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Uncertain Monsoon, Irrigation and Crop Yields

Implications for Pricing of Insurance Products

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Uncertain Monsoon, Irrigation and Crop Yields: Implications for Pricing of Insurance Products

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Abstract

A significant body of literature interested in studying the impact of weather risks on agricultural performance has modeled crop yields as a function of either levels or deviations in seasonal rainfall. However, an aspect that has received little attention in the literature relates to the impact of timing of the arrival of the monsoon on agricultural performance. In this paper, using a pan-India district-level panel dataset for a period of 50 years, we investigate three interrelated issues that are critical for managing the weather-induced agricultural risks. One, we examine the impact of timing of the arrival of the monsoon on crop yields. Two, we assess the mitigation benefits of irrigation against a delayed monsoon. And three, by simulating premium rates for an area yield insurance product at varying levels of irrigation coverage, we argue for differential pricing of insurance products for irrigated and rainfed crops or regions.

Keywords: Monsoon onset, Crop yields, Irrigation, Crop insurance, Premiums
JEL Classification: **Q10, Q18, Q50, G22**

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"Village 'folklore' suggests that the timing of the monsoon is the most important aspect of weather (and uncertainty)."

— Binswanger and Rosenzweig (1993)

1 Introduction

Farmers face several types of production and market risks, but it is the weather risks that explain much of the variation in returns from farming (Binswanger and Rosenzweig, 1993; Hess et al., 2002; Hardaker et al., 2004; Moschini and Hennessy, 2001). Weather risks assume a greater significance in developing countries where agriculture is rain-dependent and farmers lack the adaptive capacity, in terms of their access to information, institutions, infrastructures, and finances, to cope with such risks (Walker and Ryan, 1990; Binswanger and Rosenzweig, 1993; Giné et al., 2008). Importantly, the frequency of weather risks has increased in the recent past and is predicted to increase in the plausible future climate scenarios, threatening the sustainability of agriculture and agriculture-based livelihoods (IPCC, 2007; Porter et al., 2014).

A significant body of literature studying the impacts of weather risks on agricultural performance has modeled crop yields as a function of either levels or deviations in seasonal rainfall (Walker and Ryan, 1990; Kumar and Parikh, 2001; Kurukulasuriya et al., 2011; Alauddin and Sarker, 2014; Kala, 2017; Chuang, 2019; Tambet and Stopnitzky, 2019; Shahzad and Abdulai, 2020; Burke and Emerick, 2016). However, an aspect that has received little attention in the empirical literature relates to the impact of the timing of the monsoon on agricultural performance. Agriculture in much of the developing world, especially in Asia and Africa, is rain-dependent; and a significant departure in monsoon from its normal arrival date might adversely affect agricultural productivity (Fafchamps, 1993; Naylor et al., 2007; Talathi et al., 2008; Giné et al., 2008). Laux et al. (2008) note that in South and Southeast Asia, planting dates are closely associated with the onset of monsoon and a two-week delay in its arrival significantly reduces crop yields. In other words, the performance of agriculture is determined not only by the quantum of rainfall but also by its timing.

Nonetheless, only a few studies have directly focused on the link between the timing of monsoon and agricultural productivity (Binswanger and Rosenzweig, 1993; Giné et al., 2008; Kala, 2017). Binswanger and Rosenzweig (1993), while studying the relationship between agricultural profits and weather risk in the semi-arid tropics of India, acknowledge that the timing of monsoon is the most important weather variable determining the variability of agricultural profits in rural India. The measures of monsoon onset, however, are arbitrarily defined in such studies. Binswanger and Rosenzweig (1993) consider the onset of monsoon as the date after which there is at least 20 mm of rainfall on several consecutive days after the first day of June. Kala (2017) follows a similar approach and considers accumulative rainfall of 120 mm in June as critical for the sowing of crops. Giné et al. (2008) define monsoon arrival based on the self-reported minimum quantum of rainfall required by farmers to start sowing operations. However, these studies are based on a small sample of farm households from the semi-arid tropics of India and hence are unable to capture the spatial heterogeneity in monsoon arrival and the adaptation measures (e.g., irrigation) that farmers follow to manage the effects of delayed monsoon. Irrigation plays an important role in buffering crop yields against the rainfall deficit and can act as a substitute for delayed rainfall (Fishman, 2018; Birthal et al., 2015). Finally, these studies consider aggregate farm profits as an outcome, ignoring heterogeneity in crops-specific responses to changes in the onset of rainfall.

In this paper, using a district-level panel dataset for a period of 50 years and constructing a localized monsoon onset index developed and well established in the climatology and meteorology literature (Liebmann and Marengo, 2001; Bombardi and Carvalho, 2009), we investigate three interrelated issues that are critical for managing the weather-induced agricultural risks: (i) we examine the impact of timing of monsoon on crop yields, (ii) we quantify the mitigation benefits of irrigation against delayed monsoon, and (iii) utilizing results from (i) and (ii) we simulate the actuarially fair premium rates for an area yield insurance contract under varying levels of irrigation coverage.

Our results show that in the past half century, the onset of monsoon in India has shifted forward by about a day from its normal arrival date and the probability of an extreme delay in the monsoon arrival has increased. In general, there appears to be an inverted U shape relationship between crop yields and the timing of monsoon, meaning that an early as well as delayed monsoon leads to suboptimal outcomes not only for the rainy season or *Kharif* season crops but also for crops grown in the post-rainy season or the *Rabi* season. A 10-day delay in the onset of monsoon can reduce yields of Kharif crops ranging from 1.1% for maize to 4.2% for pearl millet. Its effect on Rabi crops, however, is relatively weak. Further, we find that irrigation, apart from contributing to yield improvements, also acts as a buffer against the delayed monsoon. Its mitigation benefits, however, vary across crops and regions and accordingly our simulations indicate a need for differential pricing of insurance products for irrigated and rainfed crops or regions.

By analyzing the relationship between the onset of monsoon and crop performance and the role of irrigation as an adaptation mechanism, this paper makes a few important contributions to the literature on the impacts of climate change on Indian agriculture. One, although there is ample empirical evidence that deficient rainfall has a detrimental effect on crop yields, in this paper, we specifically look into the sensitivity of crops to the timing of arrival of monsoon. The importance of the timing of rainfall in India and other tropical developing countries cannot be overstated. About half of India's agriculture is rainfed and its performance is largely determined by the quantum and distribution of rainfall. Over 80% of the annual rainfall in India is received from the southwest monsoon during June to September. This is the main cropping season in India and is often termed as the Kharif season. The post-rainy period from October to March is termed as the Rabi season. The crops grown in these seasons rarely overlap, except a few vegetables and perennial horticultural and plantation crops, and significantly differ in their water requirements. The monsoon rains and their timing not only influence the performance of Kharif crops but also of the crops grown in the subsequent season utilizing residual moisture of the monsoon (Joshi et al., 2007; Jat et al., 2014). All major agricultural operations including sowing, transplanting and harvesting are planned around the arrival of monsoon and a delay in it disturbs the planning that farmers might have done at the beginning of the agricultural year. The availability of sufficient moisture in the soils is critical for planting of crops, and inadequate moisture often delays sowing, especially in the rainfed regions. Moreover, agronomic studies have shown that delayed sowing reduces vegetative growth, leading to lower biomass production and yield loss (Miller, 1992; Cao and Moss, 1994; Shah et al., 1994; Shah and Akmal, 2002; Klein et al., 2002).

Two, this paper also connects to the literature on farmers' adaptation measures to changes in rainfall patterns. In the context of Indian agriculture, Fishman (2018) shows that irrigation reduces the harmful effects of increased variability in rainfall and has the potential to mitigate future threats from such changes. Birthal et al. (2015) show that irrigation has played a key role in mitigating the effect of droughts on rice yield in India. Similarly, Taraz (2017) has shown that farmers in India increase investment in irrigation in response to increasing variability in rainfall. Going a step further, we establish that irrigation can also reduce the sensitivity of crop yields to variation in the onset of rainfall.

Three, it adds to the existing literature on the pricing and demand for index-based crop insurance products. A key finding in this literature is that the demand for index-based insurance products is highly price-sensitive; this is considered to be one of the reasons for low uptake of crop insurance in developing countries (Giné et al., 2008; Cole et al., 2013, 2014; Clarke, 2016; Hill et al., 2016). Our findings, however, show that the appropriate insurance premium rate varies across crops and spatially along the irrigation landscape; failing to account for this in setting insurance premium rates results in overpricing of insurance products for regions where irrigation or other adaption measures implicitly provide partial insurance against weather shocks.

The rest of the paper is organized as follows. Section 2 discusses briefly the available empirical literature. Section 3 describes the data used in the analysis and the localized rainfall onset index. Section 4 lays out the empirical model used to estimate the relationship between monsoon arrival and crop yields. Section 5 presents the model results. Finally, section 6 concludes.

2 Background and literature

The impacts of climate change on agricultural production have been extensively studied in the literature (Mendelsohn et al., 1994; Krishna Kumar et al., 2004; Schlenker et al., 2005; Mendelsohn et al., 2006; Deschênes and Greenstone, 2007; Schlenker and Roberts, 2008). It is predicted that climate change will affect agricultural production through both global increases in average temperature and precipitation and changes in their variability in terms of increasing the frequency of unforeseen weather events like droughts, hailstorms and delayed monsoon (Kumar and Parikh, 2001; Burke and Emerick, 2016; Taraz, 2018). Developing countries, like India, have greater vulnerability to such climate vagaries as a large proportion of the population depends upon agriculture for their livelihoods (Stern and Stern, 2007; Lal et al., 2012). Moreover, in a country like India, agriculture is primarily rainfed and lacks appropriate financial and technical support, and faces infrastructure bottlenecks, credit constraints and marginalized landholdings, which further increase the weather vulnerability of agriculture production (Krishna Kumar et al., 2004; Lal et al., 2012; Jain et al., 2015).

