observed that the errors exhibited the presence of heteroscedasticity, and contemporaneous correlation. A Prais–Winsten regression was thus estimated, under two different assumptions on correlation:

(1) Within panels, there is AR (1) autocorrelation and the coefficient of the AR (1) process is common to all of the panels, and
(2) Within panels, there is AR (1) autocorrelation and that the coefficient of the AR (1) process is specific to each panel (i.e., panel-specific AR (1) autocorrelation) (Cameron and Trivedi, 2009)

The regression equation which is estimated for all three crops is as follows:

$$\mathrm{Ln}(\mathrm{YIELD}_{\mathrm{it}}) = \alpha_i + \gamma_t + X'_{\mathrm{it}}\beta + \sum \varepsilon^* f(W_{\mathrm{it}}) + \mu_{\mathrm{it}},$$

where α_i refers to the district-level fixed effects, which are quite useful in capturing unobserved heterogeneity across districts and γ_t refers to the year-specific dummies

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[19] Kumar and Somanathan (2009) give the change in district boundaries across four census periods (1971, 1981, 1991 and 2001).

which control for annual differences in yield, common to all the districts (Deschênes and Greenstone, 2007).[20] The X_{it} refers to the district and year-specific agricultural variables, whereas the W_{it} refers to the climatic variables (namely rainfall and temperature). State and year fixed effects were not estimated, given that the sample size would be too small to run a robust panel-data estimation.

5. Results

5.1. *Rice*

Tables 1 and A.5 give the results of the regression estimation for rice, taking the temperature variable as the 12-month average of the monthly average temperatures, and defining the rainfall variable as the total annual rainfall. Table 1 gives the regression results with district and year fixed effects, while Table A.5 gives the results using panel-specific errors. The results are robust, even if panel-specific AR (1) serial autocorrelation is assumed. The coefficients on the district and year fixed effects have been suppressed.

Table 1 reveals that with district year fixed effects, both the rainfall and maximum temperature variables are found to be significant, even at the 1% level of significance. Higher rainfall leads to higher yield of rice, whereas higher temperatures lower the yield. Interestingly, the coefficient on the quadratic term for temperature is positive: higher temperatures would mean lower yield rates, but higher temperatures have a smaller harmful effect. Both the irrigation and fertilizer consumption variables are highly significant, which is expected given that rice production is highly input-driven in large parts of the country, and the signs are intuitive (higher the proportion of land under rice irrigated, higher is the yield, and higher the fertilizer consumption used for rice, higher is the yield of rice). These results also hold once panel-specific errors are taken into account (Table A.5).

Table 1. Rice with district and year fixed effects.
Number of obs = 5185 R-squared = 0.8154
Wald chi^2 (190) = 28462.47 Prob > chi^2 = 0.0000

Ln yield	Coeff.	Panel corrected std. errors	z	$p > \|z\|$	95% Confidence interval	
Log (rainfall)	0.2115207	0.0200441	10.55	0.000	0.172235	0.250806
Average temperature	−0.6837534	0.2009669	−3.40	0.001	−1.077641	−0.289865
(Average temperature)^2	0.0134426	0.0038944	3.45	0.001	0.0058098	0.021075
Fertiliser	0.0012841	0.0001478	8.69	0.000	0.0009945	0.001574
Irrigation	0.5507108	0.0280250	19.65	0.000	0.4957827	0.605639
Intercept	6.8290360	2.6206870	2.61	0.009	1.692585	11.96549

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[20] Dell *et al.* (2009), Deschênes and Greenstone (2007), and Guiteras (2009) all use the fixed-effects formulation.

Table 2. Pearl millet with district and year fixed effects.
Number of obs = 2656 R-squared = 0.6911
Wald chi^2 (117) = 6396.79 Prob > chi^2 = 0.0000

Ln yield	Coeff.	Panel corrected std. errors	z	$p > \|z\|$	95% Confidence interval	
Log (rainfall)	0.4860142	0.0501995	9.68	0.000	0.3876249	0.5844035
Average Temperature	0.1927766	0.5366864	0.36	0.719	−0.859109	1.244663
Average Temperature^2	−0.0048134	0.0102908	−0.47	0.640	−0.024983	0.0153563
Fertiliser consumption	−0.0000939	0.0005254	−0.18	0.858	−0.001124	0.0009358
Irrigation	0.6060767	0.1354882	4.47	0.000	0.3405247	0.8716286
Intercept	−5.295802	7.051081	−0.75	0.453	−19.11567	8.524062

5.2. *Pearl millet (bajra)*

Tables 2 and A.6 produce similar results for pearl millet as for rice. The errors are assumed to be (serially) independent in this case as well. Table 2 gives the results for district and year fixed effects, while Table A.6 gives results using panel-specific errors. The coefficients on fixed effects have been suppressed.

