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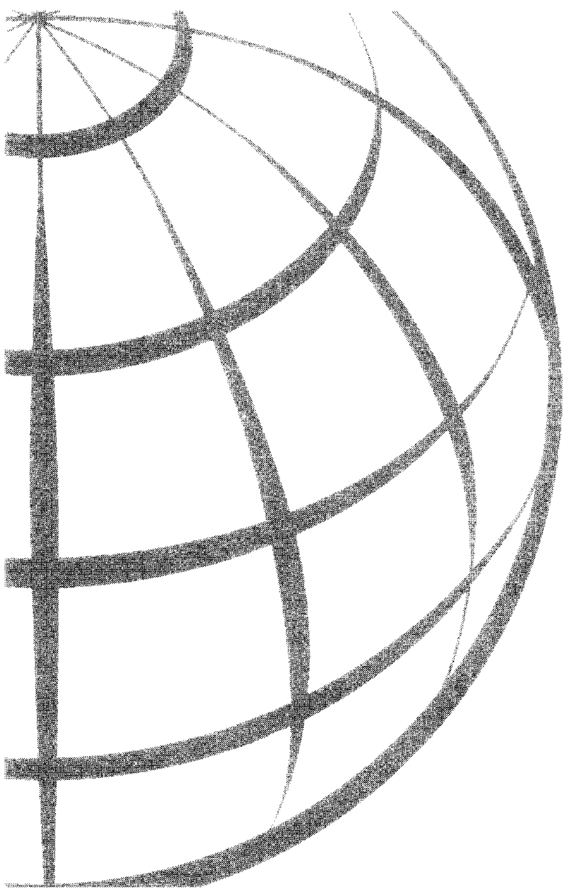
Measuring the Impact of Climate Change on Indian Agriculture



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Measuring the Impact of Climate Change on Indian Agriculture

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FOREWORD

The impact of climate change on agriculture in industrial countries has been studied by many scientists and economists. However, less is known about the economic impact of climate change on developing countries. With their warmer climates, labor-intensive low-capital practices, and alternative crop mixes, and with their less-developed market structures, developing countries are likely to respond differently to possible climate change scenarios than are industrial countries. A recent study applied several analytical frameworks, using data from India, to measure the climate responsiveness of the Indian agricultural sector. The results, reported here, indicate the potential for substantial private adaptation in developing countries.

Alexander F. McCalla
Director
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ABSTRACT

New scientific evidence made scientists more confident that greenhouse gases may lead to future climate change. Research on measuring the economic impacts climate change might cause has proceeded world-wide, but most of the empirical research has focused on developed countries. It has been commonly believed that developing countries are more vulnerable to climate change because of their reliance on low-capital agriculture. It has been assumed, but never tested, that low-capital agriculture would have more difficulty adapting to climate changes.

Country-wide economic analyses have been completed only for the United States even though experts have extrapolated results to all countries. Agronomic studies of crop yield reductions support this wisdom implying large potential agricultural damages in India, for example. The vulnerability of low-capital agriculture to climate change, however, depends upon whether the affected farmers can adjust to changing climates. The recent research in the United States suggests that adaptation by private producers would reduce *damages* to agriculture from climate change, and carbon fertilization would actually lead to net agricultural *benefits* from climate change.

The set of studies in this report, explores farm performance across climates in India. The goal of the study is to examine farm behavior and test if there is any evidence that farmers in developing countries, such as India, currently adjust to their local climates. The reported studies measure the climate sensitivity of low-capital agriculture. They test whether actual farm performance is as sensitive to climate as agronomic models predict assuming no adaptation. The studies also compare the climate sensitivity of low-capital farms against the results already calibrated for United States agriculture.

The analyses feature the Ricardian approach, a cross sectional analysis of farm performance across different climate zones. The method uses an economic measure of farm performance: farm value or net farm income. Performance is compared across a large landscape where farms exist in different local climates. By regressing farm performance on long term climate, one can empirically measure long run climate sensitivity. Other important factors determining economic performance, such as access to markets and soil quality must also be included in the analysis. The approach carefully measures long run climate responses, and not short-run adjustments or weather effects. Although the method does not explicitly identify how farmers have adjusted, the measure of economic performance captures the consequences of all the adjustments farmers currently undertake in responding to their local climates.

Each of the Ricardian studies emphasizes a different methodology--all leading to similar estimates of climate change impact. The pooled data analysis (Chapter 4) examines overall expected effects. The year by year analysis (Chapter 5) examines annual fluctuations in climate sensitivity, while controlling for annual prices and weather. The climate-technology study (Chapter 6) examines the interaction between endogenous technology and climate sensitivity in India and Brazil, respectively.

The results indicate that existing farms are only mildly climate sensitive implying a substantial amount of adaptation. This adaptation is predicted to reduce potential warming damages by one-third to one-half. The analysis further suggests that the climate response

functions for farmers in India and Brazil are similar to the estimated functions for United States farmers. Low-capital agriculture appears to be no more climate sensitive than modern farms.

These results suggest that warming alone will hurt agriculture in tropical (developing) countries relative to temperate countries. Damages from 8-12% are predicted by the Ricardian models. These results, however, do not include the effect of carbon fertilization. Carbon fertilization reduces the predicted damages in the agronomic models from 28% to 16%. Adding a 12% increase from carbon fertilization to the Ricardian estimates would drive the overall effects to near zero. The net results suggest that global warming will have only small effects on aggregate developing country agricultural sectors.

The adaptation being measured in these Ricardian studies is largely private efforts by farmers to maximize net income given local environmental conditions. Each farmer is making different choices depending upon the conditions he/she faces. Because these subtle adaptations make farmers better off, we expect that farmers will engage in these activities as climate changes. These subtle adjustments reduce the overall sensitivity of agriculture to climate change.

Technical change has been important to both India and Brazil over the years, substantially increasing productivity. However, agronomic research has not systematically focused on changing the climate sensitivity of crops. Investments in new technology have consequently not historically changed climate sensitivity in India or Brazil. This does not rule out the possibility of an important public research response to warming, it merely indicates that historic efforts have had no effect.

Although aggregate agricultural sectors may not be at risk to climate change, individual farmers may still suffer large damages. Some areas will suffer from higher than average temperature changes and some areas may experience deleterious precipitation effects. The entire sector may not be affected because these effects will average out, but this does not protect local areas. Further, the aggregate sectors in developing countries may be less sensitive because important components of these sectors tend to lie in more temperate zones. Damages in marginal areas may have little impact on the aggregate because they contribute little to the aggregate outcome today. Poor people dependent on these local areas may be highly vulnerable to warming even when national agricultural impacts are minimal.

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Chapter 4 in this volume is based on Chapter 2 of Sanghi's 1997 University of Chicago Ph.D. Dissertation "Global Warming and Climate Change Sensitivity: Brazilian and Indian Agriculture." The work leading to Chapter 4 had benefited greatly from comments by Sherwin Rosen, George Tolley, Robert Evenson, and Participants in the Agricultural Economics Workshop and Natural Economics Seminar at the University of Chicago and Yale University, respectively.

The help extended by Indian Meteorological Department in providing the climate and weather data sets used in Chapter 5, is gratefully acknowledged. The first author of Chapter 5 would like to acknowledge the extensive help received from Apurva Sanghi in handling various aspects of the work.

Chapter 6 in this report is based largely on McKinsey's unpublished 1997 Yale Ph.D. Dissertation, "Climate and Technology Impacts in Indian Agriculture."

Michele Rigaud prepared the first version of each chapter for publication, and Fulvia Toppin prepared the final version of each chapter, including typesetting of the entire report.

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1 OVERVIEW

Ariel Dinar and Robert Mendelsohn

INTRODUCTION

As scientists are more confident now that greenhouse gases will lead to future climate change there has been growing interest in understanding the economic impacts climate change might cause. Many observers are concerned that changes in climate will in turn lead to significant damages to both market and nonmarket sectors. In an effort to understand the entire picture of the effects of climate change, it is necessary to examine all sectors affected by climate change, although systems that are highly managed like agriculture may be less sensitive than systems that are managed less.

Although several sectors have been studied, none have received more attention than agriculture. Research on this topic has proceeded world-wide, but most of the empirical research has focused on developed countries. Country-wide economic analyses have been completed only for the United States (Smith and Tirpak 1989 and Mendelsohn and Neumann 1998), but experts have extrapolated results to all countries (IPCC 1996b).

In the United States, the initial studies suggested large negative agricultural effects in terms of crop yield reduction, loss of fertile soils, and increased cost of production (Smith and Tirpak 1989). More recent analyses, that have incorporated more up to date climate forecasts and adaptation, however, consistently find that American agriculture will be resilient to climate change (Crosson 1993; Kaiser et al. 1993; and Mendelsohn, Nordhaus, and Shaw 1994). The agricultural sectors of other developed countries in temperate climates are expected to react similarly.

There have been many studies of climate change impact on agriculture in the United States and other developed countries (IPCC 1996a) but only two world-wide agricultural studies (Rosenzweig and Parry 1992 and Darwin et al. 1995). These world-wide analyses, however, have limited empirical evidence in developing countries. For example, Rosenzweig and Parry limit their inquiry to grains and Darwin et al. base their evaluation only on broad ecosystem types.

However, it is not clear what effect climate change will have on agriculture in the rest of the world because, agricultural systems are different in developing countries. These agricultural systems may be less adaptable, and tropical and subtropical ecosystems may respond differently to climate change. Developing countries may be more vulnerable to climate change than developed countries because of the low-capital intensity of developing economies, the incomplete markets, the predominance of agriculture and other climate sensitive sectors, and their relatively warm baseline climates. However, empirical research in developing countries is limited so these hypotheses have yet to be tested.

Further, no studies have measured what adaptation is likely to occur in developing countries. Recent research in the United States suggests that private adaptation is a critical component of climate change impacts (Mendelsohn and Neumann 1998). The absence of information about adaptation in developing countries consequently needs to be addressed.

This report provides information on a series of associated analyses done on the agricultural system in India. The analyses utilize available information in the country to estimate the climate sensitivity of agriculture. Although we apply methodologies developed in the United States, careful attention is paid (see next section) to adapting these methods to developing country conditions. For example, the studies pay careful attention to technological development, family labor, and incomplete cost data.

The analysis features the Ricardian approach which compares agricultural outcomes across farms under different climate conditions. It comprises background studies and Ricardian studies. Chapter 2 provides an extensive literature review that includes studies addressing also climate change impact on sectors other than agriculture. In Chapter 3 several Global Change Models (GCM) are employed to provide a range of temperature and rainfall values that may result from predicted changes in carbon dioxide levels in the future. Results from these GCM models are used later for simulation of Ricardian models' results. Each of the Ricardian studies emphasize a different methodology. The pooled data analysis (Chapter 4) examines long run response of farms to climate by Indian farming districts. The year by year analysis (Chapter 5) explains annual fluctuations in climate sensitivity by using regressions of a cross section of Indian agricultural districts for several years. This analysis measures how climate sensitivity varies from year to year in response to several variables, including prices, weather. The climate-technology study (Chapter 6) of Indian districts explores the role endogenous technology plays on farmer's climate sensitivity. The analysis examines whether technology has altered climate sensitivity and whether climate change might alter technical change..

In the next section, we briefly explain the methodology used in each chapter. In third section we summarize the overall results from India, and we conclude with some general policy observations and directions for continued research.

THE ANALYTICAL FRAMEWORK

The analyses in the studies rely upon the Ricardian method, an empirical approach that was developed by Mendelsohn et al. (1994). The Ricardian model examines a cross section of farms (in the case of India the unit analysis is a district) across the studied country. India is a country large enough so that farms face a variety of climates. By examining the economic performance of farms across different climates, one can estimate climate sensitivity. Economic performance is measured, in the different studies, through annual net revenues. These economic welfare measures include expected effects such as differences in crop productivity, but they also include less obvious effects such as impacts on costs of fertilizer, pesticides, and operations.

The Ricardian analysis is a natural experiment, an experiment which occurs in nature and is not controlled by the researcher. One of the drawbacks of a natural experiment is that uncontrolled factors can bias the results. Bias will occur if the uncontrolled factor (such as land quality) is correlated with the variables of interest (in this case climate), affects net revenues, and is omitted from the analysis. In the Ricardian model, it is therefore important to try to measure and statistically control for variables which might affect farm value or net revenue and be correlated with climate. The analyses consequently include measures of soils, market access, solar radiation, technology, household labor, and capital. However, in all cases, these measures are not perfect so that some component of these variables may still be affecting the results. This is the primary weakness of the Ricardian method and paradoxically the strength of the production function approach. The production function models are largely based on controlled experiments done in laboratory and field settings so they are not subject to these same problems.

The most important advantage of this empirical cross sectional approach is that the measurements include private adaptation. Private adaptation entails changes that farmers make to adjust their operations to the environment they are in. Some of these adaptations increase productivity and some reduce costs. The issue this study addresses is whether there is evidence of adaptation of Indian farmers to changes in climate. If they do, the expectation is that they would change behavior in response to climate change.

A valid criticism of the Ricardian approach is that it has historically assumed no price effects. Past studies have assumed that prices will not be affected by any change in the exogenous variables, namely climate. With the US studies (e.g., Mendelsohn et al., 1994), the Ricardian analyses were largely limited to a single time period so that prices were virtually identical across the sample. By assuming zero price effects, the Ricardian models tended to underestimate damages and overestimate benefits (Cline 1996 and Mendelsohn and Nordhaus 1996). However, this bias was calculated to be small in most relevant examples of climate change (Mendelsohn and Nordhaus 1996). In the multi-year India study (Chapter 5), a repeated cross-section of districts is utilized which permits exploration of the role output prices play. The results suggest that prices do not explain much of the intertemporal variation in net revenues and their omission does not appear to significantly bias the climate coefficients.

Among the methodological and empirical difficulties addressed by the studies in this report we should mention several which have some more general implications:

1. Input prices are difficult to measure. Specifically, a great deal of the labor in developing country farms, such as in India, is provided by family members who are not paid competitive wages. We do not have a good measures of the amount of time the family members devote to farming. In order to control for household labor, dummy variables were included which identify farms which rely on household labor. Unfortunately, the farms which rely most heavily on family labor are also likely to be smaller, use more labor intensive technologies, and consume some or all of their production. It is consequently difficult to interpret the dummy variable.
2. Animal work is poorly priced. Although we have official prices for bullocks in India, these prices do not reflect the cost of keeping a bullock but rather simply the price of buying one. Since some areas grow bullock feed and others do not, we suspect that the cost of keeping a bullock might vary across India. Again, we proxy for the cost of bullocks by treating them as a fixed input and introducing bullocks per hectare as an independent variable.

Many farms are subsistence. Not only do these farms depend solely on farm labor, but they are largely the sole consumers of their own output. Subsistence farms thus face different input prices (depending on family size and wealth) and different output prices (depending on personal consumption and market access). The data from this study focuses on purchased inputs and sold outputs. We consequently believe the analysis captures only the market farm sector and does not represent subsistence farms.

Summary of the Studies' Results

Reviewing, in Chapter 2, a wide range of the existing studies on agricultural impacts of climate change, reveals a number of useful insights, some of which are also reported in the studies in Chapters 4-6.

1. The overall impacts of climate change on global agriculture, even assuming large local impacts, is expected to be small when trade is incorporated.
2. Carbon fertilization could offset the harmful impacts of climate change so that yields may be only marginally affected.
3. Adaptation is likely to mitigate some harmful effects so that with carbon fertilization, yields are likely to increase at least in developed countries.
4. Less is known about the ability of developing countries to adapt to climate change so certain climate scenarios may still cause regional disasters even if global production is not affected.
5. Only the major grains, which favor cool temperate zones, have been extensively studied so the effects of climate change on the remainder of agriculture types remains uncertain.

The purpose of the study reported in Chapter 2 is to develop climate scenarios - based on the projections of several GCMs - to be used as input to an analysis of the impacts of potential climate warming on agriculture in India. The study uses the projections from three GCMs to develop projections of temperature and precipitation in India under a scenarion of doubling of CO_2 from pre-industrial levels. Three models used, the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and the Goddard Institute for Space Studies (GISS) models, as a basis for assessing the impacts of climate warming on the region.

The information produced by the GCMs indicates that the continued emission of trace gases into the earth's atmosphere will likely result in increases in both temperature and precipitation for India. While there will be significant spatial variation in the expected increases, data are presented for the country as a whole. Micro-scale modeling of climate systems is not advanced enough to make reasonable projections at a local scale, and the general projections must suffice. Solar radiation and evapo-transpiration likely will not change appreciably (or, at least, the models are inconsistent in their projections of these variables). Changes in soil moisture are unknown, since it depends on other factors besides the ones projected by the GCMs, including runoff, soil depth and percolation.

The three Ricardian studies of India (Chapters 4, 5, and 6) produce consistent results of climate change impact on Indian agriculture. All three studies find Indian agriculture sensitive to warming. Specifically, the studies find that net revenues fall precipitously with warmer April's but also are sensitive to warmer January and July temperatures. Crop revenues increase with

October temperatures. Net revenues are also sensitive to precipitation, but the effects are smaller and offsetting. Wetter January's increase farm values and wetter April's reduce farm values. July and October effects are small. Because the effects across seasons are small and offsetting, changes in annual precipitation have little effect.

