SANDEE

Working Paper, No 85–14

The Impact of Climate Change on Rice Production in Nepal

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ECONOMICS & THE ENVIRONMENT

Published by the South Asian Network for Development and Environmental Economics (SANDEE)
PO Box 8975, EPC 1056, Kathmandu, Nepal.
Tel: 977-1-5003222 Fax: 977-1-5003299

SANDEE research reports are the output of research projects supported by the South Asian Network for Development and Environmental Economics. The reports have been peer reviewed and edited. A summary of the findings of SANDEE reports are also available as SANDEE Policy Briefs.

National Library of Nepal Catalogue Service:

Prakash K Karn
The Impact of Climate Change on Rice Prduction in Nepal

(SANDEE Working Papers, ISSN 1893-1891; WP 85–14)

ISBN: 978-9937-596-15-2

Key words:
Climate change
productivity changes
agricultural impact
rice yields
Nepal

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May 2014

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SANDEE Working Paper No. 85–14

The South Asian Network for Development and Environmental Economics

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SANDEE is financially supported by the International Development Research Center (IDRC), The Swedish International Development Cooperation Agency (SIDA), the World Bank and the Norwegian Agency for Development Cooperation (NORAD). The opinions expressed in this paper are the author's and do not necessarily represent those of SANDEE's donors.

The Working Paper series is based on research funded by SANDEE and supported with technical assistance from network members, SANDEE staff and advisors.

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Abstract

This paper examines the sensitivity of rice yield in Nepal to changes in climate variables and the magnitude of potential impacts on rice productivity in the future. Our findings draw attention to the differential impacts on rice yield depending on which stage of rice development is affected. We estimate that a 1°C rise in day-time maximum temperature during the ripening phase of rice increases harvest by 27 kg. ha^{-1}, but our analyses also suggests that productivity declines when the day-time maximum temperature goes beyond 29.9°C. Since the average maximum temperature is already higher than this threshold, rice yield will likely diminish with any further increases in maximum temperature. Rainfall appears to have a strong negative effect on yield if it occurs when rice plants are in the nursery stage. Overall, under a double CO_2 scenario predicted for 2100, rice yield in Nepal is expected to drop by about 4.2 per cent relative to current production levels. However, this prediction is does not account for any long-term positive effects from adaptation and carbon fertilization or negative effects from extreme events triggered by climate change.

Key words

Climate change, productivity changes, agricultural impact, rice yields, Nepal.

The Impact of Climate Change on Rice Production in Nepal

1. Introduction

Agriculture is an important sector in the Nepalese economy, contributing to about a third of its GDP and engaging about two-thirds of its population (MoAC, 2013). Agriculture is mostly rain-fed and dominated by subsistence farming systems. Rice production, amounting to about half of the total cereal grains produced in the country, is Nepal's most important crop (Ghimire et al., 2013).

Rice is produced mainly in the Terai[1] region and contributes to the livelihood of a majority of farm households in the area. However, growth in production has been low at 1.4 per cent per year over the last two decades. Some 70 per cent of total rice produced is used for home consumption. Yet, for most subsistence farmers, rice production meets only a part of their annual household food requirements (Ghimire et al., 2013). They are, therefore, particularly vulnerable to external shocks to agriculture.

Population growth and the increase in the demand for food, on the one hand, and insufficient growth in farm productivity, on the other, have turned Nepal gradually from a food-exporting country to a food-importing country within a few decades (Pokhrel, 2013). Changes in climatic variables have further aggravated concerns over rice production and food security. For instance, the maximum temperature in Nepal has increased by 1.8°C over the period 1975 to 2006, and precipitation has become more erratic (Shrestha et al, 1999, Baidya et al., 2008). During 1977 and 1994, the Terai region has, on average, seen an increase in annual temperature of 0.04°C/yr (Shrestha, 2004).

Climate-related changes have been observed in precipitation patterns, temperature, high intensity floods, landslides, erosion and increased sedimentation (IPCC, 2007; Shrestha, 2004; Karn, 2007). There appears to be an increase in both flood and drought conditions. Changes in seasonality – weather patterns becoming less predictable, weather events typical of one season occurring in another, increasing extreme events, changes in the behavior of key crops – have meant that traditional and indigenous knowledge on climate and plants relationships have become less reliable.

Undoubtedly, changes in climatic factors have substantial impacts at the local level as they change the agro-ecosystem, resulting in loss of land, livestock and household assets (Pant 2011). Delays in the onset of the monsoon can hamper timely rice plantation and affects yields. Given the subsistence nature of Nepal's economy, a slight decline in rice yields can have a devastating impact on household food security. Some farmers have begun to take adaptation measures such as changing the agricultural calendar, changing cropping patterns, and resorting to alternate sources of irrigation etc. Interestingly, while climate-related disasters such as glacial lake outburst floods in Nepal have garnered increasing attention (Dixit, 2003; Khanal, 2005; Aryal and Rajkarnikar, 2011), little attention has been paid to other effects of climate change, for instance, the impact of climate change on agricultural crops.

A growing body of literature suggests that climate change will significantly affect the agricultural sector in developing countries, leading to serious consequences related to food production and food security, with bigger impacts on small-holder farmers and the poor (IPCC, 2007; Thornton et al., 2013; Morton, 2007). But the bulk of the available studies on potential long-term threats to the agricultural sector from climate change are based on developed countries. There are far fewer attempts to study impacts in developing countries. The present study seeks to fill this gap by analysing the impact of climate change on rice production in Nepal.

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[1] The *Terai* is the southernmost stretch of the plains, which runs across the length of Nepal from east to west, bordering India. It comprises the most fertile belt of the country.

Our main objective in this study is to determine the relative sensitivity of rice yield to climate variables, especially temperature, and to estimate the magnitude of likely impacts in Nepal. We estimate the sensitivity of rice yield to climate and assess future impacts by calculating the difference between estimated and current mean yields under projected climatic scenarios. Our findings show that rice yield is most sensitive to increases in day-time maximum temperature, which increases rice yield up to 29.9°C during the ripening phase and harms yield beyond this point.

The rest of the paper is organized as follows. Section 2 summarizes the relevant literature while Section 3 describes the study area and the data. Section 4 describes the methodology, and discusses the main results including methods for estimating future likely impacts. Section 5 offers a summary of available data and the findings. Section 6 provides conclusions and recommendations from the study.

2. Background

Numerous empirical studies suggest that climate change will have a bigger impact on agriculture in developing countries relative to developed countries (Stern 2006). However, the degree of the impact will depend upon the magnitude of the climate change and other factors. Increasing temperature will likely directly impact crops by affecting their physiology; it will also indirectly affect crops through changes in the water regime and the increased intensity of pests and diseases (Rosenzweig, 2000; Bale et al., 2002). Crops are also bound to be affected by more intense rainfall and other extreme weather events occurring at different stages of production.

Projections on a likely increase in area-averaged seasonal surface air temperature and a change in area-averaged seasonal precipitation (with respect to the baseline period from 1961 to 1990) suggest a significant acceleration in warming in South Asia over what is observed for the 20th century (Ruosteenoja et al., 2003; Christensen et al., 2007). The warming, moreover, is projected to be stronger in the Himalayan Highlands including the Tibetan Plateau and the arid regions of Asia (Gao et al., 2003). Studies further project an increase in the inter-annual variability of daily precipitation in the Asian summer monsoon (Giorgi and Bi, 2005).

There has already been an increase in the frequency and intensity of rainfall events in many parts of Asia, which largely attributed to increasing temperature. This has caused severe floods, landslides and mud flows, while the number of rainy days and the total annual amount of precipitation has decreased in some regions (Lal, 2003; Min et al., 2003; Gruza and Rankova, 2004; Zhai, 2004). The frequency and intensity of droughts seem to have increased, particularly during the summer and the normally drier months (Gruza and Rankova, 2004; Natsagdorj et al., 2005). There is also concern that the glacier melt in the Himalayan region will increase flooding and affect water resources within the next two to three decades, which would inevitably be followed by decreased river flows as the glaciers recede. The warmer climate is also expected to lead to a higher intensity of extreme weather events increasing the risk of flash floods in parts of Nepal.

Available studies offer differing estimates of the impact on crop production in Asia from increasing temperature and water stress. Many studies show that increases in atmospheric carbon dioxide can significantly stimulate growth, development and reproduction in a wide variety of C_3 plants including rice (Sage, 1995; Mandersheid and Weigel, 1997; Poorter and Navas, 2003). Projections using HadCM2[2], on the other hand, indicate a likely yield decrease up to 30 per cent in South Asia, even after accounting for the direct positive physiological effects of CO_2 (IPCC, 2007). Lal (2007), for example, projects a decline in net cereal production by at least 4-10 per cent by the end of the 21st century under the most conservative climate change scenarios. He further suggests that the drop in yields of non-irrigated rice will be significant if the temperature increase exceeds 2.5°C. Another study by Murdiyarso (2000) suggests that rice production in Asia could decline by nearly 4 per cent by the end of the 21st century as a consequence of the combined influence of the fertilization effect and the thermal stress and water scarcity. Decreases in crop yields by 2.5 to 10 per cent by 2020 and by 5 to 30 per cent by 2050 have been projected in parts of Asia under the A1FI[3] emission scenarios (Parry et al., 2004). One important factor is increasing water stress, which has already adversely affected the production of rice, maize and wheat in many parts of Asia (Tao et al., 2004).

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[2] Hadley Centre Coupled Model version 2, used in the Second Assessment Report of the IPCC.

[3] Fossil intensive, highest emissions trajectory scenario

It is interesting that studies using different modelling approaches suggest a likely decline in agricultural revenues and yields in South Asia. Agronomic studies in India, for instance, suggest that a temperature rise of 4°C would cause a fall in grain yields by 25-40 per cent (Rosenzweig and Parry, 1994). Kumar (2009), using an economic Ricardian approach, estimates an approximately 3 per cent decline in farm-level net revenue annually in India (after accounting for spatial effects), for a scenario that envisages a +2°C temperature change and a +7 per cent precipitation change.

In general, available evidence suggests that agriculture in most developed countries is likely to benefit from a modest increase in temperature since carbon fertilization effects are expected to more than compensate for adverse climatic effects. However, most developing countries that are already hot would not benefit from further warming, although adaptation and carbon fertilization are expected to mitigate these effects somewhat (Cline, 2008).