The agronomy literature shows that delayed sowing of crops results in their stunted growth and lower biomass yield, in terms of both the main product and the by-product (Laux et al., 2008; Singh et al., 2016; Detroja et al., 2018; Sandhu et al., 2019).

From experiments conducted in different states in eastern India, Singh et al. (2016) find that an early as well as delayed sowing of paddy results in lower than the optimal yield. A 15-day delay in planting could reduce yields in the range of 4% all the way to 40% depending upon the location. For pearl-millet in Gujarat, Detroja et al. (2018) report that a 10-day delay in its sowing reduces its yield by 5%. Likewise, for wheat, a one-week delay in sowing in Punjab has been reported to reduce its yield by 5-7% (Sandhu et al., 2019).

Farmers generally plan sowing and other agricultural operations based on the arrival of monsoon (Sivakumar, 1992; Sultan et al., 2005; Marteau et al., 2011). Marteau et al. (2011), in the context of West Africa, report that farmers wait for the first rains of at least 10mm to plant their crops. Sultan et al. (2005) show that planting of crops as per the timing of rainfall has a differential impact on crop yields. However, there is limited evidence on the relationship between the timing of monsoon and the performance of crops. Binswanger and Rosenzweig (1993) provide one of the earliest pieces of evidence on the effect of timing of monsoon on agriculture. They find that a one-standard-deviation delay in the arrival of monsoon in the semi-arid tropics of India could reduce agricultural profits by 15% on average, with the impact being stronger for poor households on account of their lack of investment in farm assets. Kala (2017) arrives at a similar conclusion and reports a 12% reduction in agricultural profits due to delayed monsoon. Giné et al. (2008), using data from a survey of farm households in the semi-arid tropics of India, model crop yield as a function of onset of rainfall and find that delay in the arrival of monsoon causes a significant reduction in crop yields.

Several studies report that irrigation provides partial insurance to farmers against deficient rainfall and droughts (Thorfinnson and Epp, 1953; Lobell and Bonfils, 2008; Libecap and Steckel, 2011; Hornbeck and Keskin, 2014; Alauddin and Sarker, 2014; Birthal et al., 2015; Jain et al., 2015; Fishman, 2018). But at the same time, these also report that adaptation through irrigation is constrained by over-exploitation of groundwater resources, infrastructure bottlenecks, credit constraints and interrupted supply of electricity, leading to slowing down of its adaptation benefits. Further, none of these, the exception being that of Jain et al. (2015), study adaptation benefits of irrigation against delayed monsoon. Jain et al. (2015) find that irrigation provides protection against irregularities in both the quantum and timing of rainfall.

While irrigation is an ex-post strategy, crop insurance can be an ex-ante means of mitigating the consequences of weather-induced production risks (Carter et al., 2014; Jensen and Barrett, 2017). Given the rising frequency of extreme changes in climate, the demand for crop insurance is likely to increase in the future (Di Falco et al., 2014). The index-based crop insurance products specifically designed to insure farmers against weather risks have generated considerable interest among academicians and policy-makers alike (Giné et al., 2008, 2010; Clarke et al., 2012; Cole et al., 2013; Rejesus et al., 2015; Fahad and Wang, 2018). As the payout is triggered by an index of weather risk rather than the farm-specific crop losses, the index-based insurance products are free from market failures that often arise due to information asymmetry (Giné et al., 2010; Cole et al., 2013; Carter et al., 2014; Jensen and Barrett, 2017).

In this paper, our focus is on the area yield based index insurance that has been extensively used as an instrument of managing aggregate farm risks in developed as well as developing counties. Many studies, particularly from the developed countries, provide in detail the procedure of designing and pricing of area-based yield insurance products (Miranda, 1991; Skees et al., 1997; Josephson et al., 2000; Yu and Babcock, 2010). In the context of an area yield insurance program the 'Group Risk Plan (GRP)' in the U.S., Skees et al. (1997) argue that the rating procedure of insurance contracts has to be adjusted for the differences in production conditions, such as the availability or unavailability of irrigation. Yu and Babcock (2010) propose a ratemaking procedure that can account for improvements in drought-tolerance traits of crops. In the context of the developing countries, however, the literature on the pricing of area yield insurance products is scarce (Clarke et al., 2012). Clarke et al. (2012) is perhaps the only study, which proposes a framework for pricing index insurance in large developing countries.

Our paper adds to the limited but growing literature on the pricing of area yield insurance products in developing countries. By simulating premium rates for an area yield insurance product at varying levels of irrigation, it argues for differential pricing of insurance products for irrigated and rainfed crops or regions. The Government of India, in its large scale index insurance program, the 'Pradhan Mantri Fasal Bima Yojana' (PMFBY), acknowledges the importance of irrigation in the pricing of index-based insurance products (Government of India, 2018). This paper through rigorous empirical means provides a formal justification for such an argument.

3 Data and Descriptive Statistics

3.1 Data Sources

We rely on two main sources of data for the analysis. The data on district-level crop production comes from the Tata-Cornell Institute (TCI) and the International Crop Research Institute of Semi-arid Tropics (ICRISAT) District Level Database (ICRISAT-TCI, 2015). This database provides information on the area, production and yield of major crops for 311 districts (at their 1970 boundaries) for a period of 50 years, from 1966 to 2015. Our focus is on the 11 most important crops: rice, sorghum, pearl-millet, maize, finger-millet, pigeon-pea, groundnut and cotton grown in the Kharif season; and wheat, rapeseed-mustard, and chickpea grown in the Rabi season.

The historical data on rainfall has been extracted from the high-resolution daily rainfall gridded dataset ($0.25° \times 0.25°$) of the India Meteorological Department, Ministry of Earth Sciences, Government of India.

3.2 Construction of local index for the onset of monsoon

Several approaches have been developed by climatologists to determine the date of the onset of monsoon (Liebmann and Marengo, 2001; Sijikumar et al., 2006; Bombardi et al., 2017). Generally, the onset of monsoon is determined by either the local rainfall occurrences and constraints on wet/dry days or the large scale changes in the monsoon that are not limited to rainfall alone (Vellinga et al., 2013). We follow Bombardi et al. (2017)'s procedure to estimate the monsoon arrival day for each district-year in our dataset. The advantage of this method is that rather than relying on weather models, which are designed to predict changes in global monsoon systems, it uses actual rainfall data to estimate the monsoon arrival day at the local or regional level (Bombardi et al., 2017).

There are two steps to finding the day of arrival of rainfall or the onset of monsoon. In the first step, we estimate the daily accumulated rainfall deviation as:

$$S(d) = \sum_{t=May,1^{st}}^{d} (R(t) - P_C) \tag{1}$$

where $S(d)$ is the accumulated rainfall deviation from the annual mean at day d; $R(t)$ is the daily precipitation at day t, and P_C is the daily average rainfall in a particular year. We assume the first of May of every year as the starting date for monsoon. This is done to rule out the false monsoon onsets. According to the India Meteorological Department, the southwest monsoon in India does not start before May 10, and hence a date in early May is appropriate to measure the change in rainfall arrival dates across the country. The choice of starting date is subjective and depends upon the geography and climatic conditions of the region in question (Bombardi et al., 2017). The $S(d)$, so defined, captures the occurrence of the wet days and also takes into account the combined effect of duration and intensity of rainfall.

The second step involves finding the day of the monsoon arrival using the calculated daily accumulated rainfall deviation. As an illustration of the procedure, in Figure 1 we show the accumulated rainfall deviations for the calendar year 2008 for four selected grid points lying in different states of India. The black line denotes the $S(d)$ or the accumulated rainfall deviation for each day starting May 1 or the 122^{nd} day of the calendar year. The curve first declines and shows negative values of the accumulated rainfall deviation because of the initial dry days. Once the rainy period begins, the curve also starts rising and turns positive. The monsoon arrival day is the first inflection point at which the curve is at its minimum but turns upwards thereafter. This is marked by vertical lines in Figure 1. It is important to note that the monsoon onset day varies across the states. For example, for the grid point in Andhra Pradesh, the monsoon arrives on the 200^{th} day of the year, while in Jharkhand it arrives on the 161^{st} day. Following this procedure, we find the monsoon arrival day at each grid point for every year, and then estimate the district-year monsoon onset as the average of the monsoon arrival day at all the grid points lying within a district. As complements to monsoon onset, we also calculate the number of wet days and the total rainfall during May, June, July, and August (MJJA).

3.3 Descriptive statistics

Table 1 presents the summary statistics for the calculated rainfall indices. On average, the monsoon arrives in India on the 189^{th} day of the calendar year, but there is considerable variation in its arrival time across districts, as shown in Figure 2. Figure 2 also shows some visual evidence of the temporal variation in rainfall arrival patterns. During the 1980s and 1990s, the eastern seaboard and the western coast were the first to receive monsoon rains. This pattern has shifted over time and now the peninsular region receives the first monsoon rains.

To test for the changes in the arrival date of monsoon over time, we regress the district level rainfall arrival days on a linear time trend while controlling for the district fixed effects. The results presented in column 1 of Table 2 show a positive and statistically significant trend in the arrival of monsoon. This is also visible in Figure 3(a), which plots a linear trend in rainfall arrival day. These findings imply that the timing of monsoon in the country has shifted forward by about a day on average. Further, we test whether the probability of delay in the onset of monsoon has changed over time. We define a dummy variable which is coded as 1 if the monsoon arrival day is one standard deviation greater than the mean arrival day in a district and zero otherwise. This dummy variable is regressed on a linear time trend and district fixed effects and the results are presented in Table 2. Column 2 of Table 2 and Figure 3(b) show an increase in the probability of monsoon being delayed by 0.05 percentage points, from 0.14 in 1966 to 0.19 in 2015. Figure 4 presents the average 10 year rolling variance in the monsoon arrival day. It shows that on average the variation in monsoon arrival has increased- in other words, the monsoon arrival has become more uncertain.