The pooled analysis (Chapter 4) suggests that climate change will have an overall negative impact on Indian agriculture. A warming scenario of +2.0°C rise in mean temperature and a +7% increase in mean precipitation levels will create a 12% reduction in net revenues for the country as a whole. Rising temperature is damaging and increasing precipitation is beneficial. These effects will vary by season and region. There are regional impacts from warming even within India. Coastal and inland regions of Gujurat, Maharashtra, and Karnataka are most negatively affected. The high-value agricultural regions of Punjab, Haryana, and Western Uttar Pradesh show a small loss. The agriculturally low-value, hot and dry districts of Rajasthan and Central India are negatively impacted. Districts in many Eastern states (Andhra Pradesh, Orissa and West Bengal), however, benefit mildly from warming. These regional outcomes are largely caused by initial climate differences between regions.

The repeated annual analysis (Chapter 5) measures a lower climate sensitivity than the results in Chapter 4 due to a different data set used. A warming scenario of +2.0°C rise in mean temperature and a +7% increase in mean precipitation levels will create an 8% reduction in net revenues for the country as a whole. The repeated analysis reveals also that estimated climate sensitivity varies from year-to-year. For example, annual marginal effect of temperature alone varies between -150 and +280 Rs/ha, while inclusion of weather reduces the variance to values between -100 and +100 Rs/ha. Although the average effects reported above continue to hold in most years, there are exceptions when warmer January and July temperatures appear to be beneficial. Combining effects across seasons, there are four years between 1970 and 1986, where warming appears beneficial (1974, 1976, 1978, and 1984). Neither annual weather nor annual prices can explain all of this intertemporal variation.

The climate-technology analysis (Chapter 6) introduces endogenous technical change into the model. Technical change was measured by three variables, namely, intensity of modern high yielding varieties, intensity of multiple cropping, and irrigation intensity. It was found that technology and climate interact to affect net revenue in agriculture in India. Climate affects technical change: warmer areas generally have less irrigation and modern varieties but a little more multiple cropping. Wetter areas have less irrigation, modern varieties, and multiple cropping. These results are consistent with the general observation that the most significant technological improvements have come in areas which are more temperate. However, the overall effect is small so that warming is not expected to have a substantial impact on modernization. A simulation of a combined warming scenario of +2.0°C rise in mean temperature and a +7% increase in mean precipitation levels will create a 35% reduction in net revenues for the country as a whole. Also examined in Chapter 6 is the question whether technical change has altered climate sensitivity. It was found that higher levels of technology can help reduce sensitivity to warming but may increase damages from increased rainfall. However, the magnitude of these effects is small, so that technological change has not really affected the climate sensitivity of agriculture in India.

CONCLUSION

Ricardian models were estimated for India and Brazil in order to determine the climate sensitivity of agriculture in both countries. The results of our Ricardian investigation of the climate sensitivity of Indian agriculture confirms that agriculture in both countries is sensitive to warmer temperatures. However, the analyses suggest that the climate response functions are not very different from the estimated function for the United States. The slightly more harmful effects found in India and Brazil are due to the warmer baseline conditions in these more tropical countries.

The Ricardian model, which captures farmer adaptation, predicted much smaller damages to agriculture, compared with other approaches reported in the literature. The results suggest that farmer adaptation will mitigate from 40% to 60% of the potential damages from warming. In addition to farmer adaptation, there is also a possible research response to warming. However, the study of technical change indicates only a small interaction between climate and technical change in the past.

These results suggest that overall, warming will hurt agriculture in India relative to temperate countries. However, with the mild climate scenarios predicted for the next century, carbon fertilization, and private adaptation, these effects are likely to be small.

One important policy implication that emerges from our analysis, given the important role of private adaptation, is that governments should encourage private adaptation. Private adaptation is expected to be efficient and imposes no burden on the public budget. Measures may include development and dissemination of new technologies and practices.

Although the analyses reported here provide some important initial insight into the climate sensitivity of a developing country economy, additional analyses are needed. For example, little is known about subsistence farming and what will happen to the poor families dependent on local climate conditions. Future biological research would probably have to be focused more specifically on warming for it to affect climate sensitivity. Agricultural studies should also be conducted in other regions of the world which have not yet been studied.

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2 MEASURING THE IMPACT OF AND THE ADAPTATION TO CLIMATE CHANGE IN AGRICULTURE AND OTHER SECTORS - LITERATURE REVIEW

Ariel Dinar and Heather Beach

INTRODUCTION

CLIMATE CHANGE

In recent years, there has been growing interest in curbing the rapid rise of greenhouse gases in the atmosphere in order to control future climate change. Many observers are concerned that changes in climate will in turn lead to significant damages to both market and nonmarket sectors. In an effort to understand the entire picture of the effects of climate change, it is necessary to examine all sectors affected by climate change. One such area examined is the social effect of climate change focusing on several potentially affected sectors, among which are forestry and ecosystems, coastal zones, agriculture, fisheries water resources, and energy developments (Reilly and Thomas 1993). Toman, Firor, and Darmstadter suggest that while "the potential impacts of climate change are broad, some aspects of human society are more sensitive than others" (1996, 11). Further suggesting that systems that are highly managed like agriculture may be less sensitive than systems that are managed less.

Although several sectors have been studied, none have received more attention than agriculture. In the United States, the initial studies suggested large negative agricultural effects in terms of crop yield reduction, loss of fertile soils, and increased cost of production (Smith and Tirpak 1989). More recent analyses, that have incorporated more up to date climate forecasts and adaptation, however, consistently find that American agriculture will be resilient to climate change (Crosson 1993, Kaiser et al. 1993, and Mendelsohn, Nordhaus, and Shaw 1994). The agricultural sectors of other developed countries in temperate climates are expected to react similarly. However, it is not clear what effect climate change will have on agriculture in the rest of the world because, agricultural systems are different in developing countries, these agricultural systems may be less adaptable, and tropical and subtropical ecosystems may respond differently to climate change.

There has been considerable debate whether or not the steadily increasing levels of carbon dioxide observed in the atmosphere will lead to climate change (Nierenberg 1995). Most atmospheric scientists concur that greenhouse gases will affect climate by raising temperatures and changing water cycles. The debate, at this point, is focused upon the magnitude of this change. The consensus of atmospheric scientists is presented in the Intergovernmental Panel on Climate Change (IPCC) report (1990) which predicts that world temperatures will increase by 1.5-4.5 degrees C by 2060 (from the doubling of greenhouse gases since 1880). The best guess of this group is a 2.5 degree C increase. An updated assessment, provided in the second IPCC report (Brack and Grubb 1996) suggests an increase in global mean surface air temperature of about 2 degree C by the year 2100 with a range of uncertainty of 1-3.5 degree C.

These higher world temperatures will increase the hydrological cycle activity leading to a general increase in precipitation and evapotranspiration. What scientists have not been able to predict thus far is how this world wide change will manifest itself across the planet. There are no consensus predictions of temperature and precipitation changes at the regional or local level, although there are many individual models with detailed predictions (Barron 1995). The climate change any one area might receive as a result of global change could be quite different from the global average. In addition, policy implications for climate change must be viewed separately from other types of environmental pollution since the effects of global warming is an irreversible phenomenon (Mathews 1991).

STUDIES

Impact studies should focus on measuring climate response functions for specific areas rather than focusing on limited climate scenarios because the actual climate change that any area is likely to experience is not known at this time. For example, agricultural studies could be more effective if they measure how farm outputs and net revenues are affected by a range of temperature and precipitation changes rather than a limited set of climate change scenarios. Agricultural studies must also consider the direct effect of carbon dioxide since it is clear that CO_2 has a positive influence on crop yields (Kimball 1983) and water efficiency (Woodward 1993). The magnitude of and circumstances in which this carbon fertilization effect takes place is debated (Bazzaz and Fajer 1992; Van de Geijn et al. 1993; Kimball et al. 1993; and Mooney and Koch 1994), but the importance of including this effect is unequivocal.

Although a great deal has been learned about the link between energy systems, emissions, ambient greenhouse gas concentrations, and climate change, relatively little analysis has focused on what would happen if climate changed. Global warming may affect agriculture by directly altering yields, changing water availability, or affecting soils. Most empirical work undertaken has focused on the United States. This is especially true for economic analyses of the impact of climate change on agriculture. Existing studies include: USEPA (Adams et al. 1989, 1990, 1993; Rosenzweig and Parry 1993); USDA (Kaiser and Drennan 1993; Kaiser et al. 1993; Mendelsohn, Nordhaus, and Shaw 1994; Shaw et al. 1995); and DOE (Crosson 1993). The earlier studies in this group consistently predicted that there would be large negative impacts from climate change in the form of reduced quantities qualities of yields of grain crops (See also Scimmelpfennig et al. 1996). In contrast, the more recent studies consistently predict that US agricultural systems will readily adapt to climate change, by introducing new technologies, new crop varieties, and cultivation practices, so that there will be minimal changes in yields and net profits. These results likely extend to other Organization for Economic Cooperation and Development (OECD) countries suggesting that agriculture in developed countries is not sensitive to climate change.

Less is known, however, about what effect climate change will have on the agricultural systems of developing countries. Kaiser and Crosson (1995) suggest that to be successful, the international context in which agriculture operates must be taken into account. Several studies have addressed the impact of climate change on the food supply and risk of hunger in developing countries, especially Africa (Parry 1992; Downing and Parry 1993; Rosenzweig and Parry 1993; and Parry and Rosenzweig 1994), and Egypt (Strzepek et al. 1994). A recent study by Rosenzweig and Iglesias 1994 has addressed responses of grain crops (maize, wheat, soybean, and rice) to climate change in various countries, including India and Brazil. Adaptation in these studies has been treated mainly by changing values of parameters on an *ad-hoc* basis. These studies suggest that if high amounts of adaptation are assumed, developing countries could adapt to climate change. The only problem would be isolated areas of subsistence farmers who could remain vulnerable to severe local climate effects. Although levels of adaptation are explored in these developing country studies, these studies do not model what adaptations are likely to occur. No attempt has been made to quantify how farmers have actually adapted to climates in developing countries. Without solid adaptation estimates, the existing literature has probably overestimated the impacts of climate change in developing countries. Further, like the early United States studies, the studies listed above include only grains, which capture only roughly half of the agricultural land in many developing countries (in particular 59% and 31% of the arable land in India and Brazil in 1993, respectively (FAO 1994)). A comprehensive empirical analysis of the impacts of climate change on other important crops in developing countries has yet to be accomplished.

In addition to these empirical studies that have attempted to predict the effect of climate scenarios on yields, there have been a handful of studies which have focused on the relevance of international trade. Reilly et al. (1994), and Kane, Reilly, and Tobey (1991) assume yield reduction in different parts of the world and then predict what would happen to world agricultural prices. These studies, if combined with solid estimates of impacts in each region, could eventually forecast what would happen to world agricultural prices. However, at the time these studies were completed, impacts in different regions were unknown, thus limiting the power of these international studies. Coupled with new estimates of yield changes, however, an updated version of the Reilly models could address concerns about price impacts that cannot be properly handled at the regional level.

One way climate change may impact agriculture is by reducing the available supply of water for irrigation. Through either reduction in precipitation or increase in evapotranspiration available water for irrigation may be reduced. This may be especially important in developing countries because agriculture utilizes as much as 80% of water resources (WRI 1992; Xie et al. 1993). Water availability is a key factor in agricultural productivity, especially with developing countries located in arid and semi-arid regions. Further, developing countries may not be able to afford extensive manipulations of water systems so they may face limited options to adapt to water shortages (Frederiksen 1992). For example, a recent study by Fulglestvedt et al. (1994) provides a tally of country case studies on climate change, includes few studies on impact estimates, and even fewer studies on policy reaction in developing countries.

Reviewing the full suite of studies on agricultural impacts of climate change reveals a number of useful insights:

(1) The overall impacts of climate change on global agriculture, even assuming large local impacts, is expected to be small when trade is incorporated.

(2) Carbon fertilization could offset the harmful impacts of climate change so that yields may be only marginally affected.

(3) Adaptation is likely to mitigate some harmful effects so that with carbon fertilization, yields are likely to increase at least in developed countries.

(4) Less is known about the ability of developing countries to adapt to climate change so certain climate scenarios may still cause regional disasters even if global production is not affected.

(5) Only the major grains, which favor cool temperate zones, have been extensively studied so the effects of climate change on the remainder of agriculture types remains uncertain.

MEASURING CLIMATE CHANGE (MODELS)

Agricultural impact studies must draw a link between climate change and farming because of the direct relationship between climate and agricultural production processes. The traditional approach has been to turn to a General Circulation Model (GCM) for a forecast of the climate change associated with a doubling of greenhouse gases. Each GCM model produces a specific forecast which can then be used to predict yield and farm revenue changes. This climate scenario approach is very limiting. First, there is tremendous variation across models as to what will happen in each location. Although the analyst can proceed by choosing specific forecasts, it is impossible to capture the range of impacts from a limited set of model runs. Second, the climates associated with a doubling of greenhouse gases represent one distant moment in time (around 2060). Between now and then, and continuing after, climates will gradually be changing and so the earth will experience a full range of different climates. Rather then be limited to a handful of specific scenarios, impact studies should develop response functions. As climate scenarios change, these response functions can be used to predict what will happen at each location and time period. In contrast, the climate scenario approach becomes outdated the moment one moves away from the specific changes being analyzed.

There are two main approaches to measuring climate impacts on agriculture in the literature: an agronomic production function approach and a Ricardian model. The agronomic production function approach begins with a crop simulation model and predicts changes in yield in response to climate. The yield changes are then either extrapolated to an aggregate effect as with Rosenzweig and Parry (1993), or they are introduced into an economic model as in Adams et al. (1989, 1990, 1993) or Crosson (1993). The economic models in turn estimate aggregate damages to the agricultural sector. An alternative approach is to empirically estimate the direct impact of climate on agricultural net revenues, using the Ricardian model (Mendelsohn et al. 1994; and Shaw et al. 1995). Both approaches have strengths and weaknesses and tend to complement each other.

The agronomic production function approach has the strength of being tied closely to carefully controlled experiments where specific climate or CO2 levels are varied holding all other variables constant. This eliminates one of the potential problems with the Ricardian method, that climate variables may be correlated with other omitted variables resulting in biased estimates. In order to handle the agronomic production function approach properly, farmer adaptations should be included in the modeling. Simulations should be run with a variety of different farm methods such as varying planting times, crop varieties, harvests dates, and tilling and irrigation methods. The researcher would then be able to determine which activity would maximize profit and then, could trace out actual yields and net revenues for different climates. In practice, this is too expensive, and studies using this methodology either do not incorporate adaptation at all, or at best explore a limited number of alternative farming methods. One of the limitations of the agronomic production function approach, therefore, is that it fails to properly account for adaptation and therefore usually overestimates negative impacts.

Another distinction that is often made between models is whether or not they include price effects. The Ricardian model explicitly assumes away price changes. In contrast, some of the economic models using the agronomic production function approach have emphasized price changes as part of their results (Adams et al. 1989, 1990, 1993). Given that agricultural markets are worldwide, this use of domestic studies to predict prices is questionable. Agricultural prices can only be reliably predicted using global models. However, predictions of global yields are generally quite poor in quality because there are not sufficient measurements of both climate and yields at all sites. Attempts such as Rosenzweig and Parry (1994), Darwin et al. (1994), and Reilly et al. (1994) represent best efforts to date to measure global prices. However, each of these studies suffers from inaccurate measurements of climate-induced supply changes, especially in developing countries. For example, Darwin (1994) and Darwin et al. (1994) use a global model that includes 8 world regions (US, Canada, European Community, Japan, China and several other east Asia Countries, some Southeast Asia countries, Australia and New Zealand, and the rest of the world). These studies use a Computerized General Equilibrium (CGE) model that aggregates information on land and climatic resource changes (based on a Geographic Information System (GIS)) and changes in climate that are predicted by GCMs. Although comprehensive, the CGE model requires detailed knowledge of land and agricultural uses which cannot be accurately measured. Further, the authors have no way of reliably predicting how these large land areas would actually react to climate change. By providing sound measurements of impacts in developing countries, our results should complement these global models and help them generate more reliable global estimates.

The agronomic production function approach begins with the basic relationship between climate and crop production. Through agronomic experiments, agronomists have calibrated models which predict the yield of specific crops depending on weather patterns. These simulation models have historically been used to predict changes in yields for specific crops (Adams et al. 1989 or Rosenzweig and Parry 1993). The outcome from these simulations is then fed through an economic model of farmer behavior which in turn leads to a partial equilibrium model of the farm sector. This agronomic production function approach is attractive in its close collaboration with agronomic science. It can also be carefully linked with hydrologic conditions. Finally, the production function approach is the only current method capable of including carbon dioxide fertilization (provided appropriate agronomic models).

Innes and Kane provide a discussion on agricultural impacts of global warming. They have generated a list of variables which they feel need to be included in the complex modeling to predict the potential effects of greenhouse gas accumulation on agricultural production and pricing (1995, 747):

(1) Effects of greenhouse gases on climate itself, including ambient temperature, precipitation, ENSO cycles, and climatic events such as cyclones and hurricanes. Such effects on the climate system may result in a complicated mosaic of changes

in climatic conditions with a wide geographical variance and strong localized effects driven primarily by precipitation patterns.