Table 2 reveals a similar impact of higher rainfall on pearl millet production, as in the case of rice (greater the rainfall, higher the yield). The variable is also found to be highly significant. While the average temperature variable is (highly) insignificant, the sign is positive, suggesting the possible hardiness of *bajra* to increasing temperatures. The sign of the temperature quadratic is negative: higher temperatures are beneficial but have a decreasing beneficial effect with further higher temperatures. It is also highly insignificant. The impact of the fertilizer variable appears to be significantly diluted in the case of pearl millet: it is highly insignificant. Irrigation has a positive (and significant) impact on the yield of *bajra*, just as in the case of rice. Table A.6 gives similar results to Table 2, in terms of the signs and significance of the climactic variables.

5.3. *Sorghum (jowar)*

Tables 3 and A.7 present the results for sorghum, assuming the same dependent variable and climatic variables as for the other two crops. Since there is a lack of serial correlation in the data, the errors are assumed to be independent. Table 3 gives the results for district and year fixed effects, whereas Table A.7 gives results using panel-specific errors. The coefficients on the fixed effects have been suppressed.

According to Table 3, higher rainfall means higher the yield, higher the average temperature, lower the yield. Higher the temperature, *lower* the rate of decrease of yield with temperature (as was the case with rice). Moreover, the fertilizer variable seems to have a counter-intuitive sign, i.e., higher the fertilizer consumption, lesser is the yield of sorghum; however it is also insignificant at the 5% level of significance. Table A.7 also gives similar results, with respect to the signs of the variables, other

Table 3. Sorghum with district and year fixed effects.
Number of obs = 2976 R-squared = 0.7075
Wald chi^2 (125) = 6027.59 Prob > chi^2 = 0.0000

Ln yield	Coeff.	Panel corrected standard errors	z	$p > \|z\|$	95% Confidence interval	
Log (rainfall)	0.3484967	0.0535765	6.5	0.000	0.243489	0.453505
Average Temperature	−1.534204	0.5299387	−2.9	0.004	−2.572864	−0.495543
Average Temperature^2	0.028572	0.0099	2.89	0.004	0.009168	0.047976
Fertiliser consumption	−0.0005637	0.0003567	−1.58	0.114	−0.001263	0.000135
Irrigation	0.415893	0.1805376	2.3	0.021	0.062046	0.76974
Intercept	17.30694	7.136662	2.43	0.015	3.319338	31.29454

than the fact that both agricultural controls become insignificant (much like pearl millet).

5.4. *Interpretation of regression results*

In the case of rice, the results reveal the strong positive effect of rainfall on its yield, across different specifications of the regression equation. The direction of impact of maximum temperature on the yield of rice is as expected — as temperatures increase, the yield of rice declines but at a decreasing rate. Inputs such as irrigation and fertilizer have positive and strong impact on the yields. These results point to the strong dependence of rice yields on both climatic factors, and agricultural inputs and is consistent with other studies for India (both at the state and at the district level) that rice yields are most likely to be affected by climate change.

The results for millets (pearl millet and sorghum) are more nuanced — as with rice higher rainfall leads to higher yields of both crops. But the effect of higher (average) temperature differs — for pearl millet it is insignificant, whereas for sorghum it is similar to rice (i.e., higher temperatures affect yield negatively though at a decreasing rate). These results corroborate with agronomic studies which suggest the pearl millet grain is resistant to drought and it is also considered more efficient in the utilization of soil moisture. It has a higher level of heat tolerance than sorghum, and is a cereal which is most resistant to high temperatures — in fact it needs slightly hotter conditions for harvest. The literature also seems to suggest sorghum is better adapted to dry and cool conditions, whereas pearl millet is better adapted to dry and hot conditions (Leder, 2009).[21]

The agricultural controls however exhibit interesting effects: Irrigation has a positive (and significant) effect on both crops. This is important from a policy perspective.