Table 3 presents the correlations between the deviation in crop yields from an exponential trend and the local monsoon onset index. Yields of all the crops show a negative and statistically significant correlation with the local rainfall onset index implying that a delayed monsoon reduces crop yields. In terms of the magnitude, the yields of pearl millet and rice show the most sensitivity to the arrival of monsoon and rapeseed and mustard the least. Although revealing, the correlations in Table 3 may hide non-linearities in the yield response to rainfall onset. Therefore in Figure 5, we plot non-parametric estimates of the relationship between deviations in crop yields and the rainfall arrival day. For all the crops, the relationship takes the shape of an inverted-U. This implies that both the early and the delayed onset of monsoon lead to sub-optimal outcomes and that there is an optimal monsoon arrival day beyond which crop yield starts declining.

4 Empirical strategy

India receives the bulk of the annual rains during the Kharif season, and therefore it is natural to assume that agricultural operations in this season are dependent on the timing of monsoon. Nonetheless, a delay in monsoon may also influence the sowing and other agricultural operations in the post-rainy Rabi season, as many of the crops in this season are sown utilizing the residual moisture from the monsoon. A delayed monsoon, therefore, also reduces the sowing window for Rabi crops.

To test whether the delay in monsoon onset has any effect on crop yields, we consider the following model

$$Y_{it} = \alpha_i + \sum_{i=1}^{N} \theta_i(\alpha_i \times T) + \beta_1 RD_{it} + \epsilon_{it} \tag{2}$$

where Y_{it} is the natural logarithm of the yield of a crop in district i in year t. α_i represents the district fixed effect that controls for time-invariant unobserved factors, for example, the geographical characteristics of districts. RD_{it} is the day of arrival of monsoon in district i in year t. Equation (2) also includes a district-specific exponential time trend $(\alpha_i \times T)$ to control for the district-specific heterogeneity in yield growth due to expansion in infrastructure, adoption of modern crop varieties and technical change.

Equation (2) models crop yield as a linear function of the timing of monsoon. However, as observed from Figure 4, the yield response to the timing of monsoon takes an inverted-U shape. To capture the nonlinear effects of the timing of monsoon, we modify Equation (2) to include a squared term of RD_{it} and specify it as:

$$Y_{it} = \alpha_i + \sum_{i=1}^{N} \theta_i(\alpha_i \times T) + \beta_1 RD_{it} + \beta_2(RD_{it} \times RD_{it}) + \epsilon_{it} \tag{3}$$

To test whether irrigation can reduce the adverse effects of delayed monsoon, we introduce the interaction of cropped area irrigated (IRR) with RD_{it} and its squared term, and re-write Equation (3) as:

$$Y_{it} = \alpha_i + \sum_{i=1}^{N} \theta_i(\alpha_i \times T) + \beta_1 RD_{it} + \beta_2(RD_{it} \times RD_{it}) + \beta_3 IRR_{it} + \beta_4(RD_{it} \times IRR_{it}) + \beta_5(RD_{it} \times RD_{it} \times IRR_{it}) + \epsilon_{it} \quad (4)$$

Equation (4) decomposes crop yield into a deterministic trend $(\alpha_i + \sum_{i=1}^{N} \theta_i(\alpha_i \times T))$ associated with the district-specific mean yield captured in α_i (i.e., yield improvements due to technological change and input-use); a monsoon and irrigation-driven deviation in yield $(\beta_1 RD_{it} + \beta_2(RD_{it} \times RD_{it}) + \beta_3 IRR_{it} + \beta_4(RD_{it} \times IRR_{it}) + \beta_5(RD_{it} \times RD_{it} \times IRR_{it}))$; and a residual noise term ϵ_{it} that captures the effects of other random factors. Since the timing of monsoon is random, Equation (4) allows us to quantify the contribution of yield risk due to variation in the timing of monsoon. The loss in yield due to delayed monsoon can be estimated as:

$$Loss = \frac{\partial Y_{it}}{\partial RD_{it}} = \beta_1 + 2\beta_2 RD_{it} + \beta_4 IRR_{it} + 2\beta_5(RD_{it} \times IRR_{it}) \quad (5)$$

Likewise, by taking the partial derivative of Equation (5) with respect to IRR_{it}, we can quantify the contribution of irrigation towards reducing yield loss due to delayed monsoon as:

$$\triangle Loss_{IRR} = \frac{\partial Loss}{\partial IRR_{it}} = \beta_4 + 2\beta_5 RD_{it} \quad (6)$$

Based on Equation (5) and (6) we formulate two hypotheses: (i) the delay in the onset of monsoon reduces crop yield, i.e., $Loss = \frac{\partial Y_{it}}{\partial RD_{it}} < 0$; and (ii) irrigation reduces the sensitivity of crops to the timing of monsoon, i.e., $\triangle Loss_{IRR} = \frac{\partial Loss}{\partial IRR_{it}} > 0$.

5 Results

We begin by validating our choice of the fixed effects model and perform the Hausman test (Table A1 in the appendix) that favors the fixed effects model over the random-effects model. The residual term, a proxy for all other production risks, may exhibit within-district serial correlation and could also be heteroskedastic. We test for heteroskedasticity using the Modified Wald test and find the χ^2 statistics to be statistically significant at the 1% level, suggesting the presence of heteroskedasticity (Table A2 in the appendix). To control for within district heteroskedasticity and serial correlation, the standard errors have been clustered at the district level.

5.1 Impact of monsoon onset on crop yields

Table 4 presents the estimates of Equation (2). The coefficient on the monsoon onset day (RD) is negative and statistically significant for all the crops, reinforcing our finding of an inverse relationship between the timing of monsoon and crop yields. Table 4 also presents the estimates of yield loss due to a 10-day delay in the onset of monsoon. We find that the Kharif crops are more affected by the delayed monsoon. A 10-day delay in the onset of monsoon reduces the yield of rice and pearl-millet by 78 and 59 kg/ha respectively, or 3.2% and 5% of their production per hectare. Sorghum and groundnut too lose more than 3% of their production. Rabi crops are also adversely affected by the delayed monsoon. These results are consistent with those reported in Binswanger and Rosenzweig (1993) and Kala (2017). We also test for the lagged effects of monsoon arrival on crop yields and the results are presented in appendix Table A3. We find that for sorghum, maize, finger millet, cotton and wheat the coefficients on lagged monsoon arrival are negative and statistically significant but the coefficient are small in magnitude and economically insignificant.

There is a possibility that the late onset of monsoon might result in seasonal rainfall deficit, aggravating its negative effects on crop yields. To test for this, we regress the quantum of Kharif season rainfall and also the number of rainy days on the arrival day of monsoon, and the results are presented in Table 5. There is a strong inverse relationship between the quantum of rainfall (and also the number of rainy days) and the onset of monsoon. A 10-day delay in the onset of monsoon results in 8.6% less rainfall than normal, and a 1.8% reduction in the number of rainy days. Another possibility is that the delayed arrival of monsoon and the rainfall deficit have a confounding effect on crop yield, that is, the loss in yield is driven not only by the late monsoon but also by the deficit in rainfall. In Table 6 we present estimates of Equation (2) with seasonal rainfall as a control. As expected, the coefficient on the timing of monsoon remains negative and highly significant for most crops, except for chickpea. The yield loss, except for maize and cotton, is reduced after controlling for the quantum of rainfall. For example, accounting for the effect of seasonal rainfall, a 10-day delay in monsoon reduces yield loss in rice by more than half.

Table 7 presents the estimates of Equation (3) that account for the non-linear effect of timing of monsoon. The coefficient on the linear term of the rainfall arrival day is positive, but is negative and statistically significant on its squared term for most crops. This implies that, although an initial delay in rainfall arrival has a positive effect on crop yield, a further delay has an adverse effect on yield. We explicitly test for the existence of an inverse U-shape relationship between the onset of monsoon and crop yields using the Sasabuchi–Lind–Mehlum (SLM) test (Lind and Mehlum, 2010). It rejects the null hypothesis of a monotonic relationship against the alternative hypothesis of the existence of an inverted U-shaped relationship between the rainfall arrival day and crop yield.

5.2 Irrigation as mitigation

Table 8 presents the estimates of Equation (4) that incorporate the interaction of the proportion of cropped area irrigated with the timing of the onset of monsoon and its squared term. Here, we refrain from interpreting the coefficients of individual interactions and discuss only the marginal effects of timing of monsoon and irrigation, both evaluated at their respective means. As expected, the marginal effect of the monsoon onset remains negative, but the marginal effect of irrigation is positive and statistically significant.

Table 8 also provides results of the tests of hypotheses formulated based on Equations (5) and (6). The null hypothesis that delayed onset of monsoon does not influence crop yields (i.e., $Loss = 0$) is rejected, as the coefficient on the partial derivative (Equation 5) is negative and statistically significant. Similarly, the null hypothesis that irrigation cannot buffer crops against the delayed onset of monsoon (i.e., $\triangle Loss_{IRR} = 0$) is also rejected. A positive and statistically significant coefficient on $\triangle Loss_{IRR}$ (Equation 6) implies that irrigation moderates the adverse effects of delayed monsoon. This finding is consistent with those reported in Birthal et al. (2015) and Fishman (2018) in the context of droughts.

Figure 6 plots the predicted yields of rice and wheat as a function of the timing of monsoon against varying levels of irrigation. It demonstrates that higher levels of irrigation augment the relationship between crop yields and the timing of monsoon in two ways. One, the yield curve at a higher level of irrigation (70%) is flatter than the curve at a lower level of irrigation (10%). This clearly shows that irrigation provides mitigation benefits against the delayed monsoon. Two, the yield curve with higher irrigation attains its maximum (if there is only one) later than the curve with lower irrigation, implying that a higher irrigation cover increases the threshold beyond which further delay in rainfall arrival starts reducing crop yields.