In order to assess the likely impacts of climate change on agriculture, researchers have commonly used the Ricardian cross-sectional approach, the production function approach, or agro-economic modelling. The Ricardian approach has been widely used to examine the impact of climate variables on land values and farm revenues (as in Mendelsohn, Nordhaus, and Shaw, 1999; Darwin, 1999; Gbetibouo and Hassan, 2005; Mendelsohn and Reinsborough, 2007; Sanghi and Mendelsohn, 2008) because the users see it as subsuming all of the adaptations people make to climatic changes. However, this approach has been criticized because it risks confounding the impacts of climate with the impacts of other unobserved characteristics of cross-sectional units, not providing information on agricultural production, and ignoring price variation and carbon fertilization effects (Mendelsohn, 2000).

The production function approach is also widely used to estimate the effects of climate change on crop yields (for example, Dixon et al., 1994; Wu, 1996; Chang, 2002; Auffhammer et al., 2006; Deschenes and Greenstone, 2007). It has been successfully used in the field of agricultural economics for a long time to identify important variables and their effect on yields. However, critics of this approach point out that it tends to overestimate the damages from climate change by failing to account for long-run compensatory responses to changes in weather such as substitutions, adaptation and new activities that may displace obsolete activities (Ierland, 2009). Notwithstanding this criticism, our study uses the production function approach to estimate climatic impacts and to forecast future yields.

3. Study Area and Data

3.1 Study Area

Nepal has three broad ecological regions, viz., the Himalayas in the north; the hills and valleys in the middle; and the Terai, which is an extension of the Indo-Gangetic plain in the south. The Terai plains constitute the major food basket of the country because it contributes a major share of the important staple foods – cereals, pulses, oil seeds, etc. Rice accounted for 35 per cent of the total cultivated area (and 46 per cent of cereal acreage) in 2009. Two-thirds of the rice area and nearly 70 per cent of the total rice production comes from the Terai. (Ghimire et al., 2013). Rice production in Nepal depends heavily on timely rainfall with a major portion of the rice planted once a year at the start of the rainy season.

Since the study intends to assess the impact of climate on rice production, the study area is limited to the Terai region which includes 20 out of 75 districts of Nepal (see colored districts in Figure 1). The Terai plain's elevation ranges from 60m to 330m, with a gentle southward slope (HMG/N 1988). It is bound in the north by the Churia hills and in the south by the Indian border. According to the 2011 national census, Terai covers roughly 17 per cent of the land of the country but is inhabited by approximately 50.3 per cent of Nepal's population.

Nepal experiences seasonal summer monsoon rainfall from June to September, which brings in about 80 per cent of annual precipitation. Heavy incessant rains as well as periods of dry spells are common during these months. Although the amount of precipitation varies considerably from place to place because of the non-uniform rugged terrain, the amount of the summer monsoon rains declines in general from the southeast to the northwest (Kansakar et al. 2004). However, the trend for monthly average temperature during the summer months is the opposite of that of rainfall; it increases from the eastern to the western part of the Terai region (GoN, 2011) (also see Figure 3 and Figure 7). Our study captures these climatic variations and their impact on rice production within the Terai region.

3.2 Data

We use a panel dataset which is available for a 25-year period (1984 – 2008) for the 20 districts in the Terai region. The data set covers annual rice yield and daily observations on weather variables.

Our data on agricultural output was collected from various district level government agencies such as the Department of Irrigation, Agricultural Input Co-operation, Department of Agriculture, Ministry of Agriculture, Central Bureau of Statistics and the District Agriculture Development Offices. The data were collected by copying office records, i.e., they were mostly available as hard copies of historical reports. Our agricultural dataset includes annual district-level observations on the area cultivated, production, yield and area irrigated for a 25-year period.[4]

We obtained data on weather variables from the Department of Hydrology and Meteorology (DHM, Government of Nepal), which collects and maintains data for select stations in all the districts. Where data for more than one meteorological station were available for a district, we took the weather data from the station closest to the rice growing area. The weather data set comprises daily data on maximum and minimum temperature, rainfall, and morning and afternoon humidity for approximately 25-41 years (1968 – 2008).

3.3 Matching Weather Data with Rice Phases

Rice has four stages in its development, i.e. nursery, vegetative, reproductive and ripening stages. Changes in weather lead to changes in when farmers plant and harvest rice. This in turn modifies how the rice crop develops in each stage. Thus, as a first step towards understanding the effect of weather on rice development, we identified rice establishment and harvest dates.[5]

Using the International Rice Research Institute's (IRRI) classification for identifying establishment and harvest dates, we divided the entire rice growing period in any one calendar year into four growth phases or months6 – Nursery (June-July), Vegetative (July-September), Reproductive (September-October) and Ripening (October-November), as show in Table 1.

We thought it would be useful to analyse separately climate effects occurring during two major phases (pre- or post-establishment). We also undertook the analyses for all four phases. Thus, we generated different sets of weather variables corresponding to the above growth phases by obtaining the mean values of weather parameters from daily data for the corresponding time period in each year.

3.4 Data Variability

The average rice yield across districts and years in the sample period is 2497±508 kg.ha-1 (Table 2). The long-term average (1968-2008) of daytime maximum temperature (Tmax) during the nursery, vegetative, reproductive and ripening phases is respectively 34.4±1.9°C, 32.9±1.2°C, 32.3±1.2°C, and 30.7±1.4°C. Similarly, the average night time minimum temperature (Tmin) during the same period for these phases is respectively 25.2±1.4°C, 25.3±1.2°C, 23.2±1.5°C and 17.5±2.2°C.

The average Tmax in the study districts, which is presented in Figure 2 indicates a slightly increasing time trend as well as more variability over time. Figure 3, which displays average Tmax (averaged over years) during different

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[4] Data on other variables such as labour, mechanization, fertilizers, seeds, planting and harvesting dates, wage rates, input and output prices, etc., are available only for the Census years, i.e., 1971, 1981, 1991, and 2001, and were not used.

[5] The establishment dates refer to when farmers plant rice and harvest dates refer to the date when the crop is harvested.

[6] We first identified the establishment and harvest dates for each district based on the best estimates that district agricultural officers could provide. However, since there was not much difference across districts from one year to the next, we settled on a common date for rice establishment and harvest during which the majority of farmers plant and harvest rice, based on the estimated number of days used by International Rice Research Institute, Philippines (IRRI 2013).

growth phases of rice across districts, shows a clear pattern of spatial variation across the study area. The average Tmax during the different growth phases varies more in the western part (i.e., the Kanchanpur district) compared to the eastern part (i.e., the Jhapa district). Reinforcing, Figure 2, average Tmax (average of all districts) for each growth phase shows a clear increasing pattern over the 40-year sample period of 1968-2008 (see Figure 4).

Drawing on the evidence from Figures 2-4, we can conclude that western districts may be affected more by climate variability and each of the growth phases is likely to be influenced by increases in average temperature. High temperature is one of the major environmental factors limiting crop growth and yield (Sheehy et al. 2005, Peng et al. 2004). The sensitivity of rice to high temperature varies with growth phase, timing of temperature changes and genotype (Singh 2001, Peng et al. 2004). High temperature during and right before the flowering phase may lead to complete sterility (Farrell et al. 2006), while high temperature during vegetative and ripening phases alters the grain-filling and thus, the grain quality of the rice (Shrivastava et al. 2012).

The average Tmin in study districts over years is presented in Figure 5. Tmin also increases slightly over the years but relatively more during the ripening phase (see Figure 6). This is important because an increase in minimum temperature in the ripening phase may cause a reduction in grain yield (Shah et al. 2011)

Across districts, while average total rainfall shows a slightly increasing trend from west to east during the nursery, reproductive and ripening phases, rainfall shows a slightly decreasing trend during the vegetative phase (see Figure 7). However, there is significant variation in rainfall from one district to another. Examining time trend over the years, average total rainfall seems almost the same during the nursery, reproductive and ripening phases although we can see a clear increasing trend during the vegetative phase (see Figure 8). If rain increases in the vegetative phase, then it is likely to affect the crop growth and biomass yield positively (Bakul et al. 2009)

4. Methods

In this study, we asked two main research questions: a) how sensitive is current rice yield in Nepal to changes in different climate variables? b) how is climatic change likely to affect rice production in the future?

In order to answer the first question, following methods developed in Welch et al. (2010), we used the production function approach. Thus, we estimated multiple regression models using the yield of the summer monsoon rice crop as the dependent variable and weather variables as independent variables. Using just the weather variables allows us to examine the full effect of these variables on yield, including the possibility of adaptation. We did not use the Ricardian cross-section approach because the small number of cross-sectional units (20 districts) would have made it difficult for us to capture the variability in weather and production parameters. Also, the lack of sufficient historical data on weather meant that we were unable to calculate and use climate normals7, used as weather variables in the Ricardian approach.

In terms of the second research question, we estimated the possible impact of weather variables on rice yield by calculating the difference between the estimated yields under IPCC projected climatic scenarios and the mean current yield. Thus, from our regression analyses we first obtained coefficients that showed the relationship between different climate variables and yield. We then predicted rice yield by evaluating these coefficients at the values of climate variables identified for the future in different IPCC scenarios. Once we obtained estimates of predicted yield, we calculate the difference between mean predicted yield and current yield to establish the effects of climate change on rice production in the future in Nepal.

4.1 Estimating Effects on Rice Yield –Model Specifications

To examine the effect of climate on rice production, we regressed rice harvest (yield) on weather variables using the following model:

$$Y_{st} = \beta_s + \beta_t + W_{st}\beta + \varepsilon_{st} \qquad (1)$$

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[7] "Normal" of a particular variable (e.g., temperature) is defined as the 30-year average. For example, the maximum temperature normal in January for a particular station would be computed by taking the average of the 30 January values (for 30 years) of monthly-averaged maximum temperatures.

where s denotes districts, t denotes year, Y_{st} is the annual total rice harvest (all rain-fed and irrigated) in district s, β is the district fixed-effect, β_t is the year fixed-effect, W_{st} is a N x K matrix of weather variables where N is the number of observations across districts and years, and K is the number of variables, β is a K x 1 vector of parameters that gives the impact of weather, and ε_{st} is the random error term that represents the impacts of factors not included in the model other than weather.

Like Welch et al. (2010), we used only weather parameters in the model and have intentionally avoided the use of farm inputs that are under farmers' control and likely to be endogenous. Omitting the price variables does not create any bias in the coefficient estimates, as weather variables are exogenous. When estimating the effects of weather variables on crop yield, it is preferable to exclude input variables from a production function in order to ensure that the estimated effects of the weather variables capture the full effects, inclusive of short-run adaptation (Welch et al. (2010).

