

Working Paper No. 91-15

Impact of Climate Change on Yield of Major Food Crops in Tamil Nadu, India

V. Saravanakumar

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:

V. Saravanakumar

Impact of Climate Change on Yield of Major Food Crops in Tamil Nadu, India

(SANDEE Working Papers, ISSN 1893-1891; WP 91-15)

ISBN: 978-9937-596-21-3

Key words:

Climate change

Agriculture

Productivity Changes

Panel Corrected Standard Errors

Regional Climate Model

India

Impact of Climate Change on Yield of Major Food Crops in Tamil Nadu, India

V. Saravanakumar

Department of Agricultural Economics
Tamil Nadu Agricultural University
Coimbatore-641003
India

January 2015

South Asian Network for Development and Environmental Economics (SANDEE)
PO Box 8975, EPC 1056, Kathmandu, Nepal

The South Asian Network for Development and Environmental Economics

The South Asian Network for Development and Environmental Economics (SANDEE) is a regional network that brings together analysts from different countries in South Asia to address environment-development problems. SANDEE's activities include research support, training, and information dissemination. Please see www.sandeeonline.org for further information about SANDEE.

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.

Advisor

Jeffery Vincent

Technical Editor

Heman Lohano

English Editor

Carmen Wickramagamage

Comments should be sent to

V. Saravanakumar

Department of Agricultural Economics, Tamil Nadu Agricultural University
Coimbatore-641 003, India

Email: sharanu2k@gmail.com

Contents

Abstract

1. Introduction	1
2. Climate Change Impacts on Crop Yield: A Review	2
3. Study Area and Data Description	3
3.1 Study Area	3
3.2 Data	3
4. Models and Estimation Approaches	4
4.1 Econometric Model	4
4.2 Estimation Methods	4
4.3 Regional Climate Model (RegCM4)	5
5. Results and Discussions	5
5.1 Descriptive Statistics	5
5.2 Results of Panel Unit Root Tests	6
5.3 Regression Results	6
5.3.1 Impact of Climate Variables on Rice Yield	6
5.3.2 Impact of Climate Variables on Sorghum Yield	7
5.3.3 Impact of Climate Variables on Maize Yield	7
5.4 Projections of Yield Sensitivities under Climate Change Scenario	7
6. Conclusions and Policy Implications	9
Acknowledgements	10
References	11

Tables

Table 1: Summary Statistics	15
Table 2: Panel Unit Root Test Statistics	15
Table 3: Testing Heteroscedasticity for Yield Response Functions	15
Table 4: Estimated Parameters from Panel Regression Model with Fixed Effects for Rice Crop	15
Table 5: Estimated Parameters from Panel Regression Model with Fixed Effects for Sorghum Crop	16
Table 6: Estimated Parameters from Panel Regression Model with Fixed Effects for Maize Crop	16
Table 7: Joint Significance Tests of Climate Variables of PCSE Regression for different Crop Yield Functions	16
Table 8: Decadal Projections of Changes in Mean Annual Temperature and Mean Annual Rainfall in Tamil Nadu using the RegCM4 Model relative to Base Period (1971-2009)	17

List of Maps

Map 1: Study Area	18
Map 2: Domain Selection	18
Map 3: Tamil Nadu State Grid Layout	19

Figures

Figure 1: Impact of Rainfall on Rice yield	20
Figure 2: Impact of Temperature on Rice yield	20
Figure 3: Impact of Rainfall on Sorghum yield	21
Figure 4: Impact of Temperature on Sorghum yield	21
Figure 5: Projections of Mean Annual Temperature in Tamil Nadu under Climate Change Scenario with RegCM4 Outputs	22
Figure 6: Projections of Mean Annual Rainfall in Tamil Nadu under Climate Change Scenario with RegCM4 Outputs	22
Figure 7: Projections of Rice Yield under a Climate Change Scenario in Tamil Nadu with RegCM4 Outputs (kg per ha)	23
Figure 8: Rice Yield Loss Projections under Climate Change scenario in Tamil Nadu relative to Base Period (1971-2009)	23
Figure 9: Projections of Sorghum Yield under a Climate Change Scenario in Tamil Nadu with RegCM4 Outputs	24
Figure 10: Sorghum Yield Loss under Climate Change scenario in Tamil Nadu relative to Base Period (1971-2009)	24
Figure 11: Projections of Maize Yield under a Climate Change Scenario in Tamil Nadu with RegCM4 Outputs	25
Figure 12: Maize Yield Loss Projections under Climate Change scenario in Tamil Nadu relative to Base Period (1971-2009)	25

Abstract

This study uses panel data for 39 years and 13 districts to estimate the yield sensitivity of major food crops to climate change in the South Indian state of Tamil Nadu. We first estimate the marginal impacts of climate variables on crop yield using Panel Corrected Standard Error (PCSE) models. These estimates are then used to identify yield sensitivities in the future based on projected climate variables from the Regional Climate Model version 4 (RegCM4). Empirical results show a quadratic (inverted U shaped) relationship between rice and sorghum yield and climate variables. As temperature and rainfall increase, crop yield initially increases up to a threshold level, and then decreases. Following the RegCM4 projections that observed warming and anomalies in rainfall will continue, this could result in a significant loss in crop productivity. Projections suggest that there may be a 10 percent decline in rice yield and 9 percent decline in sorghum yield by the end of the 21st century relative to average yields during 1971-2009. This indicates a need for new seed varieties that are less sensitive to rainfall and temperature thresholds, and, adaptation practices such as adjustments in sowing time.

Key words

Climate change, Agriculture, Productivity changes, Panel corrected standard errors, Regional climate model, India

Impact of Climate Change on Yield of Major Food Crops in Tamil Nadu, India

1. Introduction

The 20th century bears testimony to the indubitable fact of climate change as evidenced by increases in global temperatures and changes in rainfall patterns and rates (IPCC, 2001; Jung et al., 2002). In India, mean temperature, based on data from 73 meteorological stations, has shown a significant increase in warming amounting to 0.4°C over the last 100-year period (Hingane et al., 1985). IPCC has projected that by the end of the 21st century, rainfall over India will increase by 10-12 percent with more frequent and heavy rainfall days while the mean annual temperature will rise by 3-6°C (IPCC, 2014). These changes may culminate in adverse impacts on agriculture in terms of productivity loss, pest and disease increases and labor migration that will threaten food security and agricultural employment.

The impact of climate change on agriculture is generally estimated using two broad approaches – agronomic (or crop simulation) and economic modeling, particularly Ricardian approaches (World Bank Report, 2010). Agronomic methods are based on controlled experiments where crops are grown in field or laboratory settings, simulating different climate and CO₂ effects (Aggarwal and Mall, 2002, Saseendran et al., 2000; Hebbar et al., 2008; Geethalakshmi et al., 2011). However, these models do not include farmers' adaptation to changing climate conditions and can overstate the damage caused by climate change (Mendelsohn and Dinar, 1999). The Ricardian models, on the other hand, use cross-sectional data to measure the impact of climate variables on land values or net revenues (Mendelsohn et al., 1994 & 1996; Mendelsohn and Dinar, 1999 & 2003; Kavikumar, 2009). Numerous studies using the Ricardian approach suggest that changes in temperature and rainfall in India could reduce average rice yield by 15 to 25 percent, average wheat yield by 30 to 35 percent (Kavikumar and Parikh, 1998) and farm net income by 8 percent (Mendelsohn et al., 1994). However, a shortcoming of this approach is the failure to account for time-independent location-specific factors such as the unobservable skills of farmers and soil quality.

In addition to these models, researchers have also used panel data to analyze the sensitivity of yield to weather variables (Chen et al. 2004; Isik and Devadoss, 2006; McCarl et al., 2008). Panel data models with fixed effects address the problems of estimation bias due to the omission of time-independent location-specific variables. Thus, in our study, we use a panel data approach to (i) to measure the impact of climate variables on the yield of major food crops; and (ii) to project the impact of climate change on yield sensitivities using the Regional Climate Model (RegCM4).

Researchers often rely on Feasible Generalized Least Squares (FGLS) models for capturing the impact of climate variables, given heteroscedastic panel data (see e.g., McCarl et al., 2008; Kim and Pang, 2009; Barnwal and Kotani, 2010). This poses another estimation challenge because the FGLS formula for standard errors assumes that the error process is known and not estimated (Beck and Katz, 1995). But, in panel data models, the error process has a large number of unknown parameters, resulting in unreliable FGLS estimates of the standard errors of estimated coefficients. In this context, Beck and Katz (1995) propose using Panel Corrected Standard Errors (PCSE) models with Monte Carlo analysis. These models perform well and produce accurate estimates of sampling variability even in the presence of complicated panel error structures. Following Beck and Katz (1995), this study employs the PCSE model to measure the impact of climate change on the yield of major food crops in Tamil Nadu, India.

An important feature of climate impact modeling is how future climate projections are made. Many impact studies either assume certain changes in climate variables from the baseline or use projections based on coarse resolution

climate models such as Global Circulation Models (GCMs) (Chen et al., 2004). In this study, we use projections from a Regional Climate Model (RegCM4), which leads to better estimations of future climate conditions since its horizontal resolutions are finer than those of GCMs (IPCC, 2007).

2. Climate Change Impact on Crop Yields: A Review

In this section, we discuss different studies of the impact of climate change on Indian agriculture and make a case for using the panel data approach.

Agronomic models draw on controlled experiments, where crops are grown in field or laboratory settings simulating different climates and levels of CO₂, in order to estimate the yield responses of a specific crop variety to certain climates. In India, Aggarwal and Mall (2002) and Aggarwal et al. (1997), using crop simulation models (CERES-Rice and ORYZA1N), showed that an increase of 1 to 2°C temperature without any increase in CO₂ resulted in a 3 to 17 percent decrease in rice grain yield in different regions. Byjesh et al. (2010), using the InfoCrop-MAIZE model, reported that the monsoon maize yield is reduced most in the Southern Plateau (up to 35 percent), while the winter yield is reduced most in the Mid Indo-Gangetic Plains (up to 55 percent), whereas yields are relatively unaffected in the Upper Indo Gangetic Plains. In addition, a comprehensive review by Mall et al. (2006) of crop simulation modeling in India points to clear evidence of a decline in the yields of important cereal crops like rice and wheat under climate change conditions.¹ Overall, the agronomic modeling literature in India is indicative of the potential negative effects of climate change.

As previously noted, the Ricardian approach measures the impact of climate variables on land productivity or farmland values by exploiting cross-sectional differences in land use and weather patterns (Mendelsohn and Dinar, 1999 & 2003; Mendelsohn et al., 1994 & 1996). In India, due to limited data on land prices, semi-Ricardian models are estimated with net revenue used as a proxy for the rental value of land. Kavikumar and Parikh (2001), using the semi-Ricardian model, reported that a projected 2°C rise in temperature and 7 percent increase in precipitation reduces farm revenue by 9 percent. This is lower than the annual loss of 12 percent of farm-level net revenue in India estimated by Sanghi and Mendelsohn (2008). Kavikumar (2009), in a later study that included spatial features in the original Ricardian model, found that the impact of climate change on net income is lower by 3 percent in models that account for spatial features relative to those that do not. Palanisami et al. (2009) also report a negative impact on production due to increases in temperature and rainfall. While the Ricardian studies in India point to negative farm impacts of climatic change, these estimates are hampered by the non-availability of land prices and the omission of time-independent location-specific factors like soil quality.

Panel data models with fixed effects address many of the shortcomings of the agronomic and Ricardian models. A well-established tradition (Pinheiro and Bates, 2000; Zuur et al., 2009) such models have been used to study the impact of climate change on crop yields in India (Auffhammer et al., 2006, 2011), Asia (Welch et al., 2010) and Tanzania (Rowhani et al., 2011). In some other panel studies, the three-step Feasible Generalized Least Squares (FGLS) method is used to estimate panel regressions. For example, McCarl et al. (2008) and Barnwal and Kotani (2010) use FGLS to estimate the impact of climate change on mean yield and variability of yield in U.S. and Indian agriculture, respectively. McCarl et al. (2008) conclude that in the US, average corn yield and yield variation, respectively, will increase by 21 percent and 56 percent in the mid-western regions and by 29 percent and 61 percent in the northern plains. On the other hand, Barnwal and Kotani (2010) find that mean rice yield and yield variability will be negatively affected by climate change in India. Other studies of this nature include Chen et al. (2004), Isik and Devadoss (2006) and Ranganathan (2009), who estimate crop production functions with panel data using the Maximum Likelihood Estimation (MLE) procedure. However, as already noted, Beck and Katz (1995) find that the full FGLS variance-covariance estimates are typically unacceptably optimistic about the precision of the parameter estimates and recommend the use of PCSE estimates. Following this finding, our study uses the PCSE estimation method to measure crop yield sensitivities to climate change.

¹ Another agronomic approach is the Agro-Ecological Zone (AEZ) approach, which combines crop simulation models with land management decision analysis (Darwin et al., 1995; Fischer et al., 2005). This strategy combines a laboratory-type set up with real data on climatic factors and crop growth.

3. Study Area and Data Description

3.1 Study Area

Tamil Nadu is situated in the southern-most part of the Indian peninsula (see Map 1). Agriculture, a predominant sector, contributes to about 10 percent of the state's Gross Domestic Product and provides employment for about 60 percent of the rural work force. Currently, gross cropped area is 6.3 million hectares, accounting for nearly 50 per cent of the total geographical area of the state. Food crops account for 70 per cent of the gross cropped area, of which nearly half is under rice (Government of Tamil Nadu, 2010).