Tables 9 presents the marginal effects of the timing of monsoon at different levels of irrigation. The marginal effect of the onset of monsoon declines with rising levels of irrigation. Based on the estimated marginal effects in 9, we present the absolute yield loss due to an extreme delay in monsoon onset in Table 10[1]. For example, with an extreme delay in monsoon, the rice yield declines from about 17 kg/ha to 3 kg/ha as the area under irrigation increases from 10% to 90%. Similarly, for wheat, the yield loss declines from about 9 kg/hectare to 3 kg/ha. This pattern of irrigation driven decline in yield loss is consistent for all the crops.

5.3 Implications for index-based crop insurance

Our finding that irrigation mitigates the harmful effects of delayed monsoon has important implications for designing large-scale area yield insurance programs. In this section, we simulate actuarially fair premium rates for an area yield insurance contract under varying levels of irrigation. Our simulations are based on two assumptions. One, the probability of delayed monsoon in a year is determined by its historical probability distribution (Yu and Babcock, 2010). Two, the yield risk due to delayed monsoon is independent of other production risks, for example, the risk of insect pests and diseases. In particular, we assume that yield loss due to delayed rainfall is additive and independent of the multiple factors affecting the crop yield. Based on these assumptions, we can attribute the simulated premium rates entirely to the delayed monsoon.

We do simulations of premium rates at varying levels of irrigation as follows. We select only those districts that have at least 30 observations for each crop. We estimate the actual yield for each crop as the predicted yield using the fitted values from Equation (4) at 10%, 30%, 50%, 70%, and 90% level of irrigation coverage. The expected yield is estimated as the predicted yield using the fitted values from Equation (4) with the monsoon arrival day evaluated at its district mean for each crop at the above-mentioned levels of irrigation coverage. The trigger yield, the yield loss, and the

[1]The extreme delay in the monsoon arrival day is defined as one standard deviation above mean arrival day which turns out to be the 210^{1h} day of the year in our data.

premium are then calculated as:

$$Triggered\ yield_i = E_t(Expected\ yields_{it}) \tag{7}$$

$$Loss_{it} = Max\{Trigger\ yield_i - Actual\ yield_{it}, 0\} \tag{8}$$

$$Premium_i = E_t(Loss_{it}) \tag{9}$$

where subscripts i and t respectively denote the district and the year. Trigger yield for a crop in district i is set at the mean value of the expected yield for the entire period. The loss or the payout is then calculated as the difference between actual and trigger yield if the actual yield is less than the trigger yield, and zero otherwise. Finally, the actuarially fair premium is the expected value of the yield loss or the expected payout. The premium rate is calculated as:

$$Premium\ rate(\%) = \left(\frac{Premium_i}{Sum\ assured_i}\right) \times 100 \tag{10}$$

Here we assume the sum insured as the average value of the actual yield for the last 10 years (2005 to 2015). The procedure outlined above generates premium rates for each crop and for every district. Table 11 shows the mean and standard deviations of the estimated premium rates at different levels of irrigation. It can be seen from the table that premium rates decline as the area under irrigation increases from 10% to 90% across all crops. In Figure 7, we plot the premium rates for rice and wheat against the increasing level of irrigation. For both rice and wheat, the premium rate declines as the proportion of cropped area irrigated increases. However, the decline in the premium rate is higher for rice than for wheat, possibly because of rice's greater dependence on rainfall. This decline in premiums is attributable to our earlier result that irrigation augments the relationship between rainfall arrival and crop yields and indicates that irrigation can act as a partial substitute for formal crop insurance products. Farmers, therefore, will opt for the less costly mitigation strategy. Our results indicate that the pricing of area yield insurance products without taking into consideration the spatial heterogeneity in irrigation cover may accentuate the spatial and geographical errors in the pricing of such insurance contracts.

6 Conclusions

In South and Southeast Asia, sowing of crops is closely associated with the onset of monsoon and a two-week delay in monsoon can reduce crop yields considerably. This paper has addressed three interrelated issues: One, it has estimated the impact of timing of onset of monsoon on the performance of crops; two, it has assessed the role of irrigation in mitigating the adverse effects of delayed monsoon; and three, it has demonstrated the actuarial sense in linking premium rates with irrigation coverage in pricing of the area yield crop insurance contracts.

Our results show an inverted U-shape relationship between rainfall arrival and crop yields, suggesting that both early and late rainfall arrival leads to sub-optimal crop yields. We find that irrigation plays an important role in mitigating the harmful effects of delayed monsoon arrival and provides partial insurance. The simulations based on regression results show that the fair premium rates for an area yield insurance product will vary spatially with the magnitude of irrigation cover, with lower premiums in areas with higher irrigation.

Our findings have important implications for India's large scale area yield insurance programs, the Pradhan Mantri Fasal Bima Yojana (PMFBY). The PMFBY is an area-based insurance scheme that intends to support sustainable agricultural production by providing financial support, stabilizing farm incomes and encouraging the adoption of modern technologies. The main implication of this study is that the need for formal insurance products may vary depending upon the natural endowments, geographical features and access to infrastructure across regions. Taking the particular case of irrigation, we show that geographical heterogeneity and access to infrastructure, which may implicitly provide partial insurance, should be considered when pricing index insurance products for crops and regions. Our findings also help in targeting of the area yield insurance schemes. Since agriculture in regions with better irrigation is less vulnerable to weather risks, investment in irrigation can partially substitute for such insurance programs. Finally, we would like to mention that, although the paper studies pricing of area yield insurance in the context of delayed monsoon, these findings can be easily generalized to other types of weather risks and index insurance products.

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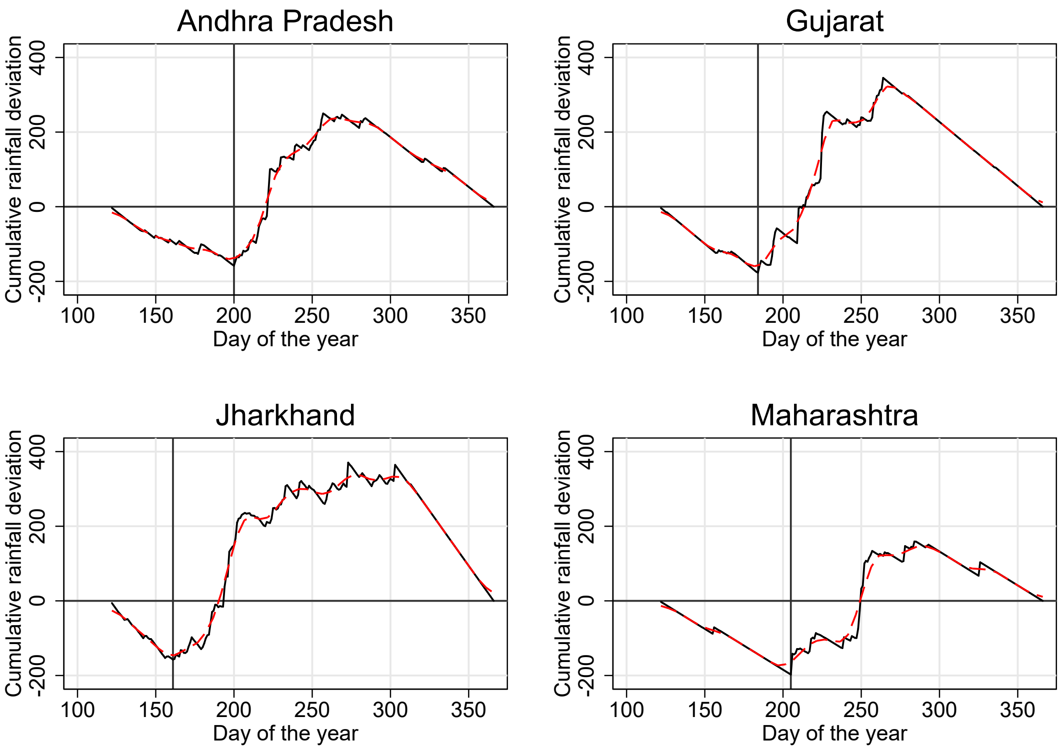
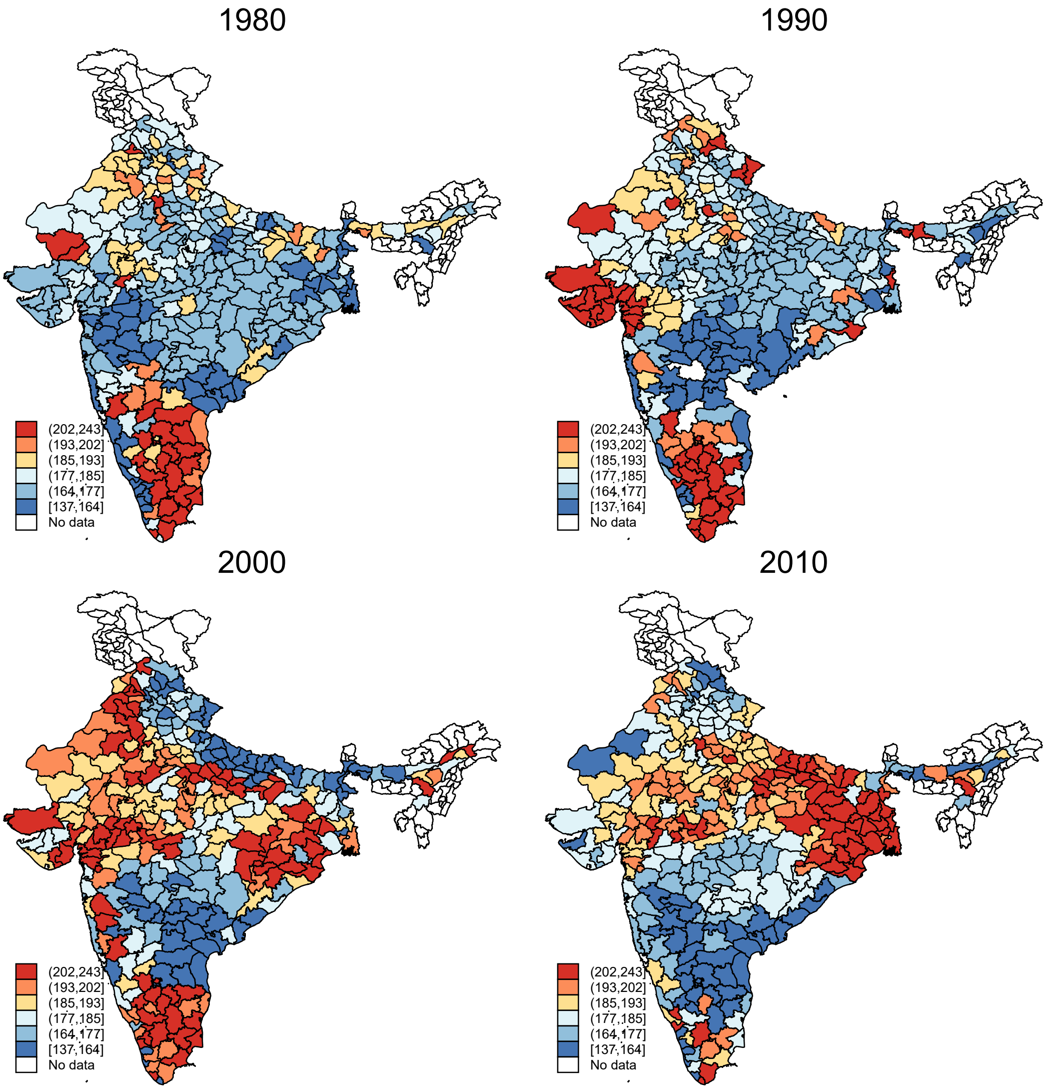
Figures