(2) Physical responses of agricultural systems to greenhouse gases and climate change. Such responses include the so-called CO2 - fertilization effect and potential changes in pest problems from warmer and more humid conditions.

(3) Behavioral responses to climate change for given technologies and institutions. Such adaptations may include not only farmer shifts in cropping patterns, planting dates, tillage practices, irrigation techniques, and other management approaches, but also regional adaptation in, for example, water delivery systems.

(4) Technological change, which may include both exogenous improvements in agricultural productivity and changes in technology induced by climatic changes.

(5) Equilibrium effects in international agricultural markets.

Innes and Kane indicate that no analysis, thus far, has successfully incorporated all of these variables.

IMPACT OF CLIMATE CHANGE

IMPACT ON NON-AGRICULTURE SECTORS

To understand the broader implications and effects of climate change, it is necessary to examine non-agriculture sectors. This sections reviews the literature examining climate change impact on: ecosystems, forestry, animal production, fisheries, water resources, and energy developments. Reilly and Thomas (1993) conduct a discussion of studies that examine these non-agriculture sectors. There is a general theme found in a majority of these sectors, a lack of comprehensive models examining the individual sectors and few combinations with a climate change model. A majority of these sectors include a complex interaction of variables which have hindered attempts at forecasting changes, even with the exclusion of the climate change component. Both man made regional changes and global climate changes impact natural ecosystems (plants and fish populations), land use, water quality, desertification, air quality, and human health and livelihood. Reilly and Thomas (1993) indicate that the most widely examined effects of climate change upon ecosystems is done on a global or regional scale. For example, Smith (1994) estimates the impact regional and global climate change have on deltaic ecosystems in the Aral Sea basin. Walker (1994) provides a discussion of two ecosystem models that are now being included as part of GCMs in a first attempt to combine atmosphere-biosphere models.

Studies on ecosystem change are impeded by lack of integration of the various ecological response models, notwithstanding, some attempts to incorporate the nutrient cycling component of ecosystem models into the gap-phase models in forests have been made (Pastor and Post 1988). The FAO (1991) reports that based on the current predictions, global climate change on forest resources are negative with few positive effects. Climate change might cause forest species to either occupy a greater land area or it could also force a species to occupy smaller areas suitable for its growth (FAO 1991). Perhaps the main effect suggested by the FAO would be the restriction of natural ranges, reduced genetic variability and the possible extinction of some species.

The literature suggests that the effects of climate change towards animal production will follow the general trend of unequal distribution of changes. An FAO report (1991) indicates that there will be both positive and negative impacts. The example used is that higher temperatures would reduce the need for housing livestock during winter periods, would decrease maintenance requirements and increase the productivity of winter pastures, restricting the need for feed concentrates. However, higher temperatures would produce negative impacts in areas where climate change involves reduction in rainfall or increased evapotranspiration. Adverse affects to rainfed forage and fodder production, and availability of crop residues would be caused by lower rainfall. In addition, perhaps the greatest impact would be on pastoral families who would migrate to arable areas to secure their livelihood (FAO 1991). The migration of human population due to climate change is another non-agricultural sector that is difficult to anticipate without being able to predict how sectors might adapt to climate change (Lonergan 1994).

The generalization of the possible impacts of climate change upon fisheries is limited by the complexity of the variables upon which fisheries are influenced: physical, chemical, and biological processes (Reilly and Thomas 1993). Climate change has the potential to effect any and all of these variables. It is reported by the FAO (1991) that as a whole, global marine fish production will not be severely impacted by climate change, with areas of high productivity possibly shifting polewards. However, individual fish species may suffer and with the variabilities of ocean currents, planning and management is likely to cause problems for individual countries (FAO 1991). In addition, Reilly and Thomas (1993) point out that the ability to make predictions is further limited because there is no combination of a comprehensive ocean model and climate change models. It is most probable that inland water fisheries will be affected by droughts and floods similarly to land resources (FAO 1991).

Studies have shown fresh water resources to be very sensitive to climate changes (Gleick 1989; FAO 1991; Lonergan 1991; Lonergan and Kavanagh 1991). Like the other non-agriculture sectors, water resources are difficult to do future change models on because of the complexities of global and regional climate systems. Gleick (1986) suggests that the foremost limitations to using GCMs to assess changes in water availability are their coarse resolution and their simplified hydrologic parameterizations. These limitations have created an increase of research to develop other methods for evaluating the water resource effects caused by climate change (Gleick 1986; Nemec and Schaake; 1982; EPA 1984). FAO reports simulations have suggested that "a 25 percent rainfall decrease and a 5 percent evapotranspiration increase, could reduce the irrigated area by 75 percent" (1991, 8). The FAO further reports that there could be a significant alteration of the balance between water supplies and water needs in major irrigation areas of arid zones due to climate change, many of these areas are located in developing countries.

Energy development has been examined in the context of how urbanization and energy use effects global warming. Parikh and Shukla (1995) conducted a cross-national study of developing countries and the impact of energy use and climate change in economic development. Their conclusions can be summarized as: a positive correlation between greenhouse emissions and countries' urbanization levels; aggregate energy use rises with urbanization; and disaggregate energy use suggest that the sectoral and fuel use shifts accompanying urbanization have greenhouse augmenting potential. Parikh and Shukla determined that cities of developing countries are facing more serious consequences as a result of local rather than global pollution. Also, developing countries are likely to encounter different energy efficient technological alternatives in the future than developed countries (Parikh and Shukla 1995).

In addition to the study of energy use in developing countries, Lonergan and Young (1989) conducted an assessment of the effects of climate warming on energy developments in an arctic climate, Canada's North. The study concluded that: GCMs provide estimates that are not suitable for assessing local impacts because they do not capture the variability of climate; the disappearance of permafrost do to increased temperatures will impact existing and planned pipelines and buildings; and in the area being studied, there will be an extreme increase of precipitation which will be of concern in terms of future design and expected impacts (Lonergan and Young 1989).

Blitzer et al. (1991) suggest that the possibilities of greenhouse gases emission reductions should be discussed using country-level models with attention to structural detail, and conducted a study modeling Egypt. Parikh and Gokarn (1993) conducted a study on climate change and India's energy policies. Their paper presents an analysis of CO2 emissions in the Indian economy and addresses the implications of alternative policies to reduce them. This study is unique in that the analysis is based on flows of energy in the economy of India using a 60 sector input-output model instead of the standard of examining energy supply structure and end-uses of energy.

IMPACT ON AGRICULTURE

Analysts have already determined that climate change will affect different areas to different extents. The impacts are dependent on the enormity and distribution changes of the weather variables, including current climate and environmental characteristics and the agricultural structure of the different areas (Bacsi et al. 1991). Decker and Achutuni (1990) suggest that while climate change will alter the way agricultural enterprises are managed, one should not conclude that the climate change will have negative impacts on agriculture and cause a decrease in levels of productivity. However, the importance of examining climate change from a long term perspective is the uncertainty it introduces.

There have been many studies conducted examining the impact of climate change on: US Agriculture (Kaiser et al. 1995; Kaiser and Crosson 1995; Mendelsohn 1996) World Agriculture (Kane et al. 1992; Karim et al 1994; Reilly 1995; Sonka 1992) Brazil (Mendelsohn 1996; Sanghi et al. 1997) China (Jin et al. 1994) Egypt (Strzepek et al. 1994) India (Dadhwal 1989; Mendelsohn 1996; Rao and Sinha 1994) Pakistan (Qureshi and Iglesias 1994) Southern Africa (Schulze et al. 1993) Southeast Asia (Parry et al. 1992;) Sri Lanka (Vidanage and Abeygunawardena 1994) to name a few.

Kaiser et al. (1995) examined potential agronomic effects of several climate change scenarios on grain (corn, wheat, and soybeans) farming in the US. The agronomic results indicated that a mild climate change scenario had a minimal negative effect on all crop yields. Corn and soybean yields were negatively affected by the more severe (hotter) climate-change scenario. Southern states were more negatively affected than northern states. Economic results suggest that crop prices are quite sensitive to the rate and form of the assumed climate-change scenario.

Under all climate change scenarios, corn and wheat area and production decline over the 100 year analysis, and soybean area and production increased over the years.

Sanghi et al. (1997) estimate the impact of climate change on agriculture in Brazil using a Ricardian Approach. Impact was estimated using agricultural yields, and land values. Although there are varying regional consequences, the net impact is negative. The Center-West region is most negatively impacted and the South region benefits mildly from warming.

Dadhwal (1989) summarizes the results of a study on the effect of temperature on wheat in India. The results of this study follow a simple approach to quantify the effect of temperature on wheat in the field by sowing the crop on different dates, testing across the large seasonal changes in temperature for the different thermal regimes found in India.

Jin et al. (1994) examined the effects of climate change on rice production in southern China. Some of their results found that the rice yields, effected by climate change alone, decreased as a result of higher temperature, which in turn shortened the growing cycle of rice and caused water stress in some regions. However, when the rice yields were examined by climate change with physiological CO2 effects, the rainfed rice yields increased in the northern and eastern sites in the study. Under all of the doubled CO2 scenarios, the temperature increased and could result in an extension of the growing season for rice in Southern China. However, the increased temperature had a negative impact on yields and shortened the simulated lifecycle of rice.

Antle (1995) bases his research on the generally agreed upon theory that the poorest countries' agriculture's are likely to be the most vulnerable to, and least capable of adapting to, climate change or other environmental disruptions. Antle discusses the climate change impacts on tropical agriculture. He suggests that increased atmospheric CO2 can raise plant productivity through CO2 fertilization, and can cause changes in temperature, rainfall, solar radiation, and wind patterns that can impact either positively or negatively on plant and animal productivity. Mendelsohn (1996) suggests that the impact of climate change research now indicates that there may be small benefits in OECD countries and only mild damages in developing countries.

FOOD SECURITY

Global food supplies have been affected for years by climate changes effecting agriculture. Areas suffering from drought are unable to produce crops. Thus far, studies examining climate changes on agriculture suggest that since the effects will be spread globally, that even though some areas will have significant reduction in agriculture capabilities, other areas may be able to balance these negative impacts with increased production. The concept of food security has developed from these studies which examine climate change and agriculture and more recently, climate change and non-agricultural sectors. A few studies have examined the implications for global food security (Gleick 1989; Oram 1989; Peterson; Parry 1990; Pimentel 1991; Downing 1993; Rosenzweig et al. 1993; Rosenzweig and Parry 1993).

Pimentel's work is based on global warming in conjunction with rapid population growth with the expectation that together they will have negative impacts on natural resources and food production (1991). Pimentel suggests several main changes in the agricultural ecosystem which will have a major impact on food production: temperature rise, rainfall changes, and pest attack.

However, Pimentel suggests that the negative effects of global warming on agriculture can be offset to a certain degree with sound agricultural adaptation and management techniques, thus further limiting the impact on the world's food production capabilities.

Parry (1990) devotes an entire chapter of his book *Climate Change and World Agriculture* on the subject, "Implications for Global Food Security." Parry emphasizes that the information currently available is extremely limited and the analyses do not take into account changes in technology and management that would alter any potential effects from climate change. In addition, the studies presented in this chapter focus only on a single scenario of climate change and a single response of yield to that change. Parry cites the working group on food security from the 1988 Toronto Conference on The Changing Atmosphere to indicate the need for additional modeling and examination of the global food sector: "While averaged global food supplies may not be seriously threatened, unless appropriate action is taken to anticipate climate change and adapt to it, serious regional and year-to-year food shortages may result, with particular impact on vulnerable groups" (1990, 105). Parry's conclusions, based on preliminary results of the limited scenarios, suggest that while there may be only minor interruption of global food supplies, the increase in food prices could seriously influence the ability of food-deficit countries to pay for importing.

Rosenzweig et al. (1993) conduct an extensive review of climate change and its impact on the World's food supply. The aim of this study was to provide a global assessment of the potential effects of climate change on crop yields, world food supply, and regions vulnerable to food deficits. It is noted by the authors that it is critical to conduct research in determining how countries, with particular attention to developing countries, can and will respond to reduced yields and increased costs of food.

The concept of food security is based on direct and indirect effects of climate change to the agricultural system, which includes not only changes to crop production, but also the hydrologic cycle. Changes to animal production and fisheries will also impact the diet of the world's population. The area of non-agriculture sectors effected by climate change needs additional attention and focus by scientists to produce the same level of results being accomplished with the future agricultural assessments.

RESPONSES AND ADAPTATIONS TO CLIMATE CHANGE

RESPONSES AND ADAPTATIONS IN NON-AGRICULTURE SECTORS

There have been few studies completed examining what the responses and adaptations in non-agriculture sectors have been previously and should be in the future. Three studies that address appropriate responses and adaptations on the subject are FAO (1991, Parry (1990) and Downing (1993).

FAO (1991) reports that the greatest risk appears to be in semi-arid areas that are already vulnerable to drought, or in low-lying coastal areas and deltas of developing countries. The FAO suggests that responses to climatic changes in these vulnerable areas would involve modifications in cropping patterns, forestry, livestock, and fishery production. In addition, out-migration from affected coastal and pastoral areas would be expected.

Parry (1990) found that substantial increases in the need for and costs of irrigation are likely to occur in order to substitute for moisture losses due to increased evapotranspiration. Additional costs are likely to be needed to control the spread of subtropical weed species into current major cereal-producing regions and increase of pests in the warmer, more humid climates.

Downing (1993) indicates that the ultimate effect of climate change will depend to a great extent on adaptive responses at several scales. Downing conducted a simple model of household food security in eastern Kenya and found that the potential of adaptive responses in the subhumid zone marginally suitable for maize. Downing suggests that there are two main ways to increase household food security, increase yields by applying fertilizer and adopt soil conservation measures. An additional strategy would be to increase the length of food storage from the current average of 3 months of consumption to a target of 6 months.

RESPONSES AND ADAPTATIONS IN AGRICULTURE

Many studies have been completed examining the responses and adaptations in agriculture previously and indicating future responses. These analyses range in suggestions from shifting the actual land use where crops are grown to genetically changing and breeding crop species for resistance. A few of these studies are discussed below.

Decker and Achutuni provide a list of five research areas which, through their research, appear to have the highest priority in need to respond to sustain agriculture under conditions of global warming (1990, 436-437):

(1) The design of simulation models for crop response which accounts for both climatic change and the direct effects of increase CO2 concentration.

(2) The use of genetic engineering to develop stress-resistant cultivars.

(3) Development of econometric models which evaluate the impacts of climate change on national farm policy alternatives and the development of foreign markets.

(4) Development of soil water models for investigating the feasibility for the movement of cropping zones.

(5) Simulation studies using climatic scenarios for determining the need for and profitability of irrigation.

Antle (1995) argues that to conduct analysis of agricultural adaptation, particularly in developing countries or regions of the world, information on the rate of climate change is critical. However, estimating this dynamic is so intensive with GCMs, resolution would have to be substantially reduced, diminishing the value of the analysis.

Darwin et al. (1994) conducted a study linking economic activities to land resources determined by climate. Despite negative impacts in some regions, Darwin et al.'s results indicate that climate change will have a relatively small impact on the long-term ability of global agricultural resources to meet future world food demands. However, these results are dependent on the ability to shift crop production to new locations. Unfortunately, many of these shifts would have to occur across international borders, which in some regions, and between some countries would be difficult to accomplish. Parry (1990) also found that there would be a need to switch crop locations to land uses that show a greater increase in productivity potential.

Kaiser and Crosson (1995) believe that the conclusion of Rosenzweig et al. (1993) that agricultural production in developed countries in the temperate zone actually might be increased by climate changes resulting from an equivalent doubling of atmospheric CO2 to be applicable to the United States if there are ample options for technological adaptation and an incentive to adopt the appropriate technologies. In addition, they found that maintaining and strengthening the international trading system to be crucial in easing the impacts of climate change on not only agriculture in the United States but around the world as well.

Rao et al. (1989) found that in India, technological innovations involving genetic alternations in conjunction with input management practices and a better understanding of the process of adaptation has resulted in moderate advances in the productivity and stability of sorghum and millet cultivated during the rainy season. While these changes have been accomplished only during the rainy season, the lessons of adaptation demonstrates and can be generalized to show how manipulations of genotype and environment have resulted in accelerated growth rates and stability in production which can be applied to similar areas of climate. In addition, analyzing areas in similar situations show the technological potential for a change in productivity and stability.

Srivastava (1989) found that breeding strategies are increasingly being directed toward the development of horizontal or generalized resistance. He indicates that barley and wheat cultivars with improved yield stability that yield satisfactorily under stress and respond to favorable conditions with substantially higher yields have been developed.

Virmani's (1989) analysis found that improved cropping systems can cope best with rainfall variability when they are applied simultaneously with an efficient set of land and water management techniques.

Jin et al. (1994) studied the effects of climate change on rice production in Southern China and ran some scenarios of possible strategies for adaptation to climate change. The resulting analysis showed that creating a new cultivar created a higher yield in five out of seven sites. Changing the planting dates of the currently used cultivars caused increased rice yields in the northern sites, but not in the southern sites. Combining the changing of both the cultivars and the planting dates significantly increased the rice yields at six of the seven site locations.