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[21] Also see ICRISAT VASAT (Virtual Academy for the Semi-Arid Tropics) (http://vasat.icrisat.org/crops/pearl_millet/pm_production/html/m4_4.2/index.html) and School of Forest Resources and Environmental Science, Michigan Technological University (http://forest.mtu.edu/pcforestry/resources/studentprojects/jon/Millet.html).

Fertilizer consumption, however, is insignificant for pearl millet and sorghum. This might be attributed to the fact that given the data limitations, the fertilizer variable is not crop-specific. However, it can be postulated that pearl millet yields are only affected by rainfall (and irrigation), whereas sorghum seems to be more sensitive to higher temperatures as well (compared to pearl millet).

6. Concluding Remarks

As mentioned in the introduction, in this paper we wanted to look at the possible effects of climate change on certain crops in India. We have looked at rice and millets — the former is the leading food grain in terms of output and area sown, while the latter (group) is a hardy crop that can withstand the vicissitudes of weather.

For rice, the evidence is overwhelming that both rainfall and temperature (the two climate variables) matter. Thus, a warmer India with more erratic rainfall as projected by climate models does not portend well for rice yields. But for rice other inputs also matter, *viz.* fertilizer and irrigation. For millets, on the other hand, rainfall is the main determinant and either temperature does not seem to affect them (as with pearl millet) or does so marginally (sorghum). Other inputs, especially fertilizer, do not seem to matter reinforcing the notion millets grow pretty much on their own.

There are now a number of recent studies that address the issues dealt with in this paper for India and other countries, for example (but not limited to) Deschênes and Greenstone (2007), Guiteras (2009), Fishman (2011), Auffhammer *et al.* (2012, 2006), and Krishnamurthy (2012). Our study has an annual district-wise focus. We are able to analyze fixed effects emanating from district and state specific characteristics. Also unlike some studies (e.g., Auffhammer *et al.*, 2006; Schlenker and Roberts, 2009; Poudel and Kotani, 2012; Sarker *et al.*, 2012), where only temperature and/or rainfall appear on the right-hand side, we have other inputs (controls) on the right hand side. These can give us some idea of the trade-offs involved in the process of climate change — if the temperatures rise, causing yields of paddy to fall, can it be compensated for by the use of more fertilizer?[22] Our focus is also deliberately crop-based. There are studies where temperature is seen to cause changes in income (in a multi-crop setting). The interpretation of these can be problematic (joint outputs, no input variation, the use of prices). We set ourselves the limited task of tracking (carefully) the changing yields over a large panel. In that the crops of interest matter to the lives of some of the world's poorest people, who would be affected by climate change, this analysis seems worthwhile.

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[22] This presupposes that the past is a good guide to the future, and no tipping points or other nonlinearities have been set in motion.

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Data Appendix

Agricultural data. The data on agricultural variables span the time period 1966–1999, and have been collected from the ICRISAT VDSA (Village Dynamics in South Asia) Apportioned Meso database. This is a district-level database that includes information on cultivated area, production and area irrigated for different crops, land use, farm harvest prices, rainfall, livestock and agricultural implements, operational holdings, and population census data for 19 states of the country. The boundaries of the districts included in this database are defined as of 1966, i.e. any data on districts that were created after 1966 are given 'back' to the parent districts from which the newer districts were created. The final database thus includes data on the parent districts only, which is inclusive of the data 'apportioned' amongst the districts created later.

The variables of interest in this database include the area under, and production of, rice, pearl millet and sorghum (measured in hectares and tons respectively), district-wise consumption of fertilizers (tons of nitrogen, phosphate and potash fertilizers used), total gross cropped area in each district (measured in hectares, and accounting for multiple cropping), and gross irrigated area under each of the three crops (measured in hectares, again accounting for multiple cropping). While the data on the area and production have been compiled into the ICRISAT database from the Statistical Abstracts of India, State Statistical Abstracts and the State Season and Crop reports, the data on fertilizer consumption has been obtained from the Fertilizer Statistics for India. Barring data gaps for a few variables in some districts, the area, input and output-related data is available at an annual frequency for all crops.