Climate in Tamil Nadu is tropical with only slight variations in summer and winter temperatures. Rainfall is from the southwest and northeast monsoons – in the last 25 years, the state has received nearly 80 percent of its annual rainfall during the northeast monsoon season. Additionally, depressions reaching the dimensions of a hurricane develop over the Bay of Bengal and the Arabian Sea, resulting in heavy wind and rainfall during the northeastern monsoonal months. Floods and cyclones can cause heavy damage to food crops during the northeast monsoon season. For instance, some 13 percent of agricultural crops were lost in 2008 as a result of the NISHA cyclone (Government of India, 2008). Since the state is entirely dependent on rains for recharging its water resources, monsoon failures also lead to acute water scarcity and severe drought. Tamil Nadu has India's third longest coastline, which offers another set of challenges. Flooding of coastal areas as a result of sea-level rise and intrusion of salt water into coastal aquifers contributes to crop losses. Thus, climate change can impact agriculture in many different ways in Tamil Nadu, making this an important state to study.

3.2 Data

We collected panel data on two weather variables, rainfall and temperature, and yield data on rice, sorghum and maize crops for all the districts of Tamil Nadu for a 39-year period from 1971 to 2009. Though the state of Tamil Nadu had only 13 districts in 1971,² many of these districts have been bifurcated or trifurcated at various points of time to reach a total of 32 districts. We aggregated the data from newly formed districts into the 13 original districts to construct a consistent panel data set.

We collected data on yield from various publications of the Government of Tamil Nadu including *Tamil Nadu: An Economic Appraisal*, *Statistical Abstract of Tamil Nadu* and *Season and Crop Reports of Tamil Nadu* (Government of Tamil Nadu, various years a, b). We collected data on rainfall and temperature from the India Meteorological Department (IMD) and the State Ground and Surface Water Resources Data Center (SGSWRDC), Chennai.

There are several points to note about our weather data. We gathered time series data on daily rainfall and maximum temperature and minimum temperature from 74 locations spread throughout Tamil Nadu. We assembled the data into a panel data set by computing annual averages. We assembled the weather data into district-level data, based on the following approach. Whenever a weather station fell completely within the administrative boundary of a district, we took the data from that particular weather station to represent data for the district. Whenever a district had more than one station, we computed the averages to represent the district data. Where an administrative district did not have any weather stations, we took the averages of the stations in the surrounding districts to represent the data for that district.

For our analyses, we considered normal rainfall (a moving average of five years) instead of annual rainfall, because farmers adapt to climate change over time. We constructed a single temperature variable, mean temperature (i.e., the average of maximum and minimum temperature), to examine the overall impact of temperature on yield for the purposes of this study.

² Chengalpattu, South Arcot, North Arcot, Salem, Dharmapuri, Coimbatore, Tiruchirapalli, Pudukkottai, Thanjavur, Madurai, Ramanathapuram, Thirunelveli and Kanyakumari.

4. Models and Estimation Approaches

4.1 Econometric Model

To understand the impact of climate change on agriculture, we estimate crop production functions using panel data. In order to take care of many sources of potential omitted variables bias, we estimate panel data models with fixed effects that control for the unobserved district-level heterogeneity that may be correlated with the explanatory variables. We examine the impact of climate change on three crops (rice, sorghum and maize). The study uses the following model with district fixed effects.

$$y_{it} = c + \theta_i + \phi t + \beta_1 T_{it} + \beta_2 T_{it}^2 + \beta_3 P_{it} + \beta_4 P_{it}^2 + \beta_5 T_{it} * P_{it} + \varepsilon_{it} \quad (1)$$

where

y_{it} is yield of a food crop (from rice, sorghum and maize) in district i in year t ;

θ_i are fixed effects for districts;

t is the trend variable which is assumed to be a proxy for capturing technological change due to crop breeding and hybridization programs, inputs management and infrastructural development programs, farmer's adaptation practices, and CO₂ fertilization effects;

T_{it} is mean temperature in district i in year t measured in degree Celsius (°C);

P_{it} is normal rainfall in district i in year t measured in millimeter (mm per annum);

ε_{it} is the error term;

c , ϕ and β_1 to β_5 are unknown parameters to be estimated.

4.2 Estimation Methods

We use two econometric models – FGLS and PCSE – to estimate productivity changes. We also show results for ordinary least square regressions. We report the estimates from the OLS, FGLS and PCSE models and compare the standard errors between FGLS and PCSE. We use the PCSE estimates to project the impact of climate change on crop yield using the Regional Climate Model (RegCM4) outputs, which predict temperature and rainfall levels in the next 90 years.

In the past, economists routinely used the FGLS to generate consistent and asymptotically efficient estimates of the standard errors (Kmenta, 1986).³ However, FGLS standard errors can underestimate true variability, at least for normal errors in finite samples (Freedman and Peters, 1984). FGLS changes the estimates of both the regression coefficients and their standard errors and runs the risk of producing inaccurate estimates of the coefficients (Chen et al., 2006). OLS estimates of coefficients are consistent but inefficient.⁴ The OLS standard errors will be inaccurate and need to be corrected taking into account panel heteroscedasticity and contemporaneous correlation of the error term. PCSE retains the OLS parameter estimates, but it replaces the OLS standard errors with estimates based on the disturbance covariance matrix that are less prone to underestimation than full FGLS estimates (Back and Katz 1995).

To obtain PCSE estimates, we denote β as a vector of the parameters of the model: c , ϕ and β_1 to β_5 . The OLS and PCSE estimator of β are identical and given by:

$$\hat{\beta}_{OLS} = \hat{\beta}_{PCSE} = (X' X)^{-1} (X' y) \quad (2)$$

The PCSE estimator for the standard error of the above estimator is given by the square roots of the diagonal terms of:

$$\text{Cov}(\hat{\beta}_{PCSE}) = (X' X)^{-1} \{X' \Omega X\} (X' X)^{-1} \quad (3)$$

³ See the FGLS estimation procedure given in Greene (2008) for more information.

⁴ The degree of inefficiency depends on the data and the exact form of the error process.

where X is the matrix of observation of explanatory variables, y is the vector of observations of the dependent variable, and Ω is the error covariance matrix, which is an $NT \times NT$ block diagonal matrix with an $N \times N$ matrix of contemporaneous covariances (where N is the number of cross sectional units, i.e., districts, and T is the number of years). If the error term satisfies the spherical assumptions, Equation (3) simplifies to the usual OLS formula, $\hat{\sigma}^2 (X'X)^{-1}$, where $\hat{\sigma}^2$ is the usual OLS estimator of the error variance.

Finally, it is essential to investigate the presence of panel unit roots for each variable before proceeding with the PCSE procedure. One important assumption related to the use of time-series cross-sectional data is that the variables under estimation are stationary (Chen et al., 2004; Chen and Chang, 2005; Granger and Newbold, 1974). To test the stationarity of the variables, we use the Im, Pesaran, and Shin (2003) unit root test.⁵ In order to detect the heteroscedasticity for the panel data constructed from 13 districts, we use the White test (Greene, 2008).

4.3 Regional Climate Model (RegCM4)

General Circulation Models (GCMs) are tools designed to simulate time series of climate variables globally, accounting for effects of greenhouse gases (GHGs) in the atmosphere. GCMs are currently the most credible tools available for simulating the response of the global climate system to increasing greenhouse gas concentrations and to provide estimates of climate variables (e.g., air temperature, precipitation, wind speed, pressure, etc.) in the future on a global scale (Ghosh and Mujumdar, 2006). However, GCMs are limited by their coarse resolution and failure to capture extreme events such as cyclone and heavy rainfall (Rupakumar and Ashrit, 2001; Murphy et al., 2007). An alternative is dynamical downscaling using high-resolution Regional Climate Models (RCMs) nested in GCMs. Downscaling is the method of producing local to regional scale information from larger scale GCM data. Dynamical downscaling includes the use of limited-area, high-resolution RCMs nested within and driven by time-dependent lateral and lower boundary conditions from a GCM (Rahman et al., 2012).

RCMs lead to better estimations of future climate conditions since their horizontal resolutions are much finer than those of GCMs (IPCC, 2007). In this study, we use the RegCM4 model, an open source RCM version 4, released in 2010 (Elguindi et al., 2010). It is largely applied to the study of regional climate and seasonal predictability around the world (Geethalakshmi et al., 2011). We ran RCMs for the 13 composite districts of Tamil Nadu with a horizontal resolution of $25 \text{ km} \times 25 \text{ km}$ and a sufficient buffer zone.

To obtain our climate projections, we first selected an area covering most of peninsular India (see Map 2 for the domain used). The boundary for the domain was 2.00 to 25.61°N and 66.45 to 90.96°E (Rajalakshmi et al., 2013). This covers 110 East West and 110 North South grid points (before removing 12 buffer grids as suggested by ICTP). We obtained outputs for Tamil Nadu, which covered 218 out of the 12,100 grid points⁶ (see Map 3 for the grid layout). Within this domain, we predicted year-wise and decade-wise mean temperature and annual rainfall from the RegCM4 climate model.

In order to run the data through the RegCM4 climate model, we had to make some assumptions about global conditions in the future. We selected the moderate CO_2 emissions A1B scenario, identified by IPCC (2000), for the RegCM4 climate model with EH50M GCM boundaries. We ran the model for 130 years, from 1971 to 2100. While the model generated a larger number of outputs, we retrieved only maximum temperature, minimum temperature and rainfall.

5. Results and Discussion

5.1 Descriptive Statistics

Table 1 presents the summary statistics of the climate and crop yield variables used in the study. Rice is the major staple food crop of Tamil Nadu, which is cultivated in three different seasons taking up around 40 percent of the total cropped area and around 55 percent of the total area of food crops. The average yield of rice was 2772 kg per

⁵ The test is valid when the errors in the district regressions are serially uncorrelated and normally and independently distributed across the districts.

⁶ The study area covered the State of Tamil Nadu in southern peninsular India which lies between 7.91°N to 13.65°N latitude and 76.17°E to 80.82°E longitude.

ha for the period from 1971 to 2009 with a standard deviation of 881 kg per ha. Sorghum was grown predominantly during the *Kharif* season (82 percent) under rain-fed conditions. The average yield of sorghum over 39 years was 1028 kg per ha with a standard deviation of 406 kg per ha. The average productivity of maize was 1446 kg per ha with a standard deviation of 1069 kg per ha. The mean level of annual precipitation was 963 mm per annum with a standard deviation of 196.9 mm and the mean annual temperature over the past four decades from 1971 to 2009 was 31.44°C with a standard deviation of 3.44°C.

5.2 Results of Panel Unit Root Tests

It is essential to investigate the presence of panel unit roots for each variable before estimation of the panel data model, as discussed in Section 4. Table 2 presents the results of Im, Pesaran, and Shin (2003) unit root test with the assumption that error term in the autoregressive process of each variable is serially uncorrelated. The test results show that the null hypothesis of the unit root is rejected for each variable with trend (yield of rice, sorghum and maize, rainfall and temperature) at the one percent significance level. Since the panel unit root results reject the null hypothesis of non-stationary, each variable is stationary. Thus, there is no need to first-difference the data to eliminate unit roots (McCarl et al., 2008; Kim and Pang, 2009; Sarker et al., 2012) and we can estimate the panel data models, as specified in Section 4.

After estimating the panel data model for each crop, we used White test to detect heteroscedasticity. Table 3 presents results of the test. The null hypothesis of homoscedasticity is rejected at the 5 percent significance level. Thus, the White test indicates the existence of panel heteroscedasticity. This warrants the use of a suitable econometric estimation procedure that takes into account the panel heteroscedasticity of the error term.

5.3 Regression Results

Tables 4, 5 and 6 present the results of panel regression with district fixed effects for OLS, FGLS and PCSE models for rice, sorghum and maize crop yield, respectively. We compared the standard errors of the PCSE model with the FGLS standard errors. As expected, the results indicate that the standard errors with FGLS are lower than PCSE for almost all estimates. This provides evidence consistent with the findings of Beck and Katz (1995), that FGLS underestimates the standard errors. Therefore, we consider only the PCSE estimates in discussing results and making inferences.

5.3.1 Impact of Climate Variables on Rice Yield

Table 4 presents the panel regressions for rice yield. We discuss the PCSE regression estimates to explain the impact of climate variables on rice yield. The R^2 value is 0.68, which indicates that the climate variables included in the model explain more than two-thirds of variations in yield.

The PCSE regression coefficients for rainfall indicate that it has a quadratic (an inverted U-shaped) relation with rice yield. The first-order term of rainfall is statistically significant at 5 percent level and has a positive sign, while the square term of rainfall is statistically significant at 1 percent level and has a negative sign. To test joint significance of rainfall and its square term, we also conduct a chi-square test for their joint significance (Table 7). The results show that rainfall and its square term are jointly significant at 5 percent significance level. These results indicate that higher rainfall increases crop yield up to a threshold level (1057 mm per annum). Rainfall beyond the threshold has a negative impact on rice yield (Figure 1). This type of quadratic relationship of rainfall with rice yield is also reported by Chen and Chang (2005) in Taiwan, Auffhammer et al. (2011) and Gupta et al. (2012) in India. The evidence of a yield depressing effect of heavy rainfall is important because available historical data indicates that heavy rainfall often occurs. In observed data over 39 years from 1971 to 2009, mean annual rainfall of Tamil Nadu state exceeds the threshold level (1057 mm) 10 times in Tamil Nadu state suggests that weather events could have often resulted in losses in rice production.