RESPONSES OF THE INTERNATIONAL TRADE AND POLICY COMMUNITY

While a large portion of the debate taking place is over how climate change occurs and at what rate is it occurring, another area under consideration is how to best deal with the phenomenon, whose responsibility is climate change reduction and at what level will policies be most effective, state, international, or globally? Many authors have conducted economic impact studies on international trade at the global and regional levels (Reilly, Hohmann, and Kane 1993; Reilly and Hohmann 1993). While other authors have focused on international policy responses to climate change (Larson and Tobey 1994; Reilly 1995; Drennen 1993; Stewart 1992; and Viscusi 1992).

Reilly and Hohmann (1992) investigate the agricultural effects of climate change recognizing that effects will simultaneously occur worldwide. The authors found that there are still significant sources of error due largely to the underlying uncertainties in many variables (e.g. the climate scenarios, agronomic factors, and increased competition for land or water due to increased demand from other sectors caused by climate change). In addition, like other studies, Reilly and Hohmann note that the models currently used in the analyses do not included technological change, population growth, or other changes that may occur simultaneously with economic growth and development.

Larson and Tobey (1994) analyze the implications of alternative policy responses to uncertain climate change within the context of a simple dynamic economic model. Larson and Tobey focus on the policy question of how best to respond in such an uncertain environment given the uncertainty surrounding predictions of future global climate change.

Stewart (1992) examines two approaches to global change policy, comprehensive and market-based. In this examination, Stewart points out that there is a need to integrate both the physical and social science in addressing all of the relevant components of the complex global system. In addition, he notes that there are three basic kinds of questions to answer before one can examine the policy prescriptions (1992, 26-27):

(1) To what extent and when will global change occur? What would be the impacts of global change, and their costs and benefits? What further scientific research is needed to resolve remaining uncertainties?

(2) What are the costs and benefits of measures to limit or adapt to global change? In light of these costs and benefits, what actions, if any, are warranted now? What is the appropriate combination of measures to limit net emissions of trace gases contributing to global change and measure to adapt to any adverse effects of global change?

(3) If limitation efforts are warranted - a big "if" that can only be decided based on a careful look at the costs, benefits, and uncertainties - how should they be designed? Should they be narrowly focused on specific activities, or comprehensive to match the global system? Should they employ traditional command-and-control regulations, or make use of market-based economic-incentive tools?

In the World Resources Institute publication *Greenhouse Warming: Negotiating a Global Regime* (1991), 9 authors present a range in discussion on the global response to greenhouse warming. The chapters discuss such topics as: Lessons from "the Ozone Hole"; Beyond Vienna and Montreal - Multilateral Agreements on Greenhouse Gases; Elements of a Framework Treaty on Climate Change; A Proposed Structure for an International Convention on Climate Change; Alternative Legal and Institutional Approaches to Global Change; Managing the Transition to a Global Warming Regime or What to Do til the Treaty Comes; and Negotiating a Regime to Control Global Warming. This document is a comprehensive approach in how to deal "globally" with climate change - through a global regime and treaties. The material presented in this document was an effort to increase the interest of the widest possible choices to be considered at several global conferences on climate change.

Reilly et al. (1993) conducted a study based on the agricultural production, price and economic welfare implications for 32 separate geographic regions computed for 9 scenarios using 3 different GCMs, estimated with and without the direct effects of carbon dioxide on plant growth, and with different levels of adaptation. The authors major conclusions were similar to other impact studies done on agricultural production, economic welfare losses tend to be more severe in developing countries, major agricultural exporters will gain significantly if global agricultural prices rise, and the CO^2 fertilization effect offsets losses due to climate change alone. Reilly et al. offer six policy relevant conclusions (1993, 34-35):

(1) Based on current analyses, climate change effects on global agriculture appear manageable and possibly beneficial for an equilibrium doubled trace gas climate, but the possibility of more severe effects cannot be ruled out until more is known about the nature of transient climate and economic models are designed that can better consider adjustment costs.

(2) International trade is an important risk pooling mechanism.

(3) Significant relative change in agricultural productivity is likely whether the net effect on global agricultural production potential is negative or positive. Attempts by countries to protect domestic agricultural producers could interfere with international trade and such trade interventions would create additional losses.

(4) The difficulty of predicting climate change at relevant scales and time frames for agricultural decision-making suggests that regional experiment stations should continue to play an important role in evaluating and selecting crops and agricultural production strategies. Considerations of climate change place greater emphasis on evaluating broader measures of success such as profitability rather than narrower measures such as yield.

(5) It is difficult to predict with confidence the direction of economic impact for specific areas; flexibility is a key to minimizing the cost of adjustment. For developing countries, increased education and economic development that includes development of manufacturing appears to increase flexibility and serve as an insurance against climatic conditions that may turn unfavorable for agriculture.

(6) Subsistence agricultural systems are most at risk because they cannot avail themselves of the risk pooling value of markets. Education, economic development, and integration of these areas into national commodity and labor markets appear to be successful insurance policies against the possibility that agricultural conditions could degrade substantially in some areas.

DISCUSSION

A great deal of effort has been put into estimating the extent of climate change under future scenarios in various parts of the world. A growing amount of effort is being invested in estimating the impact of climate change on various sectors in various countries. Like in the story about the person who lost a coin and looks for it under the light, most of the work reported in the literature is concentrated in developed countries.

Given the great deal of controversy surrounding the issue of climate change—different interpretations of the evidence, different interests of policy makers, and different evaluation of intervention options—complicates the measures that might be appropriate in dealing with such phenomena. Toman (1997) suggests a policy envelope for climate change decision making. It exists on a comprehensive framework that takes into account:

- Risks and costs (of impact and control)
- Long-term considerations
- Adaptation considerations
- Regional and international cooperation
- Distributional impacts

With these components in mind one can already suggest a direction for future work in preparing the background work, and the future scenarios and responses.

This report focuses on two aspects from the above list—adaptation and distribution. The various studies reviewed in this report suggest that there is much more flexibility introduced into the policy framework if adaptation is considered. Distributional impacts are another important pan of impact of and responses to climate change. Distributional impacts both within affected individuals and sectors, and among countries regions, indicate the need to introduce, both into research and policy, spatial effects and considerations. Distributional issues also prevail between developed and developing countries.

Given the relatively lack of information and sufficient economic analysis on impact of and adaptation to climate change in developing countries, it is probably one of the most important tasks to initiate empirical research in developing countries, who might be subject to negative impact of climate change in the future.

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3 CLIMATE WARMING AND INDIA

Steve Lonergan

INTRODUCTION

The purpose of this study is to develop climate scenarios - based on the projections of general circulation modes or GCMs of the earth's atmosphere - to be used as input to an analysis of the impacts of potential climate warming on agriculture in India. The study uses the projections from three GCMs to develop projections of temperature and precipitation in India under a doubling of CO_2 from pre-industrial levels.

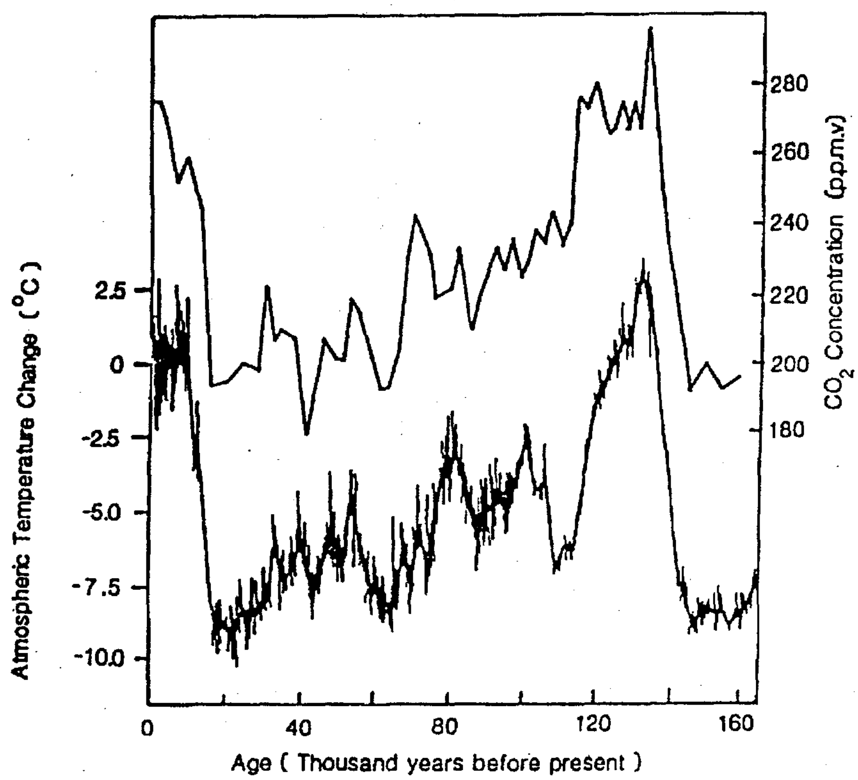
The chapter is divided into five sections. Section one is the short introduction. The second section outlines the general characteristics of climate warming - or the "enhanced greenhouse effect," and tries to clarify key aspects of the controversy over whether climate warming is occuring. Section three discusses the general circulation models (GCMs) which are used to project changes in climate under various levels of carbon dioxide in the atmosphere. These GCMs were used to generate the results presented in this paper. The fourth section highlights the key changes in climate - notably temperature, precipitation and evapo-transpiration - which are expected to occur under a doubling of CO_2 in the atmosphere. These projections focus on India, and are presented for the country as a whole and for a north-south division. The final section summarizes the conclusions of the paper.

THE GENERAL CASE OF CLIMATE WARMING

Possibly the greatest environmental threat society will fact over the next century is that of global warming, with the potential to disrupt natural and social systems throughout the world. This threat is the result of the anthropogenic emission of certain gases, most notably CO_2, CH_4, CFCs, NO_x and water vapor, into the atmosphere, contributing to a general process known as the "greenhouse effect." The term greenhouse gas has been applied to atmospheric gases that are relatively transparent to incoming short wave solar radiation but which absorb the long wave radiation from the surface of the earth and reemit it downward, warming the surface of the earth and the lower atmosphere. The primary concern to date has been with CO_2, released from the burning of coal and other carbon-based fuels and the burning and decay of the world's forests. As depicted in Figure 3.1, there is a strong relationship between atmospheric levels of CO_2 and temperature.

Since 1958, when measurements of CO_2 in the atmosphere began, its concentration has increased from 315 to over 360 parts per million (ppm). A doubling of CO_2 from pre-industrial levels - expected sometime next century - could result in a general warming of the earth's surface, although to what extent is not known, since the present concentrations of CO_2 in the atmosphere are far greater than at any previous time. Concentrations of other greenhouse gases, currently at much lower concentrations than CO_2, but potentially more potent, are increasing even more rapidly. Methane, which is emitted from wetlands, rice paddies, livestock and warming permafrost, is increasing at a rate of one percent per year (compared to 0.4% per year for CO_2). CFCs have been increasing at five percent per year, although recent international agreements have resulted in a significant decline in the global emissions of CFCs.[1] Table 3.1 lists the major greenhouse gases, their sources and their characteristics.

Figure 3.1: Relationship between atmospheric CO_2 concentrations and temperature



Source: Barnola et al. (1987)

The theory of a general warming of the world's climate has gained widespread acceptance over the past two decades, despite the reluctance of some governments to agree to emission reduction requirements. In addition, there have been numerous studies of the potential impacts of global warming, by sector (such as for health, agriculture, water and tourism) and by region (including India; ADB, 1994). Most of these studies incorporate scenarios of climate warming which are drawn from the output of large-scale computer models of the atmosphere, known as general circulation modes, or GCMs. The present study is based on the projections of three of these GCMs.

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[1] There remains some concern that CFC production in developing countries, and, particularly, China and India, will offset any reductions in emissions from industrialized countries. There is international disagreement at present over the level of financial support promised to developing nations to ensure reductions in CFC emissions will not negatively affect economic growth. To date, as of late 1996, Thailand is the only developing country to voluntarily restrict CFC emissions.

When addressing climate warming and its potential impacts, there are two issues which must be considered. First, the GCMs provide medium or long term projections of climate under various concentrations of greenhouse gases in the atmosphere. The most common projection, and the one that will be used in this study, is of a doubling of the CO_2 concentration in the atmosphere from pre-industrial levels (termed the 2 x CO_2 scenario). At present emission rates - and this is a restrictive assumption - a doubling of CO_2 is expected to occur in the middle of the next century. With this doubling, the models project, the average levels of temperature, precipitation and other climatic variables will change as well. A second, and potentially more important issue, is the short term variability that might accompany a general warming trend. Hurricanes and droughts would be more severe and more frequent; storm surges along the coasts would be higher, and the frequency and duration of periods of abnormally high temperatures would increase. In addition, much of the work on climate change and its impacts to date has been on the change in climate over time; when a CO_2 doubling will occur and what effects a gradual increase in temperature might have on physical and natural systems. Of greater concern, however, may be climate changes over space. This may be even more relevant when considering short-term climate variability (and volatility), as the economic loss due to natural hazards is much higher in developing countries.

Table 3.1: Major greenhouse gases and their characteristics

Gas	Atmospheric Concentration (ppm)	Annual Increase (%)	Lifespan (years)	Relative Efficiency	Current Contribution (%)	Principle Source
CO_2	360	0.4		1	57	coal, oil,
fossil fuel					(44)	natural gas
biological					(13)	deforestation
CFCs	.000225	5	75 - 111	15,000	25	foams, coolants
CH_4	1.675	1	11	25	12	wetlands, rice, livestock
NO_x	0.31	0.2	150	230	6	fossil fuel, deforestation

Source: Compiled from Houghton, et al. (1990)

The Global Warming Controversy

Over the past few years, there has been a number of articles published in the popular press which criticize the projections of global warming. For the most part, the criticisms focus on the inability of the GCMs to accurately represent the complexities of our climate system. Many of these articles have been stimulated by the concern on the part of some western governments of the cost of imposing CO_2 emission standards unilaterally. These have been estimated to be as high as 3% of GNP for the U.S. under a scenario of 20% reduction in 1988 levels of CO_2 emissions by the year 2010 (Manne and Richels, 1990). Despite this controversy, what should be recognized is that the major sources of greenhouse gas emissions are known and that the role of these gases in influencing climate is well understood and accepted. The controversy surrounding the general global warming which may accompany the rapid increase in greenhouse gas emissions is based on our inability to accurately predict the effect these gases will have on climate in the presence of other atmospheric processes. Climate variables, such as temperature, precipitation and solar radiation have been projected under different concentrations of greenhouse gases in the atmosphere with the general circulation models. While these models are quite sophisticated, they are not able to capture all of the complexities of our climate system. In many cases, we simply do not know what the buffering capacity of clouds will be or the effect the oceans will have on mitigating the expected global warming.

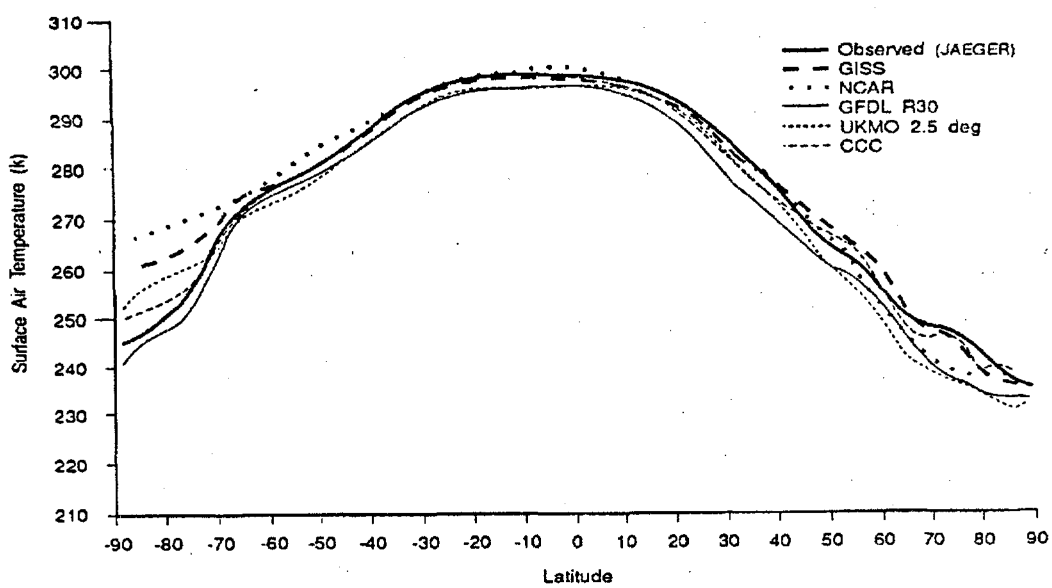
The following, however, are accepted. First, anthropogenic releases of greenhouse gases are increasing at a constant rate. Second, these gases, in the absence of other changes, will result in a general global warming. Third, there will be regional variation in the amount of warming (and changes in other climate parameters, such as precipitation). And fourth, the consequences of such warming could be very great, depending on the ability of systems to adapt to these potential changes. What is not accepted is how other earth systems, such as the oceans and clouds, will act to alter the expected warming or how natural variations in climate may mitigate many of the expected changes.