The dependent variable considered is the logarithm of yield (tons of output per hectare), for each of the three crops. The two main independent variables created from the list of ICRISAT variables are fertilizer consumption, and irrigation. The fertilizer consumption variable is defined as the district-wise consumption of fertilizer per unit of gross cropped area, hence it is identically defined for all three crops.

We define the irrigation variable as the area irrigated for a particular crop in a district, divided by the gross cropped area (for that particular crop). This variable is useful in capturing the intensity of irrigation in determining the yield of a crop.

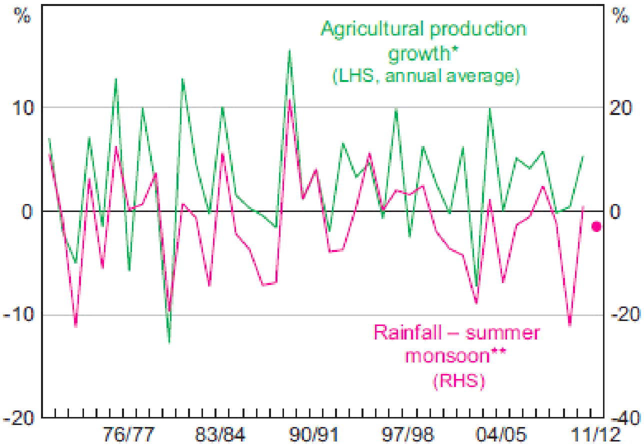
Climate data. The climatic data has been taken from the India Water Portal (www.indiawaterportal.org) which contains 102 years of district level data on rainfall, temperature, cloud cover, humidity, ground frost frequency and other variables. The database that is used to compile this meteorological dataset is the publicly available Climate Research Unit (CRU) TS2.1 dataset, out of the Tyndall Centre for Climate change Research, School of Environmental Sciences, University of East Anglia in Norwich, UK. This dataset consists of interpolated (on 0.5 degree latitude-longitude grid) global monthly data on variables such as rainfall and temperature from 1901 to 2002. The CRU data was transformed to the district level by simple linear averaging from the gridded data of the CRU dataset.

Two explanatory variables have been created using this database, namely, temperature and rainfall. We define these identically across all three crops. Temperature is the annual average temperature for a district. We also include a quadratic term for this variable. Our results do not change significantly when we use annual average maximum temperature. Rainfall is the natural log of annual rainfall in a district. In our data set, rainfall during the main growing season (June, July, August and September) accounts for roughly 70% of the annual rainfall in the case of rice and 73% and 75% for pearl millet and sorghum, respectively. Since the results are not significantly different using either growing season or annual rainfall, we use the latter. Further, since the distribution of our rainfall variable is positively skewed for all three crops, we take its natural log.

Choice of districts. The number of districts selected for each of the three crops are 153 (rice), 80 (pearl millet), and 88 (sorghum). These districts cut across all agriculturally important states of the country.

Our choice of districts is not exhaustive but accounts for the bulk of the output of the three crops. For rice, we use a threshold output of 50,000 tons on average. For pearl millet and for sorghum this figure is 25,000 tons. Thus, the districts included in our analysis account for about 95% of the total production of rice and for 98% and 97% of the production of pearl millet and sorghum, respectively. We find adding more districts does not change our results significantly.

Appendix



**Percentage deviation from long-run average.
Source: Cagliarini and Rush (2011).

A.1. India-rainfall and agricultural production.

Table A.1. Normal (average of 2005–2006 to 2009–2010) area, production, and yield of food crops in India. (Area — Million Hectares, Production — Million Tonnes, Yield — Kg./Hectare)

	Season	Area	(% of total)	Production	(% of total)	(% of total as of 1970–1971)	Yield
Rice	Kharif	39.36		80.38			
	Rabi	4.41		13.64			
	Total	43.77	35.7	94.02	42.4	(39)	2148
Wheat	Rabi	27.75	22.6	77.04	34.7	(22)	2777
Jowar	Kharif	3.43		3.54			
	Rabi	4.62		3.79			
	Total	8.05	6.6	7.33	3.3		911
Bajra	Kharif	9.26	7.5	8.29	3.7		895
Maize	Kharif	6.96		13.04			
	Rabi	1.05		4.00			
	Total	8.01	6.5	17.04	7.7		2128
Coarse Cereals*	Kharif	21.97		27.32			
	Rabi	6.31		9.14			
	Total	28.28	23.0	36.46	16.4	(28.2)	1290
Pulses	Kharif	10.65		4.99			
	Rabi	12.27		9.32			
	Total	22.92	18.7	14.31	6.5		625
Foodgrains	Kharif	71.97		112.70			
	Rabi	50.74		109.15			
	Total	122.71	100.0	221.85	100.0		1808

*Jowar, Bajra, Ragi, Small Millets, Barley and Maize.