Like rainfall, temperature also indicates an inverted U-shaped relationship with rice yield. The first-order term of temperature is statistically significant at 10 percent level and has a positive sign, while the square term of temperature is statistically significant at 10 percent level and has a negative sign (Table 4). Temperature and its square term are not jointly significant (Table 7). Thus, the effect of temperature is not estimated as precisely as

the effect of rainfall. Since almost two-thirds of total rice production takes place during the 'Samba' season which coincides with the north-east monsoons, a small increase in temperature may improve yield. A plausible reason for yield increase may be the interaction effects of temperature with elevated carbon dioxide concentration. Temperature increases can contribute to increased productivity by increasing photosynthetic activity (Lakshmanan et al., 2011), fertilizer use efficiency and possibly reducing pest manifestations (Ranganathan, 2009). However, an inverted U-shaped relationship of temperature with rice yield implies the existence of a threshold level, above which a reduction in yield would begin (Figure 2). This finding is in conformity with studies on the effect of high temperatures during the ripening phase of rice plants, which show the upper threshold temperature to be 34°C (Morita et al., 2004). Several other studies also show that increases in temperature beyond critical limits can contribute to reductions in rice yield in the future (Dash and Hunt, 2007; Geethalakshmi et al., 2011).

We used the time trend variable in this study to capture technological change, inputs management and infrastructural development programs, farmer's adaptation practices, and CO₂ fertilization effects. The results show that the coefficient estimate on time trend is positive and statistically significant at 1 percent significance level. Various agricultural technology development programs, including high-yielding varieties and irrigation infrastructure, over the 39 years as well as the CO₂ fertilization effects have contributed to improving rice yield consistently. This result reinforces findings by Attavanich and McCarl (2011), who report that the average yields of the C-3 crops (rice, wheat and soybean) are significantly and positively correlated with CO₂ concentration.

5.3.2 Impact of Climate Variables on Sorghum Yield

The PCSE results indicate that rainfall and temperature have a quadratic (an inverted U-shaped) relationship with the yield of sorghum, again implying the presence of a threshold limit (Table 5). Rainfall and its square term are jointly significant at 5 percent significance level (Table 7). Since sorghum is cultivated mostly (around 82 percent) under rainfed lands in Tamil Nadu, we expect rainfall to have a positive impact on yield. However, rainfall, when it exceeds the threshold level (100 mm per month during the growing months), has a negative effect (Figure 3). In our observed data over 39 years, mean monthly rainfall of Tamil Nadu state exceeds 100 mm per month 45 times during the major growing months of Kharif season for sorghum.

Temperature also indicates an inverted U-shaped relationship with sorghum yield (Figure 4). The first-order term of temperature is statistically significant at 5 percent level and has a positive sign, while the square term of temperature is statistically significant at 5 percent level and has a negative sign. Temperature and its square term are jointly significant at 10 percent significance level.

Our study reinforces results from previous studies (Kumar et al., 2004, CRIDA, 2009) that predict that an increase in temperature and rainfall beyond a threshold level can negatively affect sorghum yield in future. We also note that the trend coefficient in our regressions is positive and statistically significant at 5 percent.

5.3.3 Impact of Climate Variables on Maize Yield

In terms of maize yield, the PCSE results show that while both temperature and rainfall have a negative impact, the coefficients are not statistically significant (Table 6). However, rainfall is significant at 10 per cent level in the joint significance test for rainfall and squared rainfall (Table 7). Further, the interaction term between temperature and rainfall is significant at 5 percent (Table 6), which indicates that the effect of rainfall on yield is dependent on the level of temperature and vice-versa. As expected, time trend has a significant (p-value <0.01) and positive effect on maize yield. We conclude that our results related to maize yield are not as robust as the findings related to rice and sorghum.

5.4 Projections of Yield Sensitivities under Climate Change Scenario

In order to examine the impact of climate change on crop yield sensitivities in future, we obtained predicted climate outputs using RegCM4. We used the RegCM4 model to derive mean temperature and mean rainfall per day, which were converted into decadal means. This output was available for different latitude and longitudes within every 25 square kilometers (km) of Tamil Nadu. Overlaying district maps on this grid, we identified climatic data for every district to make a panel dataset of climate change projections. Auffhammer et al., (2013) suggest adding the

predicted change in climate variables obtained from climate models to weather station-based baseline climate for calculating impacts rather using climate model outputs directly for forecasting future climate. The previous studies (Kabubo-Mariara and Karanja, 2007, Kurukulasuriya and Mendelsohn, 2008, Seo and Mendelsohn, 2008, Kabubo-Mariara, 2009) also added predicted absolute change in temperature and multiplied the predicted percentage change in precipitation to weather station-based baseline climate in each district. In this study, we followed the same procedure to project rainfall and temperature.

Using RegCM4, we projected rainfall and temperature for each district from 2011 to 2100. Figures 5 and 6 present the mean annual rainfall and mean annual temperature, respectively, from 2011 to 2100 in Tamil Nadu, computed as the average of all districts in the state. Table 8 presents projected change in mean annual temperature and mean annual rainfall for different decades from 2011 to 2100 in Tamil Nadu. Results indicate that mean temperature will continuously increase over this century, with mean temperature being 3.26°C higher in the last decade of 2091-2100 relative to the base period (1971-2009). This suggests that mean temperature in the final decade of this century could be, on average, as high as 34.70°C. Results on rainfall indicate that there is no definite trend in rainfall pattern in the future. Projections in Table 8 show that mean annual rainfall decreases during first two decades 2011-20 and 2021-30 and increases subsequently in the future. In the end of the century, the rainfall is expected to be around 1042 mm, which is 9 percent increase relative to baseline rainfall.

In order to project climate impacts in the future, we used the PCSE regression coefficient estimates to compute the marginal impacts of projected changes in climate variables on crop yield for each crop (rice, sorghum and maize). As mentioned above, rainfall and temperature were projected for each district using RegCM4, we computed the climate impacts on crop yield for each district.⁷

Figure 7 presents the spatial and temporal sensitivities of rice yield (kg per ha) to projected climate variables across districts of Tamil Nadu for each decade from 2021-30 to 2091-2100. Figure 8 presents the rice yield loss, computed as the average of all districts, under the climate change scenario for each decade relative to yield of 2772 kg per ha in base period (1971-2009). The projections of yield loss show a reduction in rice yield on an average of 283 kg per ha in the last decade of the 21st century relative to the base period. Under the climate change scenario, rice yield would decline by 55 kg per ha in a decade during 2011-20, based on projected increase in temperature by 0.51°C and decrease in rainfall by 84 mm relative to the base period. In the middle of the 21st century, i.e., during the decade 2051-60, rice yield is projected to be lower by 147 kg per ha relative to base period, based on projected increase in temperature 1.56°C and 156 mm increase in rainfall in 2051-60 relative to base period. Towards the end of this century (2091-2100), yield would be around 283 kg per ha lower or 10 per cent less than the base period. This is because of the projected rise in temperature by 3.26°C and rainfall by 79.12 mm (8.22 percent) relative to base period. It is worth noting that the agronomic model, viz., the Decision Support System for Agro-technology Transfer (DSSAT), using a regional climate model called PRECIS, projects rice yield loss to be 356 kg per ha for ADT 43 rice variety over Cauvery Delta Zone of Tamil Nadu by 2100 (Geethalakshmi et al., 2011). This number is considerably higher than the yield loss (283 kg per ha by 2100) projected by this study.

Figure 9 presents the spatial and temporal sensitivities of sorghum yield (kg per ha) to projected climate variables across districts of Tamil Nadu for each decade from 2021-30 to 2091-2100. Figure 10 presents the sorghum yield loss, computed as the average of all districts, under the climate change scenario for each decade relative to yield of 1028 kg per ha in base period. The projected yield loss is 75 kg per ha per decade for sorghum in 2011-20 relative to the baseline average. In the decade 2021-30, 0.05°C decrease in temperature and 77 mm increase in rainfall relative to the preceding decade (2011-20), reduce yield loss by 68 kg per ha. Further, the results suggest an expected decline in yield 39 kg per ha during 2051-60 and 88 kg per ha during 2091-2100 relative to the base level. The projections show that sorghum yield would be 0.60 percent less by 2020 and 8.56 percent less by 2100 relative to the base period. These results mirror findings by Chen et al. (2004), who similarly examine yield variability of sorghum in the U.S. and find mixed results.

⁷ For each district and each crop, we computed projected change in crop yield using the following formula:

$$\Delta y_p = \hat{\beta}_1(T_f - T_b) + \hat{\beta}_2(T_f^2 - T_b^2) + \hat{\beta}_3(R_f - R_b) + \hat{\beta}_4(R_f^2 - R_b^2) + \hat{\beta}_5(T_f * R_f - T_b * R_b)$$

where Δy_p = Projected change in yield; T_f = Future mean temperature; T_b = Baseline mean temperature; R_f = Future mean rainfall; R_b = Baseline mean Rainfall; and $\hat{\beta}_1$ to $\hat{\beta}_5$ are coefficients of obtained from PCSE regression results.

Figure 11 presents the spatial and temporal sensitivities of maize yield (kg per ha) to projected climate variables across districts of Tamil Nadu for each decade from 2021-30 to 2091-2100. Figure 12 presents the maize yield loss, computed as the average of all districts, under the climate change scenario for each decade relative to yield of 1746 kg per ha in base period. The projection results indicates that maize yield is projected to increase by 29 and 7 kg per ha in a decade during 2011-20 and 2021-30, respectively. After that, maize yield is expected to decline by the end of the 21st century. The projected yield loss of 137 kg per ha in a decade during 2051-2060 is relatively higher as compared to other decades. The projection of yield loss due to projected changes in rainfall and temperature in Tamil Nadu show a reduction of 81 kg per ha for maize by end of this century relative to the base period. These results fall below estimated maize monsoon crop yield losses ranging between 13 percent and 35 percent and winter maize crop to ranging between 17 and 50 percent by 2050 (across the Southern Plateau and the mid-Indo Gangetic Plains of India) (Byjesh et al., 2010).⁸ Our findings suggest a productivity decline of 4.62 percent by the end of the 21st century, given a 3.26°C increase in temperature and 8.22 percent increase in rainfall at this point.

6. Conclusions and Policy Implications

This paper attempts to estimate the impact of climate change on agricultural yield in a tropical climate using Tamil Nadu, India, as example. Our study puts together a unique 39-year period (1971 to 2009) panel dataset to examine the impact of climate change on the yield of food crops, viz., rice, sorghum and maize. The methodology involves a two-step procedure. First, we use panel data on crop yields and climate variables to estimate yield response functions. Second, we project future crop yield sensitivities by using outputs from a regional climate model (RegCM4) in combination with the estimated yield functions.

Our study suggests that rice and sorghum are quite sensitive to changes in rainfall and temperature (the implications for maize are not as robust and we do not discuss these further). Rainfall and temperature have positive and significant effects on rice and sorghum yields up to a threshold level of rainfall and temperature. Beyond the threshold level, further increases in rainfall and temperature result in negative impacts on yield. The presence of thresholds in weather impacts is an important finding and shows that there is an inverted U-shaped relationship between crop yields and climate variables.

Projected temperature and rainfall using the RegCM4 model for the period from 2011 to 2100 indicate that observed warming and anomalies in rainfall in Tamil Nadu will continue. Projections suggest that there will be a reduction of 283 kg per ha per decade of rice and 88 kg per ha per decade of sorghum by 2100. This represents a 10 percent decline in rice productivity and a 9 percent decline in sorghum yield by the end of the 21st century, relative to the average yield during the base period 1971-2009.

Our study's findings related to thresholds in climate effects on crop yields need careful consideration by researchers and policy makers. On the policy side, it may be important to invest in new seed varieties that can better adjust to rainfall and temperature thresholds. There is also need for further research to explore the implications of adaptation responses such as adjustments in the sowing season. Our model is one attempt to bring together climate and agricultural data to examine potential climate impacts on Tamil Nadu. Such studies can be further improved by including additional factors such as the date and amount of released reservoir water for irrigation.

⁸ Brown and Rosenberg (1997) report an yield loss of 17 percent for every 3°C increase in temperature in central U.S and Rowhani et al., (2011) report losses of roughly 18.6 percent for an increase in 20 percent coefficient of variation (CV) in rainfall and 2°C in temperature for Tanzania.

Acknowledgements

I wish to acknowledge the financial support from the South Asian Network for Development and Environmental Economics (SANDEE). The author would like to record his gratitude to Prof. Jeffrey Vincent for valuable guidance and suggestions throughout the project. Special thanks to Prof. R. Jagannathan, Agro Climate Research Center, TNAU for providing RegCM4 outputs and Srinivasan, Senior Research Fellow for his valuable assistance in completing the analyses. Comments from Mani Nepal, Priya Shyamsundar, Heman Lohano, and the anonymous reviewer were very useful in improving the manuscript. My mentors, Balasubramanian, Paramasivam and D.K. Jain deserve special mention for their critical evaluation of the manuscript. Administrative and logistical support at various points of time offered by the SANDEE Secretariat is highly appreciated. I thank the SANDEE advisors and the grantees at the various R&T workshops for providing thoughtful comments on the research project.

