Sam Houston State University
Department of Economics and International Business
Working Paper No. 17-05
December 2017

CLIMATE CHANGE AND INDIAN AGRICULTURE: IMPACTS ON CROP YIELD

Raju Mandal
Assam University
Silchar, Cachar, Assam 788011 (India);
rajum06@gmail.com

Hiranya Nath
Department of Economics and International Business
Sam Houston State University
Huntsville, TX, USA
eco_hkn@shsu.edu

Abstract

This paper reviews the extant literature on the impacts of climate change on agriculture. We first discuss various methodologies used to study climatic impacts on crop yield. We then present a brief survey of studies from across the globe followed by a discussion on India-specific research. The empirical evidence on the effects of climate change on agriculture has been mixed: while some studies find evidence of adverse impacts others report evidence of positive effects. Applying nonparametric median regression technique to state-level time series data on average yield of rice and wheat, and on temperature and rainfall from 1968 to 2001, we further investigate the impacts of changes in these climate variables on rice and wheat yields in India. The results indicate that rising temperature has a significant negative impact and rising rainfall variability has a significant positive impact on the average rice yield. Furthermore, an increase in temperature variability over the crop year appears to have a significant positive impact on wheat yield.

***Keywords*:** India; Rice yield; Wheat yield; Climate change; Median regression

***JEL Codes*:** Q11; Q54

Acknowledgments: An abridged version of this paper has been published as a chapter under the same title in Goswami, B., Bezbaruah, M. P., and Mandal, R. (eds). Indian Agriculture after the Green Revolution: Changes and Challenges. Abingdon (UK) and New York (USA): Routledge (2017). This paper was written when Nath was a Visiting Professor at the Department of Humanities and Social Sciences, Indian Institute of Technology Guwahati, Assam, India, during the 2016-17 academic year.

Climate Change and Indian Agriculture: Impacts on Crop Yield

1. Introduction

There has been indisputable evidence of changes in temperature, precipitation, and extreme weather events. However, there is less of a consensus as to what causes these climatic changes. Since agriculture depends critically on the climatic factors, it is expected that such changes in the climate would have impacts on different aspects of agriculture. The anticipated drastic changes in temperature and rainfall patterns around the globe over the next century are likely to exacerbate the impact on agricultural productivity. Furthermore, people adapt their agricultural practices and cropping patterns in response to the evolving weather patterns. These adaptations too have an impact on agriculture. Thus, there are direct as well as indirect impacts of climate change. The study of the impacts of climate change on agriculture is extremely important particularly in the context of developing countries where a sizable portion of the population relies on agriculture for life and livelihood.

Agriculture plays a vital role in the Indian economy. Together with fishery and forestry, it accounts for about 18% of its gross domestic product (GDP). Over 58% of the rural households depend primarily on agriculture for their livelihood. Thus, it is extremely important to know the impacts of changes in weather conditions and the climate on agricultural productivity and growth. It is in this context that this paper reviews the extant literature on climatic impacts on agriculture with a special focus on the studies that have been conducted on India. The empirical evidence on the effects of climate change on agriculture has been mixed. Applying nonparametric median regression technique to state-level time series data on average yield of rice and wheat, and on temperature and rainfall, the present study further investigates the impacts of changes in these climate variables on the yields of these two crops. The results indicate that rising temperature has a significant negative impact while rising rainfall variability has a significant positive impact on the average rice yield. Furthermore, increasing temperature variability over the crop year appears to have a significant positive impact on wheat yield.

The rest of the paper is organized as follows. Section 2 discusses various methodologies and theoretical frameworks that are used to examine the impact of climate change on agriculture. In section 3, we discuss empirical evidence of climate change effects on agriculture in different parts of the world as documented in the extant literature. Section 4 presents evidence of the impacts of climate change on Indian agriculture from existing literature. We organize and discuss these empirical studies according to the methodological strands to which they belong. In section 5, we report and discuss the results from our own estimate of climatic impacts on Indian agriculture using state-level data. The final section includes our concluding remarks.

2. Methodologies for Studying Impacts of Climate Change

There are two major methodologies that have been used by the existing studies on the impacts of climate change on crop yield: agronomic or simulation method and observational method (Barnwal and Kotani, 2013).

2.1 Agronomic/Crop Modeling/Simulation Method

The agronomic or simulation models create a laboratory-type environment and examine the response of crop growth to varying climatic conditions like temperature and CO2 levels in controlled experiments.[4] In these models, the changes in crop growth and yield are simulated using experimental functional relationships (Kumar and Parikh, 2001). The advantage of these models is their ability to experimentally assess how plants respond to climate adjustments in the absence of other confounding factors (Moorthy et al, 2012). The studies that use this methodology include Adams et al (1990), Kaiser et al (1993), Rosenzweig and Parry (1994), Mearns et al (1997), Aggarwal and Sinha (1993), Lal et al (1998), and Aggarwal and Mall (2002). However, the disadvantage of this approach is that it fails to capture the adaptation measures that may be taken by the farmers in response to climate change. For example, the farmers may respond to changes in climate by altering their mix of crops, changing plantation

---

[4] White et al (2011) review the methodology for simulating impact of climate change on agriculture in details.

dates, and using inputs like fertilizers. By not allowing a complete range of adjustments, these studies overestimate damages from environmental changes (Mendelsohn et al, 1994).

Some researchers use agronomic-economic models that combine agronomic and economic models. This agronomic–economic approach first uses experiments on crops under different controlled conditions. By changing temperature, precipitations, and CO2 levels they try to find out how these factors change crop yields. These changes on crop yields are then fed into economic models that explain crop choice, productivity, and market prices (Mendelsohn, 2007).

2.2 Observational Method

This method uses observed climate data along with other variables to examine the impact of climate change on crop yield. According to Schlenker and Lobell (2010), the observational method is preferred to the simulation method as it allows investigation of how farmers react to weather shocks given various other constraints such as credit markets, lack of required inputs, while the simulation method usually has to make assumptions about these parameters. The observational method applies appropriate estimation techniques to cross-section, time series, as well as panel data.

In the cross section studies, the variations in the effect of climate change emanate from the geographic and climatic diversity across space. Using farm prices (i.e., land values) or revenues, these studies (e.g. Mendelsohn et al, 1994) account for the direct impacts of climate on yields of different crops as well as the indirect substitution of different inputs, introduction of different activities, and other potential adaptations to different climate. When farm performance is compared across space, the observation already includes all the changes each farmer has made to obtain the most from his own farm (Sanghi and Mendelsohn, 2008). Mendelsohn et al (1994) term it as the *Ricardian model*, named after David Ricardo, an Italian economist who first noted that farm property values reflect net productivity of the land. This is also known as the *hedonic approach* because it tries to find out how variations in the climatic conditions across geographical areas cause variations in land values or net revenue which is then used to infer the magnitude of climatic impact on agriculture.

The advantage of this method is that it takes into consideration the farm level adaptation. The farms in diverse environments could adapt their technologies and crop choices to suit their region (Moorthy et al, 2012). Thus, these studies account for some long-term adjustments to climate changes. However, a major limitation of the Ricardian approach is the omitted variable bias because it does not take into account time-independent location-specific factors. Notwithstanding these limitations, the Ricardian model has been used by many studies in different contexts. Examples of such studies include Mendelsohn et al (1994), Mendelsohn et al (1996), Mendelsohn and Rosenberg (1994), Kumar and Parikh (2001), Gbetibouo and Hassan (2005). The traditional Ricardian model as developed by Mendelsohn et al (1994) captures adaptation in its measurement of impacts, but the adaptations are a black box, meaning they are never explicitly measured or identified (Seo and Mendelsohn, 2008). Recently some researchers have used a *Structural Ricardian model* to explicitly identify farmers' adaptation measures and their impact on the farms. The adaptation measures include irrigation, crop choice, and livestock species choice (Kurukulasuriya and Mendelsohn, 2008; Seo and Mendelsohn, 2008).