Figure 1: **Accumulated rainfall deviation and timing of arrival of monsoon**



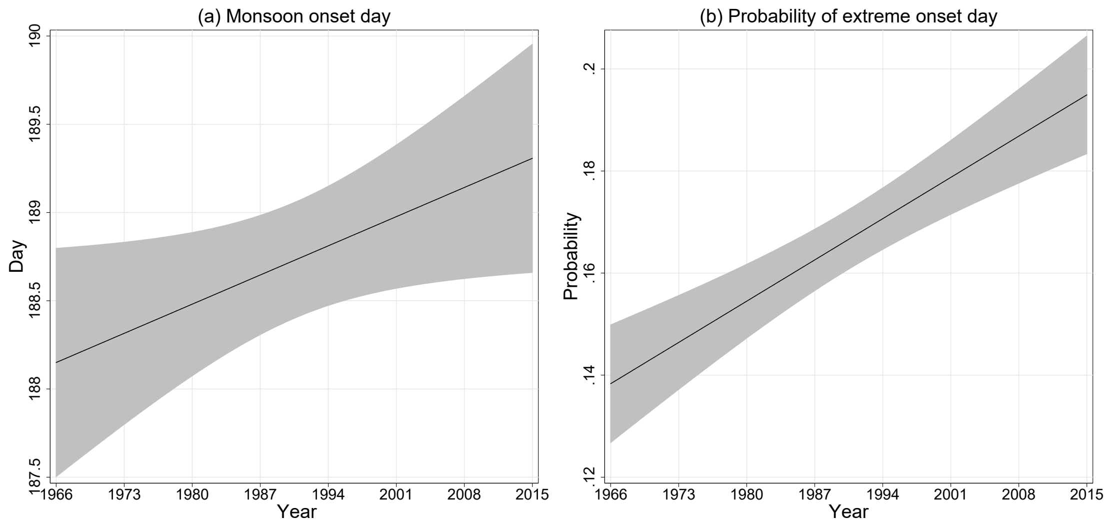
Note: This figure presents the daily accumulated rainfall deviation and the day of monsoon arrival for four states in the year 2008.

Figure 2: **Variation in monsoon onset day across districts in India**



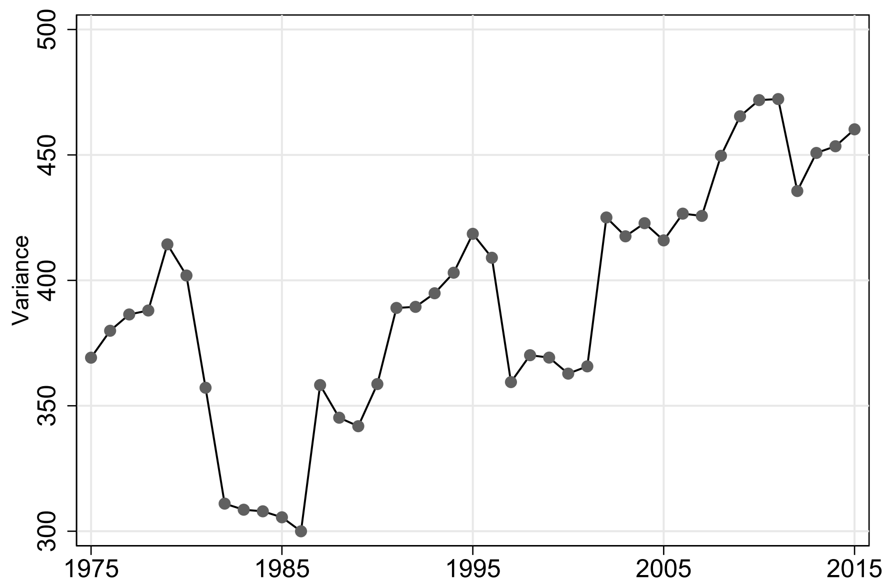
Note: This figure presents the change in spatial pattern of monsoon arrival over 1980-2010 across districts of India.

Figure 3: **Change in the monsoon onset days and the probability of delayed monsoon over 1966-2015**



Note: This figure presents the trend in monsoon arrival (figure a) and the probability of the occurrence of extreme delay in monsoon arrival (figure b) over 1966-2015.

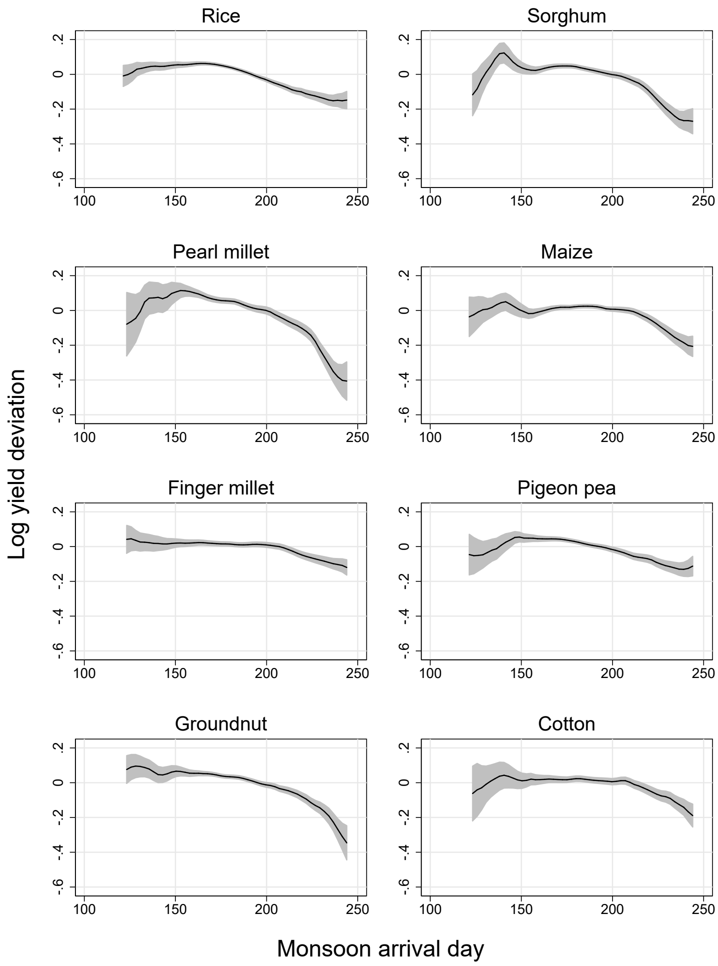
Figure 4: **Average rolling 10 year variance in monsoon arrival day 1966-2015**



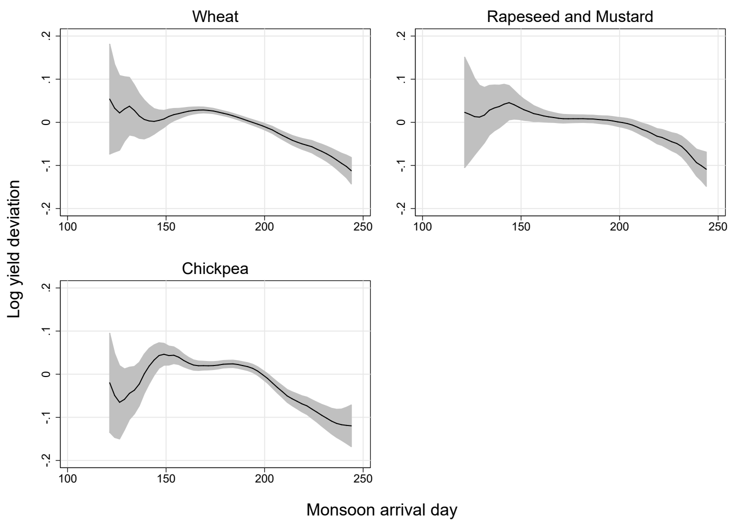
Note: This figure presents average 10 year rolling variance estimates for the rainfall arrival day over the period 1966-2015.