References

- Aggarwal, PK, Kropff, MJ; Cassman, KG; Berge, HFM (1997) 'Simulating genotypic strategies for increasing rice yield potential in irrigated, tropical environments', *Field Crops Research* 51: 5-17
- Aggarwal, PK; Mall, RK (2002) 'Climate change and rice yields in diverse agro-environments of India: effect of uncertainties in scenarios and crop models on impact assessment', *Climatic Change* 52(3): 331-343
- Attavanich, W; McCarl, BA (2011) 'The effect of climate change, CO₂ fertilization, and crop production technology on crop yields and its economic implications on market outcomes and welfare distribution', Selected Paper Presented at AAEA & NAREA Joint Annual Meeting 2011, July 24-26, 2011, Pittsburgh, PA
- Auffhammer, M; Ramanathan, V; Vincent, JR (2006) 'Integrated model shows that atmospheric brown clouds and greenhouse gases have reduced rice harvests in India', *Proc Natl Acad Sci.* 103: 19668-19672
- Auffhammer, M; Ramanathan, V; Vincent, JR (2011) 'Climate change, the monsoon, and rice yield in India', *Climatic Change* 111(2): 411-424
- Auffhammer, M; Hsiang, SM; Schlenker, W; Sobel, A (2013) 'Using Weather Data and Climate Model Output in Economic Analyses of Climate Change', *Review of Environmental Economics and Policy*, 7(2):181-198.
- Barnwal, P; Kotani, K (2010) 'Impact of variation in climate factors on crop yield: a case of rice crop in Andhra Pradesh, India', Working Paper, IUJ Research Institute, International University of Japan, Minami-Uonuma
- Beck, N; Katz, NJ (1995) 'What to do (and not to do) with time-series cross-section data', *American Political Science Review* 89(3): 634-647
- Brown, RA; Rosenberg, NJ (1997) 'Sensitivity of crop yield and water use to change in a range of climatic factors and CO₂ concentrations: a simulation study applying EPIC to the central USA', *Agricultural and Forest Meteorology* 83: 171-203
- Byjesh, K; Kumar, SN; Aggarwal, PK (2010) 'Simulating impacts, potential adaptation and vulnerability of maize to climate change in India', *Mitig Adapt Strateg Glob Change* 15: 413-431
- Chen, C-C; McCarl, BA; Schimmelpfenning, DE (2004) 'Yield variability as influenced by climate: a statistical investigation', *Climatic Change* 66: 239-261
- Chen, C-C; Chang, C-C (2005) 'The impact of weather on crop yield distribution in Taiwan: some new evidence from panel data models and implications for crop insurance', *Agricultural Economics* 33(3): 503-511.
- Chen, Xiujian; Lin, S; Reed, WR (2006) 'Another look at what to do with Time-series cross-section data', Working Paper-No. 04/2006, Department of Economics, College of Business and Economics, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
- CRIDA (2009) ICAR Network Project on Impact, Adaptation and Vulnerability of Indian Agriculture to Climate Change, Annual Report 2008-09, Central Research Institute for Dryland Agriculture (CRIDA), Indian Council of Agricultural Research, Hyderabad
- Darwin, R; Tsigas, M; Lewandrowski, J; Ranases, A (1995) 'World agriculture and climate change: economic adaptations', Economic Research Service: Agricultural Economic Report No. 703, U.S. Department of Agriculture, Washington, D.C
- Dash, SK; Hunt, JCR (2007) 'Variability of climate change in India', *Current Science* 93 (6): 782-788
- Elguindi, N; Bi, X; Giorgi, F; Nagarajan, B; Pal, J; Solmon, F; Rauscher, S; Zakey, A (2010) RegCM Version 4.0, User's Guide, ICTP, Trieste, Italy
- Fischer, G; Shah, M; Tubiello, FN; Velthuisen, VH (2005) 'Socio-economic and climate change impacts on agriculture: an integrated assessment 1990-2080', *Philosophical Transactions of the Royal Society B: Biological Sciences* 360: 2067-2083
- Freedman, DA; Peters, SC (1984) 'Bootstrapping a regression equation: some empirical results', *Journal of the American Statistical Association* 79 (385): 97-106

- Geethalakshmi, V; Lakshmanan, A; Rajalakshmi, D; Jagannathan, R; Gummidi S; Ramaraj, AP; Bhuvanewari, KL. Gurusamy and R. Anbhazhagan, (2011) 'Climate change impact assessment and adaptation strategies to sustain rice production in Cauvery basin of Tamil Nadu', *Current Science* 101(3): 342-347
- Ghosh, S; Mujumdar, PP; (2006) 'Future rainfall scenario over Orissa with GCM projections by statistical downscaling', *Current Science* 90(3): 396-404
- Government of India (2008) *Economic Survey 2007-08*, Ministry of Finance, Government of India, New Delhi.
- Government of Tamil Nadu (2010) *Season and Crop Reports Tamil Nadu 2009-10*, Department of Economics and Statistics, Government of Tamil Nadu, Chennai
- Government of Tamil Nadu (various years a) *Tamil Nadu: An Economic Appraisal*, Department of Evaluation and Applied Research, Chennai
- Government of Tamil Nadu (various years b) *Season and Crop Reports of Tamil Nadu*, Department of Economics and Statistics, Chennai
- Granger, CWJ; Newbold, P (1974) 'Spurious regressions in econometrics', *Journal of Econometrics* 2(2): 111-120
- Greene, WH (2008) *Econometric Analysis*, 7th Edition, New York: Prentice Hall
- Gupta, S; Sen, P; Srinivasan, S (2012) 'Impact of climate change on the Indian economy: evidence from food grain yields', Working Paper No. 218, Centre for Development Economics, Department of Economics, Delhi School of Economics, New Delhi.
- Hebbar, KB (2008) 'Predicting cotton production using Infocrop-cotton simulation model, remote sensing and spatial agro-climatic data', *Current Science* 95(11): 1570-79.
- Hicks, A; Duane, S (1992) 'Politics, institutions and welfare spending in industrialized democracies, 1960-1982', *American Political Science Review* 86: 658-74
- Hingane, LS; Rupa Kumar, K; Ramana Murthy, BV (1985) 'Long-term trends of surface air temperature in India', *Journal of Climatology* 5: 521-528.
- Im, KS; Pesaran, MH; Shin, Y (2003) Testing for unit roots in heterogeneous panels. *Journal of Econometrics* 115: 53-74
- IPCC (2000) Emission scenarios, a special report of IPCC Working Group III, Cambridge, UK :Cambridge University Press.
- IPCC (2001) 'The scientific basis, contribution of working group I to the third assessment report of the intergovernmental panel on climate change', in Houghton, JT; Ding, Y; Griggs, DJ; Noguer, M; van der Linden, PJ; Dai, X; Maskell, K; Johnson, CA (eds.) Cambridge, UK.: Cambridge University Press, p. 881
- IPCC (2007) 'Summary for policymakers', *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.), Cambridge, UK: Cambridge University Press.
- IPCC (2014) 'Summary for Policymakers', In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, CB; Barros, VR; Dokken, DJ; Mach, KJ; Mastrandrea, MD; Bilir, TE; Chatterjee, M; Ebi, KL Estrada, YO; Genova, RC; Girma, B; Kissel, ES; Levy, AN; MacCracken, S; Mastrandrea, PR; White, LL (eds.)]. Cambridge University Press, Cambridge, United Kingdom, pp. 1-32
- Isik, M; Devadoss, S (2006) 'An analysis of the impact of climate change on crop yields and variability'. *Applied Economics* 38: 835-844
- Jung, Hyun-Sook; Choi, Y; Joi-ho Oh; Gyu-ho Lim (2002) 'Recent trends in temperature and precipitation over South Korea', *International Journal of Climatology* 22: 1327-1337
- Kabubo-Mariara J. (2009) 'Global warming and livestock husbandry in Kenya: Impacts and adaptations', *Ecological Economics*, 68:1915-1924
- Kabubo-Mariara J; Karanja, FK (2007) 'The Economic Impact of Climate Change on Kenyan Crop Agriculture: A Ricardian Approach', Policy Research Working Paper -4334, The World Bank, Development Research Group, Sustainable Rural and Urban Development Team

- Kavikumar, KS; Parikh, J (1998) 'Climate change impacts on Indian agriculture: the Ricardian approach', *Measuring the Impact of Climate Change on Indian Agriculture*, in Dinar, A; Mendelsohn, R; Evenson, R; Parkikh, J; Sanghi, A; Kumar, K; McKinsey, J; Lonergan, S (eds), Technical Paper No. 402, World Bank, Washington, D.C.
- Kavikumar, KS; Parikh, J (2001) 'Socio-economic impacts of climate change on Indian agriculture'. *International Review of Environmental Strategies* 2(2): 277-293
- Kavikumar, KS (2009) 'Climate sensitivity of Indian agriculture: do spatial effects matter?' Working Paper No. 45, South Asian Network for Development and Environmental Economics (SANDEE), IUCN, Kathmandu, Nepal.
- Kim, MK; Pang, A (2009) 'Climate change impact on rice yield and production risk'. *Journal of Rural Development* 32(2): 17-29
- Kmenta, J (1986) *Elements of Econometrics*, 2nd Edition, New York: Macmillan
- Kumar, KK; Kumar, KR; Ashrit, RG; Deshpande, NR; Hansen, JW (2004) 'Climate impacts on Indian agriculture'. *International Journal of Climatology* 24(11): 1375-1393
- Kurukulasuriya; Mendelsohn (2008) 'A Ricardian analysis of the impact of climate change on African cropland', *African Journal of Agricultural and Resource Economics*, 2(1):1-23
- Lakshmanan, GV; Rajalakshmi, D; Bhuvanewari, K; Srinivasan, R; Sridhar, G; Sekhar, NU; Annamalai, H (2011) 'Climate change adaptation strategies in the Bhavani basin using the SWAT Model'. *Applied Engineering in Agriculture* 27(6): 887-893
- Mall, RK; Singh, R; Gupta, A; Srinivasan, G; Rathore, LS (2006) 'Impact of climate change on Indian agriculture: a review', *Climatic Change* 78(2-4): 445-478.
- McCarl, BA; Villacencio, X; Wu, X (2008) 'Climate change and future analysis: is stationarity dying?' *American Journal of Agricultural Economics* 90(5): 1241-1247
- Mendelsohn, R; Nordhaus, WD; Shaw, D (1994) 'The Impact of Global Warming on Agriculture: A Ricardian Analysis'. *American Economic Review*, 84: 753-771
- Mendelsohn, R; Dinar, A (1999) 'Climate change, agriculture and developing countries: does adaptation matter?' *The World Bank Research Observer* 14(2): 277-293
- Mendelsohn, R; Dinar, A (2003) 'Climate, water and agriculture'. *Land Economics* 79(3): 329-341
- Mendelsohn, R; Nordhaus, WD; Shaw, D (1996) 'Climate impacts on aggregate farm values: accounting for adaptation'. *Agriculture and Forest Meteorology* 80: 55-67
- Morita, S; Siratsuchi, H; Takanashi, J; Fujita, K (2004) 'Effect of high temperature on ripening in rice plant: analysis of the effect of high night and high day temperature applied to the panicle in other parts of the plant', *Japanese Journal of Crop Science* 73: 77-83
- Murphy, J; Nouger, M; Hassell, D; Hudson, D; Wilson, S; Tylor, R; Bashkaran, B; Jones, R; Mitchell, V; Jenkins, G (2007) 'The Hadley centre regional climate modeling,' Hadley Centre for Climate Prediction and Research, Met Office Hadley Centre, UK, p. 20
- Palanisami, K; Paramasivam, P; Ranganathan, CR; Aggarwal, PK; Senthilnathan, S (2009) 'Quantifying vulnerability and impact of climate change on production of major crops in Tamil Nadu, India', *Headwaters to the Ocean – Hydrological Change and Watershed Management*, in M. Taniguchi, W. C. Burnett, Y. Fukushima, M. Haigh and Umezawa Yu (eds.), London: Taylor and Francis Group, pp. 509-51.
- Pinheiro, JC; Bates, DM (2000) *Mixed-Effects Models in S and S-PLUS*, New York: Springer
- Rahman, MM; Islam, MN; Ahmed, AU; Georgi, F (2012) 'Rainfall and temperature scenarios for Bangladesh for the middle of 21st century using RegCM". *J. Earth Syst. Sci.* 121(2): 287-295
- Rajalakshmi, D; Jagannathan, R; Geethalakshmi, V (2013) Uncertainty in seasonal climate projection over Tamil Nadu for 21st century. *African Journal of Agricultural Research*. 8(32):4334-4344
- Ranganathan, CR (2009) 'Vulnerability and resilience of social-ecological systems', Working Paper on Social-Ecological Resilience Series No. 2009-008, Research Institute for Humanity and Nature, Kyoto, Japan.