General Circulation Models

Most of the predictions of climate warming discussed in both the scientific and popular literature are the result of output from three-dimensional, numerical models of the earth's atmosphere known as general circulation models or GCMs. As was noted above, these are numerical weather prediction models that simulate climate processes over long periods of time. They are generally based on five prognostic variables: temperature, humidity, surface pressure and two dimensions of wind, and are used for controlled runs, perturbed usually by changes in CO_2 until they reach an equilibrium level. Generally, runs are done on a doubling of atmospheric CO_2 concentrations from pre-industrial levels. The first GCM studies were undertaken by Manabe and Weathereld (1975) at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey. More recent studies have been undertaken at the National Centre for Atmospheric Research (NCAR) in Boulder, Colorado, the Goddard Institute for Space Studies (GISS), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU). A more complete description of these models can be found in Dickinson (1986). The most recent model to appear has been developed by the Canadian Climate Centre (CCC), a branch of the Atmospheric Environment Service within Environment Canada (however, data from the CCC model is only available for a North American "window"). The model projections are made by grid cells which are roughly 400km by 400km. All of the models show remarkable consistency with observed temperature and precipitation when run at present levels of CO_2 (see Figure 3.2), but their projections - particularly in regards to precipitation - differ considerably under a 2 x CO_2 scenario.

This study of India used output from three of the models, the GFDL, the UKMO, and the GISS models, as a basis for assessing the impacts of climate warming on the region. Despite the consistencies shown by the models, there are a number of problems which should be noted. First, they do not possess a degree of variability that is apparent in the real climate (Katz, 1988). This lack of variability is also a problem with the climate projections, since many analysts feel the greatest impact from climate warming may result from a greater magnitude and frequency of extreme events (extended droughts, more severe storms) than from gradual increases in mean temperature and precipitation. The GCMs are not able to project such changes in extreme events. Second, the models cannot provide information about temperature and precipitation changes at a small enough spatial scale to be useful for detailed impact studies. Accordingly, this analysis was done for all of India, along with an extension to the "north" and the "south" of the country. Third, the models are inadequate in treating one or more of five important feedback mechanisms in the climate system, including: water vapour; snow and sea ice; cloud cover; cloud radiative properties; and the ocean-atmosphere interface. The difficulties incorporating these feedback mechanisms into the climate models, and their potential importance in mitigating any tendency towards global warming, has contributed to the controversy surrounding the issue.

Figure 3.2: Simulation runs of GCMs versus observed data



Source: Houghton et al. (1990)

CLIMATE CHANGE PROJECTIONS FOR INDIA

The following figures and tables present monthly temperature, precipitation and soiar radiation projections for India under a 1 x CO_2 scenario (pre-industrial levels) and a 2 x CO_2 scenario, from three different GCMs. The GCMs used were from the GFDL, the GISS and the UKMO. Model outputs for the globe were obtained from the National Center for Atmospheric Research in Boulder, Colorado. Point assignments of climate projections from each of the three models were used. The points denote the center of the grid cell on which the projections are based (the size of the cells varies according to the model). The GFDL Model consists of 12 cells, the GISS model consists of 7 cells, and UKMO model consists of 13 cells.

TEMPERATURE

Figures 3.3 - 3.11 and Tables 3.2 - 3.4 present temperature, precipitation and solar radiation data by the three GCMs, by month, quarter and year. The UKMO and GFDL models project temperature increases of between 16.2 and 23.5% from the 1xCO_2 levels, respectively, with the GISS model projecting an increase of approximately 10% (Figure 3.6). Typical of GCM projections of temperature change under a doubling of CO_2, there is reasonable consistency in the results: all models project increases in temperature for all months of the year. (Figures 3.4, 3.5, and 3.8a). This is true despite the different spatial scales in which the GCMs operate. In absolute terms, temperatures are expected in increase between 2.33 C° and 4.78 C° over the entire country. Figures 3.9a, 3.10a and 3.11a show the monthly differences between the temperature scenarios by GCM. The UKMO model - which records the lowest pre-industrial temperature levels - projects the greatest increase in temperatures of 4.78 C°, an increase of over 23%. Complete data are presented in Tables 3.2 - 3.4, by GCM.

Figure 3.3: Climate change and Indiac - projections from three GCMs

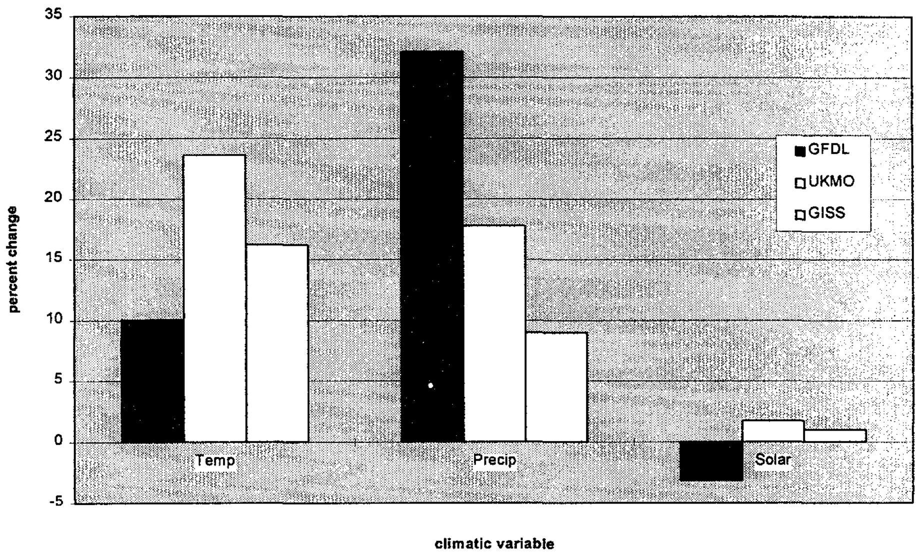


Figure 3.4: Temperature levels projected by the GCMs for India-pre-industrial levels

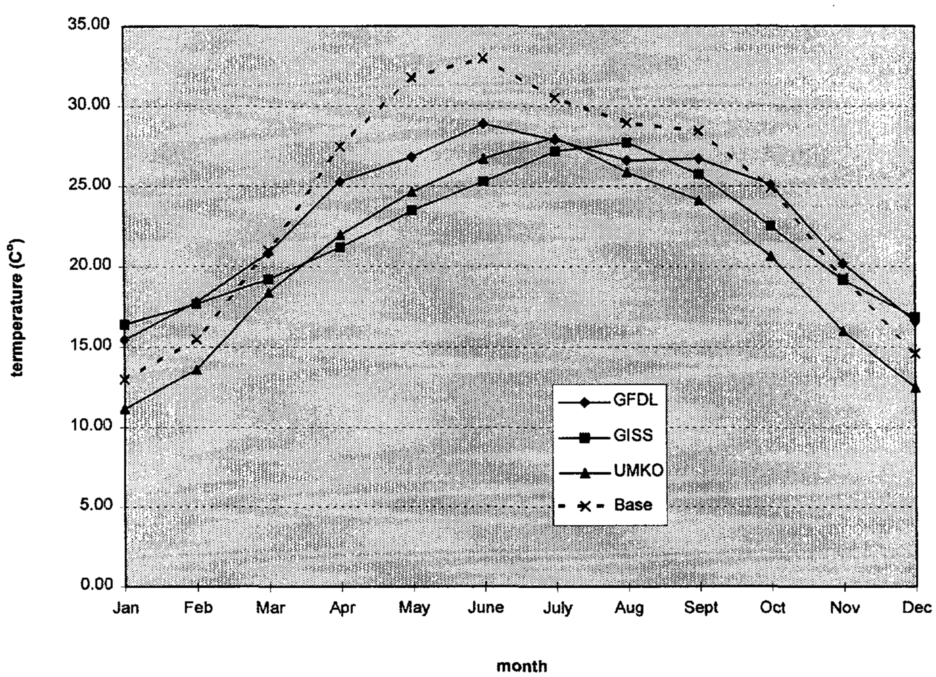
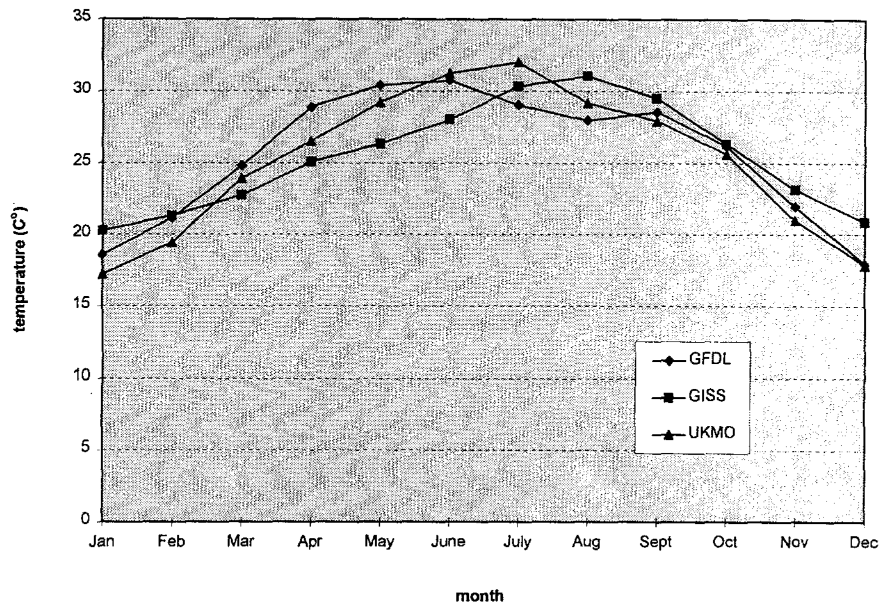


Figure 3.5: Temperature levels projected by the GCMs for India: 2 x CO_2 scenario



As noted above, the increase in temperature corresponding to a doubling of CO_2 in the atmosphere ranges from 2.3 to 4.8 C°. On a monthly basis, the increase in temperature could range from a low of 1 C° in October (GFDL model) to a high of 6 C° in January (UKMO model). It should be noted that all of these figures are likely at the upper range of projected increases; recent studies have shown that the GCMs are probably too high in their general projections of temperature.

For comparison purposes, the average monthly temperature for Delhi is depicted as a "base case" (Figure 3.4). The projections are for India as a whole, and weather and climate are very location specific. In addition, differences between the recorded temperatures and the model outputs reflect both the complexity of the atmospheric system and our inability to accurately capture this complexity.

PRECIPITATION

Figures 3.3, 3.6, 3.7, and 3.8a provide the base data for the GCM precipitation projections. Unlike the temperature projections presented above, the precipitation projections show little consistency across models, even when averaged over the entire country. This is primarily due to the complexity of precipitation patterns and the inability of the GCMs to adequately capture this complexity. The GFDL model projects the greatest annual precipitation increase (and percent increase), with most of this increase occuring during the late summer (July/August/September). On the other hand, the GISS model projects the greatest absolute level of precipitation under both scenarios; over 50% higher than either the UKMO or GFDL models (this is consistent with precipitation projections in other regions of the world, where the GISS model invariably yields the highest amounts). The variability in projections is apparent in

Figures 3.7 and 3.8. Additional data on the GCM runs are provided in Figures 3.9b, 3.10b and 3.11b, and Tables 3.2 - 3.4.

The variability in precipitation projections across models is characteristic of the degree of our knowledge about precipitation dynamics and the large regional variation in precipitation that occurs over quite small areas. The models exhibit much higher levels of precipitation during the winter months than occur naturally (Figure 3.6), and somewhat lower levels in the monsoon months. One of the models - the GISS - even seems to project the monsoon at the wrong time of year. Nevertheless, it is important to note that all the models project increases in precipitation. This consistency is somewhat unusual with the GCMs; in regions such as Southeast Asia and the Middle East, the projections are much more variable regarding precipitation.

For the purposes of modeling agricultural yields under conditions of climate warming, it is likely best to select one model to use as a base model, and incorporate the projections from that model. As noted previously, the GCMs often differ greatly in their precipitation estimates, and one must be careful to use them as alternative scenarios rather than select a single model output for analysis.

Figure 3.6: Precipitation levels projected by the GCMs for India: 1 x CO_2 scenario

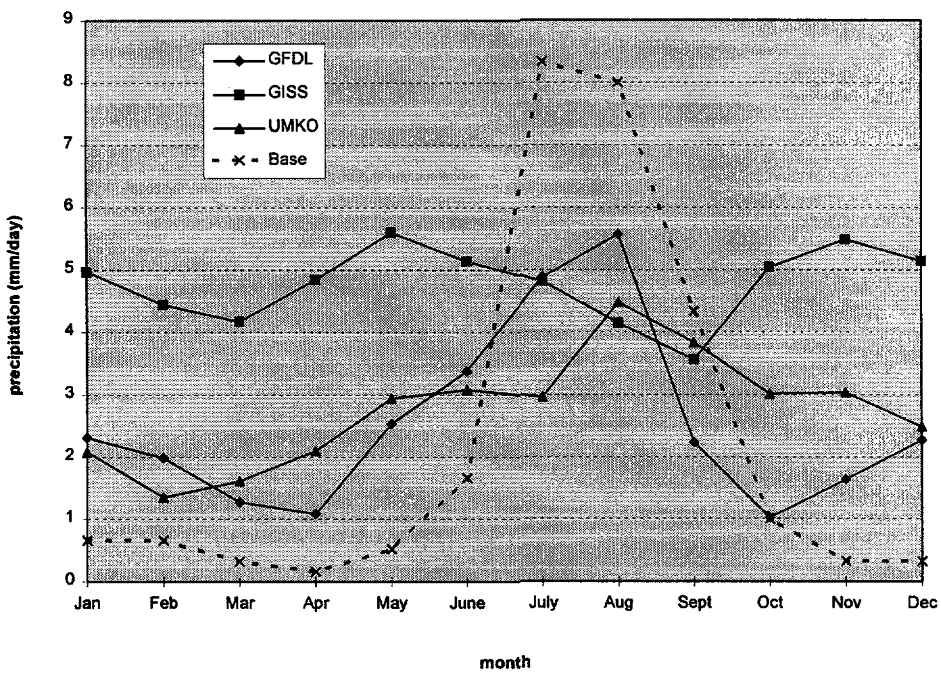


Figure 3.7: Precipitation levels projected by the GCMs for India: 2 x CO_2 scenario