Figure 5: **Crop yield deviation and timing of monsoon**

(a) Kharif

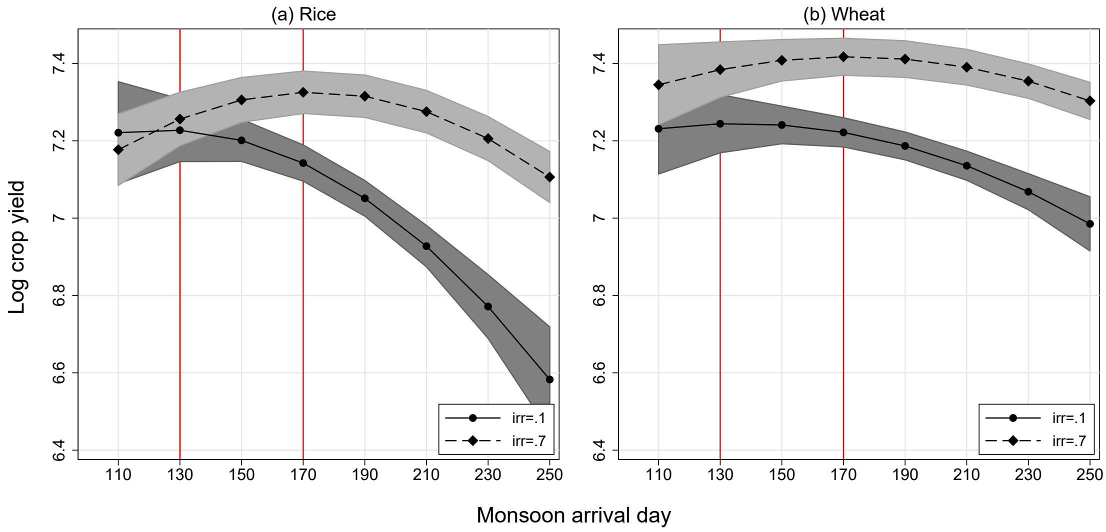


(b) Rabi



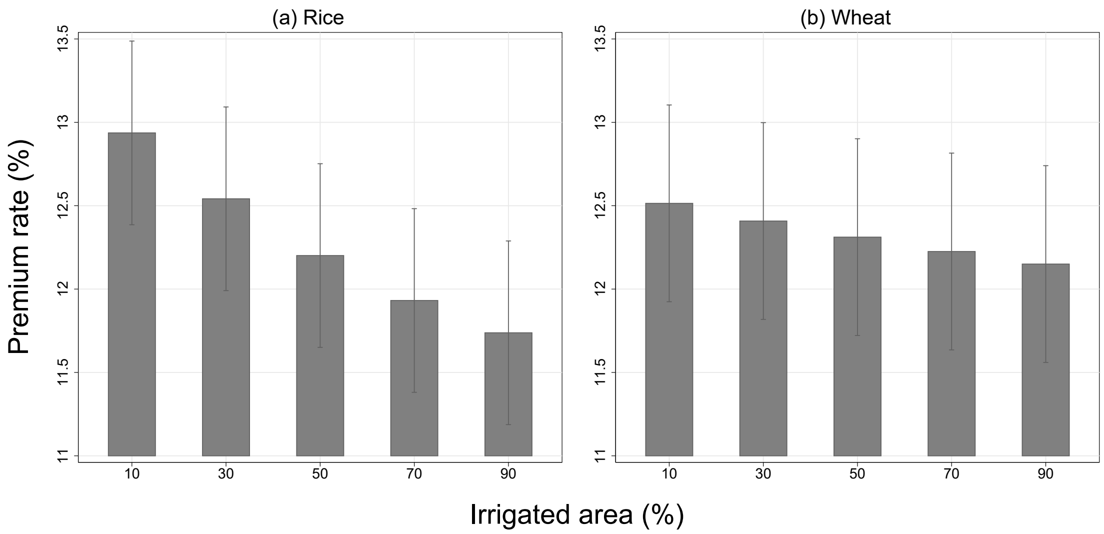
Note: This figure presents the relationship between crop yield deviation from an exponential trend and the monsoon arrival day for different crops.

Figure 6: **Role of irrigation in reducing yield loss due to delayed monsoon**



Note: The vertical lines mark the maximum of the curves. *IRR* represents the share of cropped area irrigated.

Figure 7: **Simulated premium rates for crops at different levels of irrigation**



Note: This figure shows the fair premium rates at different level of irrigation for rice and wheat crops respectively.

Tables

Table 1: **Summary statistics**

Statistic	Rainfall arrival day	Total rainfall in MJJA (mm)	Rainy days in MJJA
Minimum	121	15	15
Mean	189	894	96
Median	186	808	100
Maximum	244	5431	122
Standard deviation	21	547	18

Table 2: **Trends in timing of monsoon and probability of delayed monsoon during 1966-2015**

	(1)	(2)
	Rainfall arrival day	Delayed monsoon
Year	0.024*	0.001***
	(0.014)	(0.000)
Observations	15,550	15,550
R-squared	0.092	0.009
District FE	Yes	Yes
Mean of the dependent variable	188	0.14

Note: ***, **, and * represent the significance level at 1%, 5%, and 10% respectively. Standard errors have been shown in the parentheses. Standard errors have been clustered at the district level.

Table 3: **Correlation between crop yield deviation and monsoon arrival day**

Season	Crop	Correlation
Kharif	Rice	-.189***
	Sorghum	-.145***
	Pearl Millet	-.206***
	Maize	-.076***
	Finger Millet	-.094***
	Pigeonpea	-.109***
	Groundnut	-.175***
	Cotton	-.074***
Rabi	Wheat	-.116***
	Rapeseed and Mustard	-.059***
	Chickpea	-.101***

Note: ***, **, and * represent the significance level at 1%, 5%, and 10% respectively.

Table 4: **Estimated regression coefficients of Equation** (2)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Variables	Rice	Sorghum	Pearl Millet	Maize	Finger Millet	Pigeonpea	Groundnut	Cotton	Wheat	Rapeseed and Mustard	Chickpea
	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Rabi	Rabi	Rabi
RD	-0.0032***	-0.0036***	-0.0050***	-0.0016***	-0.0016***	-0.0025***	-0.0035***	-0.0017***	-0.0017***	-0.0011***	-0.0019***
	(0.0003)	(0.0004)	(0.0005)	(0.0002)	(0.0002)	(0.0003)	(0.0005)	(0.0003)	(0.0002)	(0.0002)	(0.0002)
Constant	7.7936***	7.1791***	7.4399***	7.4573***	7.0234***	6.9453***	7.4651***	5.5982***	7.6096***	6.5730***	6.8246***
	(0.0511)	(0.0750)	(0.0896)	(0.0423)	(0.0411)	(0.0479)	(0.0888)	(0.0601)	(0.0324)	(0.0293)	(0.0413)
Observations	14,412	11,077	9,542	13,569	5,665	12,513	11,567	7,469	13,202	11,128	13,317
R-squared	0.7698	0.6226	0.6685	0.6457	0.7172	0.5399	0.5193	0.6486	0.8108	0.6970	0.5415
Dist FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dist x Time Trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R-Squared	0.760	0.603	0.650	0.629	0.697	0.517	0.495	0.628	0.802	0.681	0.520
F stat	143.1	80.68	111.9	50.78	52.48	97.35	56.06	28.38	95.58	53.09	77.62
Average yield in kilogram per hectare	2426	907	1189	2701	1547	708	1371	409	3116	1222	900
% loss due to delay in arrival by 10 days	3.2	3.6	5	1.6	1.6	2.5	3.5	1.7	1.7	1.1	1.9
Loss in kilogram per hectare due to delay in arrival by 10 days	77.63	32.65	59.45	43.22	24.75	17.7	47.98	6.95	52.97	13.44	17.1

Note: Each column represents the results from different fixed effects regression specifications. The fixed effects associated with the specification are shown in the respective column. RD represents the day of monsoon arrival. ***, **, and * represent the significance level at 1%, 5%, and 10% respectively. Standard errors are in the parentheses. Standard errors are robust to serial correlation and heteroscedasticity within districts.

Table 5: **Relationship of volume and frequency of seasonal rainfall with timing of monsoon**

	(1)	(2)
Variables	Total rainfall in MJJA	Number of rainy days in MJJA
Rainfall arrival day	-7.684***	-0.171***
	(0.246)	(0.007)
Observations	15,550	15,550
R-squared	0.859	0.777
District FE	Yes	Yes
Adjusted R-squared	0.856	0.772
F stat	976	580.9
Mean of dependent variable	894	96.31
% reduction due to delay in arrival by 10 days	8.6	1.8
Absolute reduction due to a delay in rainfall arrival by 10 days	76.8	1.7

Note: Each column represents the results from different fixed effects regression specifications. The fixed effects associated with each specification are shown in the respective column. The dependent variables are the total rainfall and the number of rainy days in the months of the May, June, July, and August (MJJA). ***, **, and * represents the significance level at 1%, 5%, and 10% respectively. Standard errors are in the parentheses. Standard errors are robust to serial correlation and heteroscedasticity within districts.