- Reed, WR; Webb, R (2010) 'The PCSE estimator is good – just not as good as you think'. *Journal of Time Series Econometrics* 2(1): 8
- Rowhani, P; Lobell, D; Linderman, M; Ramankutty, N (2011) 'Climate variability and crop production in Tanzania'. *Agricultural and Forest Meteorology* 151: 449-460
- Rupakumar, K; Ashrit, RG (2001) 'Regional aspects of global climate change simulations: validation and assessment of climate response over Indian monsoon region to transient increase of greenhouse gases and sulfate aerosols'. *Mausam* 52(1): 229-244
- Saha, A; Havenner, A; Talpaz, H (1997) 'Stochastic production function estimation: small sample properties of ML versus FGLS'. *Applied Economics* 29: 459-69
- Sanghi, A; Mendelsohn, R (2008) 'The impacts of global warming on farmers in Brazil and India'. *Global Environmental Change* 18(4): 655-665
- Sarker, MAR; Alam, K; Gow, J (2012) 'A comparison of the effects of climate change on aus, aman and boro rice yields in Bangladesh: evidence from panel data'. *Proceedings of the 41st Australian Conferences for Economists*, Melbourne, Australia, pp. 1-28
- Saseendran, SA; Singh, KK; Rathore, LS; Singh, SV; Sinha, SK (2000) 'Effects of climate change on rice production in the tropical humid climate of Kerala, India'. *Climatic Change* 44: 495-514
- Seo, SN; Mendolsohn, R (2008) 'Measuring impacts and adaptations to climate change: a structural Ricardian model of African livestock management'. *Agricultural Economics*, 38:151-165
- World Bank Report (2010) *Economic Evaluation of Climate Change Adaptation Projects: Approaches for the Agricultural Sector and Beyond*, World Bank Series on Development and Climate Change, World Bank, Washington, DC
- Zuur, AF; Ieno, EN; Walker, N; Saveliev, AA; Smith, GM (2009) *Mixed Effects Models and Extensions in Ecology with R* (Statistics for Biology and Health), New York: Springer

Tables

Table 1: Summary Statistics

Variable	Unit	Mean	Standard Deviation	Minimum	Maximum
Rice yield	kg/ha	2,772	881.29	311	4,774
Sorghum yield	kg/ha	1,028	406.29	294	2,466
Maize yield	kg/ha	1,746	1,069	164	8,336
Rainfall	mm	963	196.9	653.7	1,716.5
Temperature	Celsius	31.44	3.44	16.68	37.19

Table 2: Panel Unit Root Test Statistics

Test	t-bar statistics
Rice yield	-4.78***
Sorghum yield	-4.05***
Maize yield	-3.28***
Rainfall	-4.49***
Temperature	-3.63***

*** p<0.01

Table 3: Testing Heteroscedasticity for Yield Response Functions

	χ^2 Statistics	p-value
Rice yield	167.49	7.9e-05
Sorghum yield	117.44	0.0197
Maize yield	174.36	2.4e-07

Table 4: Estimated Parameters from Panel Regression Model with Fixed Effects for Rice Crop

Dependent Variable: Rice Yield			
	OLS	FGLS	PCSE
Trend	49.58*** (2.136)	53.03*** (1.982)	49.58*** (5.065)
Rainfall	8.35** (3.716)	3.89 (3.422)	8.35** (3.772)
Rainfall Square	-0.0028*** (0.001)	-0.00167* (0.00094)	-0.0028*** (0.0009)
Temp	287.24** (129.59)	336.86** (161.294)	287.24* (143.86)
Temp Square	-4.449** (2.092)	-5.697** (2.277)	-4.449* (2.414)
Temp x Rainfall	-0.085 (0.076)	-0.038 (0.074)	-0.085 (0.079)
Constant	-6076.43 (3249.01)	-4364.63 (3729.96)	-6076.43 (3371.37)
Observations	507	507	507
R-square	0.679	0.734	0.679

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table 5: Estimated Parameters from Panel Regression Model with Fixed Effects for Sorghum Crop

Dependent Variable: Sorghum Yield			
	OLS	FGLS	PCSE
Trend	6.057*** (1.445)	5.097*** (1.228)	6.057** (2.524)
Rainfall	8.555** (3.323)	4.900 (3.082)	8.555** (3.533)
Rainfall Square	-0.00342*** (0.00117)	-0.00270*** (0.000851)	-0.00342*** (0.00128)
Temp	215.5** (92.04)	96.79 (80.71)	215.5** (99.78)
Temp Square	-3.128** (1.330)	-1.826* (0.962)	-3.128** (1.390)
Temp x Rainfall	-0.0439 (0.0663)	0.0140 (0.0695)	-0.0439 (0.0611)
Constant	-6,397** (2,628)	-2,732 (2,533)	-6,397** (2,778)
Observations	429	429	429
R-square	0.422	0.536	0.422

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table 6: Estimated Parameters from Panel Regression Model with Fixed Effects for Maize Crop

Dependent Variable: Maize Yield			
	OLS	FGLS	PCSE
Trend	50.29*** (3.778)	42.07*** (2.848)	50.29*** (9.963)
Rainfall	-4.637 (8.128)	8.939 (7.016)	-4.637 (8.094)
Rainfall Square	-0.00267 (0.00316)	-0.00572** (0.00271)	-0.00267 (0.00298)
Temp	-3.280 (217.9)	-24.27 (207.7)	-3.280 (239.6)
Temp Square	-4.509 (3.566)	-0.565 (2.894)	-4.509 (4.149)
Temp x Rainfall	0.287* (0.151)	0.0792 (0.118)	0.287** (0.144)
Constant	3,945 (6,077)	-3,170 (5,641)	3,945 (6,188)
Observations	429	429	429
R-square	0.406	0.415	0.406

Standard errors in parentheses: *** p<0.01, ** p<0.05, * p<0.1

Table 7: Joint Significance Tests of Climate Variables of PCSE Regression for different Crop Yield Functions

Crops	Joint Variables	χ^2 Statistics	p-value
Rice	Rainfall and Squared Rainfall	8.81	0.012
	Temperature and Squared Temperature	4.32	0.1339
Sorghum	Rainfall and Squared Rainfall	7.30	0.0252
	Temperature and Squared Temperature	5.30	0.0705
Maize	Rainfall and Squared Rainfall	5.40	0.0673
	Temperature and Squared Temperature	4.50	0.1056

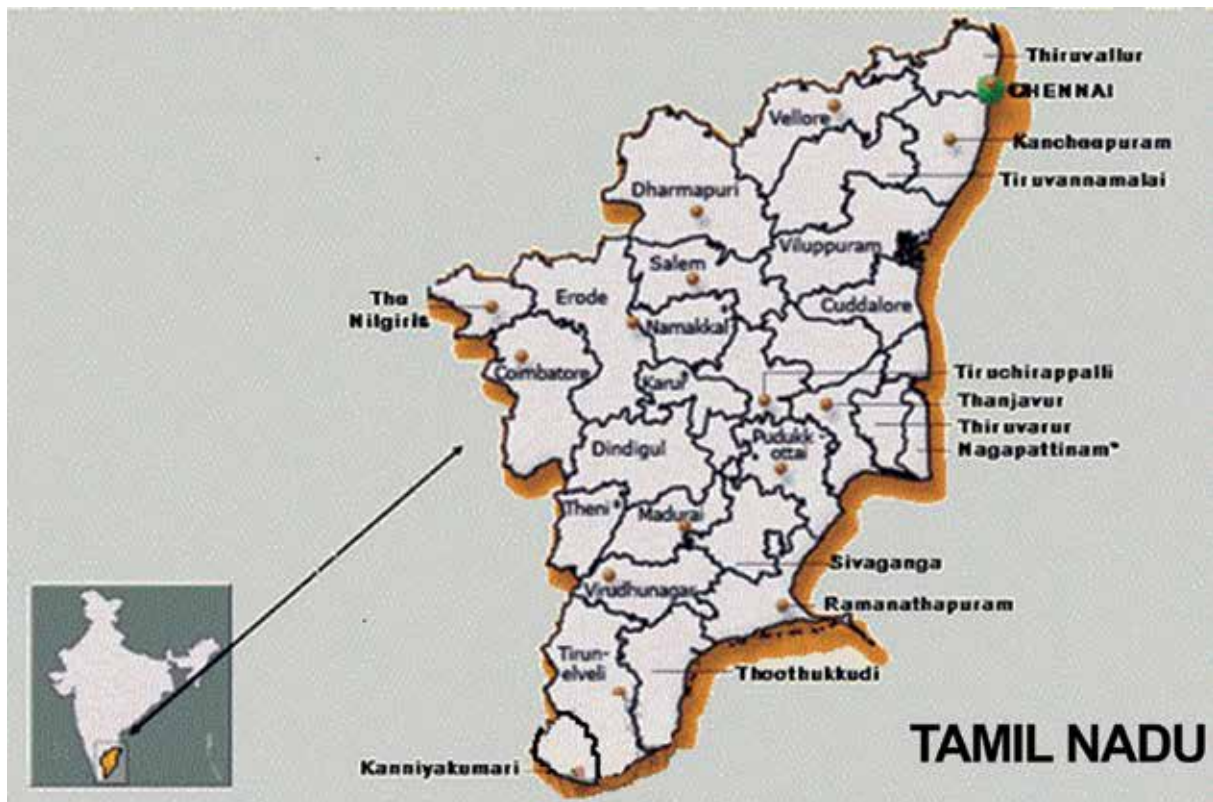
Table 8: Decadal Projections of Changes in Mean Annual Temperature and Mean Annual Rainfall in Tamil Nadu using the RegCM4 Model relative to Base Period (1971-2009)

Period	Δ Temperature (°C)	Δ Rainfall (mm)	Δ Temperature (%)	Δ Rainfall (%)
2011-20	0.51	-82.98	1.63	-8.62
2021-30	0.46	-5.79	1.47	-0.60
2031-40	0.86	83.76	2.74	8.70
2041-50	1.26	46.70	4.02	4.85
2051-60	1.56	156.32	4.97	16.23
2061-70	2.31	40.53	7.36	4.21
2071-80	2.46	164.04	7.83	17.03
2081-90	2.81	85.30	8.95	8.86
2091-2100	3.26	79.12	10.38	8.82

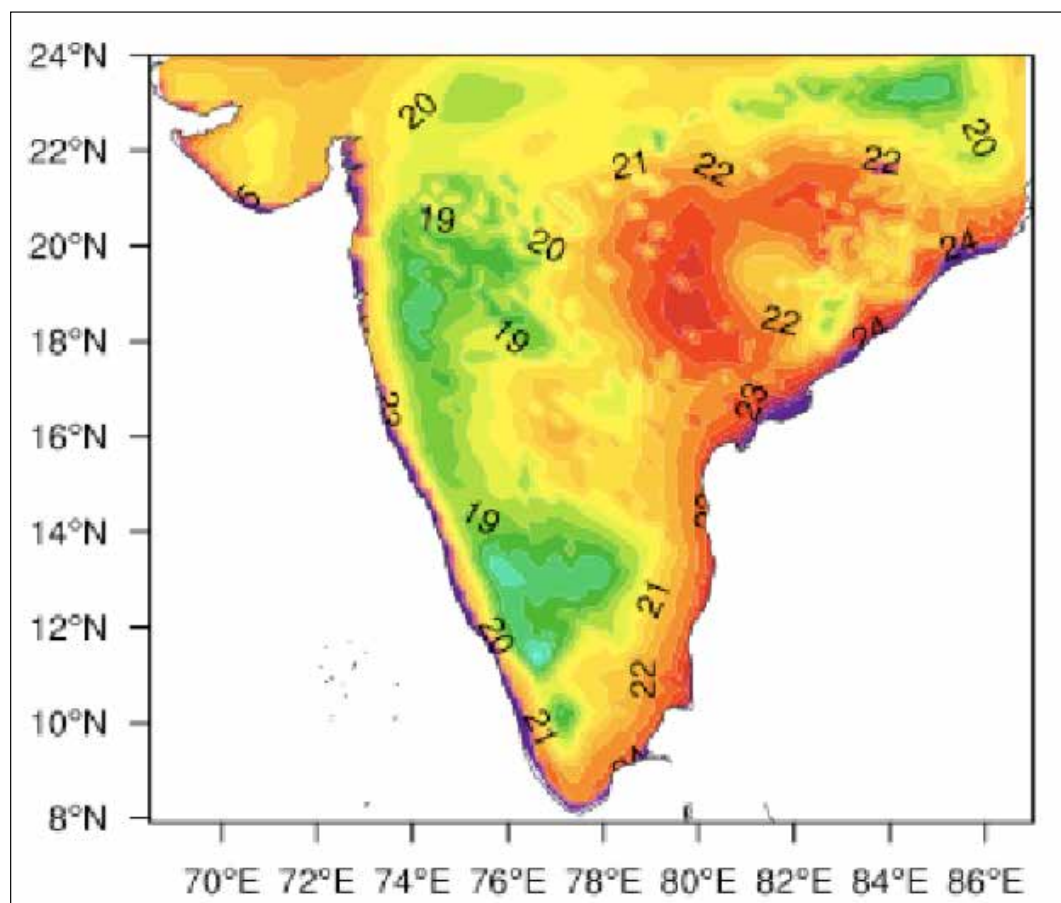
In base period, mean temperature= 31.44°C; Mean rainfall = 963 mm