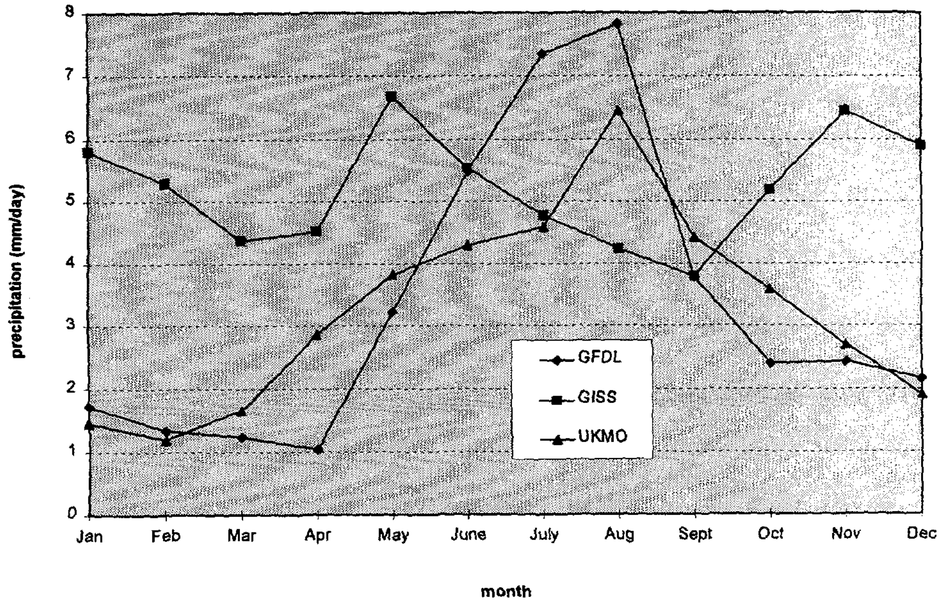
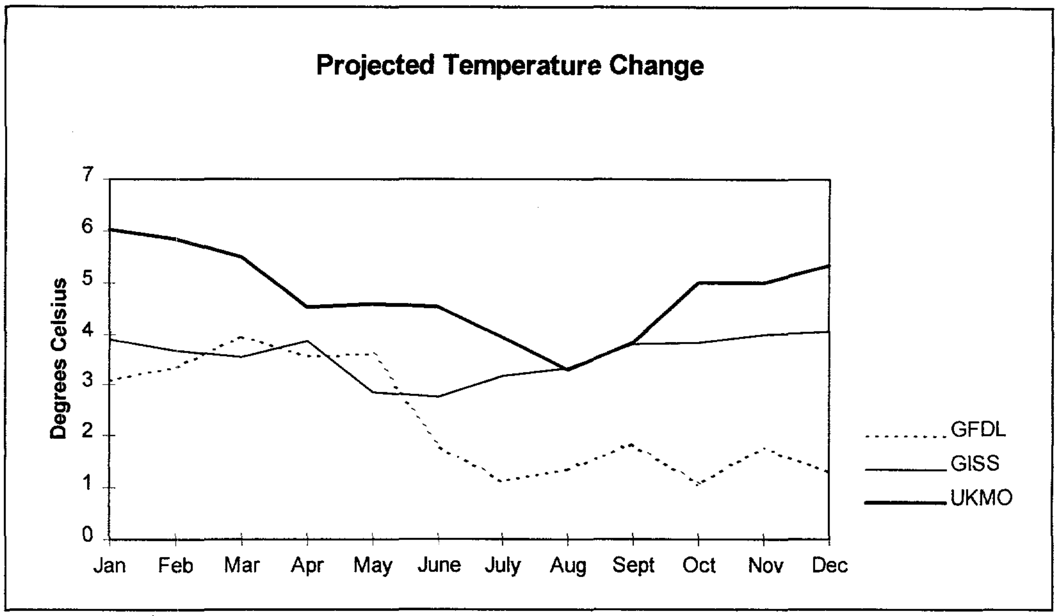
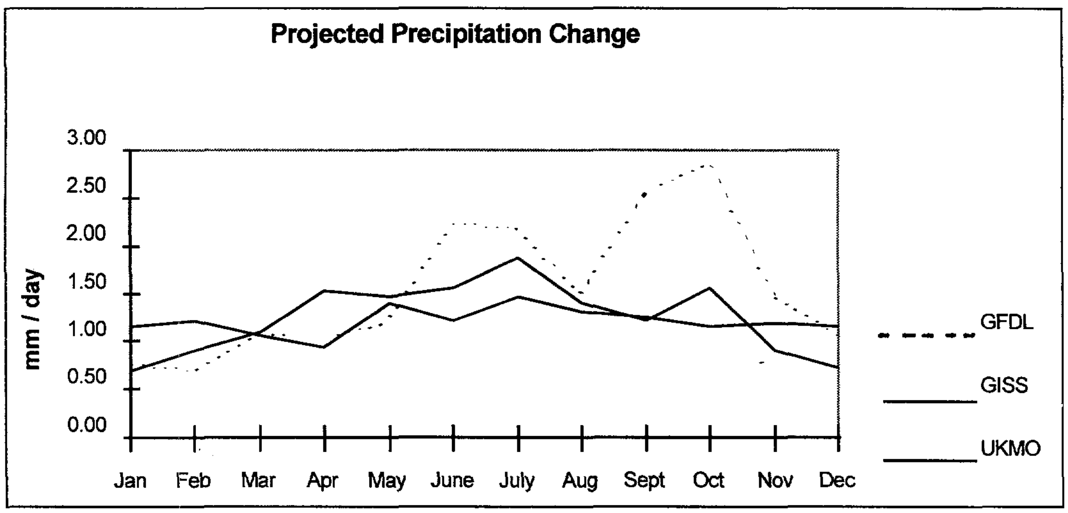


Figure 3.8: Projected temperature and precipitation changes for India from a 1 x CO2 to a 2 x CO2 scenario, by month

a



b



EVAPORATION

What influence will these expected temperature and precipitation levels have on water resources in the region? One of the most important will be the impact on evapo-transpiration, which will affect water supply. Although detailed data on surface water availability and use are not readily accessible for India (at least not at a level that would be appropriate for this modelling), rough estimates of the change in evaporation due to climate warming were made to illustrate the potential impact on water availability. Two natural factors may affect the amount of water available for human consumption in the future; precipitation and evaporation. As a rough approximation, changes in evaporation resulting from climate warming were approximated using a combination of energy-budget and mass transfer approaches based on the Penman equation (Penman, 1948). The key variable is solar radiation, and the models vary with respect to projections in evapo-transpiration, just as they do with solar radiation. On average, evapo-transpiration will be within 5% of present levels, higher or lower depending upon the particular GCM one is using.

SOIL MOISTURE

Soil moisture may be an important variable affecting crop growth, along with the distribution of precipitation and the depth of the soil. The GCMs used in this study do not project changes in soil moisture, since this factor is determined not only by precipitation, but by runoff, percolation, evaporation and rainfall distribution. Any attempt at estimating soil moisture at the broad spatial level used by the GCMs would invariably yield erroneous results, and hence projections are not included here.

It is important, however, to note that precipitation is expected to increase according to all the models. Depending on the intensity of rainfall, this may also increase soil erosion, and have the effect of reducing agricultural productivity.

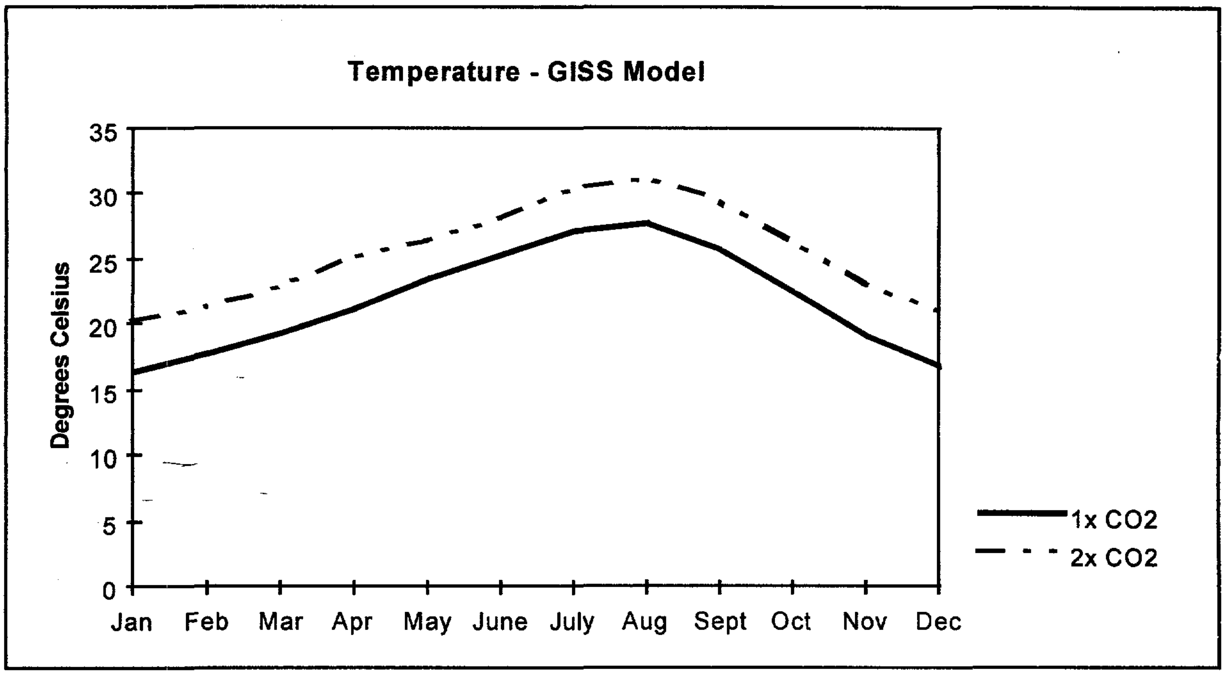
CONCLUSION

The information presented above indicates that the continued emission of trace gases into the earth's atmosphere will likely result in increases in both temperature and precipitation for India. While there will be significant spatial variation in the expected increases, data are presented for the country as a whole. Micro-scale modeling of climate systems is not advanced enough to make reasonable projections at a local scale, and the general projections must suffice. However, for the purposes of this study, the country was arbitrarily divided into "north" and "south" to determine whether there was a significant difference in the projections in these two regions. The results are presented graphically in the Appendix.

While agricultural yield is a function of many variables, it is relevant to note that temperature and precipitation in India will likely increase under conditions of global warming, while solar radiation and evapo-transpiration likely will not change appreciably (or, at least, the models are inconsistent in their projections of these variables). Changes in soil moisture are unknown, since it depends on other factors besides the ones projected by the models, including runoff, soil depth and percolation.

Figure 3.9: Changes in temperature and precipitation between a 1 x CO2 and a 2 x CO2 scenario for India, GISS model

a



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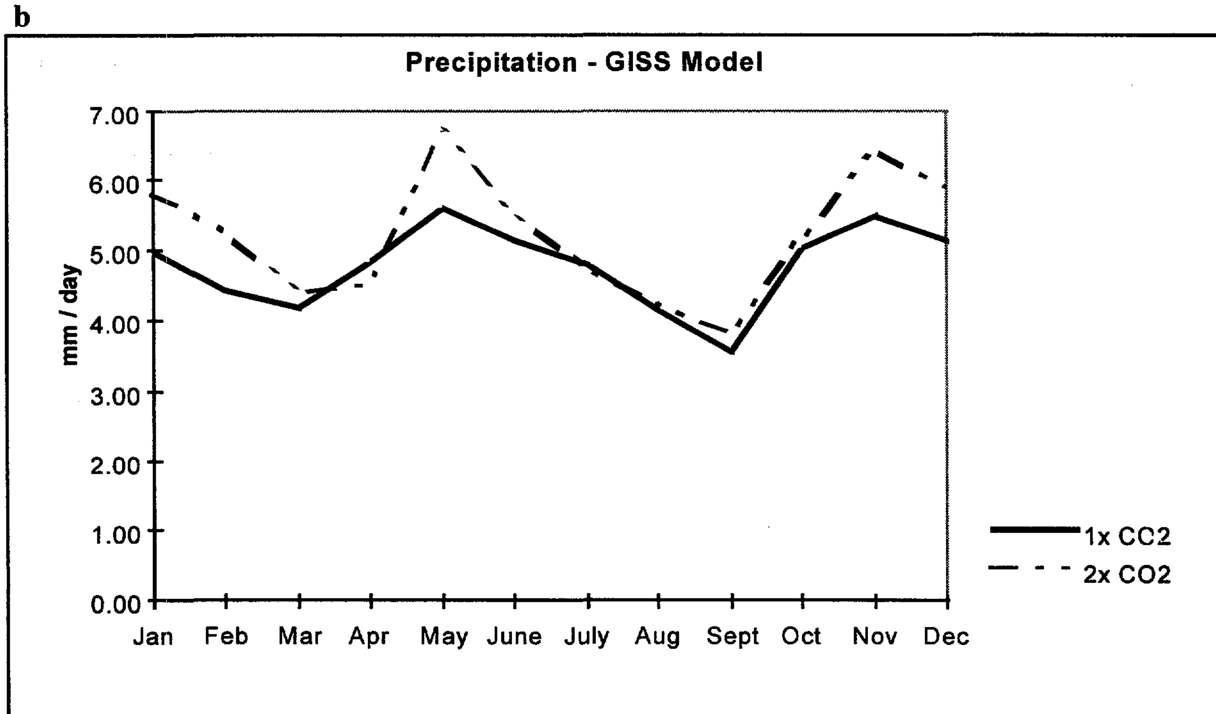
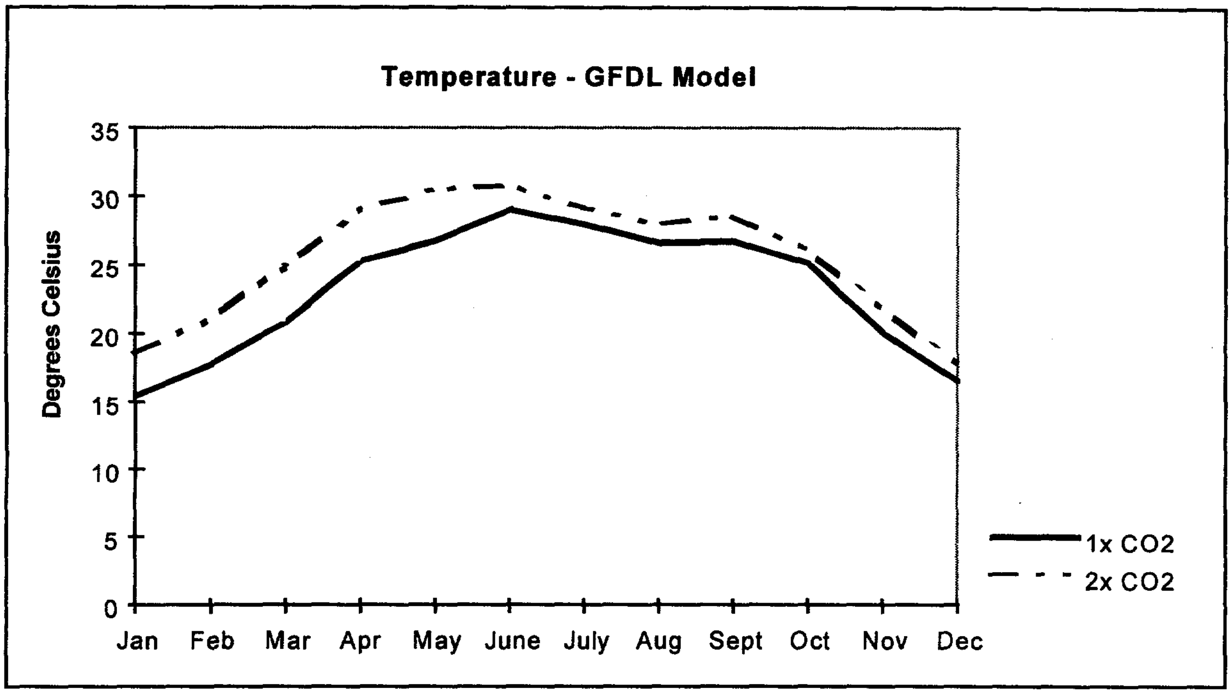


Figure 3.10: Changes in temperature and precipitation between a 1 x CO2 and a 2 x CO2 scenario for India, GFDL model

a



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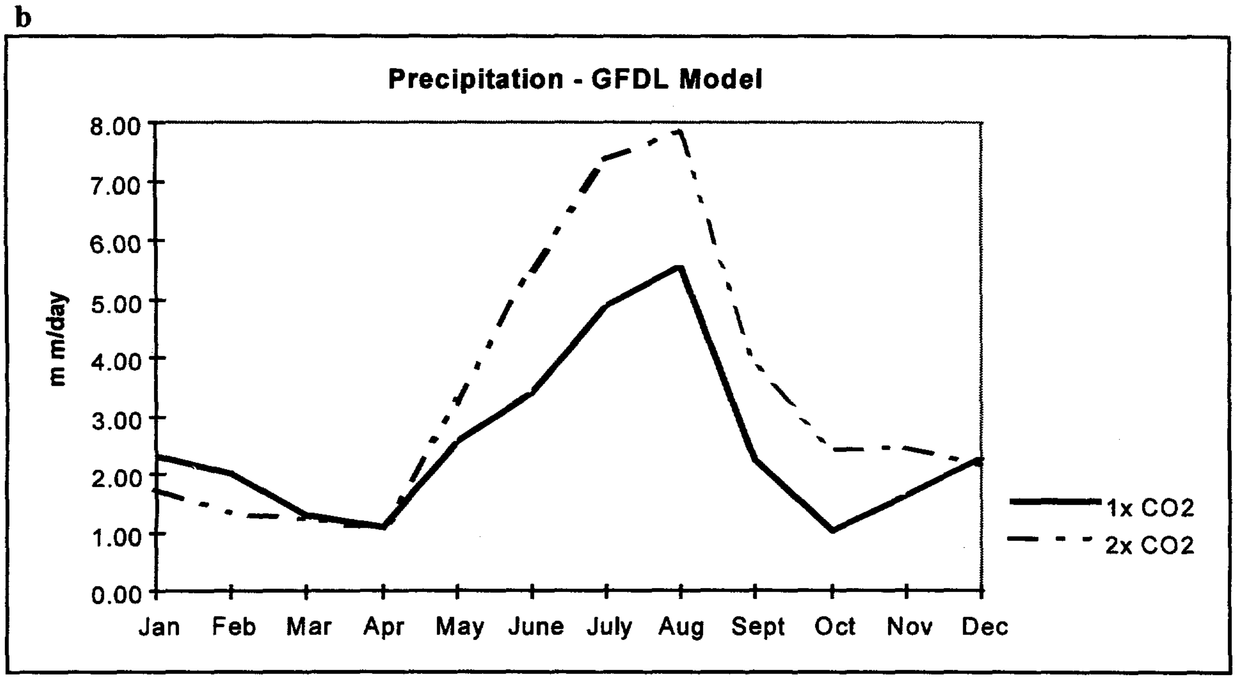
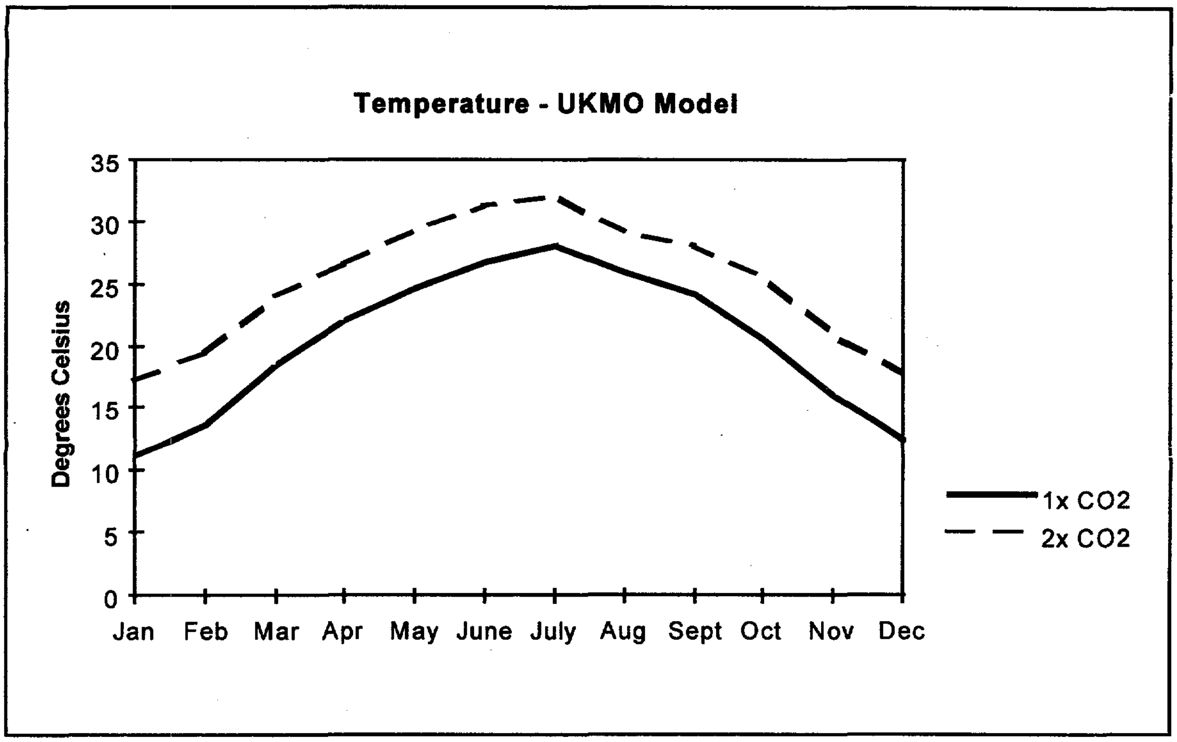