We estimated six models with different specifications to examine the robustness of the effects of climate variables on yield. We used different sets of weather variables for the sets of rice growth phases as discussed in section 3.3. The set of models estimated in this paper includes:

Model 1:	Yield = f (temperature (max, min))
Model 2:	Yield = f (temperature (max, min), rainfall)
Model 3:	Yield = f (temperature (max, min), rainfall, humidity (AM, PM))
Model 4:	Yield = f (vapour pressure deficit (VPD)[8], temperature (min))
Model 5:	Yield = f (vapour pressure deficit (VPD), temperature (min), rainfall)
Model 6:	Yield = f (vapour pressure deficit (VPD), temperature (min), rainfall, humidity (AM))

Model 1 starts with a simple specification with rice yield as the dependent variable and minimum and maximum temperature as the only independent variables. We gradually incorporate other weather variables as independent variables in successive models.

Our models follow Welch et al. (2010) and use day time temperature and night time temperature as key explanatory variables. Some studies investigating the impacts of climate change on agriculture in future have used temperature variables differently. Deschênes and Greenstone (2007), for instance, have used the concept of growing-degree days while Schlenker and Roberts (2009) have used the number of days in 1°C temperature bins. We did not use growing-degree days; and were unable to use the temperature bins approach due to the lack of sufficient observations for the purpose of estimating the rice yield precisely.

Vapor Pressure Deficit (VPD), defined as the difference (deficit) between the amount of moisture in the air and how much moisture the air can hold when it is saturated, is another important variable. It provides estimates of heat stress and is calculated as VPD = (1-humidity/100)*saturation vapor pressure (SVP).

We estimated all six models for two rice growth periods (two phases and four phases) using linear and quadratic forms. Thus, in total we estimated 24 models (6*2*2). These models span the likely range of functional relationships between rice yield and weather. We estimate a number of models because there is no strong theory to guide the specification of yield functions. Thus, a reasonable way forward is to use a range of possible empirical specifications and then using statistical criteria to select among them.

Our regressions use time series data and are estimated with district fixed effect models and robust standard errors. The fixed effect models control for unobserved factors that are unique to districts that could confound the weather effects. We included a time dummy (for years) in the models to control for technological developments over time, which could confound the temperature effects and other time-dependent unobserved factors, including CO_2 fertilization, that are not covered in the models. Although we tested the models for autocorrelation, the correction was ignored as the rho- value was small and insignificant.

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[8] VPD provides estimates of heat stress and was calculated as VPD = (1-humidity/100)*saturation vapor pressure (SVP).

We used Box-cox transformations for identifying appropriate functional forms. Based on the results from Box-cox transformations, we used the rice yield without any transformation, as the dependent variable in all the models, and also estimated quadratic models.

4.2 Estimating Future Impacts

A number of Global Circulation Models (GCMs) and Regional Circulation Models (RCMs) have made climate projections for future. However, there exists a great deal of uncertainty and there is a wide range of estimates available for different parts of the globe for different points of time. There is no specific model and projection available specific to Nepal that considers its geographic heterogeneity and microclimatic conditions. Nepal is represented by just three grid points in most GCMs, providing some differentiation between east, central and western parts of the country, but the approach ignores its complex geography and varied micro-climatic and weather conditions. The most appropriate projections from GCM/RCMs for Nepal can be strongly biased for most parts of the country, reducing confidence in these projections (NCVST, 2009). Though RCMs use finer resolutions than GCMs, they are still unable to capture the dynamics of Nepalese precipitation (NCVST, 2009).

Given the uncertainties on future climate change projections for Nepal, we used two sets of projections to identify climate conditions in the future. The first set of projections is based on high resolution climate data available from the National Center for Atmospheric Research (NCAR) climate model CCM3, which is a general circulation model (Govindasamy et al., 2003). The CCM3 model assumes a double CO_2 emissions scenario and climate change is estimated for year 2100. From this database, we obtained district-wise projections for the year 2100 for: a) average monthly maximum temperature (Tmax) corresponding to the ripening phase of the calendar year, and b) rainfall corresponding to the reproductive phase for each district from this source.

According to our available observed data, the average $Tmax_{ripening}$ or maximum daytime temperature during the ripening stage during the last one decade (1999 to 2008) is 30.9°C. The CCM3 model projects Tmax for 2100 (for the month corresponding to the ripening phase) to be 32.5°C. This represents a 1.6°C increase in temperature (Govindasamy et al., 2003). Likewise, the observed decadal average total rainfall during the reproductive phase is 194.5mm, which is projected to increase by 2100 to 283.9 mm (a 89.3 mm increase).

The second set of projections we used is from the Nepal Climate Vulnerability Study Team's dataset (NCVST, 2009). This dataset includes climate projections for: a) different years (2030, 2050 and 2090), b) different seasons (pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November), winter (December-February) and the annual average), and c) three regions (eastern, central part and western) of Nepal. Though the projected increase in annual mean temperature has a wide range for each year, the NCVST multi-model mean shows an increase of 1.4°C, 2.8°C and 4.7°C respectively in temperature for year 2030, 2060 and 2090 relative to the period 1970-1999. Projected mean annual rainfall does not show a clear trend and varies widely, but most models suggest an increase in rainfall towards the end of the century. The multi-model mean increase in annual rainfall projected for 2030, 2060 and 2090 are respectively 2%, 7% and 16% relative to the base period of 1970-1999. Table 7 presents the rainfall and temperature projections we used for predicting the future based on the CCM3 and the NCVST data.

In order to predict future climate impacts, we first calculated the mean values of yield (for each district) of the variables $Tmax_{ripening}$, its square term, and $Rainfall_{reproductive}$ from the observed data during the last one decade of our sample period. Then, we used the predicted values in the future to estimate predicted changes in rice yield in the following manner.

$$Yield = b_1.Tmax_{ripening} - b_2.Tmax^2_{ripening} - b_3.Rainfall_{reproductive} \qquad (2)$$

$$Y_p = b_1(T_f - T_c)_{ripening} - b_2(T_f^2 - T_c^2)_{ripening} - b_3(R_f - R_c)_{reproductive} \qquad (3)$$

Where,
Y_p = Projected change in yield
T_f = Future Average Tmax
T_c = Current Decadal Average Tmax
R_f = Future Average Rainfall

R_c = Current Decadal Average Rainfall
b_1, b_2, and, b_3 are coefficients of $Tmax_{ripening}$, square term of $Tmax_{ripening}$, and $rainfall_{reproductive}$ respectively obtained from regression Model-20.

As discussed, projected changes in yield are calculated for two sets of future projections of temperature and rainfall (see Table 7).

5. Results and Discussion

5.1 Regressions Results

To examine the effect of climate variables on rice yields, we estimated multiple regressions for two sets of rice growth phases (two phase and four phase), using two functional forms (linear and quadratic) and six different specifications of independent variables.[9] All 24 models include some combination of temperature, rainfall, VPD and humidity as independent variables. Collectively, these models covers the likely range of functional relationships between rice yield and weather.

An overview of results (from Table 3, Table 4, Table 5 and Table 6), based on an examination of AIC, BIC[10], Adjusted-R^2 and F-statistics, indicates: a) the 4-phase models are preferable to 2-phase models in terms of the number of significant coefficients of climatic variables; b) the quadratic models are superior to the linear ones; and c) the models with VPD are better than those with Tmax. Because different models have a slightly different number of observations, where BIC fails to provide an accurate comparison, we use an additional test to strengthen our choice. In such cases, we used the p-value from an F-test[11] of the significance of the entire set of explanatory variables (the lowest p-value indicates the best model).

Among the 4-phase models, we examined the BIC to choose between quadratic and linear models. The BIC and p value (F-statistics) favor quadratic Model-24 and linear Model-15. However, since quadratic Model-24 does not have any significant variables, we use linear Model-15 to explain the effects of climate on rice yield. Thus, in the rest of this section we examine the effect of climate variables on rice yield when rice development is categorized into its four different phases (see linear Model-15 in Table 5).

Model-15 in Table 5 indicates that Tmax has a **positive and significant effect on yield** by affecting the ripening phase (the overall effect, across all phases, is in-significant). This finding is consistent with that of Welch et al. (2010) and with quadratic models 19 and 20 (Table 6), which indicate that Tmax increases yield but at a decreasing rate during the ripening phase. Given the linear specification of Model-15, we interpret the estimated coefficients as marginal effects. Thus, we estimate each 1°C increase in Tmax during the ripening phase, increases rice yield by 27.3 $kg.ha^{-1}$, other variables remaining constant. We note, however, that quadratic Model 20 suggests that rice yield will decline beyond a threshold level of 29.9°C.

Tmin does not show any significant effects on yield in any of the rice development phases (Table 5), a result that is in-consistent with other recent studies. Several authors (Welch et al. (2010), Lobell and Asner (2003), and Peng et al. (2004)) show that night-time temperature is more important than day-time temperature on rice growth and that increasing night-time temperatures may reduce rice yield in tropical regions.[12] For instance, Peng et al. (2004) find that for every 1°C increase in the mean night-time temperature, rice yield declines by 10 per cent during the dry season. The insignificant Tmin coefficient in our models could be partly driven by the lack of a measure of solar radiation, for which data were un-available.

Model-15 shows that rainfall **during the nursery phase** has a **negative and significant effect on rice yield** (Table 5). This result is reinforced in nearly all the models that include rainfall. Rice plants require less water during the nursery stage, thus, more rainfall and/or the depressed solar radiation caused by cloudiness (during rainfall)

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[9] In addition to these models, we estimated models with alternate definitions of temperature (average and difference), but the results do not change.

[10] Akaike Information Criterion (AIC), and Bayes-Schwarz Information Criterion (BIC) are the standard statistical criteria that allows to compare the performance of models with varying numbers of explanatory variables but with same number of observations.

[11] F test of the significance of the entire set of explanatory variables, excluding district and year dummies.

[12] Given the predicted 2.0–4.5°C increase in global mean temperature by the end of this century, the minimum night-time temperature will increase at a much faster rate than the maximum day-time temperature (IPCC 2007), which in general could affect rice yield negatively.

during the nursery stage will result in lowering yields. Rainfall, while insignificant during the individual phases of vegetative[13], reproductive and ripening, becomes jointly significant and positive when all three phases are considered, indicating its importance (see Table 5).[14]

Model-15 shows that morning humidity has a **negative and significant effect** on rice yield while afternoon humidity has a **positive and significant effect**. Our study suggests that both morning and afternoon humidity may matter and have differential effects.