Maps

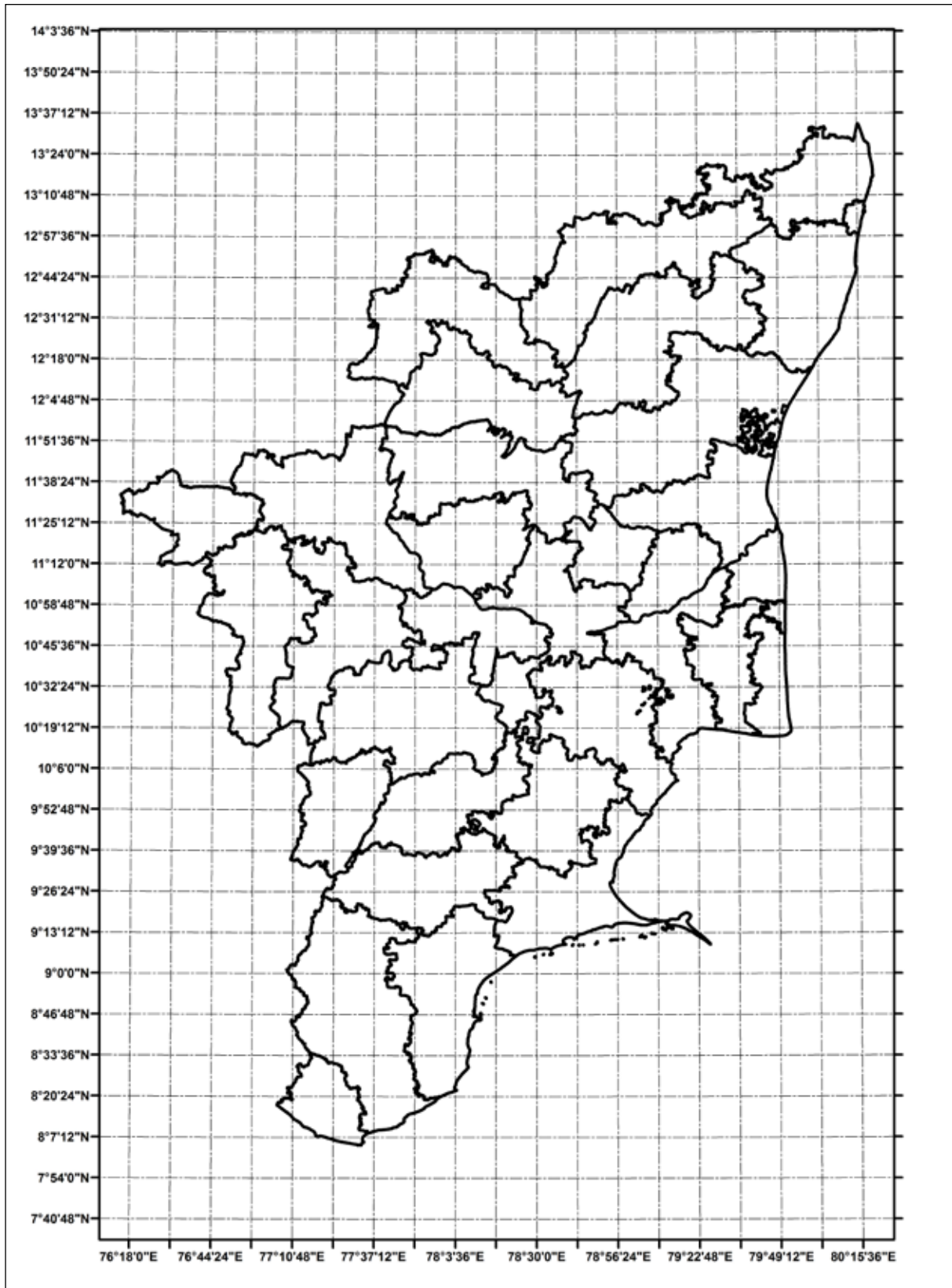
Map 1: Study Area



Map 2: Domain Selection



Map 3: Tamil Nadu State Grid Layout



Figures

Figure 1: Impact of Rainfall on Rice yield

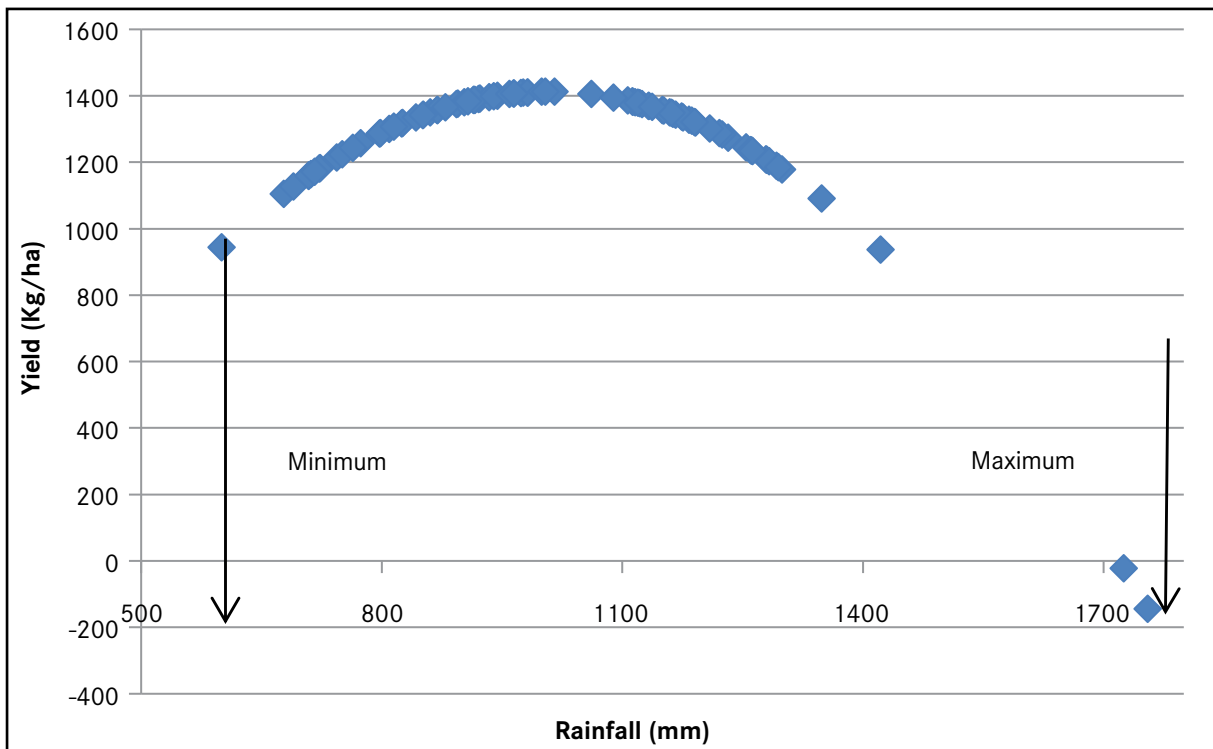


Figure 2: Impact of Temperature on Rice yield

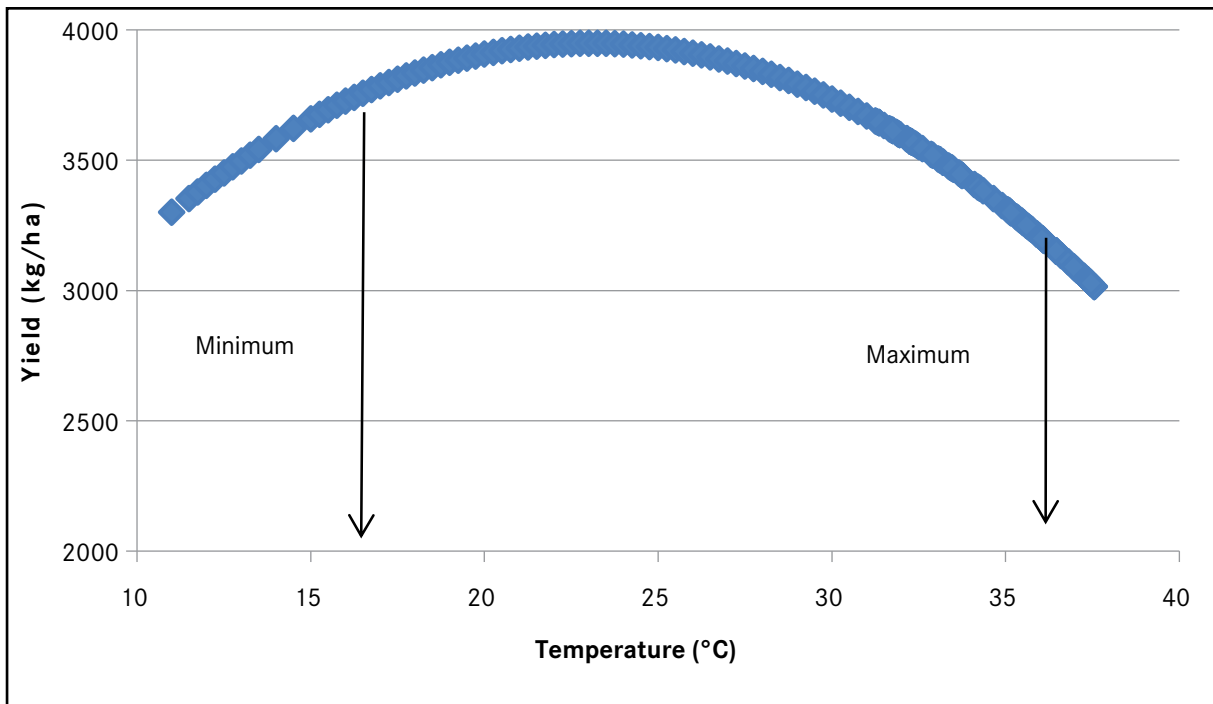


Figure 3: Impact of Rainfall on Sorghum yield

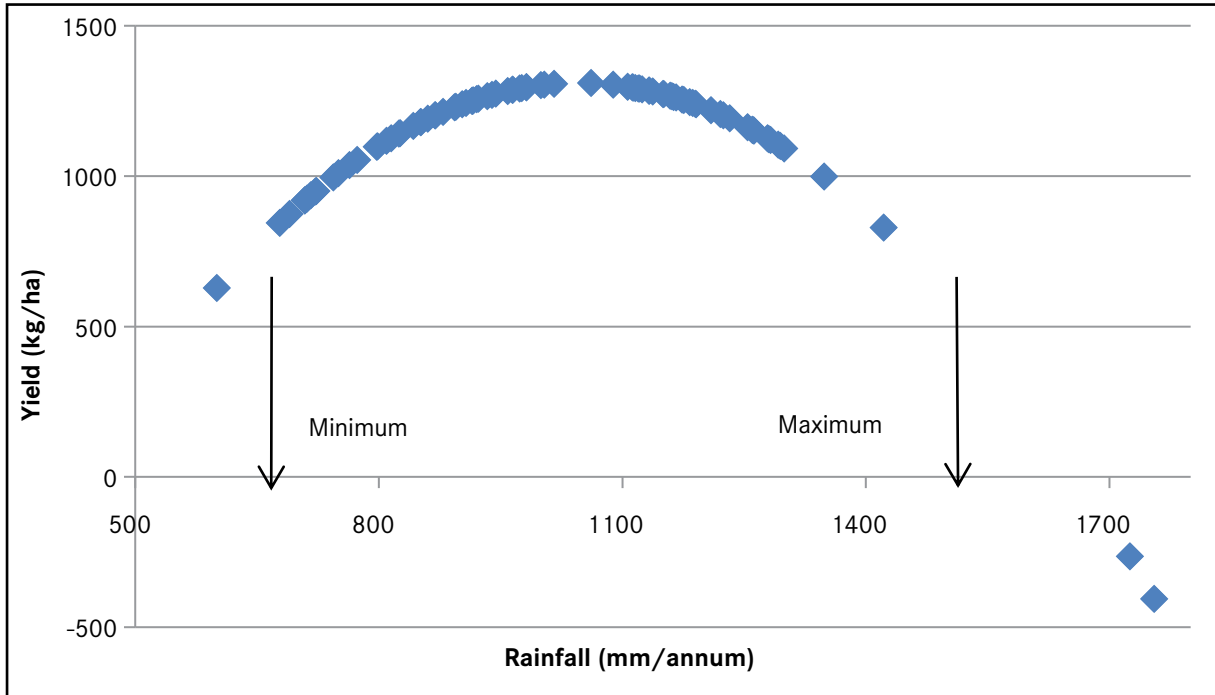


Figure 4: Impact of Temperature on Sorghum yield

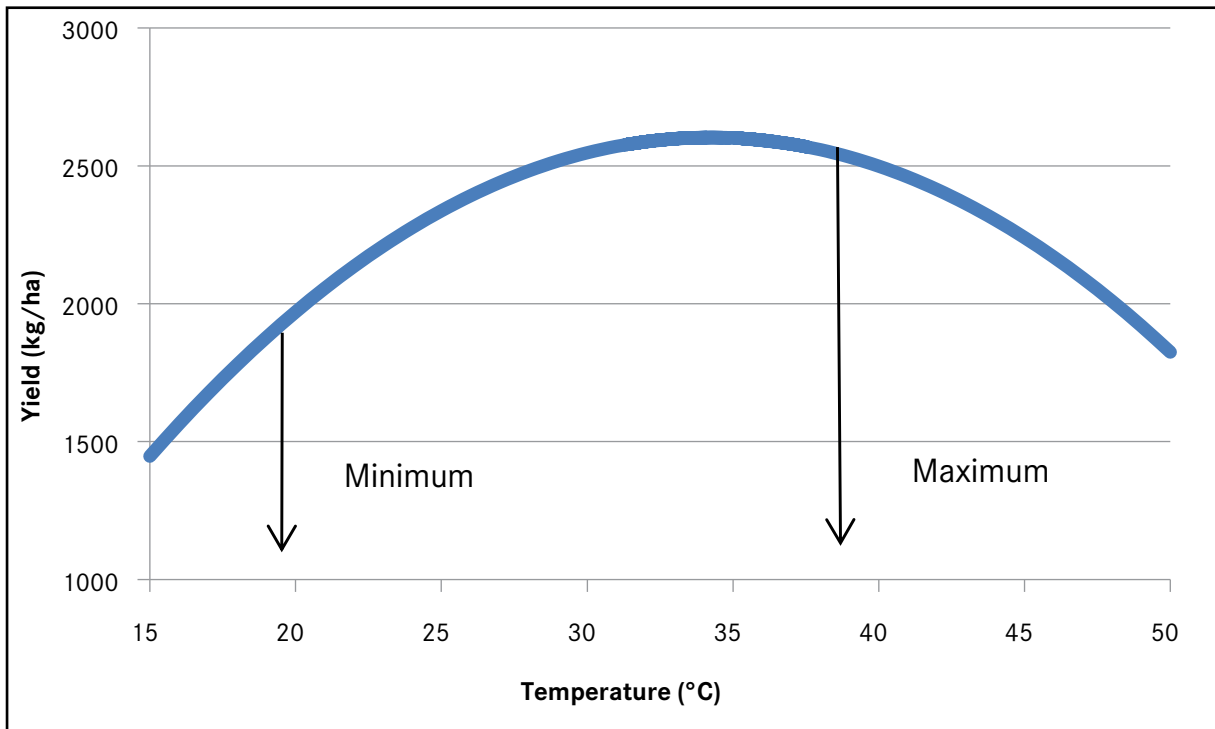


Figure.5: Projections of Mean Annual Temperature in Tamil Nadu under Climate Change Scenario with RegCM4 Outputs (degree Celsius)