In studies using time series and panel data, researchers often use a *stochastic production function approach* developed by Just and Pope (1978). The beauty of this approach is that while others seek to estimate the impact of climate change on mean yield, it captures the impact on both mean and variability of yields. Another advantage of this method is that it does not impose dependence between the effect on yield variability and on mean yield of a crop (Chen et al, 2004). Chen et al (2004) did some important work using this approach and many others followed (Isik and Devadoss, 2006; McCarl et al, 2008; Cabas et al, 2010; Poudel and Kotani, 2013).

The panel data models use data on relevant variables at various levels of spatial disaggregation: country, state, district, and so on. By introducing time-invariant spatial (cross-section) fixed effects, as claimed by Deschenes and Greenstone (2008), it offers a possible solution to the omitted variable bias. Schlenker and Lobell (2010) also discuss other advantages of using panel data model. The primary limitation of this approach, however, is that farmers cannot implement the full range of adaptations in response to a single year's weather realization, and consequently its estimates may overstate the damages associated with climate change (Deschenes and Greenstone, 2008). Other studies that use panel data approach include Guiteras (2009), Schlenker and Roberts (2009), Schlenker and Lobell (2010) and Lobell et al (2011).

Some recent research use quantile regression (QR) technique. Unlike the conventional parametric linear regression techniques, this non-parametric approach allows to consider the climatic impacts on the entire distribution of rice yield and not merely on its conditional mean. Thus, it provides a richer characterization of the data by uncovering the heterogeneity in the impacts of climatic changes. This is important because, as Barnwal and Kotani (2013) argue, the potential non-stationarity of climatic variables and crop yield unfolds the possibility of asymmetric effects of temperature, rainfall, and other covariates across the conditional distribution of rice yield. Other advantages of QR over ordinary least square (OLS) regression include the fact that while OLS estimates can be inefficient in case of non-normal errors, QR estimates are robust to non-normal errors and outliers. Furthermore, by allowing for different coefficients at different quantiles, the technique takes care of potential heteroskedasticity. The relatively limited number of studies that use this technique include Barnwal and Kotani (2013), Krishnamurthy (2012), Sarkar et al (2012), and Mandal and Nath (2017).

3. The Impacts of Climate Change on Agriculture: Empirical Evidence From across the Globe

There is a substantial empirical literature on how climate changes impact agriculture using data on various crops from different parts of the world. The initial studies mostly focused on developed countries (e.g., Kaiser et al, 1993; Mendelsohn et al, 1994; Adams et al, 1998; Lewandrowski and Schimmelpfennig, 1999). However, some of the relatively recent studies examine climatic impacts on agriculture in developing countries as well (e.g., Sanghi and Mendelsohn, 2008; Moula, 2009; Deressa and Hassan, 2009; Sarker et al, 2012; Poudel and Kotani, 2013). This section reviews this literature that investigates the climate change impacts on agriculture drawing empirical evidence from both developed and developing countries. It especially focuses on the nature of impacts and its geographical characterization.

The empirical literature demonstrates that there have been considerable variations in the impacts of climate change on crop yield across regions and crops. These variations are primarily due to differences in the current levels of climatic conditions across geographical regions and also because of the fact that different crops have varied sensitivities to climatic conditions. An increase in temperature, for example, can have both positive and negative impact on crop yields depending on the latitude of a region and the temperature sensitivity of a particular crop. In the middle and high latitudes, increased temperatures lengthen growing seasons and expand crop producing areas pole-ward, thereby benefiting countries in these regions (Rosenzweig and Hillel, 1995). Further, as Parry et al (1999) show, climate change increases yields in high and mid-latitudes and decrease yields at lower latitudes. Rosenzweig and Iglesias (1994) further note that for a 4°C warming and assuming CO2 fertilization effect, yields in mid and high latitude countries (e.g. the northern U.S. and Canada) may increase, but yields in low latitude countries (e.g. Brazil) decline. Magrin et al (2005) in a study on Argentina find a positive impact of climate change on crop yields. Overall, the biophysical effects of climate change on agricultural production will be positive in some agricultural systems and regions, and negative in others, and these effects will also vary through time (Parry et al, 2004).

However, several other studies find temperature to have a negative impact on crop yields. This is mainly because an increase in temperature leads to higher respiration rates, speeding up of seed formation, and, consequently, to lower biomass production resulting in lower yields (Adams et al, 1998). This negative effect of temperature rise is especially pronounced in semi-tropical and tropical conditions because many crops are already at their tolerance limits of temperature in those regions (Jayaraman, 2011). Ortiz et al (2008) present evidence in support of this for wheat in certain zones of the Indo-Gangetic plains where optimal temperatures already exist. Even in high latitudes, temperature increases beyond 1–3°C would result in lower yields. Increase in precipitation, on the other hand, may benefit semi-arid and other water-short areas by increasing soil moisture while it may aggravate problems in regions with excessive water (Adams et al, 1998). Some of these results are also validated by Rosenzweig and Parry (1994) who find that while some countries in the temperate zone would benefit from climate change, many countries in the tropical and subtropical zones would be vulnerable to its adverse impacts.

The positive impacts of climate change as documented in some studies are mainly associated with the augmentation of CO2 concentration and partly due to moderate temperatures in high altitudes. An increase in CO2 concentration in the atmosphere enhances water use efficiency and net photosynthesis rate by crops thereby contributing to crop yield. Luo et al (2003) present evidence of increase in wheat yield under all scenarios of CO2 levels in South Australia. Climate change may indirectly affect crop production via changes in the incidence and distribution of pests and pathogens, increased rates of soil erosion and degradation, and increased tropospheric ozone levels due to rising temperatures and water run-off (Adams, 1986; Adams et al, 1998).

Attavanich and McCarl (2014) study the effects of increases in CO2 concentration and projected climate change on the mean and variance of U.S. yield for corn, sorghum, soybeans, winter wheat and cotton. In general, an increase in CO2 concentration leads to higher mean yields for these crops. Furthermore, increases in climate variability decreases mean crop yields and increases their variance. The effect of CO2 fertilization is generally found to be outweighing the effect of climate change on mean crop yields in many regions resulting in an increase in the yields of these crops.

Al-Bakri et al (2010) in their study on Jordan find the responses of wheat and barley to be different under different climate change scenarios. For both crops, there is a positive relationship between a change in rainfall and a change in expected yield. An increase in air temperature is expected to reduce yield of barley. In contrast, an increase in temperature is likely to increase wheat yield in most cases.

For South Africa, Benhin (2008) reports that a 1% increase in temperature leads to about US$ 80.00 increase in net crop revenue while a 1 mm/month fall in precipitation leads to US$ 2.00 fall with significant seasonal differences in impacts. Using selected climate scenarios, the study predicts that crop net revenues are expected to fall by as much as 90% by 2100 with small-scale farmers being most affected.

Researchers have also examined the effects of changes in temperature and rainfall variability on crop yield. Variability is measured either by temporal variations in these climate variables or by extreme (maximum and minimum) temperature or rainfall measures. For example, Cabas et al (2010) note that average crop yield increases with warmer temperatures and a longer growing season which is only partially offset by the decreases due to a rise in the variability of temperature and rainfall in Southwestern Ontario, Canada. The positive impact of a longer growing season offsets the negative effect of greater heat and rainfall variability resulting in higher average yields in the future.