Table 6: **Estimated regression coefficients of Equation (2) with timing of monsoon and total seasonal rainfall**

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Variables	Rice	Sorghum	Pearl Millet	Maize	Finger Millet	Pigeonpea	Groundnut	Cotton	Wheat	Rapeseed and Mustard	Chickpea
	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Rabi	Rabi	Rabi
RD	-0.0014***	-0.0031***	-0.0042***	-0.0027***	-0.0015***	-0.0014***	-0.0027***	-0.0017***	-0.0005**	-0.0004**	-0.0003
	(0.0002)	(0.0004)	(0.0004)	(0.0003)	(0.0002)	(0.0003)	(0.0004)	(0.0003)	(0.0002)	(0.0002)	(0.0002)
Total rainfall in MJJA	0.0002***	0.0001**	0.0001***	-0.0001***	0.0000	0.0002***	0.0001***	-0.0000	0.0001***	0.0001***	0.0002***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Constant	7.2281***	7.0293***	7.2215***	7.7934***	6.9851***	6.5957***	7.2119***	5.6113***	7.2616***	6.3582***	6.3408***
	(0.0570)	(0.0753)	(0.0878)	(0.0658)	(0.0523)	(0.0644)	(0.0746)	(0.0727)	(0.0461)	(0.0528)	(0.0574)
Observations	14,412	11,077	9,542	13,569	5,665	12,513	11,567	7,469	13,202	11,128	13,317
R-squared	0.7757	0.6230	0.6693	0.6477	0.7173	0.5425	0.5214	0.6486	0.8132	0.6979	0.5483
Dist FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dist x Time Trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R-squared	0.766	0.603	0.650	0.632	0.697	0.520	0.497	0.628	0.805	0.682	0.527
F stat	74.40	40.95	57.69	50.24	28.34	68.93	28.36	16.70	90.97	32.12	72.76
Average yield in kilogram per hectare	2426	907	1189	2701	1547	708	1371	409	3116	1222	900
% loss due to delay in arrival by 10 days	1.4	3.1	4.2	2.7	1.5	1.4	2.7	1.7	0.5	0.4	0.3
Loss in kilogram per hectare due to delay in arrival by 10 days	33.96	28.12	49.94	72.93	23.21	9.91	37.02	6.95	15.58	4.89	2.70

Note: Each column represents the results from different fixed effects regression specifications. The fixed effects associated with the specification are shown in the respective column. The dependent variable is the log of crop yield for different crops in the Kharif and Rabi seasons. RD represents the monsoon arrival day. Total rainfall in MJJA is the total amount of rainfall in the months of May, June, July, and August. ***, **, and * represent the significance level at 1%, 5%, and 10% respectively. Standard errors have been shown in the parentheses and have been clustered at the district level.

Table 7: **Estimated regression coefficients of Equation** (3)

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	Rice	Sorghum	Pearl Millet	Maize	Finger Millet	Pigeonpea	Groundnut	Cotton	Wheat	Rapeseed and Mustard	Chickpea
	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Rabi	Rabi	Rabi
RD	0.0094***	0.0287***	0.0306***	0.0225***	0.0127***	0.0096***	0.0201***	0.0170***	0.0079***	0.0062**	0.0123***
	(0.0020)	(0.0036)	(0.0048)	(0.0029)	(0.0022)	(0.0034)	(0.0053)	(0.0041)	(0.0020)	(0.0025)	(0.0025)
$RD \times RD$	-0.0000***	-0.0001***	-0.0001***	-0.0001***	-0.0000***	-0.0000***	-0.0001***	-0.0000***	-0.0000***	-0.0000***	-0.0000***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Constant	6.5912***	4.0954***	4.0244***	5.1695***	5.6752***	5.7947***	5.2137***	3.8153***	6.6922***	5.8740***	5.4676***
	(0.1813)	(0.3255)	(0.4300)	(0.2676)	(0.2095)	(0.3137)	(0.4760)	(0.3836)	(0.1878)	(0.2373)	(0.2340)
Observations	14,412	11,077	9,542	13,569	5,665	12,513	11,567	7,469	13,202	11,128	13,317
R-squared	0.7706	0.6265	0.6727	0.6483	0.7187	0.5407	0.5234	0.6501	0.8113	0.6973	0.5429
Dist FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dist x Time Trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R-squared	0.760	0.607	0.654	0.632	0.699	0.518	0.499	0.629	0.803	0.681	0.522
F stat	75.87	50.91	62.31	46.38	40.86	49.59	36.68	19.38	52.57	28.84	43.24
Sasabuchi–Lind–Mehlum test											
H_0 : Monotone or U shape											
H_1: Inverse U shape (t-statistic)	1.48*	6.42***	5.63***	6.74***	3.23***	3.02**	5.92***	3.72***	2.39***	5.89***	5.34***

Note: Each column represents the results from different fixed effects regression specifications. The fixed effects associated with the specification are shown in the respective column. RD represents the rainfall arrival day. We have also presented the results of SLM test. ***, **, and * represent the significance level at 1%, 5%, and 10% respectively. Standard errors are in the parentheses. Standard errors are robust to serial correlation and heteroscedasticity within district.

Table 8: **Estimated regression coefficients of Equation (4)**

Variables	(1) Rice	(2) Sorghum	(3) Pearl Millet	(4) Maize	(5) Finger Millet	(6) Pigeonpea	(7) Groundnut	(8) Cotton	(9) Wheat	(10) Rapeseed and Mustard	(11) Chickpea
	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Rabi	Rabi	Rabi
RD	0.00959*	0.05285***	0.06264***	0.03662***	0.01414***	0.01294*	0.03414***	0.03464***	0.00528	0.00664	0.01190**
	(0.00521)	(0.00634)	(0.01021)	(0.00634)	(0.00541)	(0.00725)	(0.01279)	(0.00814)	(0.00365)	(0.00519)	(0.00515)
$RD \times RD$	-0.00004***	-0.00015***	-0.00018***	-0.00010***	-0.00004***	-0.00004**	-0.00010***	-0.00009***	-0.00002**	-0.00002	-0.00004***
	(0.00001)	(0.00002)	(0.00003)	(0.00002)	(0.00001)	(0.00002)	(0.00003)	(0.00002)	(0.00001)	(0.00001)	(0.00001)
IRR	-0.66111	5.59559***	6.14564***	2.48439**	0.27544	0.26014	2.50900	4.90591***	-0.02297	-0.26102	-0.39362
	(0.78814)	(1.11444)	(1.46802)	(1.00337)	(1.03034)	(1.18170)	(1.94904)	(1.62911)	(0.66658)	(0.88681)	(0.92965)
$RD \times IRR$	0.00472	-0.05994***	-0.06923***	-0.02616**	-0.00274	-0.00372	-0.02978	-0.04702***	0.00171	0.00381	0.00369
	(0.00848)	(0.01147)	(0.01576)	(0.01058)	(0.01117)	(0.01243)	(0.02047)	(0.01674)	(0.00672)	(0.00926)	(0.00970)
$RD \times RD \times IRR$	0.00001	0.00017***	0.00020***	0.00007***	0.00001	0.00002	0.00010*	0.00012***	0.00000	-0.00001	-0.00000
	(0.00002)	(0.00003)	(0.00004)	(0.00003)	(0.00003)	(0.00003)	(0.00006)	(0.00004)	(0.00002)	(0.00002)	(0.00003)
Constant	6.67154***	1.81603***	1.12895	3.82448***	5.55008***	5.49922***	3.97158***	1.95170**	6.87618***	5.78308***	5.51691***
	(0.47169)	(0.59123)	(0.93364)	(0.59813)	(0.49888)	(0.67706)	(1.18890)	(0.78367)	(0.35495)	(0.49014)	(0.47989)
Observations	12,635	10,366	8,947	11,897	5,087	11,024	10,455	6,679	11,471	9,588	11,810
R-squared	0.77417	0.63458	0.67590	0.64486	0.71901	0.55329	0.51814	0.63363	0.83097	0.70761	0.55848
Dist FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dist x Time Trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R-squared	0.763	0.615	0.657	0.626	0.698	0.529	0.492	0.611	0.822	0.689	0.535
F stat	43.63	22.91	32.87	22.83	20.70	21.48	21.26	9.110	28.66	13.26	21.01
Average Marginal Effects											
RD	-0.00339***	-0.00276***	-0.00416***	-0.00115***	-0.00159***	-0.00223***	-0.00305***	-0.00112***	-0.00147***	-0.000954***	-0.00167***
	(0.000259)	(0.000358)	(0.000371)	(0.000711)	(0.000239)	(0.000268)	(0.000336)	(0.00115)	(0.000359)	(0.00115)	(0.000359)
IRR	0.435***	0.309**	0.334**	0.169**	0.212***	0.265**	0.322**	0.305*	0.373***	0.274***	0.203**
	(0.0858)	(0.134)	(0.136)	(0.000248)	(0.0794)	(0.000251)	(0.000977)	(0.000359)	(0.0704)	(0.000181)	(0.0843)
Average yield in kilogram per hectare	2426	907	1189	2701	1547	708	1371	409	3116	1222	900
% Loss due to delay in arrival by 10 days	3.4	2.8	4.2	1.1	1.6	2.2	3.1	1.1	1.5	1.0	1.7
Loss in kilogram per hectare due to delay in arrival by 10 days	82.48	25.40	49.94	29.71	24.75	15.58	42.50	4.50	46.74	12.22	15.30
Tests of hypotheses (at mean of RD and IRR)	[186, 0.318]	[187, 0.316]	[188, 0.349]	[186, 0.321]	[186, 0.297]	[186, 0.331]	[187, 0.323]	[189, 0.297]	[186, 0.291]	[187, 0.336]	[186, 0.306]
$H_0 : Loss = 0$	-0.00360***	-0.00256***	-0.00409***	-0.000921***	-0.00143***	-0.00226***	-0.00310***	-0.000892***	-0.0016***	-0.0010***	-0.0016***
	(0.000284)	(0.00116)	(0.000358)	(0.0708)	(0.000253)	(0.000839)	(0.000326)	(0.000320)	(0.0002)	(0.0002)	(0.0002)
$H_0 : \Delta Loss(IRR) = 0$	0.00683***	0.00272**	0.00649***	0.00104***	0.00194**	0.00359***	0.00587***	-0.00207**	0.0025***	0.0019***	0.0030***
	(0.000797)	(0.000370)	(0.00116)	(0.000228)	(0.000946)	(0.119)	(0.133)	(0.177)	(0.0006)	(0.0007)	(0.0007)

Note: Each column represents the results from different fixed effects regression specifications. The fixed effects associated with the specification are shown in the respective column. RD represents the rainfall arrival day and IRR represents the share of cropped area irrigated. ***, **, and * represent the significance level at 1%, 5%, and 10% respectively. Standard errors are in the parentheses. Standard errors are robust to serial correlation and heteroscedasticity within district.