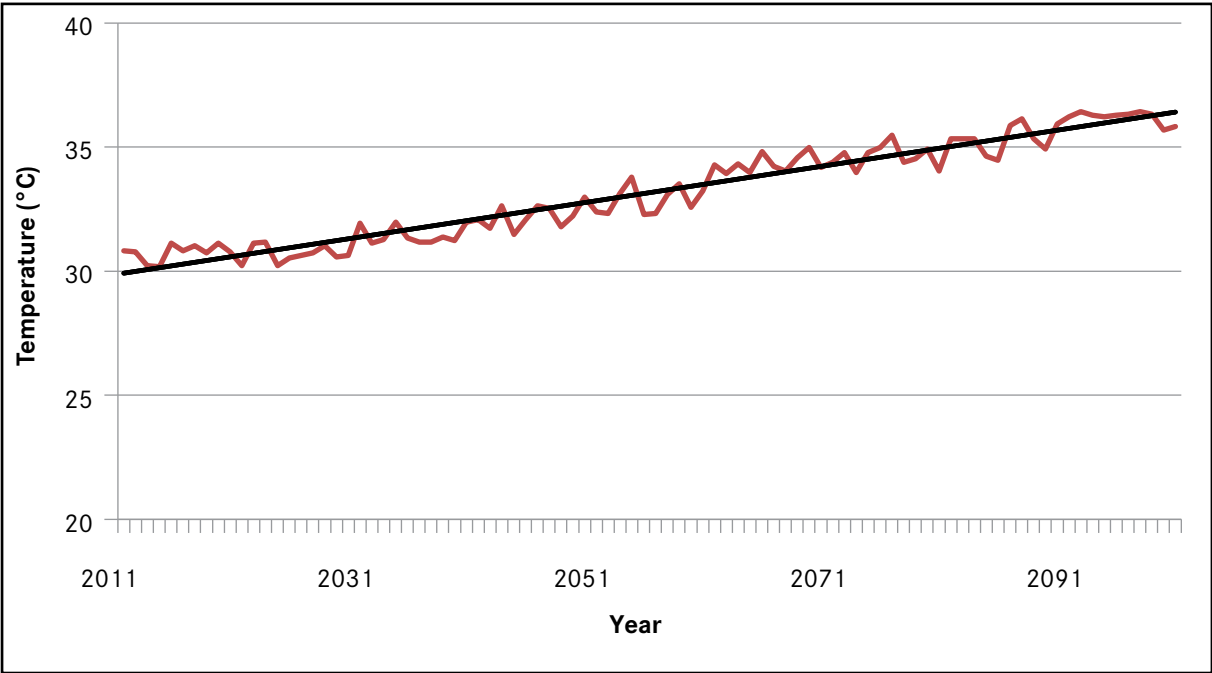


Figure.6: Projections of Mean Annual Rainfall in Tamil Nadu under Climate Change Scenario with RegCM4 Outputs (mm per annum)

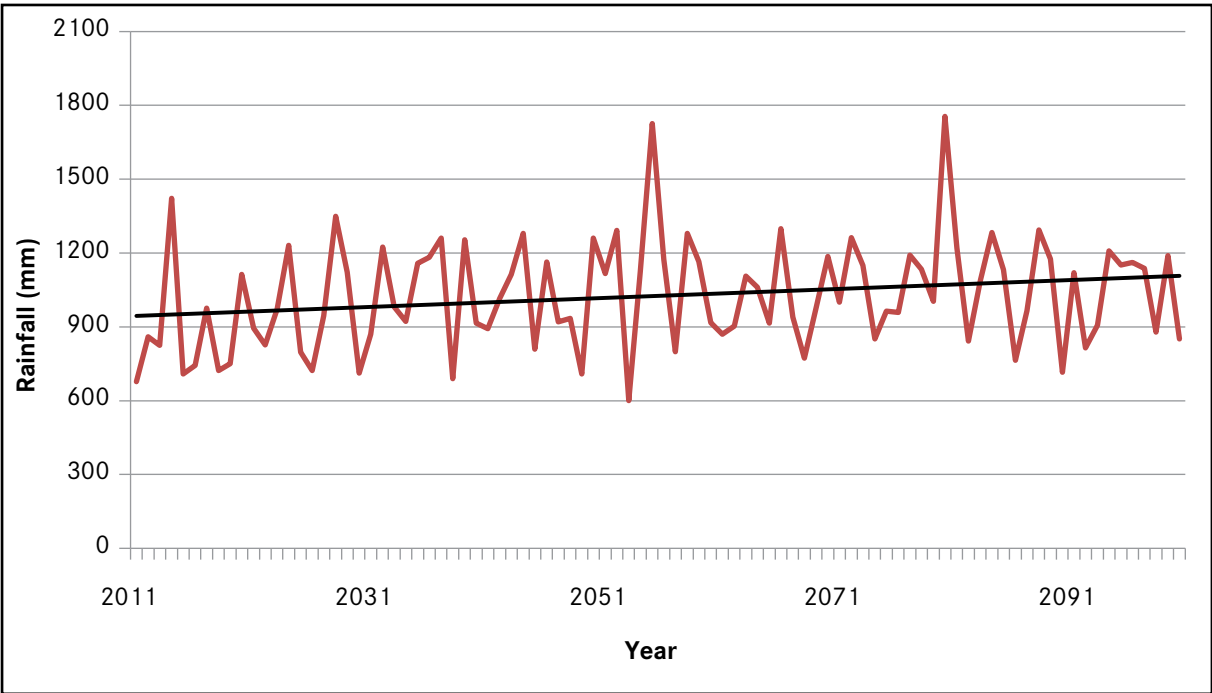


Figure 7: Projections of Rice Yield under a Climate Change Scenario in Tamil Nadu with RegCM4 Outputs (kg per ha)

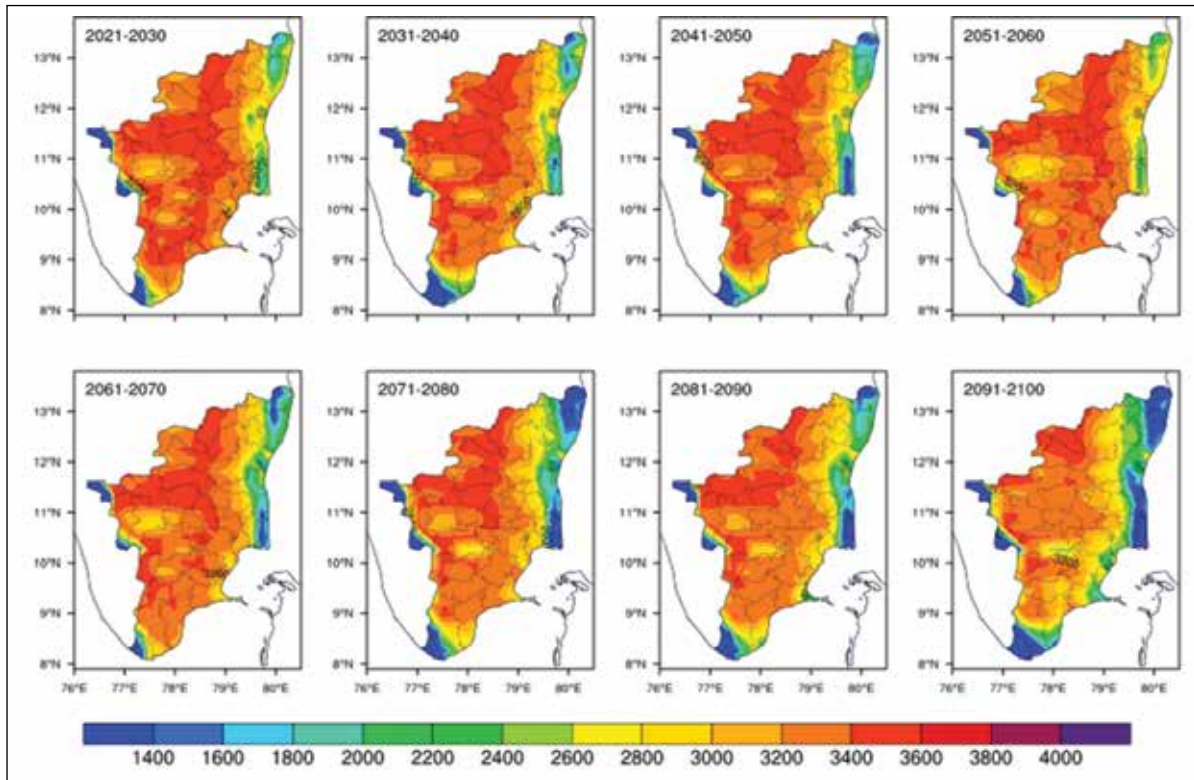


Figure 8: Rice Yield Loss Projections under Climate Change scenario in Tamil Nadu relative to Base Period (1971-2009) (kg per ha)

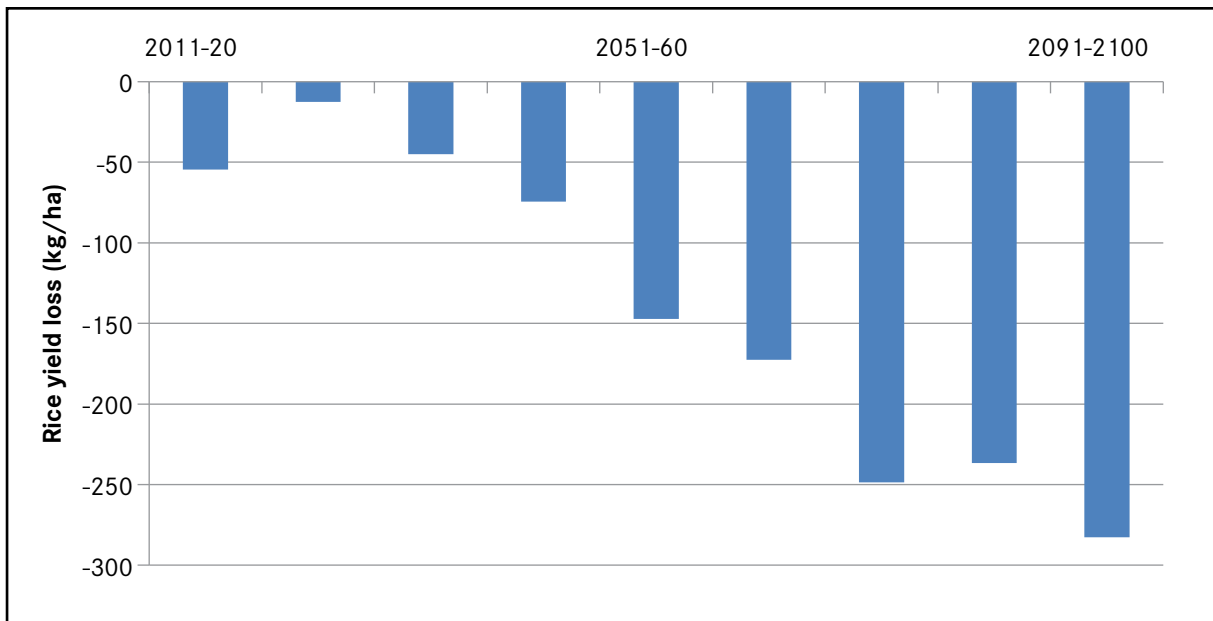


Figure 9: Projections of Sorghum Yield under a Climate Change Scenario in Tamil Nadu with RegCM4 Outputs (kg per ha)