Note: Figures in parentheses are shares in total food grain production in 1970–1971.

Source: Agricultural Statistics at a Glance, Directorate of Economics and Statistics, Department of Agriculture and Cooperation, Government of India (Adapted from Table 4.3).

Table A.2. Irrigated and un-irrigated area by size classes under different food crops, 2005–2006. ('000 hectares)

	Irrigated						Un-irrigated					
	Marginal	Small	Semi-medium	Medium	Large	Total	Marginal	Small	Semi-medium	Medium	Large	Total
Paddy	8,325.5	5,707.5	5,117.2	3,980.8	1,522.0	24,653.0	5,160.7	4,458.6	4,071.9	2,655.7	820.8	17,168
Wheat	5,362.5	4,071.2	4,696.2	4,985.1	2,269.8	21,384.8	444.0	528.0	620.8	585.0	205.0	2,382.9
Other cereals	40.7	28.7	28.9	18.7	6.6	123.6	46.3	63.2	73.2	75.2	44.4	302.3
Total Cereal	14,346.2	10,502.8	10,757.5	9,966.4	4,233.9	49,806.8	8,632.7	8,790.9	9,350.1	8,106.6	4,041.7	38,922

Marginal	less than 1 hectare
Small	1 — less than 2 hectares
Semi-medium	2 — less than 4 hectares
Medium	4 — less than 10 hectares
Large	10 hectares or more

Crop	% area marginal and small	% area large	% area irrigated
Paddy	56.6%	5.6%	58.9%
Wheat	43.8%	10.4%	90.0%

Source: Department of Agriculture and Cooperation, Agricultural Census Division.

Table A.3. Summary statistics.

Variable/crop	Unit	Rice				Pearl millet (*Bajra*)				Sorghum (*Jowar*)			
		Mean	Std. dev.	Min	Max	Mean	Std. dev.	Min	Max	Mean	Std. dev.	Min	Max
Rainfall	mm	1094.3	470.55	192.2	3663.8	782.5	347.02	48.5	2531.9	936.2	430.33	48.5	3595.8
Temperature	°C	25.82	1.44	20.49	32.69	26.09	1.13	20.98	29.17	26.22	1.38	20.49	29.17
Area	000 hectares	185.4	159.76	0.7	1106.65	119.94	151.77	0	1174	147.62	140.36	0	836.7
Production	000 tons	288.4	299.12	0	2418.9	59.2	66.35	0	456	100.1	98.95	0	692.2
Fertiliser consumption	tons/hectare	57.53	55.33	0	408.22	43.51	44.24	0	245.81	42.58	45.45	0.04	301.6
Irrigation	proportion (0 to 1)	0.53	0.39	0	1	0.09	0.17	0	1	0.04	0.08	0	0.89
Yield (Production/area)	tons/hectare	1.58	0.84	0	5.54	0.65	0.40	0	2.36	0.73	0.41	0	4.20

Table A.4. States and districts considered for each crop.