5.2 Findings on the Future Impacts of Climate Change

For the purpose of predicting the future impacts of climate change in 2100, we use Model-20. This is because data for the future were only available for temperature and rainfall variables. Furthermore, Model-20 has the lowest BIC among the regression modes that only include the variables Tmax Tmin and Rainfall.[15] This Model provides the strongest evidence of statistically significant effects, especially for $\text{Tmax}_{\text{ripening}}$ and $\text{Tmax}_{\text{ripening squared}}$, which are both significant at the 5% level. $\text{Rainfall}_{\text{reproductive}}$ is significant at the 10 per cent level in this model.

Tmax shows strong evidence of a non-linear relationship with yield during the ripening phase (see Models 19 and 20), i.e., temperature first increases yield and then with even higher temperatures, it has a negative effect on yield. We calculate the turning point for the effect of daytime temperature on rice yield using coefficients from Model-20. This estimation indicates the turning point[16] i.e. the temperature at which yield begins to be negatively affected by temperature, is at 29.9°C. Any increase in temperature beyond this point during the ripening phase reduces the rice yield. The past decade's (1999 to 2008) mean temperature during this phase was 30.7°C, which is already higher than the turning point. This suggests that yield is already adversely affected by day time temperature.

We estimate the possible future impacts of weather variables on rice yield based on equations [2] and [3]. We use the previously identified two different sets of projections by calculating the difference between the estimated yield under the projected climatic scenario and the mean current yield obtained from Model-20.

The average $\text{Tmax}_{\text{ripening}}$ during the last one decade of our sample is 30.9°C and the observed total rainfall (averaged over the last decade) during the reproductive phase is 194.5mm. The first set of climate projections for the year 2100 (Govindasamy et al., 2003) have Tmax for the month corresponding to ripening phase at 32.5°C (or a 1.6°C increase) and rainfall at 283.9mm (a 89.3mm increase). Thus, change in yield for the first set of projections is given by:

$$Y_p = 430.71(32.5 - 7.21(1056 - 953.2) - 0.58(283.9 - 194.5) \qquad (4)$$

$$= -\ 103.9\ \text{kg.ha}^{-1}$$

This calculation indicates that an increase in temperature under a scenario that has CO_2 doubling, which is predicted for 2100, would cause a decline in rice yield by 104 kg.ha^{-1} or about 4.2 per cent of the current mean yield.

Similarly, using the second set of projected climate data on temperature and rainfall obtained from the Nepal Climate Vulnerability Study Team (NCVST, 2009) in the above equation, rice yield is estimated to decline by 1.5%, 4.2% and 9.8% relative to the current level by the year 2030, 2060 and 2090, respectively.

While our models predict climate triggered decreases in future in rice yields in Nepal, some caveats apply. The production function approach used for this estimation can exaggerate agricultural loss caused by climate change because it allows for only short-run adaptive responses by farmers. Moreover, though the effect of CO_2 fertilization is controlled in estimating the current effects of climate variables, the estimates of future change in yield do not

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[13] Model 15 shows that rainfall has a positive though insignificant impact during the vegetative phase, which is consistent with the finding in Welch et al. (2010), where solar radiation has a negative impact during the vegetative phase. The positive effect of rainfall is expected in the vegetative phase since rainfall and solar radiation tend to be negatively correlated, with more rain resulting in more cloud cover and less solar radiation.

[14] If we take all the different phases together, the effect of rainfall is insignificant at the 5% level.

[15] The model with the lowest BIC, Model 21, was not suitable for projecting the effects of climate change because it included humidity, for which future data were not available.

[16] $-[\text{Coefficient of Tmax}_{\text{ripening}}/(2^* \text{ Coefficient of Tmax}^2_{\text{ripening}})] = -430.71/(2^*(-7.21)) = 29.9°\text{C}$

account for possible increases in yield due to CO_2 fertilization. Thus, the projected change in the future is a gross estimate of the impact of climate change on rice and not a net estimate (i.e., it does not net out the CO_2 fertilization effect or account for improvements in technology driven productivity).

6. Conclusions and Policy Recommendations

In this study, we use panel data for the last 25 years from 20 major rice-growing districts in Nepal to understand the link between climate variables and rice production. We also project and identify the likely effects of climatic changes on rice production in the future.

Our findings suggest a robust and significant non-linear relationship between maximum daily temperature and rice yields. Increases in maximum temperature during the ripening phase contribute to an increase in rice yield up to a critical threshold of 29.9°C. When maximum temperature goes beyond this threshold, rice yield declines. We note that current average maximum temperature for the decade of 1999 to 2008 is already 30.8°C. Thus, it is expected that rice yields are already being negatively affected by increases in the daily maximum temperature.

There are other interesting results that emerge. Precipitation has a negative effect on yield if rainfall increases in the nursery stage. Likewise, higher morning humidity is expected to harm rice growth while afternoon humidity helps growth positively.

Our prediction of future changes rice yield is based on two different modelling efforts to predict rainfall and temperature in the future. Our first estimate suggests that rice yields will decline by 4.2 per cent yield relative to current levels by 2100. The second set of models predicts an estimated loss of rice yield ranging from 1.5 per cent by year 2030 to 4.2 per cent by 2060 and 9.8 per cent by 2090. These findings are in line with many other studies that have projected a loss of crop yields ranging from 3 to 30 per cent in the future for the region (Murdiyarso, 2000; Parry et al., 2004; Kumar, 2009; Cline, 2007).

We note the estimated yield losses account for only short-run adaptation and ignore positive long-term effects of CO_2 fertilization. At the same time, we have also not considered other effects triggered by climate related changes, such as changes in the water regime and an increase in extreme events, including droughts, storms, floods, inundation, landsides, debris flow, soil erosion and avalanches, etc. On the positive side, technological development may counteract some of these adverse effects and also improve productivity.

Two important recommendations emerge from this work. First, since rising temperature beyond a critical threshold level seems to have a negative effect on rice yield, future agricultural research should focus on the development of high-temperature–tolerant rice varieties. Second, the present study is hampered by a lack of information on solar radiation and reliable information on economic variables such as prices. Thus, a more comprehensive assessment or field experiment that factors in spatial and temporal variations as well as the missing weather and economic variables would help improve our understanding of climate impacts on rice yield.

Acknowledgements

I express my heartfelt gratitude to the South Asian Network for Development and Environmental Economics (SANDEE) for giving me an opportunity to conduct this research by supporting it technically and financially. I extend my heartiest thanks to Professor Jeff Vincent for his technical support at every step of my work until report preparation. His coaching and guidance have been of immense value in my work and learning. My sincere thanks go to Dr. Priya Shyamsundar for her critical review and suggestions to improve this work, to Dr. Mani Nepal who provided on-going feedback, to SANDEE advisors and associates for their comments and suggestion, and to Professor Carmen Wickramagamage for editing this document. I wish to thank my colleagues at Heifer International Nepal and especially Ms. Neena Joshi for supporting me and inspiring to undertake this research and work on climate change issues.

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Tables

Table 1: Rice crop stages and their duration

Phases	Crop stage	Days	Duration
Phase 1:	Nursery (pre-establishment):	25	09 June – 03 July
Phase 2:	Vegetative:	68	04 July – 09 September
Phase 3:	Reproductive:	35	10 September – 14 October
Phase 4:	Ripening:	30	15 October – 13 November

Table 2: Characteristics of Study Sites: Means and Standard Deviations of Rice Yield, and Temperatures (max, min) during Rice Growing Period

District	Yield (kg.ha^{-1})	T_{max} (°C)				T_{min} (°C)			
		Nursery	Vegetative	Reproductive	Ripening	Nursery	Vegetative	Reproductive	Ripening
Kanchanpur	2402.2	35.6	33.1	32.4	29.8	25.2	25.0	22.4	15.2
	(311.8)	(1.8)	(0.9)	(0.8)	(0.9)	(1.1)	(0.9)	(1.1)	(2.1)
Kailali	2395.2	35.1	32.5	31.9	29.7	25.7	25.5	22.9	16.1
	(354.3)	(1.6)	(0.6)	(0.9)	(0.8)	(0.8)	(0.9)	(1.2)	(1.8)
Bardiya	2652.0	35.8	33.3	32.7	30.4	25.4	25.6	23.3	16.3
	(403.2)	(1.4)	(0.5)	(0.8)	(0.7)	(1.0)	(0.6)	(1.0)	(1.2)
Banke	2225.6	35.4	32.9	32.1	30.2	25.5	25.7	23.1	16.4
	(637.8)	(1.9)	(0.6)	(0.9)	(1.0)	(1.4)	(0.8)	(1.1)	(1.5)
Dang	2525.2	31.4	29.8	29.5	27.5	22.8	22.6	19.7	13.0
	(506.5)	(1.3)	(0.5)	(0.6)	(0.7)	(0.9)	(0.8)	(1.1)	(1.3)
Kapilvastu	2068.0	35.3	33.1	32.7	31.1	25.4	25.4	23.5	18.2
	(387.1)	(1.8)	(0.7)	(1.1)	(1.3)	(1.1)	(0.5)	(1.2)	(1.2)
Rupandehi	2474.8	34.5	33.0	32.5	30.8	25.5	25.7	23.5	17.7
	(450.2)	(1.3)	(0.6)	(0.8)	(0.8)	(1.3)	(0.6)	(0.6)	(1.0)
Nawalparasi	2672.3	37.1	34.5	33.1	30.9	26.2	25.6	22.9	17.0
	(343.5)	(2.6)	(2.0)	(1.6)	(1.7)	(1.3)	(1.0)	(1.9)	(1.9)
Chitwan	2847.7	34.2	33.0	32.4	30.3	24.7	25.0	22.8	16.3
	(276.4)	(1.3)	(0.8)	(1.0)	(1.1)	(1.1)	(0.7)	(0.9)	(1.4)
Parsa	3126.1	34.1	34.1	33.1	31.0	22.0	20.4	20.6	21.2
	(420.0)	(0.1)	(0.3)	(0.3)	(0.4)	(4.5)	(7.8)	(6.1)	(5.4)
Bara	3201.6	34.2	32.8	32.6	31.3	25.6	25.5	23.5	18.0
	(411.7)	(1.2)	(0.6)	(0.8)	(1.1)	(0.9)	(1.3)	(0.8)	(1.2)
Rautahat	2180.4	36.0	34.3	33.8	32.7	24.9	25.6	24.1	19.4
	(388.1)	(1.2)	(1.2)	(0.7)	(0.9)	(1.6)	(0.9)	(1.2)	(1.8)
Sarlahi	2298.8	34.8	33.5	33.0	31.5	26.1	26.1	24.2	18.4
	(276.3)	(1.3)	(0.6)	(0.5)	(0.8)	(0.8)	(0.5)	(1.3)	(1.3)
Mahottari	2187.3	34.4	33.5	33.2	30.7	26.0	26.0	25.2	20.6
	(289.5)	(1.1)	(0.8)	(1.0)	(2.8)	(0.6)	(0.7)	(0.6)	(2.8)
Dhanusha	2259.2	33.6	32.5	31.9	30.6	25.8	25.9	24.3	19.2
	(463.3)	(1.1)	(0.7)	(0.6)	(0.9)	(0.8)	(0.9)	(1.0)	(1.3)
Siraha	2179.2	34.0	32.8	31.9	30.6	25.3	25.2	23.4	19.2
	(402.8)	(0.9)	(1.0)	(1.0)	(1.0)	(0.8)	(1.0)	(1.4)	(2.0)
Saptari	2238.7	34.1	33.5	33.1	32.2	25.0	25.1	23.7	19.0
	(405.2)	(1.1)	(1.0)	(1.2)	(1.4)	(1.6)	(0.8)	(0.8)	(1.5)
Sunsari	2662.5	32.6	32.1	31.9	30.8	24.9	25.1	23.0	17.5
	(351.6)	(0.5)	(0.4)	(0.8)	(0.8)	(0.5)	(0.6)	(0.6)	(1.2)
Morang	2644.2	32.6	32.1	31.8	30.6	25.2	25.4	23.5	18.2
	(439.1)	(0.7)	(0.6)	(0.8)	(0.8)	(0.6)	(1.3)	(1.4)	(1.5)
Jhapa	2692.3	33.0	32.8	32.5	31.4	23.3	23.8	22.1	17.0
	(529.9)	(0.7)	(0.8)	(1.1)	(0.9)	(1.9)	(1.7)	(1.8)	(1.9)
Overall	2496.7	34.4	32.9	32.3	30.7	25.2	25.3	23.2	17.5
	(507.9)	(1.9)	(1.2)	(1.2)	(1.4)	(1.4)	(1.2)	(1.5)	(2.2)