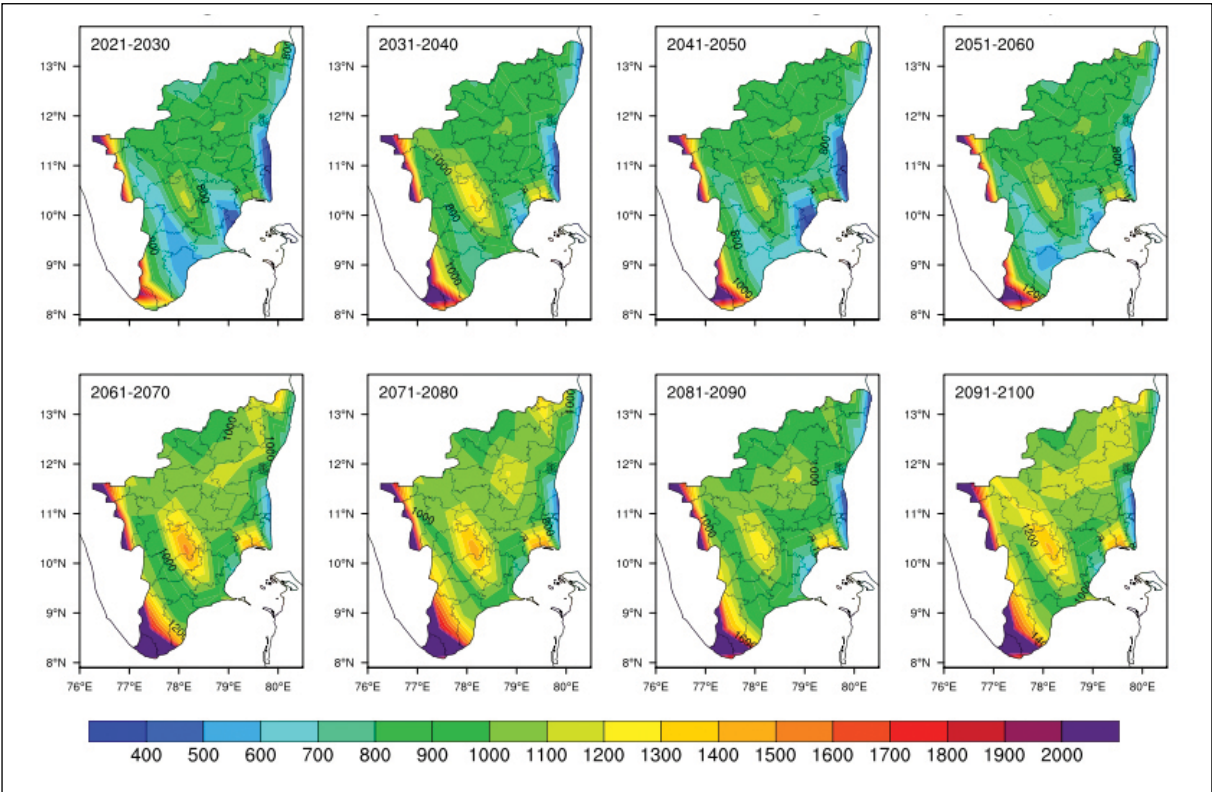


Figure 10: Sorghum Yield Loss under Climate Change scenario in Tamil Nadu relative to Base Period (1971-2009) (kg per ha)

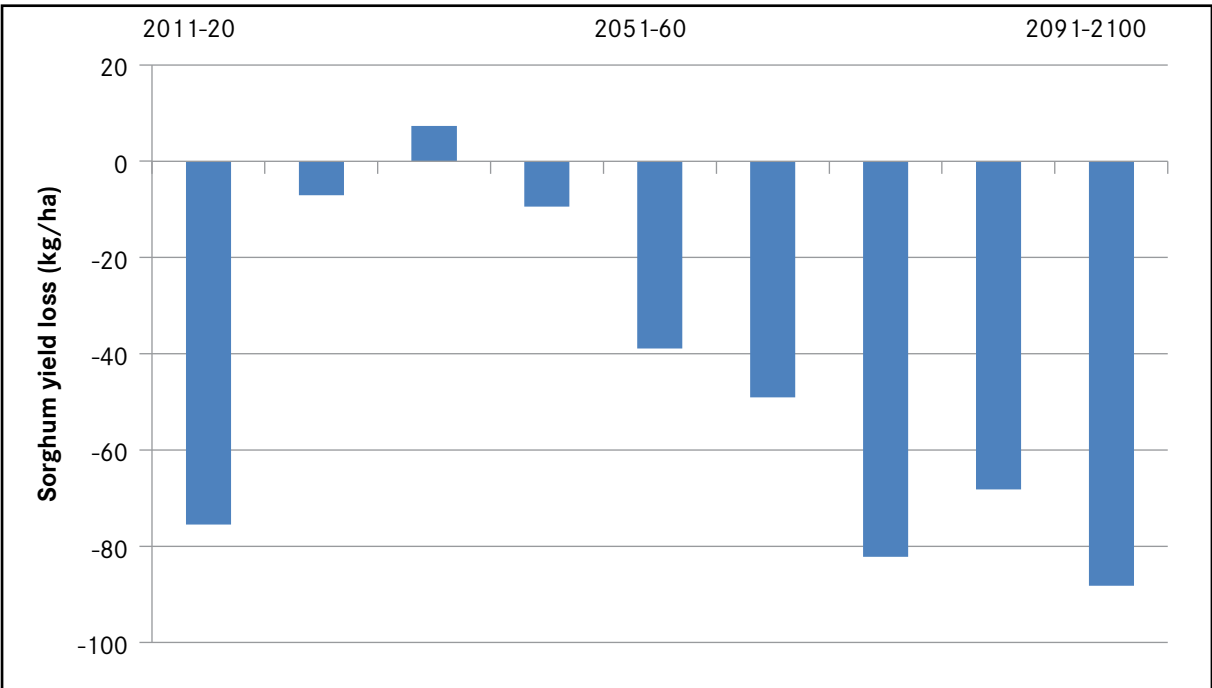


Figure 11: Projections of Maize Yield under a Climate Change Scenario in Tamil Nadu with RegCM4 Outputs (kg per ha)

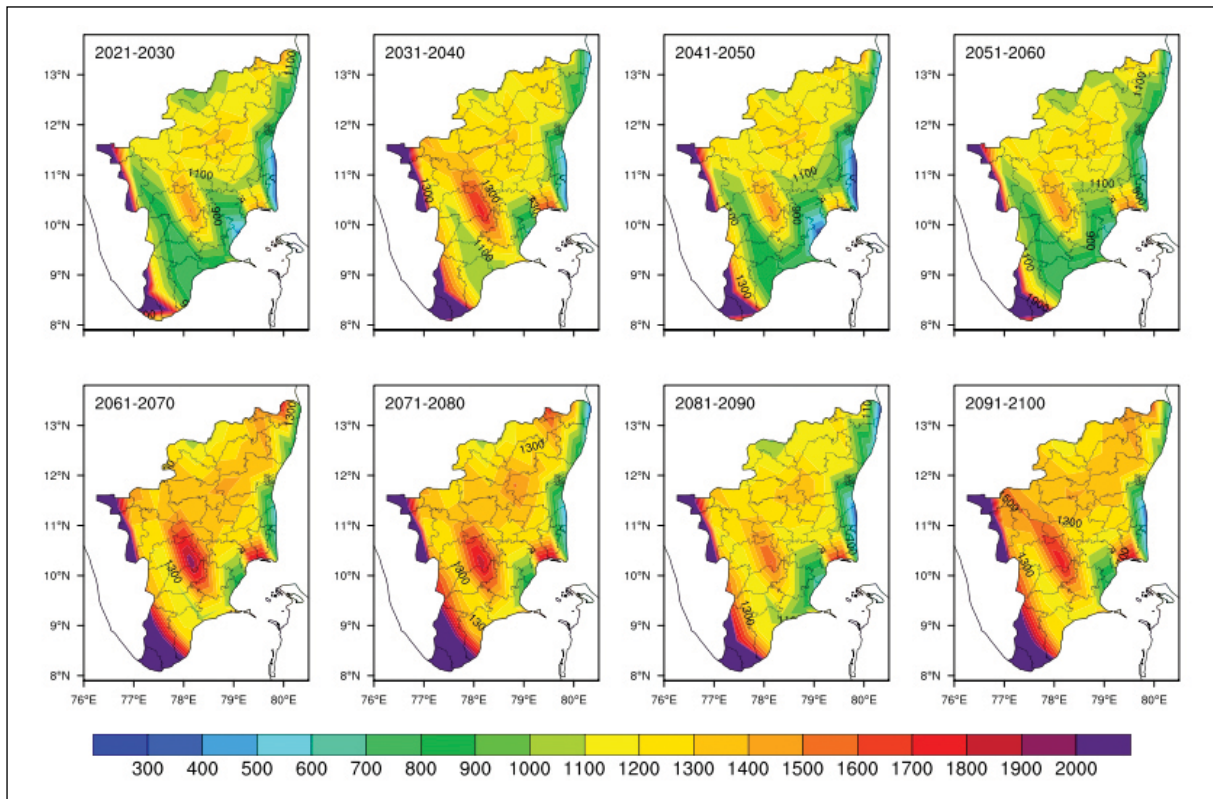
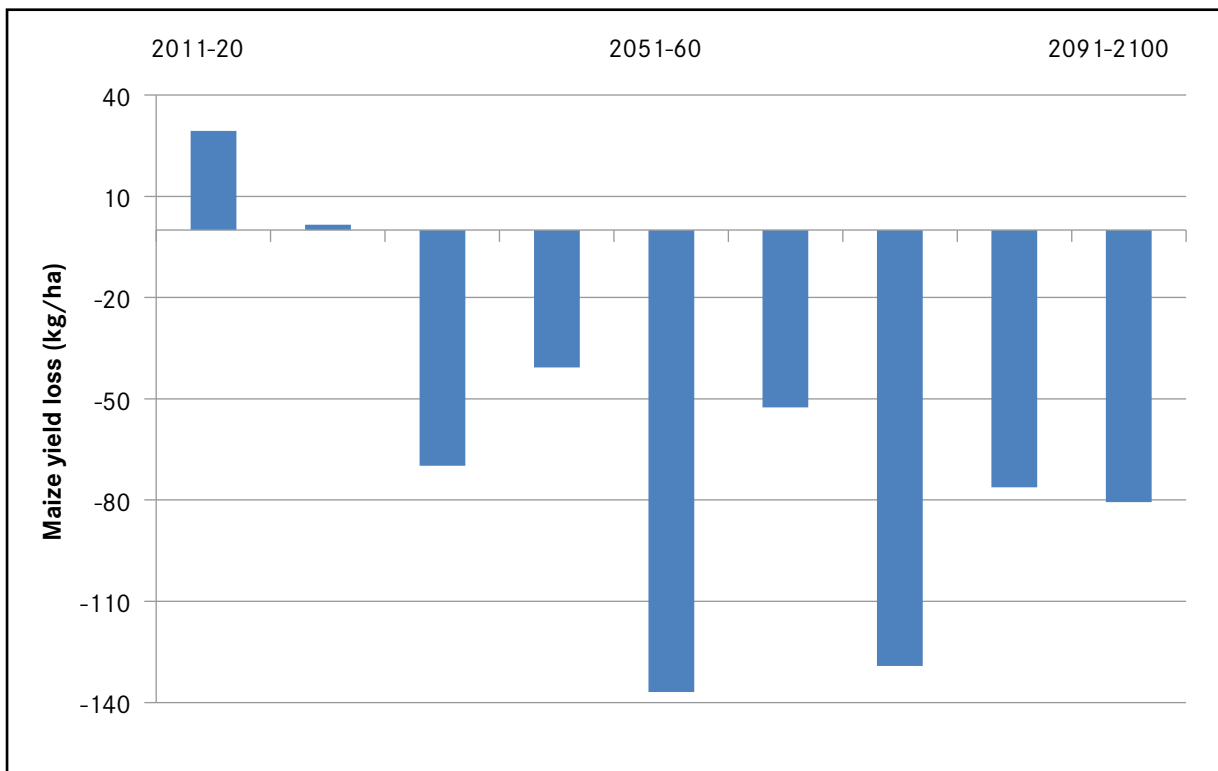
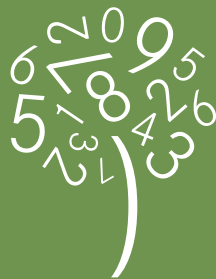


Figure 12: Maize Yield Loss Projections under Climate Change scenario in Tamil Nadu relative to Base Period (1971-2009) (kg per ha)





SANDEE

P.O. Box 8975, E.P.C 1056, Lalitpur, Nepal

Street address: c/o ICIMOD, Khumaltar, Lalitpur, Nepal

Tel: 977 1 5003222, **Fax:** 977 1 5003299, **Email:** info@sandeeonline.org, **Web:** www.sandeeonline.org

SANDEE Sponsors