Rice		Pearl millet (*Bajra*)		Sorghum (*Jowar*)	
State	District	State	District	State	District
Andhra Pradesh	Adilabad	Madhya Pradesh	Gwalior	Maharashtra	Ahmednagar
	Anantapur		Guna		Akola
	Chittoor		Morena		Amravati
	Cuddapah		Indore		Aurangabad
	East Godavari		Jhabua		Bid
	Guntur		Rajgarh		Buldana
	Hyderabad		Bhind		Jalgaon
	Karimnagar	Haryana	Hisar		Nagpur
	Khammam		Mahendragarh		Nanded
	Krishna		Rohtak		Sangli
	Kurnool		Gurgaon		Solapur
	Mahbubnagar		Jind		Usmanabad
	Medak	Tamil Nadu	South Arcot		Yavatmal
	Nalgonda		North Arcot		Nasik
	Nellore		Salem		Dhulia
	Nizamabad		Tiruchirapalli		Pune
	Srikakulam		Madurai		Satara
	Visakhapatnam		Ramanathapuram		Kolhapur
	Warangal		Tirunelveli		Parbhani
	West Godavari	Uttar Pradesh	Aligarh		Wardha
West Bengal	24 Parganas		Mainpuri		Chandrapur
	Bankura		Farukkhabad	Karnataka	Belgaum
	Birbhum		Etawah		Bellary
	Burdwan		Varanasi		Bijapur
	Cooch Behar		Deoria		Chitradurga
	Hooghly		Pratapgarh		Gulbarg
	Howrah		Budaon		Mysore
	Jalpaiguri		Etah		Raichur
	Malda		Mathura		Shimoga
	Midnapore		Moradabad		Dharwad
	Mushidabad		Allahabad		Bidar
	Nadia	Karnataka	Bellary	Madhya Pradesh	Chhindwata
	Purulia		Belgaum		Dewas
	West Dinajpur		Bijapur		Dhar
Bihar	Bhagalpur		Raichur		East Nimar
	Champaran		Gulbarga		Guna
	Gaya	Andhra Pradesh	Guntur		Mandsaur
	Munger		Nellore		Rajgarh
	Patna		Kurnool		Sehore
	Purnea		Anantapur		Shajapur
	Saharsa		Chittoor		Shivpuri
	Shanabad		Nizamabad		West Nimar
	Hazaribagh		Medak		Tikamgarh
	Ranchi		Nalgonda		Gwalior

Table A.4. (*Continued*)

Rice		Pearl millet (*Bajra*)		Sorghum (*Jowar*)	
State	District	State	District	State	District
	Singhbhum		Vishakhapatnam		Indore
Karnataka	Bangalore	Gujarat	Ahmedabad		Ratlam
	Belgaum		BanasKantha		Ujjain
	Bellary		Bhavnagar		Vidisha
	Chikmagalur		Kheda		Betul
	Chitradurga		Kachch	Andhra Pradesh	Adilabad
	Coorg		Mehasana		Anantapur
	Dakshina Kannada		Rajkot		Hyderabad
	Gulbarga		SabarKantha		Khammam
	Hassan		Junagarh		Kurnool
	Kolar		Surendranagar		Mahbubnagar
	Mandya	Rajasthan	Alwar		Medak
	Mysore		Barmer		Nalgonda
	Raichur		Bikaner		Nizamabad
	Shimoga		Churu		Warangal
	Tumkur		Jaipur		Guntur
	Uttara Kannada		Jalore		Nellore
Madhya Pradesh	Balaghat		Jhunjhunun		Cuddapah
	Chattarpur		Jodhpur		Karimnagar
	Chhindwata		Nagaur	Tamil Nadu	Coimbatore
	Damoh		Sikar		Madurai
	Jabalpur		Pali		Tiruchirapalli
	Mandla		Bharatpur		South Arcot
	Narsimhapur		SawaiMadhopur		North Arcot
	Panna		Ganganagar		Salem
	Rewa	Maharashtra	Nasik		Tirunelveli
	Sagar		Dhule	Gujarat	Bharuch
	Satna		Jalgaon		Kachch
	Seoni		Ahmadnagar		Surat
	Shahdol		Pune		Surendranagar
	Sidhi		Satara		Vadodara
	Tikamgarh		Sangli		BanasKantha
	Durg		Solapur		Mehsana
	Raigarh		Aurangabad	Rajasthan	Ajmer
	Raipur		Parbhani		Bundi
	Surguja		Beed		Jaipur
Orissa	Balangir		Osmanabad		Jhalawar
	Balasore		Buldana		Jodhpur
	Dhenkanal		Akola		Kota
	Ganjam		Amravati		Nagaur
	Kalahandi	Punjab	Bhatinda		Pali
	Kandhamal				Tonk
	Keonjhar				Sawai Madhopur
	Mayurbhanj				Chittorgarh
	Sundargarh				

Table A.4. (*Continued*)