Figure 3.11: Changes in temperature and precipitation between a 1 x CO2 and a 2 x CO2 scenario for India, UKMO model

a



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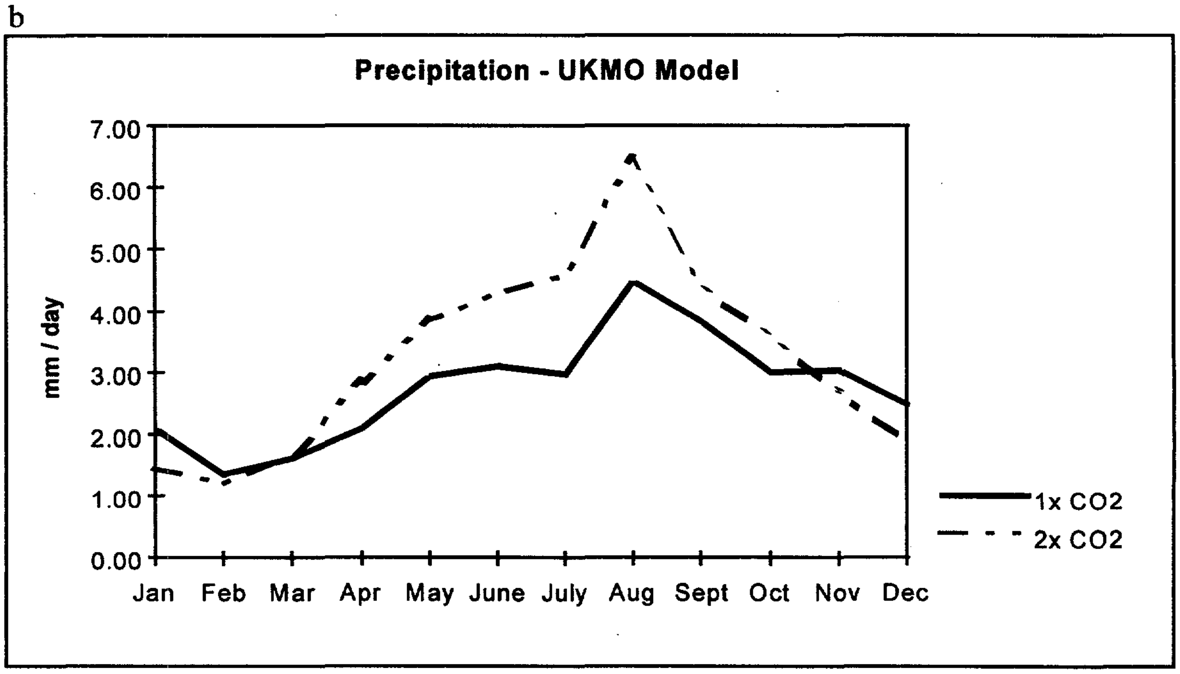


Table 3.2: Temperature and precipitation projections (GISS model)

GISS MODEL	Temperature (C)			Precip (mm/day)			Solar Rad (W/m2)		
	1x CO2	2x CO2	Change	1x CO2	2x CO2	Change	1x CO2	2x CO2	Ratio
Annual Avg	**21.88**	**25.43**	**3.55**	**4.78**	**5.21**	**0.43**	**229.52**	**231.85**	**1.010**
Jan Avg	16.41	20.27	**3.86**	4.97	5.81	**0.84**	150.71	153.71	**1.020**
Feb Avg	17.67	21.31	**3.64**	4.44	5.29	**0.84**	179.86	184.43	**1.025**
Mar Avg	19.23	22.74	**3.51**	4.17	4.37	**0.20**	228.71	227.57	**0.995**
Apr Avg	21.20	25.09	**3.89**	4.84	4.51	**-0.33**	259.71	265.86	**1.024**
May Avg	23.49	26.34	**2.86**	5.60	6.69	**1.09**	273.86	272.86	**0.996**
June Avg	25.30	28.03	**2.73**	5.14	5.53	**0.39**	285.57	284.43	**0.996**
July Avg	27.20	30.36	**3.16**	4.81	4.77	**-0.04**	297.86	294.14	**0.988**
Aug Avg	27.74	31.07	**3.33**	4.14	4.24	**0.10**	290.14	291.86	**1.006**
Sept Avg	25.76	29.54	**3.79**	3.56	3.80	**0.24**	265.43	267.57	**1.008**
Oct Avg	22.53	26.36	**3.83**	5.04	5.19	**0.14**	212.71	219.14	**1.030**
Nov Avg	19.17	23.16	**3.99**	5.49	6.44	**0.96**	164.86	170.00	**1.031**
Dec Avg	16.84	20.90	**4.06**	5.14	5.90	**0.76**	144.86	150.57	**1.039**
1st Quarter (JFM)	17.77	21.44	**3.67**	4.53	5.16	**0.63**	186.43	188.57	**1.011**
2nd Quarter (AMJ)	23.33	26.49	**3.16**	5.20	5.58	**0.38**	273.05	274.38	**1.005**
3rd Quarter (JAS)	26.90	30.32	**3.42**	4.17	4.27	**0.10**	284.48	284.52	**1.000**
4th Quarter (OND)	19.51	23.47	**3.96**	5.22	5.84	**0.62**	174.14	179.90	**1.033**

Table 3.3: Temperature and precipitation projections (GFDL model)

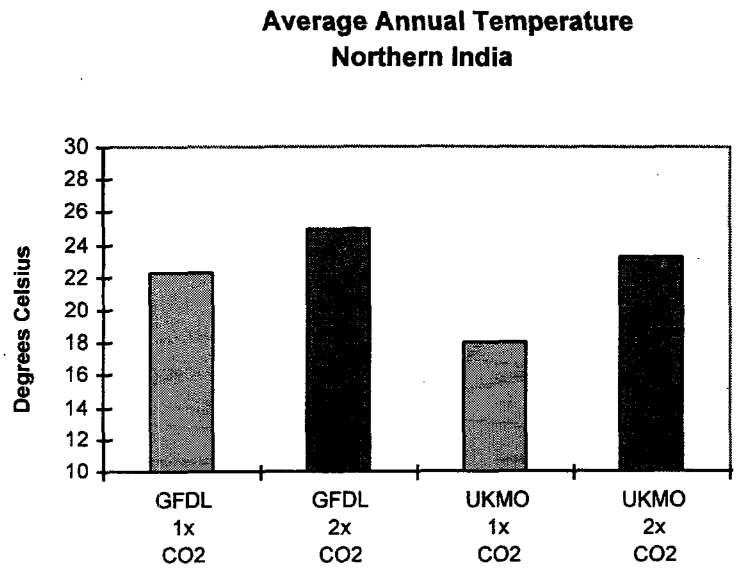
GFDL MODEL									
	Temperature (C)			Precip (mm/day)			Solar Rad (W/m2)		
	1x CO2	2x CO2	Change	1x CO2	2x CO2	Change	1x CO2	2x CO2	Ratio
Annual Avg.	**23.20**	**25.53**	**2.33**	**2.52**	**3.33**	**0.81**	**175.70**	**170.10**	**0.968**
Jan	15.46	18.56	**3.10**	2.32	1.73	**-0.58**	134.75	142.00	**1.054**
Feb	17.81	21.16	**3.35**	1.99	1.33	**-0.66**	160.25	171.92	**1.073**
Mar	20.85	24.82	**3.97**	1.28	1.23	**-0.04**	198.00	200.08	**1.011**
Apr	25.32	28.90	**3.58**	1.08	1.04	**-0.04**	219.33	221.08	**1.008**
May	26.83	30.43	**3.59**	2.54	3.22	**0.68**	208.08	205.67	**0.988**
June	28.93	30.75	**1.83**	3.38	5.48	**2.09**	201.83	183.50	**0.909**
July	27.93	29.05	**1.12**	4.88	7.34	**2.46**	183.17	168.00	**0.917**
Aug	26.63	27.98	**1.35**	5.57	7.82	**2.25**	167.67	157.00	**0.936**
Sept	26.73	28.58	**1.85**	2.23	3.79	**1.56**	181.33	166.08	**0.916**
Oct	25.12	26.21	**1.09**	1.02	2.39	**1.38**	178.08	157.75	**0.886**
Nov	20.20	21.98	**1.78**	1.63	2.43	**0.79**	148.58	138.50	**0.932**
Dec	16.59	17.92	**1.33**	2.28	2.15	**-0.13**	127.33	129.58	**1.018**
1st Quarter (JFM)	18.04	21.51	**3.47**	1.86	1.43	**-0.43**	164.33	171.33	**1.043**
2nd Quarter (AMJ)	27.03	30.03	**3.00**	2.34	3.24	**0.91**	209.75	203.42	**0.970**
3rd Quarter (JAS)	27.10	28.54	**1.44**	4.23	6.32	**2.09**	177.39	163.69	**0.923**
4th Quarter (OND)	20.64	22.03	**1.40**	1.64	2.32	**0.68**	151.33	141.94	**0.938**

Table 3.4: Temperature and precipitation projections (UKMO model)

UKMO MODEL									
	Temperature (C)			*Precip (mm/day)*			*Solar Rad (W/m2)*		
	1x CO2	2x CO2	**Change**	1x CO2	2x CO2	**Change**	1x CO2	2x CO2	**Ratio**
Annual Avg.	**20.31**	**25.10**	**4.78**	**2.75**	**3.24**	**0.49**	**244.34**	**248.62**	**1.017**
Jan Avg	11.17	17.18	**6.02**	2.08	1.45	**-0.63**	180.77	194.46	**1.076**
Feb Avg	13.61	19.42	**5.82**	1.35	1.19	**-0.16**	225.77	235.23	**1.042**
Mar Avg	18.41	23.93	**5.52**	1.62	1.65	**0.04**	258.54	266.54	**1.031**
Apr Avg	21.98	26.52	**4.55**	2.10	2.85	**0.75**	281.77	284.46	**1.010**
May Avg	24.65	29.23	**4.58**	2.95	3.82	**0.88**	297.38	298.77	**1.005**
June Avg	26.72	31.25	**4.53**	3.08	4.29	**1.21**	311.46	304.00	**0.976**
July Avg	28.08	32.04	**3.96**	2.97	4.58	**1.62**	288.00	280.08	**0.972**
Aug Avg	25.90	29.20	**3.30**	4.48	6.45	**1.98**	251.31	249.77	**0.994**
Sept Avg	24.12	27.95	**3.83**	3.83	4.42	**0.59**	258.62	260.08	**1.006**
Oct Avg	20.65	25.63	**4.98**	3.02	3.59	**0.58**	233.23	238.62	**1.023**
Nov Avg	16.01	20.98	**4.98**	3.04	2.69	**-0.35**	180.31	192.15	**1.066**
Dec Avg	12.49	17.84	**5.35**	2.49	1.92	**-0.58**	164.92	179.23	**1.087**
1st Quarter (JFM)	14.39	20.18	**5.78**	1.68	1.43	**-0.25**	221.69	232.08	**1.047**
2nd Quarter (AMJ)	24.45	29.00	**4.55**	2.71	3.66	**0.95**	296.87	295.74	**0.996**
3rd Quarter (JAS)	26.03	29.73	**3.70**	3.76	5.15	**1.39**	265.97	263.31	**0.990**
4th Quarter (OND)	16.38	21.48	**5.10**	2.85	2.73	**-0.12**	192.82	203.33	**1.055**

Appendix: Figures and Tables of Climate Warming, Using a North/South India Breakdown

Figure 3A.1: Annual average temperature and precipitation projections for northern India for two GCMs



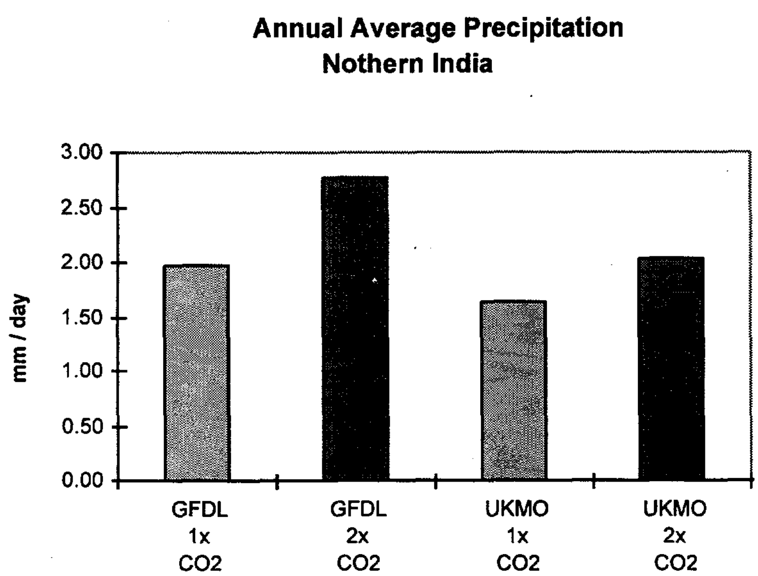
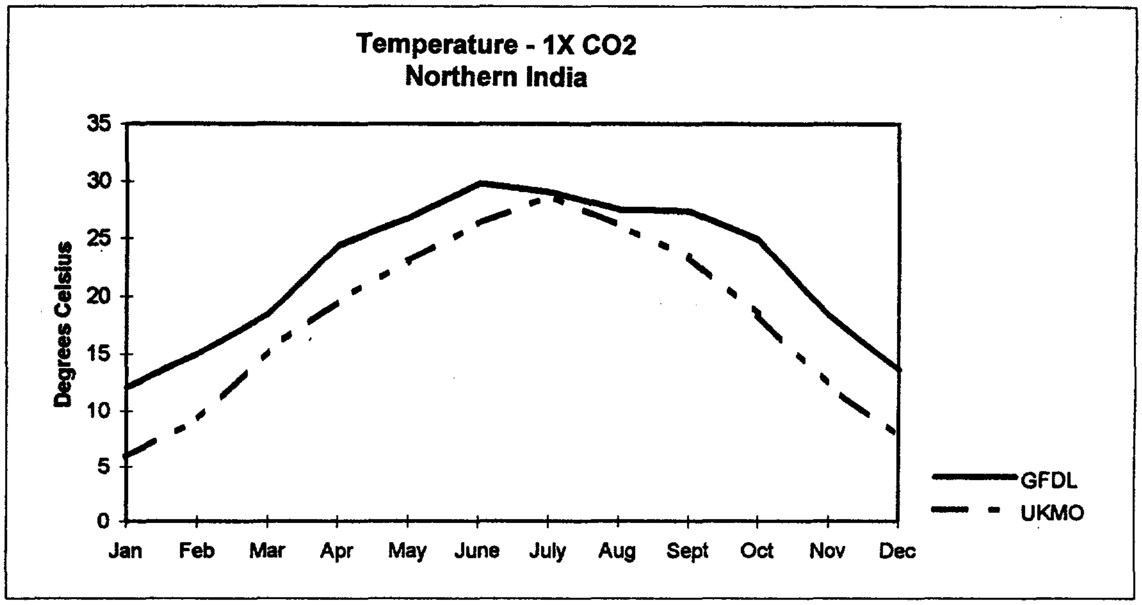