N.B. The rice yield which is calculated for summer monsoon across years (1968-2008), the main season and temperatures are shown by growth phases. Figures in parentheses are standard deviations.

Table 3: Two Phase Models with Linear Specification (Dependent Variable: Rice Yield)

Variables	Linear Models with Tmax			Linear Models with VPD		
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**
	Tmax & Tmin	**add rain**	**add humidity**	**VPD & Tmin**	**add rain**	**add humidity**
Tmax: nursery	-8.21 (19.89)	-12.81 (20.29)	-22.30 (22.50)			
Tmax: post-est	45.13 (35.23)	50.19 (37.54)	56.31 (37.19)			
Tmin: nursery	12.91 (12.62)	11.57 (12.40)	8.06 (12.74)	5.02 (12.89)	1.99 (13.33)	2.18 (12.88)
Tmin: post-est	12.95 (15.96)	12.97 (16.38)	19.44 (16.17)	20.25 (16.77)	24.14 (16.70)	24.45 (17.64)
Rainfall: nursery		-0.22 (0.15)	-0.25 (0.16)		-0.23 (0.15)	-0.22 (0.15)
Rainfall: post-est		0.02 (0.03)	0.01 (0.04)		-0.00 (0.04)	-0.01 (0.04)
HumidAM: nursery			-1.48 (4.51)			-3.15 (5.00)
HumidAM: post-est			-2.88 (7.06)			-1.74 (7.24)
HumidPM: nursery			-1.21 (3.25)			
HumidPM: post-est			6.60 (6.22)			
VPD: nursery				0.92 (32.73)	-14.52 (32.60)	-36.28 (47.45)
VPD: post-est				-49.60 (96.49)	-33.43 (95.73)	-53.04 (104.55)
Observations	403	403	394	394	394	394
R-squared	0.62	0.62	0.63	0.62	0.62	0.62
Number of Districts	20	20	19	19	19	19
Joint Significance of Variables: (p-values)						
Tmax: nursery & post-est	0.454	0.424	0.319			
Tmin: nursery & post-est	0.273	0.330	0.339	0.388	0.336	0.370
Rainfall: nursery & post-est		0.295	0.305		0.312	0.384
VPD: nursery & post-est				0.877	0.855	0.652
BIC	5,677	5,673	5,540	5,551	5,547	5,546

N.B. All models include fixed effects for districts and years in addition to the variables shown. Units for explanatory variables: °C for Tmax and Tmin, mm for rainfall, per cent for Humidity, and kPa for Vapor Pressure Deficit (VPD)

Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table 4: Two Phase Model with Quadratic Specifications (Dependent Variable: Rice Yield)

Variables	Quadratic Models with Tmax			Quadratic Models with VPD		
	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12
	Tmax &Tmin	add rain	add humidity	VPD and Tmin	add rain	add humidity
Tmax: nursery	358.92	308.94	304.39			
	(392.31)	(381.53)	(328.36)			
Tmax: nursery, quad	-4.99	-4.32	-4.28			
	(5.44)	(5.30)	(4.61)			
Tmax: post-est	721.04	688.68	522.64			
	(898.52)	(916.82)	(765.94)			
Tmax: post-est, quad	-10.33	-9.78	-7.37			
	(13.58)	(13.84)	(11.53)			
Tmin: nursery	172.50	175.83	108.97	134.88	162.82	140.41
	(210.57)	(202.86)	(165.96)	(201.75)	(199.47)	(196.03)
Tmin: nursery, quad	-3.32	-3.43	-2.18	-2.70	-3.36	-2.93
	(4.24)	(4.07)	(3.33)	(4.08)	(4.01)	(3.93)
Tmin: post-est	-13.80	10.68	98.33	-30.42	-14.04	108.82
	(327.89)	(333.82)	(317.93)	(376.90)	(385.35)	(338.05)
Tmin: post-est, quad	0.43	-0.11	-1.78	1.12	0.85	-1.85
	(7.34)	(7.50)	(7.11)	(8.39)	(8.55)	(7.55)
Rainfall: nursery		0.02	0.00		-0.07	-0.04
		(0.32)	(0.33)		(0.27)	(0.29)
Rainfall: nursery, quad		-0.00	-0.00		-0.00	-0.00
		(0.00)	(0.00)		(0.00)	(0.00)
Rainfall: post-est		-0.04	-0.12*		-0.07	-0.10
		(0.07)	(0.06)		(0.07)	(0.08)
Rainfall: post-est, quad		0.00	0.00*		0.00	0.00
		(0.00)	(0.00)		(0.00)	(0.00)
HumidAM: nursery			-79.19			-67.16
			(62.67)			(62.68)
HumidAM: nursery, quad			0.51			0.42
			(0.41)			(0.41)
HumidAM: post-est			-208.99**			-257.02***
			(76.95)			(76.54)
HumidAM: post-est, quad			1.23**			1.52***
			(0.47)			(0.46)
HumidPM: nursery			40.92*			
			(22.04)			
HumidPM: nursery, quad			-0.30*			
			(0.16)			
HumidPM: post-est			8.94			
			(74.13)			
HumidPM: post-est, quad			-0.00			
			(0.50)			
VPD: nursery				173.16	161.64	253.63
				(126.69)	(127.38)	(161.19)
VPD: nursery, quad				-42.96	-42.52	-66.54
				(34.72)	(34.42)	(38.69)
VPD: post-est				-373.71	-368.16	-43.21
				(449.74)	(448.92)	(512.31)
VPD: post-est, quad				138.27	140.53	-39.30
				(189.36)	(193.38)	(206.82)
Observations	403	403	394	394	394	394
R-squared	0.62	0.63	0.64	0.62	0.62	0.63
Number of Districts	20	20	19	19	19	19
Joint Significance of Variables: (p-values)						
Tmax: nursery & square term	0.662	0.720	0.656			
Tmax: post-est & square term	0.420	0.426	0.523			
Tmin: nursery & square term	0.631	0.652	0.808	0.800	0.675	0.712
Tmin: post-est & square term	0.955	0.949	0.555	0.490	0.356	0.333
Rainfall: nursery & square term		0.394	0.172		0.235	0.149
Rainfall: post-est & square term					0.613	0.435
VPD: nursery & square term				0.396	0.461	0.251
VPD: post-est & square term				0.660		
BIC	5,669	5,667	5,523	5,547	5,542	5,531

N.B. All models include fixed effects for districts and years in addition to the variables shown. Units for explanatory variables are: °C for Tmax and Tmin, mm for rainfall, per centage for Humidity, and kPa for Vapor Pressure Deficit (VPD)

Robust standard errors in parentheses; *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 5: Four Phase Models with Linear Specifications (Dependent Variable: Rice yield)