Sarker et al (2012) in a study on climate change impact on yields of different varieties of rice in Bangladesh find that maximum temperature and rainfall have positive impact on *Aus* yield while maximum temperature and rainfall have positive impact and minimum temperature has negative impact on *Aman* yield. In contrast, they find that maximum temperature has a negative impact and minimum temperature has a positive impact on *Boro* yield.

Welch et al (2010) find that minimum temperature has negative and maximum temperature has positive impacts on rice yields in Asia. The negative impact could be explained by increased respiration losses during vegetative phase and reduced grain-filling duration and endosperm cell size during ripening phase. Chen et al (2004) while examining the impacts of annual average climate conditions on major agricultural crops across the U.S. find the effects to differ by crop. More rainfall causes corn yield levels to rise while decreasing yield variance. Temperature has the reverse effects. For sorghum, higher temperatures reduce yields and yield variability. More rainfall increases sorghum yields and yield variability.

Knox et al (2012) assess the projected impacts of climate change on the yield of eight major crops in Africa and South Asia using a systematic review and meta-analysis of data from 52 original publications. They show that the projected mean change in yield of all crops is −8% by the 2050s in both regions. Across Africa, estimated mean yield changes are found to be of the magnitudes of −17% (wheat), −5% (maize), −15% (sorghum) and −10% (millet) and across South Asia of −16% (maize) and −11% (sorghum). However, no mean change in yield is detected for rice.

Mendelsohn et al (1994) in their pioneering study note that higher winter and summer temperatures are harmful for crops while higher fall temperatures and higher winter and spring rainfall are beneficial for crops. Additionally, higher summer or fall rainfall is found to be harmful. Furthermore, they find evidence of non-linear impacts of climatic factors.

According to Mendelsohn (2007), the estimated global combined impacts of temperature and precipitation changes vary from a loss of 0.05% to a gain of 0.9% of agricultural GDP. The greenhouse effect is responsible for between 2.6% and 5.4% of the increase in agricultural production between 1960 and 2000. Most of this impact is due to the beneficial impacts of carbon fertilization. Consistent with the findings discussed above, climate change has also made some small contributions, generally helping mid and high latitude countries and slightly damaging low latitude countries. The percentage gains from warming, however, have been larger in developed countries (3–6%) compared to developing countries (0.4–2%).

A study on the climate sensitivity of Brazilian and Indian agriculture by Sanghi and Mendelsohn (2008) reports that temperature has a more powerful effect on farm values and net revenues than does precipitation. The study finds that if temperature rises by 2^0 C with an 8% increase in precipitation, agricultural net revenue may fall 12% in India and 20% in Brazil without carbon fertilization. Given a broader range of possible climates, global warming could cause annual damages in Brazil between 1% and 39% and between 4% and 26% in India by the end of the next century, although some of these effects may be potentially offset by carbon fertilization.

Seo et al (2005) find that while warming is harmful, increases in rainfall are beneficial for agriculture in Sri Lanka. The expected benefit ranges from 11 per cent to 122 per cent of the current net revenue. In contrast, the loss due to increases in the temperature ranges from 18 per cent to 50 per cent of the current agricultural productivity.

Isik and Devadoss (2006) examine the impact of climate change on crop yield and yield variability for wheat, barley, potato, and sugar beet yields in the state of Idaho in the US. Their results show that climate change has modest effects on the mean crop yields, but it significantly reduces the variance and covariance for most of the crops considered. Precipitation has a negative impact on the mean yield of wheat, barley, potato and sugar beets. Temperature has a positive impact on the mean yield of wheat, sugar beets and potato while it has a negative impact on the mean yield of barley and potato. Furthermore, increases in the rainfall and temperature tend to reduce the variability of wheat yields and barley. The effect of precipitation on potato yield variability is positive. The precipitation has a negative impact and the temperature has a positive impact on variance of sugar beet yields.

Poudel and Kotani (2013) examine the impact of climatic variations on yield and its variability for rice and wheat in central region of Nepal. An increase in the variance of both temperature and rainfall has adverse effects on crop production. But a change in the mean level of temperature and rainfall induces heterogeneous impacts depending on growing seasons, altitudes and types of crops grown. Moreover, climate variations induce greater impacts on rice yields while they do not seem to have much of an effect on wheat yields.

Deschenes and Greenstone (2007) predict that climate change will lead to a 4 percent increase in annual agricultural profits in the U.S. Moreover, the estimates of the effect of climate change on the value of agricultural land range from -18 percent to 29 percent.

Schlenker and Roberts (2009) find evidence of a non-linear impact of temperature rise on the crop yields in the U.S. According to them, yields increase up to a particular level of temperature beyond which the same decline. More specifically, yields increase with temperature up to 29° C for corn, 30° C for soybeans, and 32° C for cotton but temperatures above these thresholds are very harmful.

Schlenker and Lobell (2010) investigate the impact of climate change on five important African crops in sub-Saharan Africa (SSA) using the panel data model. They estimate that, by mid-century, the mean of aggregate production changes in SSA would be −22, −17, −17, −18, and −8% for maize, sorghum, millet, groundnut, and cassava respectively. Furthermore, that the countries with the highest average yields have the largest projected yield losses, suggesting that well-fertilized modern seed varieties are more susceptible to heat related losses.

Overall, the empirical evidence on climatic impacts on agriculture has been mixed. There are wide variations in the impacts of climate change on agriculture across different regions and crop varieties.

4. The Impacts of Climate Change on Indian Agriculture

Against the backdrop of a huge population size along with changes in land use patterns, the Indian economy is faced with the enormous challenge of food and nutrition security. The challenge has been exacerbated due to ongoing global climate change that has the potential of adversely affecting the agricultural sector of the country where majority of the population depends on it for their life and livelihood and who, being poor, have the limited capacity to adapt to the adverse effects.

There are several recent studies that investigate climatic impacts on agriculture in India. The results reported in these studies that use different methodologies and datasets on a variety of crops are mixed. This section reviews this literature and summarizes the findings.[5]

Most studies examining the impacts of climate change on Indian agriculture use crop simulation models. Several of them find evidence of a negative impact of climate change on crop yields. Soora et al (2013) while examining regional vulnerabilities of rice yields to climate change in India find that rice yield would decline in all three climate change scenarios that they consider. Irrigated rice yields are projected to decline by 4% by 2020, 7% by 2050 and 10% by 2080. Rainfed rice yields, on the other hand, are likely to decline by 6% by 2020, and marginally (<2.5%) by 2050 and 2080 under the projected climate change scenarios. They also find evidence of spatial variation in the magnitude of climate change impacts. Singh et al (2017) projects an overall reduction in productivity of rice crop in all main rice producing states in India. Due to an increase in temperature the crop will mature early and yield will decrease in the future decades. Likewise, the study by Aggarwal et al (2010) on the Upper Ganga Basin reveals that climate change is likely to adversely affect rice and wheat yields. Irrigated rice yield is likely to decline up to 23% in several parts of the study region and the yield loss is projected to be higher in the high rainfall zones where rainfall is projected to increase further. Climate change is also likely to adversely affect the wheat yields in nine out of eleven districts under consideration. The projected increase in CO2 will not be enough to compensate for the adverse effects of temperature rise. Furthermore, a study by Mishra et al (2013) shows a decrease in the rice and wheat yields in the upper and middle Indian Ganga Basin (IGB) during 2011–2040. The results for lower IGB, however, are somewhat contradictory. In the upper IGB the projected rate of change in rice yield ranges from -5.9 to −43.2% while in the lower IGB it ranges between +1.2 and −22.6%. Similarly, the projected rate of change in wheat yield varies from −6.1 to −20.9% in the upper IGB as compared to 5.4 to −1.7% in the lower IGB.