Rice		Pearl millet (*Bajra*)		Sorghum (*Jowar*)	
State	District	State	District	State	District
Punjab	Amritsar				
	Bhatinda				
	Firozpur				
	Gurdaspur				
	Hoshiarpur				
	Jalandhar				
	Kapurthala				
	Ludhiana				
	Patiala				
	Rupnagar				
	Sangrur				
Tamil Nadu	Chengalpattu				
	Coimbatore				
	Kanyakumari				
	Madurai				
	North Arcot				
	Vellore				
	Salem				
	South Arcot				
	Cuddalore				
	Thanjavur				
	Tiruchirapalli				
	Tirunelveli				
Uttar Pradesh	Allahabad				
	Azamgarh				
	Bahraich				
	Ballia				
	Banda				
	Barabanki				
	Bareilly				
	Basti				
	Bijnor				
	Budaon				
	Deoria				
	Etawah				
	Faizabad				
	Fatehpur				
	Ghazipur				
	Gonda				
	Gorakhpur				
	Hardoi				
	Jaunpur				
	Kheri				
	Lucknow				
	Mirzapur				

Table A.4. (*Continued*)

Rice		Pearl millet (*Bajra*)		Sorghum (*Jowar*)	
State	District	State	District	State	District
	Moradabad				
	Muzaffarnagar				
	Pilibhit				
	Pratapgarh				
	Rae Bareilly				
	Rampur				
	Saharanpur				
	Shahjahanpur				
	Sitapur				
	Sultanpur				
	Unnao				
	Varanasi				
Gujarat	Ahmedabad				
	Bulsar				
	Kaira/Kheda				
	Surat				
	PanchMahals				
Haryana	Hissar				
	Jind				
	Ambala				
	Karnal				
	Rohtak				
Maharashtra	Thane				
	Raigad/Kolaba				
	Ratnagiri				
	Pune				
	Satara				
	Kolhapur				
	Bhandara				
	Chandrapur				

Table A.5. Rice with district and year fixed effects, and panel-specific errors.
Number of obs = 5185 R-squared = 0.7778
Wald chi^2 (190) = 22192.76 Prob > chi^2 = 0.0000

Lnyield	Coeff.	Panel corrected standard errors	z	$p > \|z\|$	95% Confidence interval	
Log (rainfall)	0.2357468	0.0179538	13.13	0.000	0.20058	0.270935
Average temperature	−0.5838474	0.2023554	−2.89	0.004	−0.98046	−0.18723
(Average temperature)^2	0.0114678	0.0039342	2.91	0.004	0.00376	0.019178
Fertiliser	0.0013451	0.0001646	8.17	0.000	0.00102	0.001667
Irrigation	0.4976373	0.0334035	14.90	0.000	0.43216	0.563107
Intercept	5.410467	2.624947	2.06	0.039	0.265665	10.55527

Table A.6. Pearl millet with district and year fixed effects, and panel-specific errors.
Number of obs = 2656 R-squared = 0.6842
Wald chi^2 (117) = 5762.80 Prob > chi^2 = 0.0000

Lnyield	Coeff.	Panel corrected standard errors	z	$p > \|z\|$	95% Confidence interval	
Log (rainfall)	0.4856686	0.0477349	10.17	0.000	0.3921099	0.5792274
Average Temperature	0.5113752	0.5587276	0.92	0.360	−0.583711	1.606461
Average Temperature^2	−0.0112851	0.0107241	−1.05	0.293	−0.032304	0.0097338
Fertiliser consumption	0.0006407	0.0005577	1.15	0.251	−0.000452	0.0017338
Irrigation	0.5679651	0.1374566	4.13	0.000	0.298555	0.837375
Intercept	−9.175211	7.322669	−1.25	0.210	−23.52738	5.176956

Table A.7. Sorghum with district and year fixed effects, and panel-specific errors.
Number of obs = 2976 R-squared = 0.6959
Wald chi^2 (125) = 4673.75 Prob > chi^2 = 0.0000

Lnyield	Coeff.	Panel corrected standard errors	z	$p > \|z\|$	95% Confidence Interval	
Log (rainfall)	0.3417012	0.0487404	7.01	0.000	0.246172	0.437231
Average Temperature	−1.699692	0.5261875	−3.23	0.001	−2.731001	−0.668383
Average Temperature^2	0.0319681	0.0098312	3.25	0.001	0.012699	0.051237
Fertiliser consumption	−0.0002169	0.0003833	−0.57	0.571	−0.000968	0.000534
Irrigation	0.2691421	0.1948928	1.38	0.167	−0.112841	0.651125
Intercept	19.37152	7.076383	2.74	0.006	5.502063	33.24098

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