Variables	Linear Models with Tmax			Linear Models with VPD		
	Model 13	**Model 14**	**Model 15**	**Model 16**	**Model 17**	**Model 18**
	Tmax &Tmin	**add rain**	**add humidity**	**VPD and Tmin**	**add rain**	**add humidity**
Tmax: nursery	-10.48 (24.47)	-21.07 (25.80)	-36.86 (31.75)			
Tmax: vegetative	29.00 (28.63)	55.21* (31.44)	62.37 (36.02)			
Tmax: reproductive	13.35 (16.24)	-1.72 (22.63)	-20.53 (27.61)			
Tmax: ripening	5.29 (16.40)	5.43 (14.36)	27.31** (12.93)			
Tmin: nursery	22.50 (17.02)	16.19 (17.91)	12.27 (19.75)	16.13 (17.00)	8.40 (17.37)	7.49 (17.34)
Tmin: vegetative	-20.97 (28.84)	-14.75 (26.64)	-14.82 (35.73)	-21.75 (31.74)	-9.52 (29.34)	-12.74 (32.09)
Tmin: reproductive	28.57 (22.87)	32.91 (24.01)	38.38 (26.67)	31.78 (20.75)	30.93 (22.29)	32.32 (22.15)
Tmin: ripening	-6.18 (10.70)	-8.52 (10.21)	-9.51 (11.60)	-6.70 (9.82)	-7.17 (11.06)	-4.38 (10.40)
Rainfall: nursery		-0.27* (0.15)	-0.31** (0.15)		-0.29* (0.14)	-0.28* (0.15)
Rainfall: vegetative		0.09* (0.05)	0.09 (0.05)		0.06 (0.05)	0.06 (0.05)
Rainfall: reproductive		-0.19 (0.14)	-0.23 (0.17)		-0.13 (0.13)	-0.16 (0.14)
Rainfall: ripening		-0.48 (0.42)	-0.46 (0.43)		-0.53 (0.46)	-0.54 (0.45)
HumidAM: nursery			-4.93 (5.93)			-4.77 (5.85)
HumidAM: vegetative			4.81 (10.45)			7.57 (11.32)
HumidAM: reproductive			7.00 (6.47)			6.80 (5.71)
HumidAM: ripening			-8.29** (3.71)			-8.32** (3.88)
HumidPM: nursery			-1.19 (3.92)			
HumidPM: vegetative			3.37 (9.04)			
HumidPM: reproductive			-6.39 (4.29)			
HumidPM: ripening			6.50** (3.04)			
VPD: nursery				0.74 (31.11)	-20.32 (29.49)	-52.44 (42.09)
VPD: vegetative				-45.56 (91.63)	10.59 (86.94)	98.50 (152.75)
VPD: reproductive				107.12* (59.05)	70.02 (70.09)	89.78 (72.40)
VPD: ripening				-86.15* (42.14)	-83.71* (44.03)	-127.41* (64.75)
Observations	393	393	381	381	381	381
R-squared	0.62	0.63	0.64	0.62	0.63	0.63
Number of Districts	20	20	19	19	19	19
Joint Significance of Variables: (p-values)						
Tmax: all 4 stages	0.730	0.432				
Tmax: nursery, veg & reprod			0.403			
Tmax: veg & reprod		0.202				
Tmin: all 4 stages	0.442	0.336	0.330	0.421	0.451	0.449
Rainfall: all 4 stages					0.0984	
Rainfall: veg, reprod & ripening			0.0308			
Rainfall: veg & reprod		0.0933				0.154
Rainfall: reprod & ripening		0.0250				0.0204
VDP: nursery & veg				0.884	0.789	0.355
VPD: reprod & ripening				0.104	0.191	0.158
BIC	5538	5527	5343	5369	5360	5354

NB: All models include fixed effects for districts and years in addition to the variables shown. Units for explanatory variables are:°C for Tmax and Tmin, mm for rainfall, per centage for humidity, and kPa for Vapor Pressure Deficit (VPD)

Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table 6: Four Phase Model with Quadratic Specifications (Dependent Variable: Rice Yield)

Variables	Quadratic Models with Tmax			Quadratic Models with VPD		
	Model 19	Model 20	Model 21	Model 22	Model 23	Model 24
	Tmax & Tmin	add rain	add humidity	VPD and Tmin	add rain	add humidity
Tmax: nursery	525.07 (482.49)	445.38 (450.46)	329.96 (435.32)			
Tmax: nursery, quad	-7.38 (6.81)	-6.38 (6.39)	-4.92 (6.16)			
Tmax: vegetative	-83.62 (599.01)	43.92 (595.18)	211.22 (682.91)			
Tmax: vegetative, quad	1.86 (8.84)	0.37 (8.82)	-2.14 (10.11)			
Tmax: reproductive	193.97 (345.88)	170.54 (416.36)	-207.13 (299.61)			
Tmax: reproductive, quad	-2.87 (5.27)	-2.71 (6.33)	2.76 (4.57)			
Tmax: ripening	324.70** (138.84)	430.71*** (145.34)	238.93 (177.52)			
Tmax: ripening, quad	-5.41** (2.41)	-7.21*** (2.48)	-3.74 (3.11)			
Tmin: nursery	73.72 (177.02)	151.84 (218.34)	15.31 (199.13)	15.03 (202.65)	130.93 (244.09)	86.87 (226.79)
Tmin: nursery, quad	-1.09 (3.65)	-2.88 (4.38)	-0.19 (4.04)	-0.06 (4.23)	-2.68 (4.99)	-1.80 (4.59)
Tmin: vegetative	200.21 (209.43)	81.64 (210.01)	113.43 (384.33)	101.92 (461.39)	-94.51 (462.34)	-53.32 (426.93)
Tmin: vegetative, quad	-4.76 (4.49)	-2.14 (4.39)	-2.84 (8.09)	-2.61 (9.71)	1.56 (9.68)	0.67 (9.08)
Tmin: reproductive	-45.49 (281.18)	45.73 (302.22)	258.83 (256.00)	166.19 (268.84)	278.09 (320.84)	358.49 (298.84)
Tmin: reproductive, quad	1.60 (5.97)	-0.29 (6.39)	-4.74 (5.47)	-3.03 (5.84)	-5.41 (6.94)	-7.13 (6.51)
Tmin: ripening	16.80 (93.89)	12.19 (91.21)	-1.27 (110.12)	16.10 (89.30)	25.44 (91.45)	34.34 (99.70)
Tmin: ripening, quad	-0.82 (2.63)	-0.80 (2.54)	-0.41 (3.06)	-0.80 (2.45)	-1.07 (2.52)	-1.24 (2.84)
Rainfall: nursery		-0.13 (0.35)	-0.23 (0.36)		-0.16 (0.29)	-0.20 (0.30)
Rainfall: nursery, quad		-0.00 (0.00)	-0.00 (0.00)		-0.00 (0.00)	-0.00 (0.00)
Rainfall: vegetative		0.12 (0.09)	0.14 (0.12)		0.13 (0.10)	0.13 (0.11)
Rainfall: vegetative, quad		-0.00 (0.00)	-0.00 (0.00)		-0.00 (0.00)	-0.00 (0.00)
Rainfall: reproductive		-0.58* (0.32)	-0.70* (0.35)		-0.60* (0.32)	-0.61* (0.30)
Rainfall: reproductive, quad		0.00 (0.00)	0.00* (0.00)		0.00* (0.00)	0.00* (0.00)
Rainfall: ripening		-0.67 (0.89)	-0.40 (0.86)		-0.44 (0.89)	-0.45 (0.83)
Rainfall: ripening, quad		0.00 (0.00)	-0.00 (0.00)		-0.00 (0.00)	-0.00 (0.00)
HumidAM: nursery			-99.54 (59.57)			-85.38 (70.21)
HumidAM: nursery, quad			0.61 (0.39)			0.52 (0.46)
HumidAM: vegetative			-182.42 (122.69)			-164.28 (133.68)
HumidAM: vegetative, quad			1.15 (0.74)			1.05 (0.79)
HumidAM: reproductive			-74.81 (101.90)			-109.28 (90.35)
HumidAM: reproductive, quad			0.47 (0.61)			0.68 (0.55)
HumidAM: ripening			18.12 (28.40)			15.80 (29.40)
HumidAM: ripening, quad			-0.17 (0.18)			-0.16 (0.19)
HumidPM: nursery			49.77** (22.92)			
HumidPM: nursery, quad			-0.36** (0.17)			

Table 6: Four Phase Model with Quadratic Specifications (Dependent Variable: Rice Yield)

Variables	Quadratic Models with Tmax			Quadratic Models with VPD		
	Model 19	Model 20	Model 21	Model 22	Model 23	Model 24
	Tmax & Tmin	add rain	add humidity	VPD and Tmin	add rain	add humidity
HumidPM: vegetative			10.41 (125.91)			
HumidPM: vegetative, quad			-0.05 (0.81)			
HumidPM: reproductive			-8.74 (48.64)			
HumidPM: reproductive, quad			0.03 (0.31)			
HumidPM: ripening			4.21 (15.07)			
HumidPM: ripening, quad			0.01 (0.11)			
VPD: nursery				199.87 (129.35)	187.84 (129.67)	274.94 (176.57)
VPD: nursery, quad				-50.65 (35.55)	-52.24 (34.47)	-79.14* (41.10)
VPD: vegetative				-534.37 (471.63)	-507.63 (467.22)	67.04 (723.61)
VPD: vegetative, quad				223.15 (203.58)	235.81 (202.68)	0.24 (305.93)
VPD: reproductive				-26.61 (266.74)	-62.59 (261.79)	29.17 (286.30)
VPD: reproductive, quad				67.58 (120.06)	63.20 (120.00)	14.86 (127.19)
VPD: ripening				91.99 (164.42)	124.34 (159.48)	-31.24 (187.62)
VPD: ripening, quad				-72.99 (57.66)	-85.76 (55.48)	-33.66 (57.61)
Observations	393	393	381	381	381	381
R-squared	0.63	0.64	0.66	0.62	0.64	0.65
Number of dist	20	20	19	19	19	19
Joint Significance of Variables: (p-values)						
Tmax: nursery & square term	0.562	0.610	0.657			
Tmax: veg & square term	0.391	0.143	0.222			
Tmax: reprod & square term	0.824	0.881	0.563			
Tmin: nursery & square term	0.493	0.717	0.953	0.761	0.866	0.921
Tmin: veg & square term	0.511			0.751	0.819	0.822
Tmax: ripening & square term		0.0259	0.119			
Tmin: reprod & square term				0.366	0.348	0.214
Tmin: ripening & square term				0.394	0.369	0.535
BIC	5526	5511	5321	5362	5347	5333

NB: All models include fixed effects for districts and years in addition to the variables shown. Units for explanatory variables are:°C for Tmax and Tmin, mm for rainfall, per cent for Humidity, and kPa for Vapor Pressure Deficit (VPD)

Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

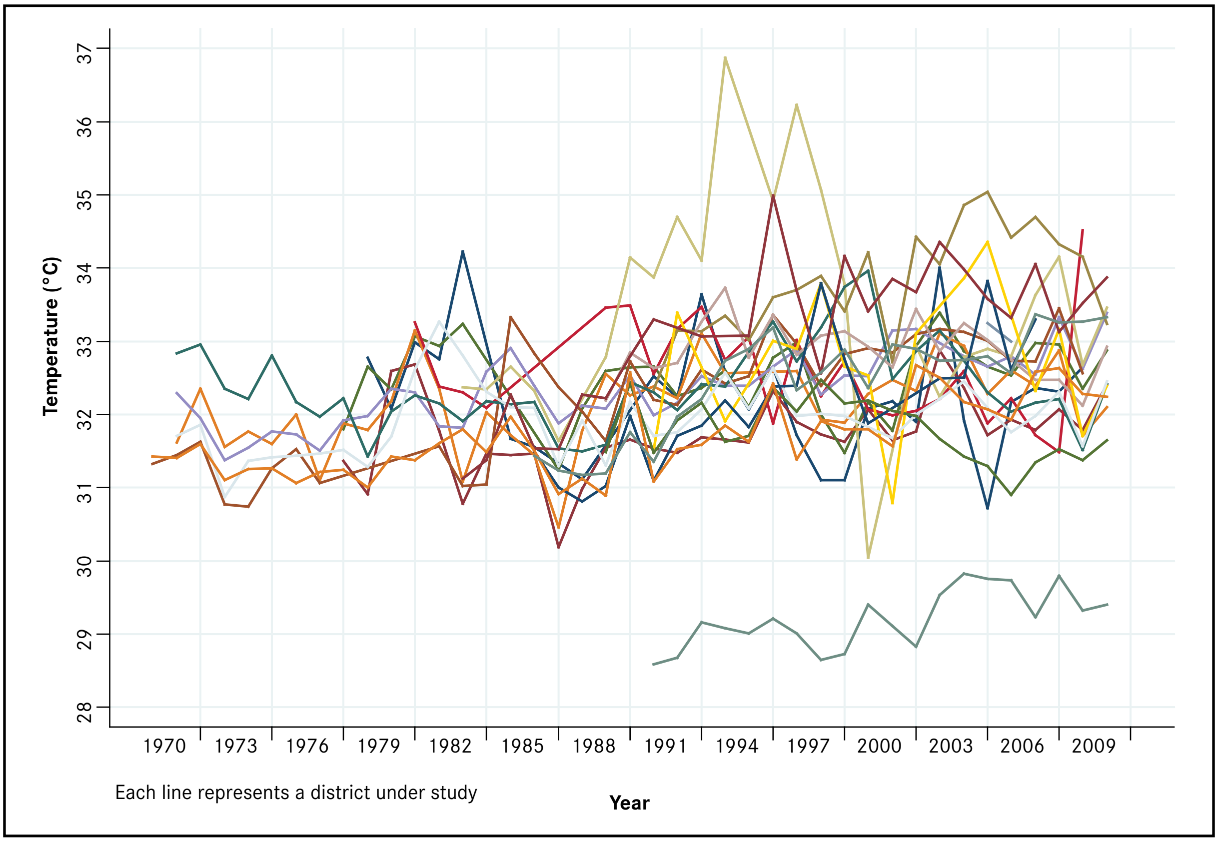
Table 7: Projected increase in weather parameters for Nepal and estimated impact on rice yield

			Projected Future Changes					
	Observed Av monthly max. temp & rainfall (2000-2009)		**NCVST**			**CCM3**		
By year	**Avg. max temp (°C)**	**Avg Rainfall (mm)**	**Projected temp increase (°C)**	**Projected rainfall increase (%)**	**Estimated yield decline from current level ($kg.ha^{-1}$)**	**Projected temp level (°C)**	**Projected rainfall level (mm)**	**Estimated yield decline from current level ($kg.ha^{-1}$)**
2000-2009	30.8	194.5						
2030			1.4	2%	-36.8 (1.5%)			
2060			2.8	7%	-105.2 (4.2%)			
2090			4.7	16%	-245.9 (9.8%)			
2100						32.5	283.9	103.9 (4.2%)

Figures

Figure 1: Map of the Terai Region (Colored districts are study area)

Figure 2: Average temperature (maximum) during the rice growth period over years in different districts



Each line represents a district under study

Figure 3: Temperature (max) across District and Growth Phases

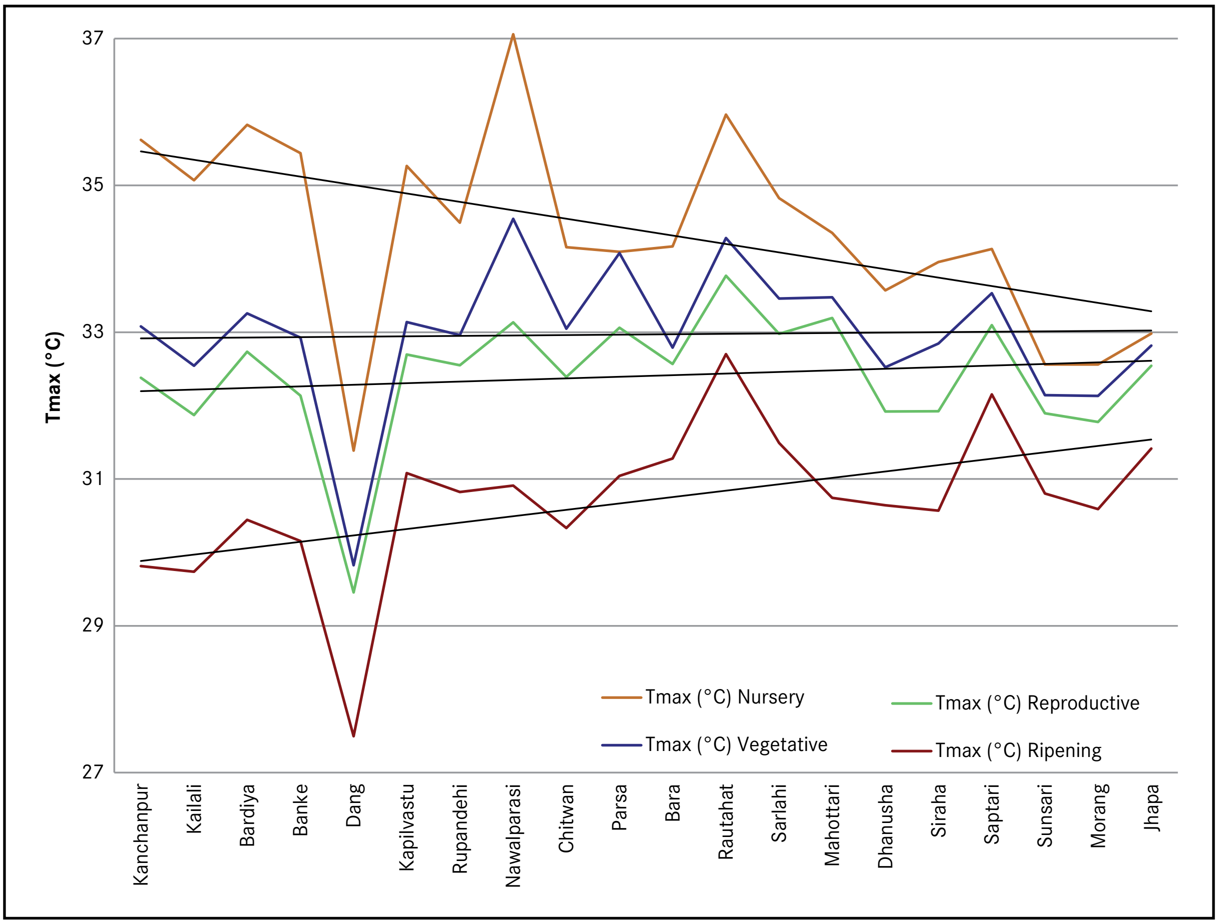


Figure 4: Temperature (max) during Rice Growth Phases across Years

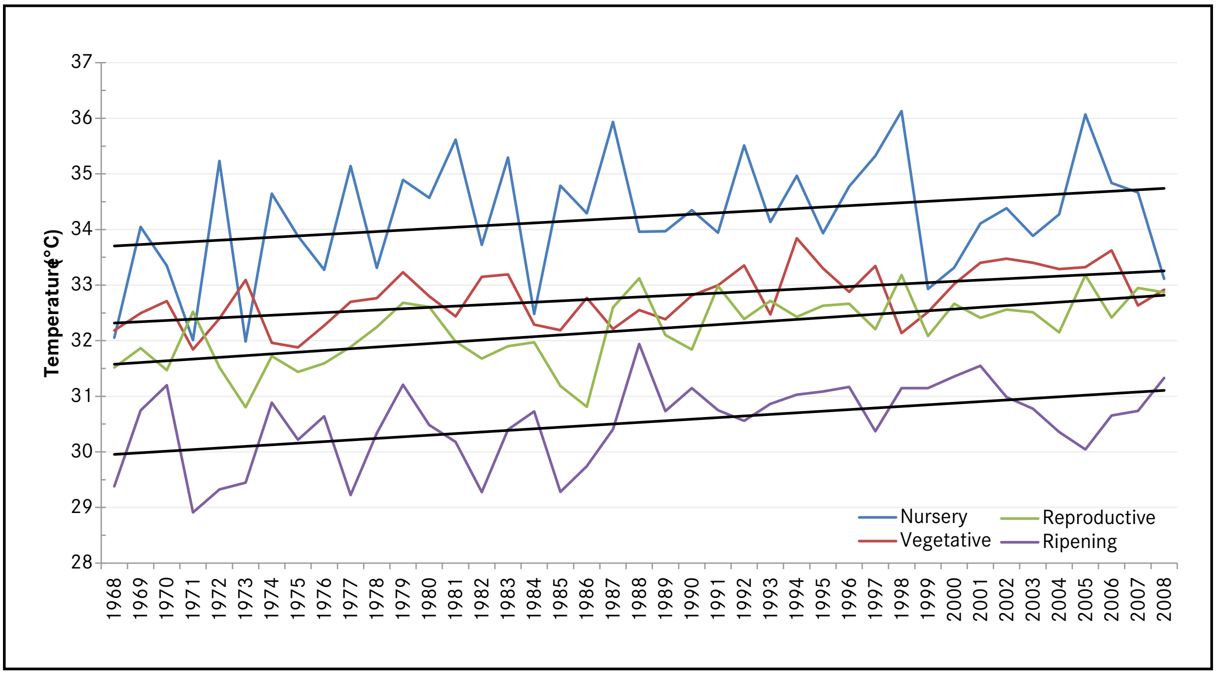


Figure 5: Average min. temperature during rice growing period over years in different districts