Aggarwal and Sinha (1993) show that an increase of 2^0C in temperature would reduce grain yields in most places. Moreover, they find evidence of heterogeneous climatic impacts

---

[5] The results of the major empirical studies on the climate change impact on various crops in India along with the methodologies employed are summarized in Table A1.

across latitudes. In sub-tropical (above 23^0C) environment, there is a small decrease in yields (1.5 -5.8%). However, in tropical locations the decrease of 17-18% is substantial. Irrigated yields increase slightly for latitudes with temperature greater than 27^0C but decrease in all other areas. The decrease in yield is much higher in lower latitudes. Using a crop growth simulation model, Mall et al (2004) indicate that a rise in surface air temperature along with doubling of CO2 concentration could pose a serious threat to soybean growth and hence the yield under three future climate change scenarios. The simulated decline in soybean yield due to thermal stress ranges between 12% and 21%.

A study of the impact of projected climate change on Indian mustard by Bhoomiraj et al (2010) shows that mustard yields are likely to decline in both irrigated and rainfed conditions with spatial variations in magnitude across different mustard growing regions of the country. Under both irrigated and rainfed conditions, yield reductions would be higher in eastern India (67 and 57%) followed by central (48 and 14%) and northern India (40.3 and 21.4%). This is due to the fact that the eastern part of the country is projected to experience the maximum temperature rise by 2080. In contrast, the northern region is expected to experience relatively lower temperature during the crop growing period. But rainfed crop is more susceptible to changing climate in north India due to projected reduction in rainfall under the future climate change scenarios.

Kumar et al (2015) study climate change impact on potato yield in the Indo-Gangetic Plains and predict that climate change would reduce potato yields by ~2.5, ~6 and ~11% in the study region in 2020 (2010-2039), 2050 (2040-2069) and 2080 (2070-2099) time periods.

In contrast to the above, some other crop simulation studies document evidence of a positive impact of climate change on Indian agriculture. For example, Saseendran et al (2000) report a projected increase of 12% in rice yield due to climate change. According to this study, the negative impact of a rise in temperature would be more than compensated by the positive impacts of the fertilization effect of projected elevation of CO2 and increase in rainfall. Likewise, Lal et al (1998) project wheat and rice yields to increase by 28% and 15% respectively under doubling of CO2. However, the positive impact of elevated CO2 on these two crops would nearly be cancelled out for an increase in temperature by 3^0C and 2^0C respectively. While wheat is sensitive to an increase in maximum temperature, rice is vulnerable to a rise in minimum temperature. The study also reports that the combined effect of rising CO2 and temperature increase is an increase in wheat and rice yield by 21% and 4% respectively under existing irrigation practice.

Aggarwal and Mall (2002) further predict that direct effect of climate change on rice crops in different agro-climatic regions in India would always be positive irrespective of the various uncertainties. They consider the following climate change scenarios: an increase of 0.1^0C in temperature and 416 parts per million (ppm) in CO2 (2010 scenario) and an increase of 0.4^0C in temperature and 755 ppm in CO2 (2070 scenario) as the optimistic scenarios whereas an increase of 0.3^0C in temperature and 397 ppm in CO2 (2010 scenario) and an increase of 2^0C in temperature and 605 ppm in CO2 (2070 scenario) as the pessimistic scenarios of climate change. They find that the rate of increase in rice yields ranges between 1.0 and 16.8% under the pessimistic scenarios depending on the level of management and model used. These increases range between 3.5 and 33.8% under the optimistic climate change scenario.

The study by Abeysingha et al (2016) on the Gomti River Basin of India reveals that there would be an increase in mean annual rice yield in the range of 5.5–6.7%, 16.6–20.2% and 26–33.4 % during the 2020s, 2050s and 2080s, respectively. Similarly, mean annual wheat yield is also likely to increase by 13.9–15.4%, 23.6–25.6% and 25.2–27.9 % for the same future time periods. In a study on northwest India, Attri and Rathore (2003) find that under a modified climate (i.e., increase in maximum and minimum temperatures by 1.0 °C and 1.5 °C respectively along with doubling of CO2) there would be yield enhancements of the order of 29–37% and 16–28% under rainfed and irrigated conditions respectively. However, they further add that any increase of maximum temperature beyond 1°C and of minimum temperature over 1.5 °C may reduce grain yield even under enhanced CO2. Dubey et al (2014) in their study on north-west plains of Uttarakhand report that the yields of all varieties of wheat would increase significantly under elevated CO2 concentration but would decrease significantly with increasing temperatures.

Kumar et al (2011) show that due to climate change irrigated rice and potato in the northeastern (NE) region, rice in the eastern coastal region and coconut in the Western Ghats (WG) are likely to gain. However, irrigated maize, wheat and mustard in the NE and coastal regions and rice, sorghum, and maize in the WG may lose.

The studies that use methodologies other than crop growth simulation models have also found mixed evidence of climate change impact on Indian agriculture. Burney and Ramanathan (2014) investigate the impact of climate change and air pollution on Indian agriculture applying the panel regression method to data on rice and wheat yield, temperature, precipitation, pollution variables for some selected states. Their results indicate that a 1°C increase in temperature leads to a yield decline, on average, of 4% for wheat and 5% for rice. According to this study, the majority of losses in rice and wheat yields are attributable to short-lived climate pollutants.

Guiteras (2009) examines the impact of temperature and rainfall on combined yield (in monetary terms) of five major food and one cash crop, namely, rice, wheat, jowar, bajra, maize and sugarcane using panel data for 200 districts of India for 40 years (1960-1999). According to this study, the projected climate change would reduce major crop yields by 4.5 to 9% over the medium term (2010-2039) and by 25% or more over the long-term (2070-2099) in the absence of long-run adaptation.

Barnwal and Kotani (2013) study the impact of climate change on rice yield in Andhra Pradesh using quantile regression. They find evidence of substantial heterogeneity in the impacts of climatic variables across the yield distributions. The direction of the climatic impacts on rice yields is found to be highly dependent on the agro-climatic zones. In most agro-climatic zones *kharif* rice yield is found to increase with an increase in average temperature. Moreover, the monsoon-dependent *kharif* rice is more sensitive to temperature and precipitation, while the winter season *rabi* rice is largely resilient to changes in the levels of climate variable. Mandal and Nath (2017) conduct a similar study for Assam and show that there is substantial heterogeneity in the impacts of changes in temperature and rainfall across seasonal rice varieties (autumn, winter and summer), agro-climatic zones and the distribution of rice yield.[6]

---

[6] Rice grown in Assam is categorized into three seasonal types, viz, autumn, winter and summer rice on the basis of their harvesting periods. However, the harvesting periods have now been advanced to a great extent following the deployment of short duration high yielding variety (HYV) seeds. Autumn rice, locally known as *Ahu*, is usually sown in February–March and harvested in July–August. Winter (or *Sali*) rice is sown in July–August and harvested in November–December. Summer (or *Boro*) rice is sown in November–December and harvested in March–April.