Table 9: **Estimated marginal effects of monsoon arrival at different levels of irrigation**

		10	30	50	70	90
Kharif Season	Rice	-0.007	-0.005	-0.004	-0.003	-0.001
		(0.0009)	(0.0006)	(0.0004)	(0.0003)	(0.0005)
	Sorghum	-0.009	-0.007	-0.005	-0.003	-0.001
		(0.001)	(0.0007)	(0.0006)	(0.0006)	(0.0008)
	Pearl Millet	-0.013	-0.001	-0.007	-0.004	-0.001
		(0.0014)	(0.001)	(0.0006)	(0.0005)	(0.0008)
	Maize	-0.005	-0.005	-0.004	-0.003	-0.002
		(0.0007)	(0.0005)	(0.0004)	(0.0004)	(0.0005)
	Finger Millet	-0.004	-0.003	-0.003	-0.002	-0.002
		(0.0007)	(0.0004)	(0.0003)	(0.0005)	(0.0008)
	Pigeon pea	-0.005	-0.004	-0.003	-0.002	-0.001
		(0.0008)	(0.0006)	(0.0005)	(0.0005)	(0.0007)
	Groundnut	-0.009	-0.007	-0.005	-0.003	-0.001
		(0.0017)	(0.0011)	(0.0006)	(0.0005)	(0.001)
	Cotton	-0.004	-0.003	-0.003	-0.002	-0.001
		(0.0008)	(0.0006)	(0.0005)	(0.0006)	(0.0008)
Rabi Season	Wheat	-0.003	-0.002	-0.002	-0.001	-0.001
		(0.0004)	(0.0003)	(0.0002)	(0.0002)	(0.0003)
	Rapeseed and Mustard	-0.002	-0.002	-0.002	-0.001	-0.001
		(0.0005)	(0.0004)	(0.0003)	(0.0003)	(0.0004)
	Chickpea	-0.004	-0.003	-0.003	-0.002	-0.002
		(0.0006)	(0.0004)	(0.0003)	(0.0004)	(0.0005)

Note: Each column represents the point estimates of losses incurred due to delay in monsoon onset and are calculated at the 210^{th} day of monsoon onset which is one standard deviation above mean arrival day. Standard errors have been shown in parentheses.

Table 10: **Crop yield loss due to an extreme delay in monsoon arrival at different levels of irrigation (in kilogram per hectare)**

	Crop	10	30	50	70	90
Kharif Season	Rice	16.98	13.58	10.19	6.55	3.15
	Sorghum	8.34	6.44	4.63	2.72	0.90
	Pearl Millet	15.10	11.53	7.96	4.28	0.71
	Maize	14.85	12.42	9.99	7.83	5.40
	Finger Millet	5.88	5.10	4.33	3.56	2.78
	Pigeon pea	3.54	2.90	2.27	1.63	0.99
	Groundnut	11.93	9.19	6.31	3.56	0.82
	Cotton	1.55	1.31	1.10	0.86	0.61
Rabi Season	Wheat	9.35	7.48	5.92	4.36	2.80
	Rapeseed and Mustard	2.93	2.57	2.20	1.83	1.34
	Chickpea	3.60	3.15	2.70	2.25	1.80

Note: Each column represents the amount of yield loss due to an extreme delay in monsoon onset. The losses are calculated from the estimated marginal effects in 9 at the 210^{th} day of monsoon arrival which is one standard deviation above mean arrival day.

Table 11: **Average premium rate at different levels of irrigation**

	Crops	10	30	50	70	90
Kharif Season	Rice	12.94	12.54	12.20	11.93	11.74
		(4.63)	(4.72)	(4.81)	(4.87)	(4.87)
	Sorghum	13.75	12.79	11.86	10.99	10.20
		(7.20)	(7.18)	(7.19)	(7.23)	(7.26)
	Pearl Millet	18.42	17.16	15.95	14.82	13.82
		(6.21)	(6.20)	(6.24)	(6.31)	(6.37)
	Maize	13.94	13.54	13.14	12.76	12.40
		(6.41)	(6.42)	(6.44)	(6.46)	(6.47)
	Finger Millet	8.58	8.34	8.11	7.90	7.70
		(5.26)	(5.28)	(5.30)	(5.33)	(5.35)
	Pigeon pea	8.15	7.77	7.42	7.10	6.84
		(4.82)	(4.92)	(5.00)	(5.08)	(5.14)
	Groundnut	12.08	11.16	10.28	9.50	8.89
		(5.11)	(5.22)	(5.37)	(5.54)	(5.62)
	Cotton	14.90	14.27	13.68	13.14	12.67
		(7.01)	(6.99)	(6.97)	(6.93)	(6.86)
Rabi Season	Wheat	12.51	12.41	12.31	12.23	12.15
		(4.82)	(4.87)	(4.92)	(4.95)	(4.96)
	Rapeseed and Mustard	11.75	11.70	11.64	11.60	11.56
		(5.07)	(5.09)	(5.10)	(5.10)	(5.09)
	Chickpea	10.13	10.02	9.92	9.84	9.77
		(5.81)	(5.86)	(5.90)	(5.93)	(5.95)

Note: This table presents the summary statistics of the simulated premium rates at different levels of area under irrigation. Standard deviations are in parentheses.

Appendix

Table A1: **Hausman test statistics (Fixed effects vs. Random effects)**

Season	Variables	Log linear	Log quadratic
Kharif	Log of Rice yield chi2 (302)	2198***	1486***
	Log of Sorghum yield chi2 (265)	1969***	1736***
	Log of Pearl Millet yield chi2 (246)	1214***	1105***
	Log of Maize yield chi2 (295)	2032***	1764***
	Log of Finger Millet yield chi2 (176)	883***	745***
	Log of Pigeonpea yield chi2 (280)	1848***	1551***
	Log of Groundnut yield chi2 (266)	1921***	1780***
	Log of Cotton yield chi2 (191)	1368***	1118***
Rabi	Log of Wheat yield chi2 (280)	2709***	2433***
	Log of Rapeseed and Mustard yield chi2 (278)	2414***	2025***
	Log of Chickpea yield chi2 (292)	2289***	1901***

***, **, and * represent the significance level at 1%, 5%, and 10% respectively.

Table A2: **Modified Wald test for heteroskedasticity**

Season	Variables	Log linear	Log quadratic
Kharif	Log of Rice yield chi2 (307)	121254***	74212***
	Log of Sorghum yield chi2 (270)	13732656***	1.155e+52***
	Log of Pearl Millet yield chi2 (257)	1.204e+52***	3.251e+08***
	Log of Maize yield chi2 (298)	50314***	6934730***
	Log of Finger Millet yield chi2 (194)	8.028e+53***	7786754***
	Log of Pigeonpea yield chi2 (284)	2422078***	2.861e+54***
	Log of Groundnut yield chi2 (269)	2.121e+11***	2.201e+55***
	Log of Cotton yield chi2 (204)	7.259e+50***	4.765e+55***
Rabi	Log of Wheat yield chi2 (288)	4.067e+53***	48293***
	Log of Rapeseed and Mustard yield chi2 (288)	1.117e+54***	4.293e+51***
	Log of chickpea yield chi2 (295)	1.270e+54***	3.943e+09***

***, **, and * represent the significance level at 1%, 5%, and 10% respectively.

Table A3: **Lagged effects of monsoon arrival on crop yields**

Variables	(1) Rice	(2) Sorghum	(3) Pearl Millet	(4) Maize	(5) Finger Millet	(6) Pigeonpea	(7) Groundnut	(8) Cotton	(9) Wheat	(10) Rapeseed and Mustard	(11) Chickpea
	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Kharif	Rabi	Rabi	Rabi
RD_{it}	-0.0032***	-0.0037***	-0.0050***	-0.0017***	-0.0017***	-0.0025***	-0.0035***	-0.0018***	-0.0017***	-0.0011***	-0.0019***
	(0.0003)	(0.0004)	(0.0005)	(0.0002)	(0.0002)	(0.0003)	(0.0005)	(0.0003)	(0.0002)	(0.0002)	(0.0002)
RD_{it-1}	0.0001	-0.0004**	0.0004	-0.0004**	-0.0004*	-0.0003	0.0004**	-0.0010***	-0.0004***	0.0001	0.0000
	(0.0002)	(0.0002)	(0.0003)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0003)	(0.0001)	(0.0002)	(0.0002)
RD_{it-2}	-0.0001	-0.0002	0.0001	0.0000	-0.0002	0.0007***	-0.0001	0.0002	-0.0000	0.0002	0.0004**
	(0.0001)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0003)	(0.0001)	(0.0002)	(0.0002)
Constant	7.8071***	7.3429***	7.3693***	7.5674***	7.1593***	6.8781***	7.4032***	5.7805***	7.7120***	6.5282***	6.7503***
	(0.0752)	(0.1019)	(0.1305)	(0.0755)	(0.0785)	(0.0893)	(0.1187)	(0.1420)	(0.0624)	(0.0819)	(0.0879)
Observations	13,842	10,628	9,166	13,069	5,404	12,067	11,130	7,178	12,699	10,766	12,792
R-squared	0.7732	0.6181	0.6689	0.6580	0.7301	0.5652	0.5168	0.6496	0.8189	0.7010	0.5422
Dist FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dist x Time Trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R-Squared	0.763	0.597	0.649	0.642	0.710	0.543	0.491	0.628	0.810	0.684	0.520
F stat	55.92	29.49	39.54	22.90	20.68	39.17	26.50	13.74	29.33	20.90	36.89

Note: Each column represents the results from different fixed effects regression specifications. The fixed effects associated with the specification are shown in the respective column. RD represents the day of monsoon arrival. ***, **, and * represent the significance level at 1%, 5%, and 10% respectively. Standard errors are in the parentheses. Standard errors are robust to serial correlation and heteroscedasticity within districts.