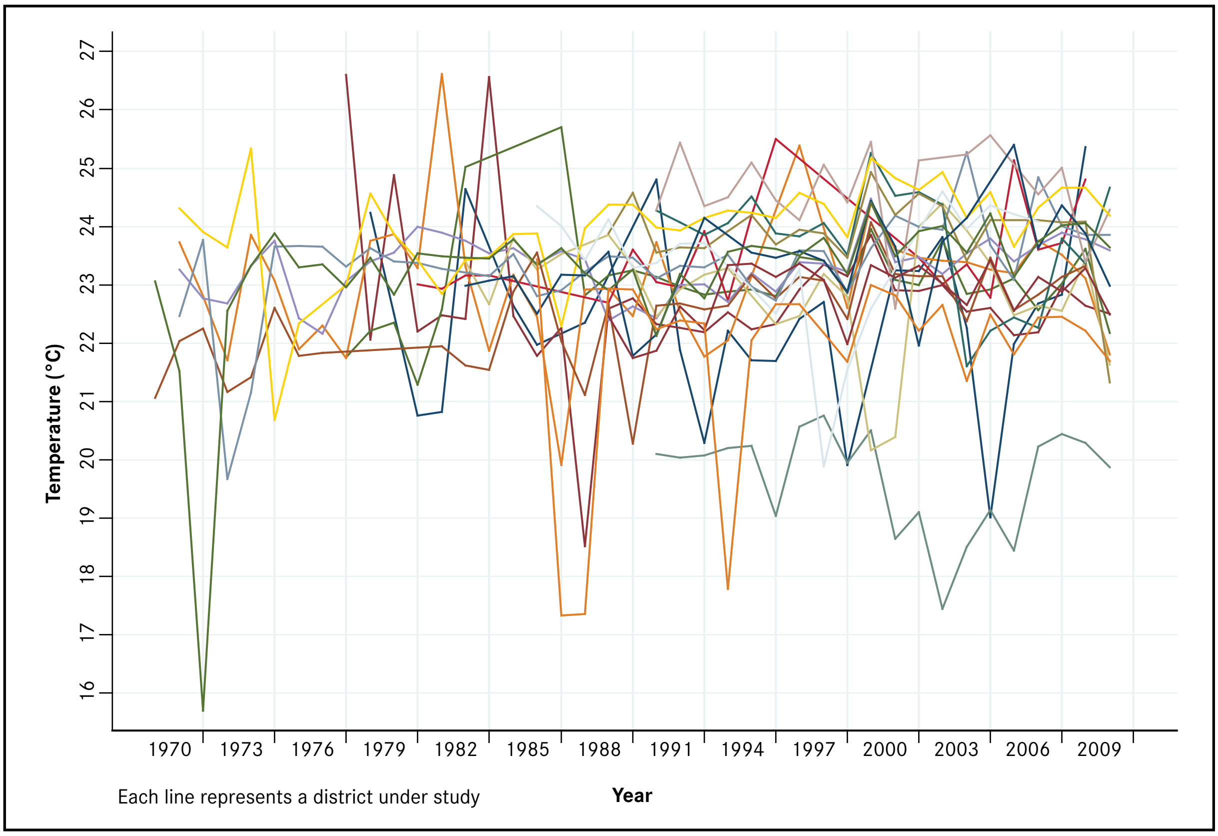


Figure 6: Temperature (min) during Rice Growth Phases across Years

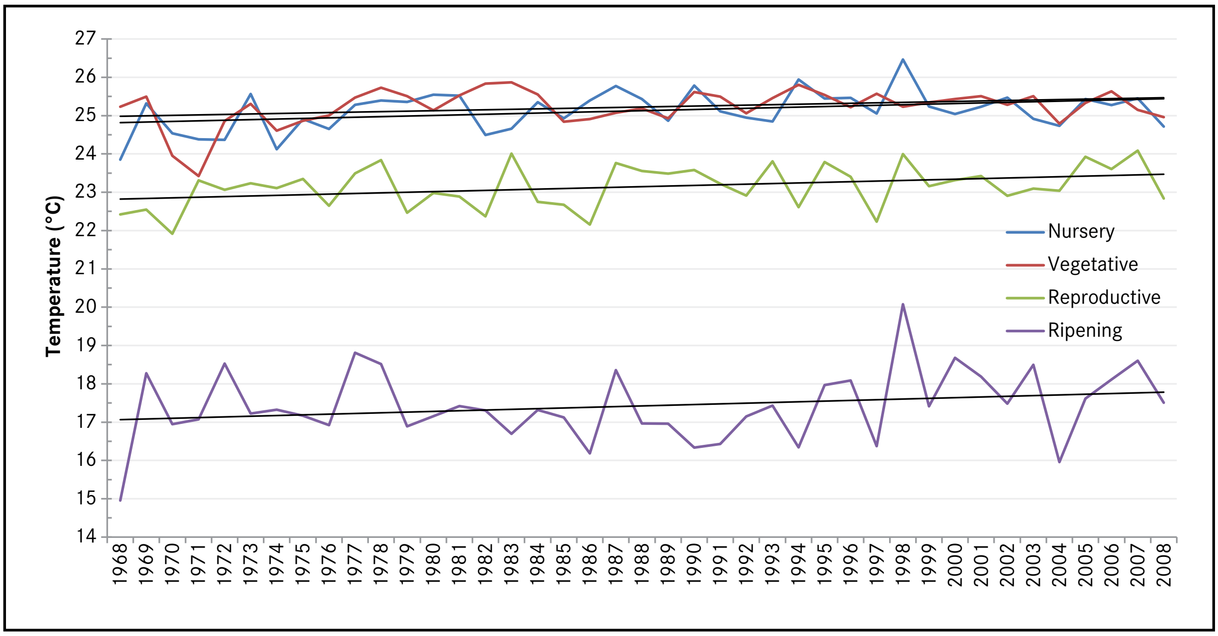


Figure 7: Average Total Rainfall across Districts during Different Growth Phases

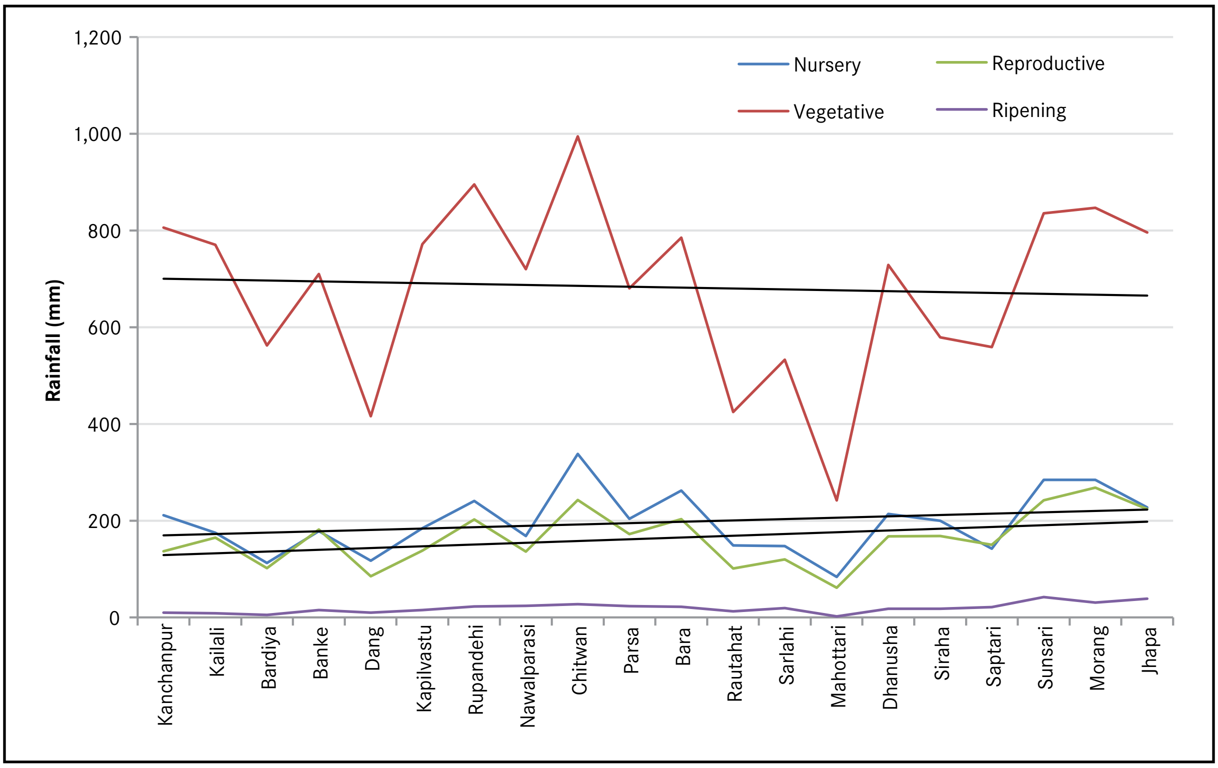
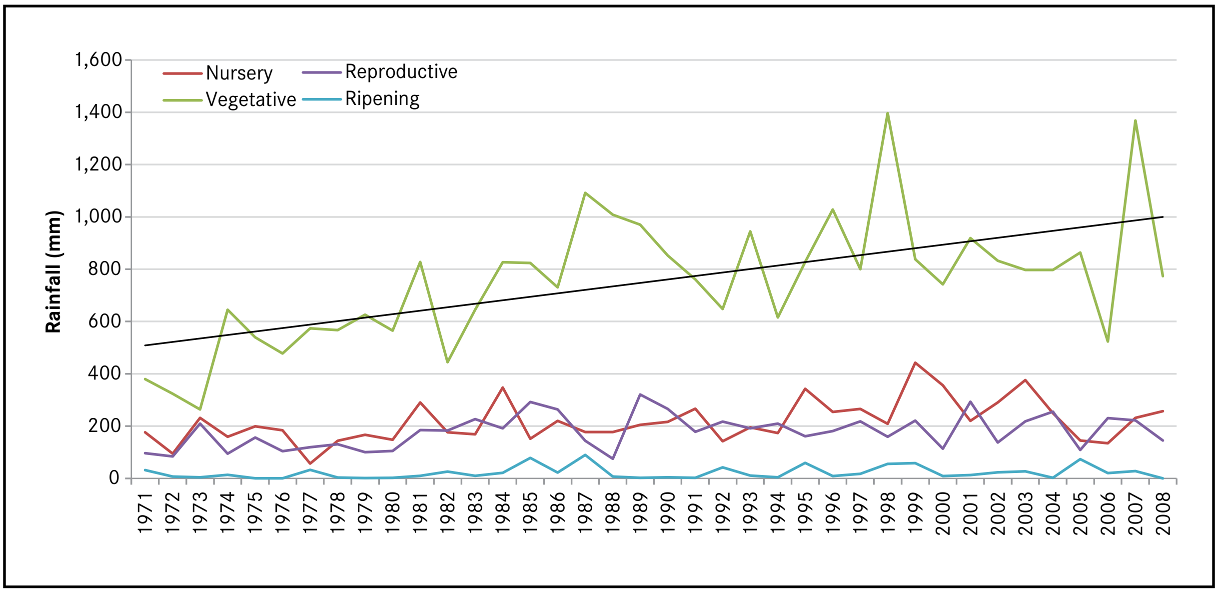


Figure 8: Average Total Rainfall across Years during Different Growth Phases



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