Applying the Ricardian approach to farm-level data, Kumar (2011) examines the impact of climate change on farm level net revenue in India. The estimated climate response function is found to be non-linear. The temperature coefficients are larger in magnitude than the precipitation coefficients indicating relatively higher sensitivity of crop growth to temperature changes. Higher precipitation is beneficial in winter and autumn seasons but harmful during spring and summer. With a 2^0C increase in temperature along with 7% increase in precipitation, the results from the study indicate an annual decline of 3% in farm level net revenue. The estimates of climatic impacts with India-specific climate change scenarios along with regional distributions of the impacts reveal that with the exception of the eastern states of Bihar and West Bengal and the inland region of Karnataka, climate change is likely to have an adverse impact on agriculture in the rest of the country. Likewise, in a separate study Kumar and Parikh (2001) report that under the climate change scenario of a $+2^0$C temperature and +7% rainfall change the total farm net revenue would decline by about 8.4%. The negative impacts of temperature change more than compensate for the small positive impacts due to precipitation change.

Using data from nine rice producing states Auffhammer et al (2006) show that rainfall has a positive impact on rice harvest while minimum temperature has a negative impact. They further note that the simultaneous reductions in atmospheric brown clouds and greenhouse gases (GHGs) would have complementary positive impacts on rice harvests. Rao et al (2014) find a negative impact of rising minimum temperature on *kharif* paddy yields in India. As per their estimates, the decline in *kharif* paddy yield ranges between 411 and 859 kg per hectare for every 1°C rise in minimum temperature across regions. Gupta et al (2012) observe that rainfall increases rice yield at a decreasing rate whereas maximum temperature reduces it at an increasing rate. The net effect will depend on the relative strength of these two effects. In case of pearl millet and sorghum also, rainfall increases yield at a decreasing rate.

Using the Just-Pope stochastic production function framework, Gupta et al (2013) further examine the impact of climate change on mean and variability of yield of rice and millets in India. The study shows that an increase in temperature decreases yield and its variability of rice and sorghum. But variability of temperature increases the variability of their yields. In contrast, an increase in rainfall increases their mean yield and reduces their variability.

Variability of rainfall has positive and negative impacts respectively on average yield and its variability in case of rice. For sorghum, rainfall variability reduces mean yield but increases its variability. In case of pearl millets, an increase in temperature decreases mean yield but increases its variability. Variability of temperature raises variability of its yield. An increase in rainfall increases its yield but reduces its variability. Variability of rainfall reduces mean yield but increases its variability for pearl millets.

Krishnamurthy (2012) studies the impact of climate change across yield distributions of rice and wheat in India using quantile regression technique. The results indicate significant reduction in wheat yields of up to 12% in all regions and at most quantiles under scenarios with a reasonable temperature increase. The reductions are found to be larger at upper quantiles. However, in case of rice there is a very modest (up to 2%) increase in yield at the intermediate quantiles and a modest reduction in yield (up to 3%) at upper and lower quantiles. There are significant regional differences in impacts at different quantiles.

From the above discussion it is clear that there is mixed evidence of climatic impacts on agricultural productivity and growth in India. While some studies provide evidence of positive impacts others present that of negative impacts. The heterogeneity in terms crops, topography, existing and projected agro-climatic conditions, and agronomic characteristics across different regions plays a very important role in generating these mixed results. Appendix I presents a summary of this literature.

5. Climatic Impacts on Rice and Wheat Yield in India: Further Evidence from State-level Data

In this section, we examine the impacts of climate variables (i.e., temperature and rainfall) on the average yield of rice and wheat, the two most important staple food crops of the country, using state-level time series data.[7] We consider annual average temperature and total rainfall during a crop year (July to June) as our main climate variables. Additionally, we include annual temperature variability (as measured by the standard deviation of monthly temperature) and annual rainfall variability (as measured by the standard deviation of monthly rainfall).

---

[7] Rice and wheat are the two major crops of India in terms of acreage share.

The empirical model is specified as follows:

$$yield_{it} = \beta_0 + \beta_1 T_t + \beta_2 temp_{it} + \beta_3 rain_{it} + \beta_4 temp\_var_{it} + \beta_5 rain\_var_{it} + \sum_{i=1}^{n-1} \gamma_i Dum_i + \varepsilon_{it} \quad (1)$$

where T is the time trend, *temp* denotes average temperature, *rain* denotes total rainfall, *temp_var* is the temperature variability, *rain_var* is the rainfall variability, dum_i is the dummy variable for state i, and ε is the white-noise error term; i indexes states (i= 1, 2, …., n) and t indexes time period. We use median regression to estimate equation (1).[8] Median regression (more generally, quantile regression) is a nonparametric regression technique that does not require classical assumptions regarding the distribution of the regression error terms and therefore appropriate for heteroscedastic data. To examine robustness of the results, we also estimate a pooled least square (PLS) regression.

The dataset covers 23 major states of India from 1968 to 2001.[9] We obtain data on average yields of rice and wheat (output in kilogram per hectare) from the Directorate of Economics and Statistics (DES), Government of India. The data are extracted and compiled from the official website of DES (http://eands.dacnet.nic.in/StateData_66-76Year.htm, accessed on July 4, 2014). The climate data on temperature and rainfall used in this study are obtained from http://www.indiawaterportal.org/met_data/ (accessed on 25th March, 2017) that provides district level monthly data on different weather variables.[10] The district level data thus sourced are aggregated to construct state level average temperature and rainfall data. Using the state level weather data obtained above, we construct data on four weather variables. From the temperature data, we calculate mean and standard deviation of average temperature during a crop year. From the monthly rainfall data, we calculate annual rainfall and standard deviation of rainfall for the respective states. Note that the agricultural data are reported for the crop year that begins in July and ends in June of the subsequent calendar year.

---

[8] Sarker et al (2012) use median regression to examine the climatic impacts on rice yield in Bangladesh.

[9] Those states for which a consistent data on the relevant variables are available are considered here. The sample includes Andhra Pradesh, Arunachal Pradesh, Assam, Bihar, Gujarat, Haryana, Himachal Pradesh, Jammu and Kashmir, Karnataka, Madhya Pradesh, Maharashtra, Manipur, Meghalaya, Mizoram, Nagaland, Orissa, Punjab, Rajasthan, Sikkim, Tamil Nadu, Tripura, Uttar Pradesh and West Bengal. For our analysis of wheat yield, we had to drop Manipur and Mizoram.

[10] This data set is based on 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. For details, visit http://www.indiawaterportal.org/articles/background-meteorological-datasets.

For consistency, we map the constructed annual data on climatic variables to corresponding crop year.[11]

[Insert Table 1]

We first conduct panel unit root tests to examine if the variables are stationary so that we do not have to worry about the issue of spurious regression. In particular, we perform two most commonly used panel unit root tests: Levin-Lin-Chu (LLC) and Im-Pesaran-Shin (IPS) tests.[12] The test results are reported in Table 1. In each case, we reject the null hypothesis of unit root indicating that the variables are stationary and we can use them in the regression models in their levels.

[Insert Table 2]

Table 2 presents our regression results of climate change impacts on rice and wheat yield across the states of India. Our results indicate that an increase in average temperature reduces rice yield. This is consistent with the findings of several previous studies. However, rainfall variability has a positive impact on rice yield indicating that more variations in rainfall over the crop year are beneficial to this crop. When we use PLS method, average temperature is found to have a negative impact on rice yield. Thus, the result with respect to the impact of rising temperature on rice yield is robust to the use of different estimation techniques. As for wheat yield, temperature variability has a significant positive impact on its yield and this result is also robust. It implies that a higher variability in temperature over the crop year is good for wheat yield. Average temperature has a negative effect on wheat yield but it is statistically significant only when we use PLS to estimate the regression model.[13] The reasons for the findings with regard to the impacts of rainfall and temperature variability are not readily comprehensible. For a better understanding of these results further agronomic research will be helpful.

---

[11] For example, climatic data for the year 1968-69 refer to a period from July 1968 to June 1969.

[12] These tests are described in Levin et al (2002) and Im et al (2003).

[13] Among the control variables, the time trend has a significant positive effect on both rice and wheat yield. This may have captured the beneficial effect of technological progress. Most state dummies that capture time invariant state-specific factors are statistically significant under both models suggesting that there are important differences in median yield across states. However, we do not report the coefficients in the table to save space.

Note that these results are indicative at the best. We have used aggregate data and it would be desirable to use more disaggregate data. Further, we would like to include other inputs such as fertilizer, irrigation etc. that are important for yields. However, relevant data are not consistently available.

6. Concluding Remarks

The empirical evidence on the effects of climate change on agriculture has been mixed: while some studies find evidence of adverse impacts others report evidence of positive effects. Applying nonparametric median regression technique to state-level time series data on average yield of rice and wheat and on temperature and rainfall from 1968 to 2001, the present study further investigates the impacts of changes in these climate variables on rice and wheat yields in India. The results indicate that rising temperature has a significant negative impact and rising rainfall variability has a significant positive impact on the average rice yield. Furthermore, an increase in temperature variability over the crop year appears to have a significant positive impact on wheat yield.

The studies discussed above show that different aspects of climate change (i.e. changes in temperature, rainfall, CO2) may have differential effects on agriculture in India. Furthermore, the impacts are conditional on so many confounding factors: type of crops, topography, existing agro-climatic conditions, agronomic characteristics, available technology, and peoples' coping strategies. It seems to suggest that aggregate studies covering a large geographic region may gloss over these heterogeneities that are so critical for investigating climatic impacts. Therefore, it is imperative that researchers conduct more micro-level region-specific studies so that coping strategies and policies can be customized according to these specificities. Since collection, storage, and dissemination of data have become much easier now than before due to the unprecedented advances in the information and communication technologies (ICTs), researchers may take advantage of the enormous information to investigate climatic impacts. In fact, using real time data they may constantly update such analysis and may provide useful information to those who are involved in innovation and designing strategies and policies to cope with the adverse impacts of climate change.

Table 1. Unit Root Test Results

Variable	Levin-Lin-Chu (LLC) Test		Im-Pesaran-Shin (IPS) Test	
Exogenous variables in the test equation →	Intercepts only	Intercepts and trends	Intercepts only	Intercepts and trends
	(1)	(2)	(3)	(4)
Rice Yield	-2.27 **	-11.65***	-3.14***	-11.72***
Wheat Yield	-1.56*	-11.93***	-3.57***	-12.06***
Average Temperature	-13.46***	-20.04***	-12.12***	-19.17***
Total Rainfall	-22.44***	-21.68***	-20.68***	-18.91***
Temperature Variability	-19.60***	-16.09***	-21.01***	-19.15***
Rainfall Variability	-24.64***	-24.91***	-22.01***	-21.49***

Note: *** significant at the 1% level; ** significant at the 5% level; *** significant at the 10% level.

Table 2. Regression Results (Sample Period: 1968-2001)

Explanatory variables	Rice yield		Wheat yield	
	Median Regression	Pooled Regression	Median Regression	Pooled Regression
	(1)	(2)	(3)	(4)
Constant	2755.83*** (688.47)	3932.85*** (734.14)	779.87 (1132.00)	1834.83** (758.33)
Trend	26.95*** (0.97)	27.93*** (1.69)	24.95*** (1.33)	29.50*** (2.50)
Average Temperature	-43.74* (24.22)	-91.48*** (28.06)	-37.29 (37.78)	-82.57*** (26.09)
Total Rainfall	-0.07 (0.07)	0.09 (0.18)	0.02 (0.17)	0.08 (0.25)
Temperature Variability	26.96 (34.90)	38.72 (55.09)	127.98*** (47.74)	180.06** (73.83)
Rainfall Variability	1.54*** (0.58)	-0.02 (1.58)	0.71 (1.39)	-1.07 (2.25)
Pseudo-R^2/R^2	0.60	0.69	0.58	0.65
No. of states	23	23	21	21
No. of observations	765	765	659	659

Note: the standard errors are in parentheses. *** significant at the 1% level; ** significant at the 5% level; * significant at the 10% level.

Appendix I

Climate Change Impacts on Indian Agriculture: Summary of Selected Studies

Table A.1: Climate Change Impacts on Yields/Returns from Crops in India

Crops	Region	Impacts on Yield	Reference	Method
Rice	All India	Irrigated rice yield to decline by 4-10% (different scenarios). Rainfed rice yields are likely to decline by <2.5-6% (different scenarios)	Soora et al (2013)	Crop Simulation
	NE Region	Increase	Kumar et al (2011)	Crop Simulation
	Eastern coastal region	Increase	Kumar et al (2011)	Crop Simulation
	Western Ghat	Decline	Kumar et al (2011)	Crop Simulation
	Gomti River Basin, India	5.5%-33.4% increase (different scenarios)	Abeysingha et al (2006)	Soil and Water Assessment Tool (SWAT) hydrological model
	Upper Ganga Basin	Decline upto 23% (irrigated rice)	Aggarwal et al (2010)	Crop Simulation
	All India	Decline	Singh et al (2017)	Crop Simulation
	Kerala	Increase	Saseendran et al (2010)	Crop Simulation
	All India	Increase (1%-33.8%)	Aggarwal and Mall (2002)	Crop Simulation
	All India	Decline	Burney Ramanathan (2014)	Panel regression
	Andhra Pradesh	Heterogeneous impacts (across yield distributions)	Barnwal and Kotani (2013)	Quantile regression
	Nine states of India	Increase/decrease (rainfall/minimum temperature rise)	Auffhammer et al (2006)	Multivariate regression methods
	All India	Decline (minimum temperature rise): kharif paddy	Rao et al (2014)	Correlation
	All India	Increase/decrease (rainfall/maximum temperature rise)	Gupta et al (2012)	Production function appraoch
	All India	Increase/decrease (rainfall/ temperature rise)	Gupta et al (2013)	FGLS

	All India	Increase/decrease (across yield distributions)	Krishnamurthy (2012)	Quantile regression
	Northwest India	Increase	Lal et al (1998)	Crop Simulation
Wheat	Northwest	16-37% increase	Attri and Rathore (2003)	Crop Simulation
	Gomti River Basin, India	13.9%-27.9% increase (different scenarios)	Abeysingha et al (2016)	Soil and Water Assessment Tool (SWAT) hydrological model
	All India	Increase/decrease (region & scenario dependent)	Aggarwal and Sinha (1993)	Crop Simulation
	Upper Ganga Basin	Decline	Aggarwal et al (2010)	Crop Simulation
	Uttarakhand	Increase/decrease (variety and scenario specific)	Dubey et al (2014)	Crop Simulation
	Varanasi	Increase/decrease(CO2/temperature rise)	Yadav et al (2015)	Crop Simulation
	All India	Decline	Burney Ramanathan (2014)	Panel regression
	All India	Decline	Krishnamurthy (2012)	Quantile regression
	Northwest India	Increase	Lal et al (1998)	Crop Simulation
	Indian Ganga Basin (IGB)	Increase/decline (location dependent)	Mishra et al (2013)	Crop Simulation
Soybean	All India	Decline	Mall et al (2004)	Crop Simulation
Mustard	All India	Decline	Bhoomiraj et al (2010)	Crop Simulation
Potato	Indo-Gangetic Plains (IGP)	Decline	Kumar et al (2015)	Crop Simulation
Aggregated farm/ combined crops	All India	Decline (4.5% - 25%: scenario specific)	Guiteras (2009)	Panel data regression
	All India	Decline	Kumar (2011)	Ricardian method
	All India	Decline	Kumar and Parikh (2001)	Ricardian method
	All India	Decline	Sanghi and Mendelsohn (2008)	Ricardian method

Source: Compiled from sources cited in column (4) above.

References

Abeysingha, N.S., Singh, M., Islam, A. and Sehgal, V.K. (2016). Climate change impacts on irrigated rice and wheat production in Gomti River basin of India: a case study. *SpringerPlus* (Open Access), 5:1250, DOI: 10.1186/s40064-016-2905-y.

Adams, R., Rosenzweig, C., Pearl, R., Ritchie, J., McCarl, B., Glyer, D., Curry, B., James, J., Boote, K. and Allen, H. (1990). Global Climate Change and US Agriculture, *Nature*, 345, pp. 219-223.

Adams, R.M. (1986). Agriculture, forestry and related benefits of air pollution control. *American Journal of Agricultural Economics*, 68, pp.885–894.

Adams, R.M., Hurd, B.H., Lenhart, S. and Leary, N. (1998). Effects of global climate change on agriculture: an interpretative review. *Climate Research*, 11, pp.19-30.

Aggarwal, P.K., Kumar, S.N. and Pathak H (2010). Impacts of climate change on growth and yield of rice andwheat in the Upper Ganga Basin. WWF Report.

Aggarwal, P.K. and Mall R.K. (2002). Climate change and rice yields in diverse agro-environments of India, II: Effect of uncertainties in scenarios and crop models on impact assessment. *Climatic Change*, 52, pp. 331-343.

Aggarwal, P.K. and Sinha, S.K. (1993). Effect of Probable increase in carbon dioxide and temperature on wheat yields in India. *Journal of Agricultural Meteorology*, 48(5), pp. 811-814.

Al-Bakri, J., Suleiman, A., Abdulla, F. and Ayad, J. (2010). Potential impact of climate change on rainfed agriculture of a semi-arid basin in Jordan. *Physics and Chemistry of the Earth*, 35, pp. 125-134.

Attavanich, W. and McCarl, B.A. (2014). How is CO2 affecting crop yields and technological progress? A statistical analysis. *Climatic Change*, 124(4), pp. 747-762, DOI: 10.1007/s10584-014-1128-x.

Attri, S.D. and Rathore, L.S. (2003). Simulation of impact of projected climate change on wheat in India. *International Journal of Climatology*, 23, pp. 693-705.

Auffhammer, M., Ramanathan, V. and Vincent, J.R. (2006). Integrated model shows that atmospheric brown clouds and green house gases have reduced rice harvests in India. *Proceedings of the National Academy of Sciences*, 103(52), pp. 19688 – 19672.

Barnwal, P. and Kotani, K. (2013). Climatic impacts across agricultural crop yield distributions: An application of quantile regression on rice crops in Andhra Pradesh, India. *Ecological Economics*, 87, pp. 95 – 109.

Benhin, J.K.A. (2008). South African crop farming and climate change: An economic assessment of impacts. *Global Environmental Change*, 18, pp. 666-678.

Boomiraj, K., Chakrabarti, C., Aggarwal, P.K., Choudhary, R. and Chander, S. (2010). Assessing the vulnerability of Indian mustard to climate change. *Agriculture, Ecosystems and Environment*, 138, pp. 265–273.

Burney, J. and Ramanathan, V. (2014). Recent climate and air pollution impacts on Indian agriculture. *Proceedings of the National Academy of Sciences*, 111(46), pp. 16319–16324.

Cabas, J., Weersink, A. and Olale, E. (2010). Crop yield response to economic, site and climatic variables. *Climatic Change*, 101, pp. 599-616.

Chen, C.C., McCarl, B.A. and Schimmelpfenning D.E. (2004). Yield variability as influenced by climate: a statistical investigation. *Climatic Change*, 66, pp. 239-261.

Deressa, T.T. and Hassan, R.M., 2009. Economic impact of climate change on crop production in Ethiopia: evidence from cross-section measures. Journal of African Economies, 18, pp. 529–554.

Deschenes, O. and Greenstone, M. (2007). The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather. *American Economic Review*, 97(1), pp. 354-385.

Dubey, S.K., Tripathy, S.K., Pranuthi, G. and Yadav, R. (2014). Impact of projected climate change on wheat varieties in Uttarakhand, India. *Journal of Agrometeorology*, 16(1), pp. 26-37.

Gbetibouo, G.A. and Hassan, R.M. (2005). Measuring the economic impact of climate change on major South African field crops: a Ricardian approach. *Global and Planetary Change*, 47, pp. 143-152.

Guiteras, R. (2009). The impact of climate change on Indian agriculture. Department of Economics, University of Maryland, College Park, M.D.

Gupta, S., Sen, P. and Srinivasan, S. (2012). Impact of climate change on the Indian economy: Evidence from foodgrain yields. Working Paper No. 218; CDE, Delhi School of Economics.

Gupta, S., Sen, P. and Jain, P. (2013). Impact of Climate Change on the foodgrain yields and their variability in India. Paper presented at the Fourth National Research Conference on Climate Change, IIT Madras, October 27.

Im, K.S., Pesaran, M. H. and Shin, Y. (2003). Testing for Unit Roots in Heterogeneous Panels. *Journal of Econometrics*, 115, pp. 53-74.

Isik, M. and Devadoss, S.C. (2006). An analysis of the impacts of climate change on crop yields and yield variability. *Applied Economics*, 38, pp. 835-844.

Jayaraman, T.(2011). Climate change and agriculture: A review article with special reference to India. *Review of Agrarian Studies*, 1(2), pp. 16-78.

Kaiser, H.M., Riha, .SJ., Wilks, D.S., Rossiter, D.G. and Sampath, R. (1993). A farm-level analysis of economic and agronomic impacts of gradual climate warming. *American Journal of Agricultural Economics*, 75, pp. 387–398

Knox, J., Hess, T., Daccache, A. and Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, 7: 034032 (Open Access), doi:10.1088/1748-9326/7/3/034032

Krishnamurthy, C.K.B. (2012). The Distributional Impacts of Climate Change on Indian Agriculture: A Quantile Regression Approach. Working Paper 69/2012, Madras School of Economics.

Kumar, K.S.K. (2011). Climate sensitivity of Indian agriculture: do spatial effects matter?. *Cambridge Journal of Regions, Economy and Society*, 4, pp. 1- 15.

Kumar, K.S.K. and Parikh, J. (2001). Indian agriculture and climate sensitivity. *Global Environmental Change*, 11, pp. 147-154.

Kumar, S.N., Govindakrishnan, P.M., Swarooparani, D.N., Nitin ,C., Surabhi, J. and Aggarwal, P.K. (2015). Assessment of impact of climate change on potato and potential adaptation gains in the Indo Gangetic Plains of India. *International Journal of Plant Production*, 9 (1), pp. 151-170.

Kumar, S.N. and Aggarwal, P.K. (2013). Climate change and coconut plantations in India: Impacts and potential adaptation gains. *Agricultural Systems*, 117, pp. 45-54.

Kumar, S.N., Aggarwal, P.K., Rani, S., Jain, S., Saxena, R. and Chouhan, N. (2011). Impact of climate change on crop productivityin Western Ghats, coastal and northeasternregions of India. *Current Science*, 101(3), pp. 332-341

Kurukulasuriya, P. and Mendelsohn, R. (2008). Crop Switching as an Adaptation Strategy to Climate Change. *African Journal Agriculture and Resource Economics*, 2(1), pp. 105-125.

Lal, M., Singh, K.K., Rathore, L.S., Srinivasan, G., Saseendran, S.A. (1998). Vulnerability of rice and wheat yields in NW India to future changes in climate. *Agricultural and Forest Meteorology*, 89, pp. 101-114.

Levin, A., Lin, C. and Chu, C. J. (2002). Unit Root Tests in Panel Data: Asymptotic and Finite-Sample Properties. *Journal of Econometrics*, 108, pp. 1-24.

Lewandrowski, J., Schimmelpfennig, D., 1999. Economic implications of climate change for U.S. agriculture: assessing recent evidence. Land Economics, 75, pp. 39–57.

Luo, Q., Williams, M., Bellotti, W. and Bryan, B. (2003). Quantitative and visual assessments of climate change impacts on South Australian wheat production. *Agricultural Systems* , 77(3), pp. 173–86.

Magrin, G.O., Travasso, M.I. and Rodriguez, G.R. (2005). Changes in climate and crop production during the 20th century in Argentina. *Climatic Change*, 72, pp. 229-249.

Mall, R.K., Lal, M., Bhatia, V.S., Rathore, L.S. and Singh, R. (2004). Mitigating climate change impact on soybean productivity in India: a simulation study. *Agricultural and Forest Meteorology*, 121, pp. 113-125.

Mandal, R., and Nath, H.K. (2017). Heterogeneous climatic impacts on agricultural production: evidence from rice yield in Assam, India. *Asian Journal of Agriculture and Development* (forthcoming).

McCarl, B.A., Villavicencio, X. and Wu, X. (2008). Climate change and future analysis: Is stationarity dying?. *American Journal of Agricultural Economics*, 90(5), pp. 1241-1247.

Mearns, L.O., Rosenzweig, C., Goldberg, R. (1997). Mean and variance change in climate scenarios: Methods, agricultural applications and measures of uncertainty. *Climatic Change*, 35, pp. 367-396.

Mendelsohn, R., Nordhaus, W.D. and Shaw, D. (1994). The Impact of Global Warming on Agriculture: A Ricardian Analysis. *American Economic Review*, 84(4), pp. 753-771.

Mendelsohn, R. and Rosenberg, N.J. (1994). Framework for integrated assessments of global warming impacts. *Climatic Change*, 28 (1–2), pp. 15–44.

Mendelsohn, R., Nordhaus, W.D. and Shaw, D. (1996). Climate impacts on aggregate farm value: accounting for adaptation. *Agricultural and Forest Meteorology*, 80 (1), pp. 55–66.

Mendelsohn, R. (2007). Past climate change impacts on agriculture. In Evenson, R. and Pingali, P. (Ed.), *Handbook of Agricultural Economics*, Volume 3, Paper 60, pp. 3010-3031.

Mishra, A., Singh, R., Raghuwanshi, N.S., Chatterjee, C. and Froebrich, J. (2013). Spatial variability of climate change impacts on yield of rice and wheat in the Indian Ganga Basin. *Science of the Total Environment*, 468-469, pp. S132-S138.

Moorthy, A., Buermann, W. and Rajagopal, D. (2012). The Impact of Climate Change on Crop Yields in India from 1961 to 2010. Mimeo.

Moula, E.L., 2009. An empirical assessment of the impact of climate change on smallholder agriculture in Cameroon.Global Planetary Change, 67, pp. 205–208.

Ortiz, R., Sayre, K.D., Govaerts, B., Gupta, R., Subbarao, G.V., Ban, T., Hodson, D., Dixon, J.M., Ortiz-Monasterio, J.I. and Reynolds, M. (2008). Climate change: Can wheat beat the heat?. *Agriculture, Ecosystems and Environment*, 126(1-2), pp. 46-58.

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M. and Fischer, G. (2004). Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change*, 14, pp. 53-67.

Parry, M., Rosenzweig, C., Iglesias, A., Fischer, G. and Livermore, M. (1999). Climate change and world food security: a new assessment. *Global Environmental Change*, 9(Supplement 1), pp. S51–S67.

Poudel, S. and Kotani, K. (2013). Climatic impacts on crop yield and its variability in Nepal: do they vary across seasons and altitudes?. *Climatic Change*, 116, pp. 327-355.

Rao, B.B., Chowdary, P.S., Sandeep, V.M., Rao, V.U.M. and Venkateswarlu, B. (2014). Rising minimum temperature trends over India in recent decades: Implications for agricultural production. *Global and Planetary Change*, 117, pp. 1-8.

Rosenzweig, C. and Hillel, D. (1995). *Climate Change and the Global Harvest: PotentialImpacts on the Greenhouse Effect onAgriculture*. New York, N.Y.: Oxford University Press.

Rosenzweig, C. and Iglesias, A. (eds.) (1994). *Implications of climate change for international agriculture: crop modeling study*. EPA 230-B-94-003. U.S. EPA Office of Policy, Planning and Evaluation, Climate Change Division, Adaptation Branch, Washington, DC.

Rosenzweig, C. and Parry, M.L. (1994). Potential impact of climate change on world food supply. *Nature*, 367, pp.133-138.

Sanghi, A. and Mendelsohn, R. (2008). The impacts of global warming on farmers in Brazil and India. *Global Environmental Change*, 18, pp. 655-665.

Sarker, A.R., Alam, K. and Gow, J. (2012). Exploring the relationship between climate change and rice yield in Bangladesh: An analysis of time series data. *Agricultural Systems*, 112, pp. 11-16.

Saseendran, S.A., Singh, K.K., Rathore, L.S., Singh, S.V. and Sinha, S.K. (2000). Effects of climate change on rice production in the tropical humid climate of Kerala, India. *Climatic Change*, 44, pp. 495-514.

Schlenker, W. and Lobell, D.B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, 5: 014010, doi:10.1088/1748-9326/5/1/014010.

Schlenker, W. and Roberts, M.J. (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences* 106 (37), pp. 15594 –15598.

Seo, S.N., Mendelsohn, R. and Munasinghe, M. (2005). Climate change and agriculture in Sri Lanka: a Ricardian valuation. *Environment and Development Economics*, 10, pp. 581-596.

Seo, S.N. and Mendelsohn, R. (2008). Measuring Impacts and Adaptations to Climate Change: A Structural Ricardian Model of African Livestock Management. *Agricultural Economics*, 38(2), pp. 151-165.

Singh, P.K., Singh, K.K., Bhan, S.C., Baxla , A.K., Singh, S., Rathore, L.S. and Gupta, A. (2017). Impact of projected climate change on rice (*Oryza sativa* L) yield using CERES-rice model in different agroclimatic zones of India. *Current Science*, 112(1), pp. 108-115.

Soora, N.K., Aggarwal, P.K., Saxena, R., Rani, S., Jain, S. and Chauhan, N. (2013). An assessment of regional vulnerability of rice to climate change in India. *Climatic Change*, 118(3), pp. 683-699.

White, J.W., Hoogenboom, G., Kimball, B.A. and Wall, G. W. (2011). Methodologies for simulating impacts of climate change on crop production. *Field Crops Research*, 124, pp. 357-368.

Welch, J.R., Vincent, J.R., Auffhammer, M., Moya, P.F., Dobermann, A. and Dawe, D. (2010). Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. *Proceedings of the National Academy of Sciences,* 107(33), pp. 14562-14567.

Yadav, M.K., Singh, R.S., Singh, K.K., Mall, R.K., Patel, C.B., Yadav, S.K. and Singh, M.K. (2015). Assessment of climate change impact on productivity of different cereal crops in Varanasi, India. *Journal of Agrometeorology*, 17(2), pp. 179-184.