Figure 3A.2: Temperature projections under two scenarios for northern India



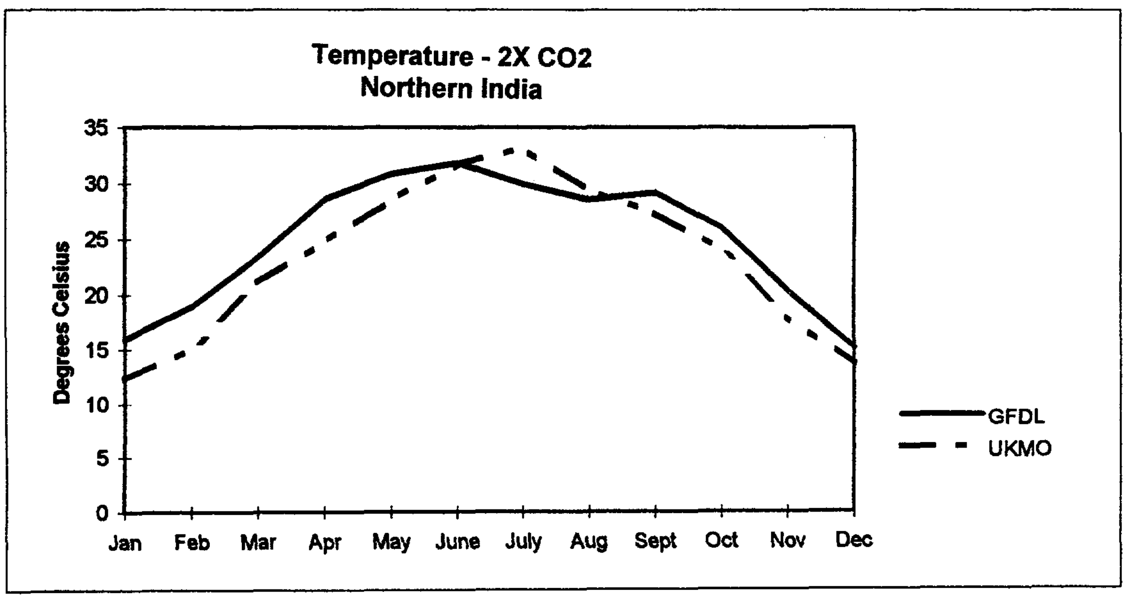
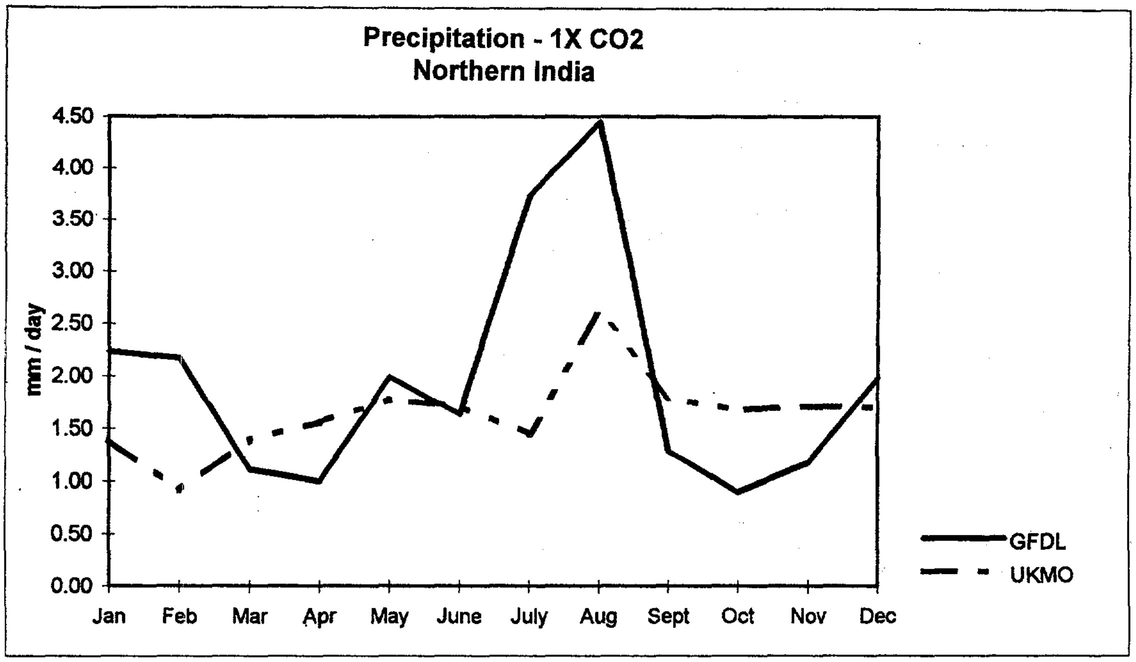


Figure 3A.3: Precipitation projections under two scenarios for northern India



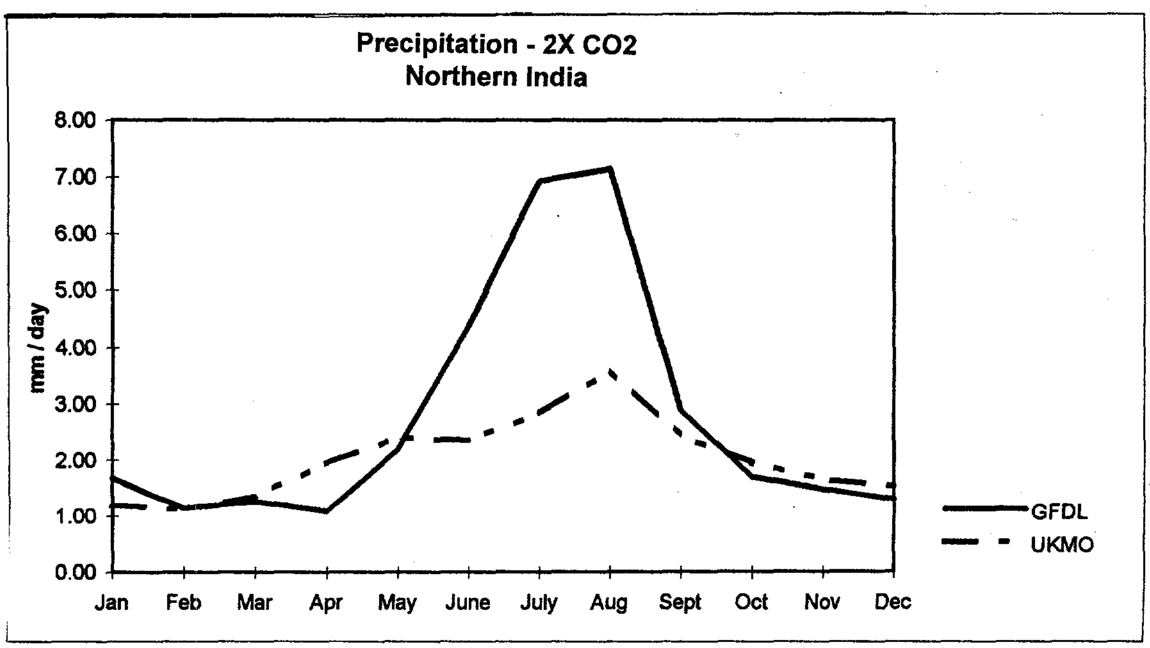
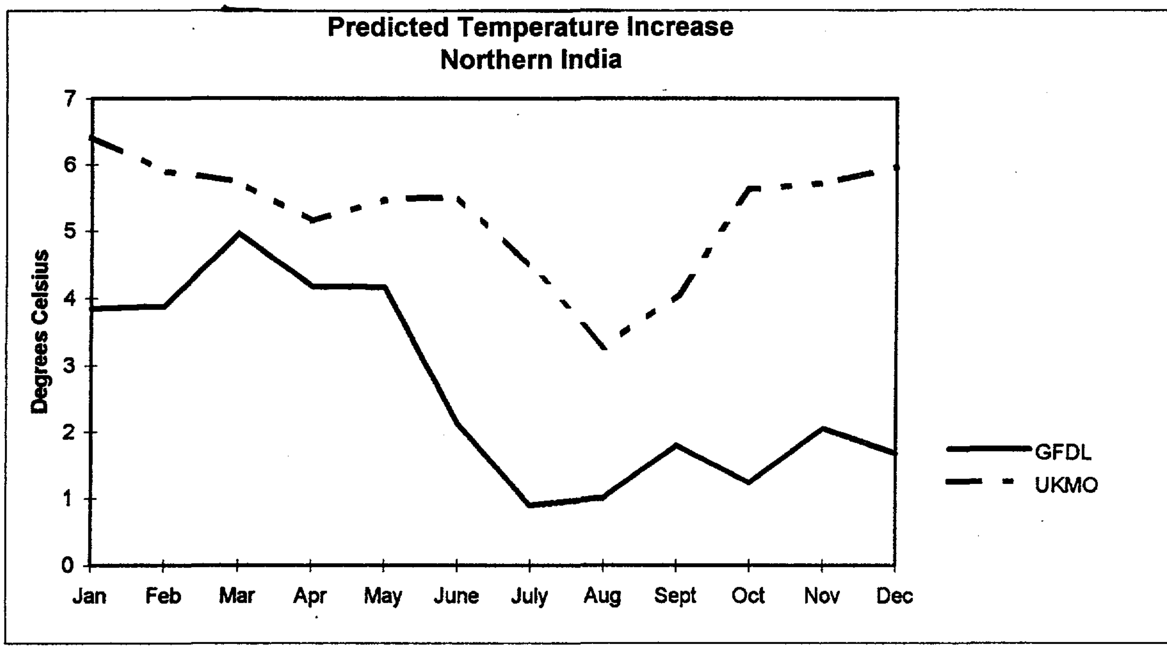


Figure 3A.4: Projected increases in temperature and precipitation under two GCMs, by month, for northern India



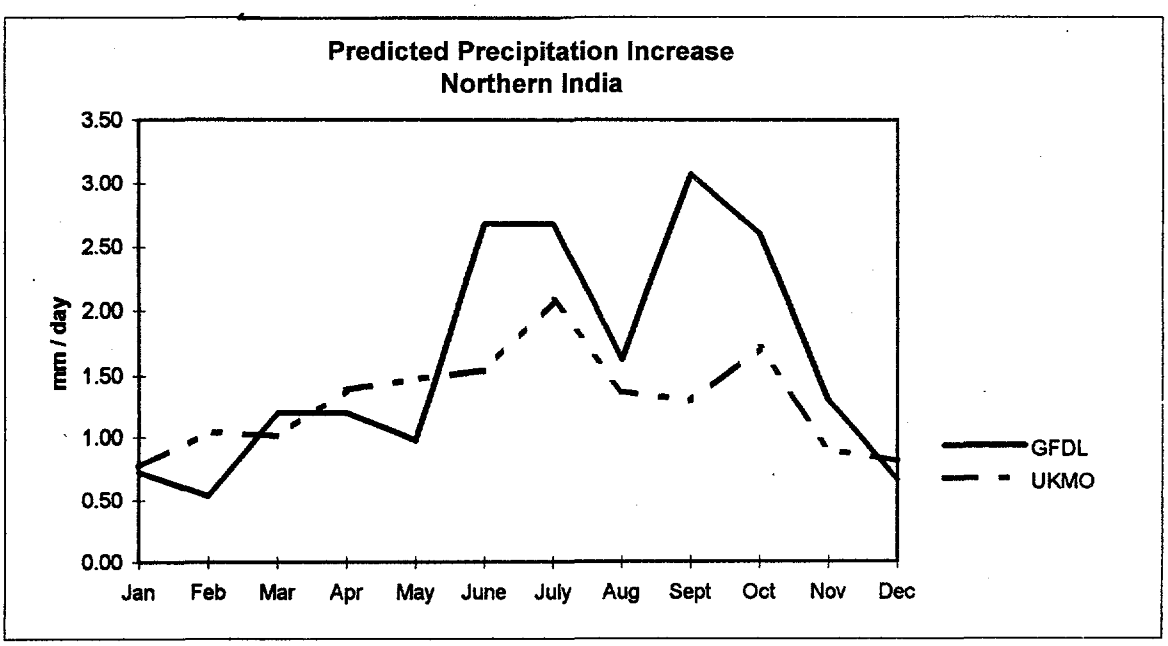
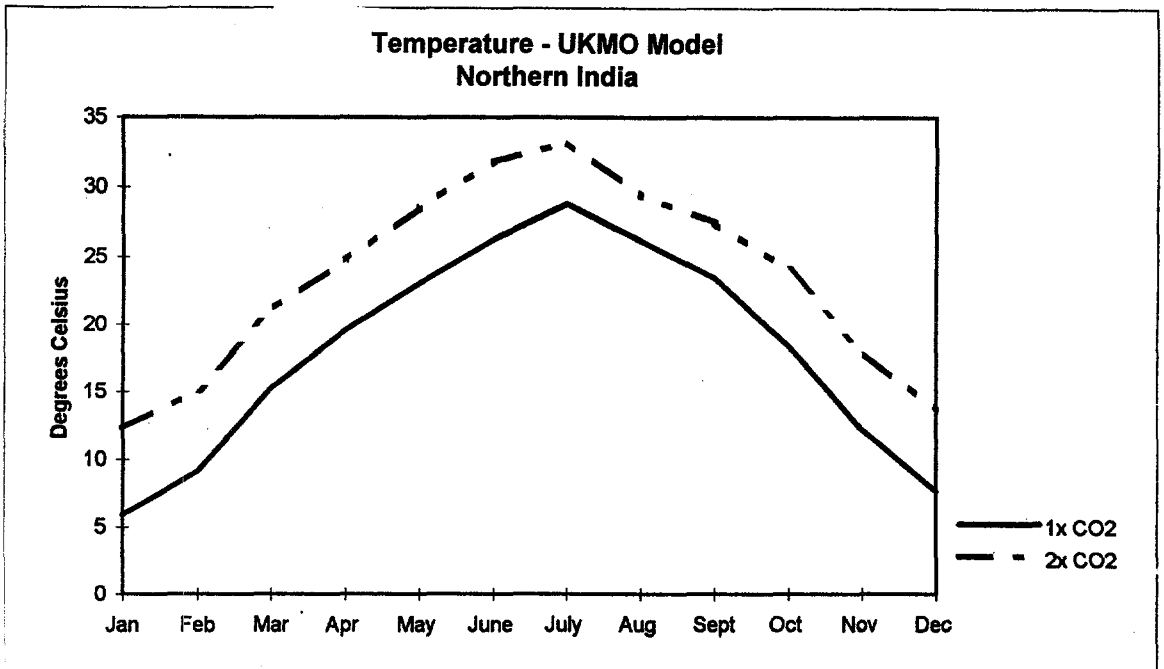


Figure 3A.5: UKMO projections for northern India



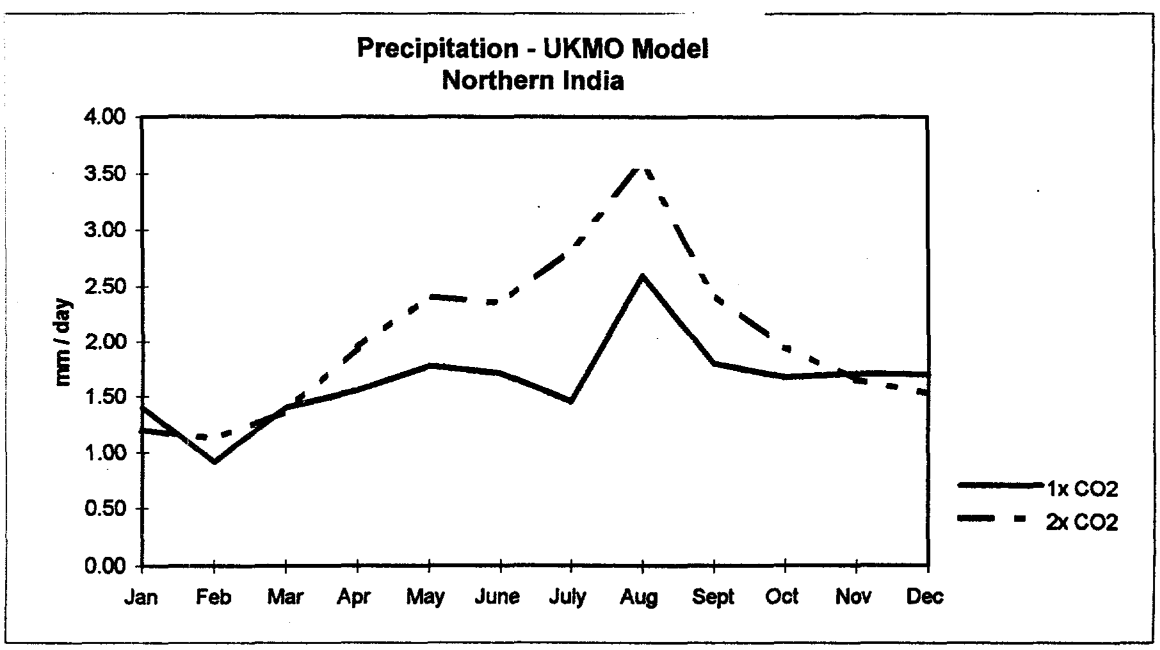
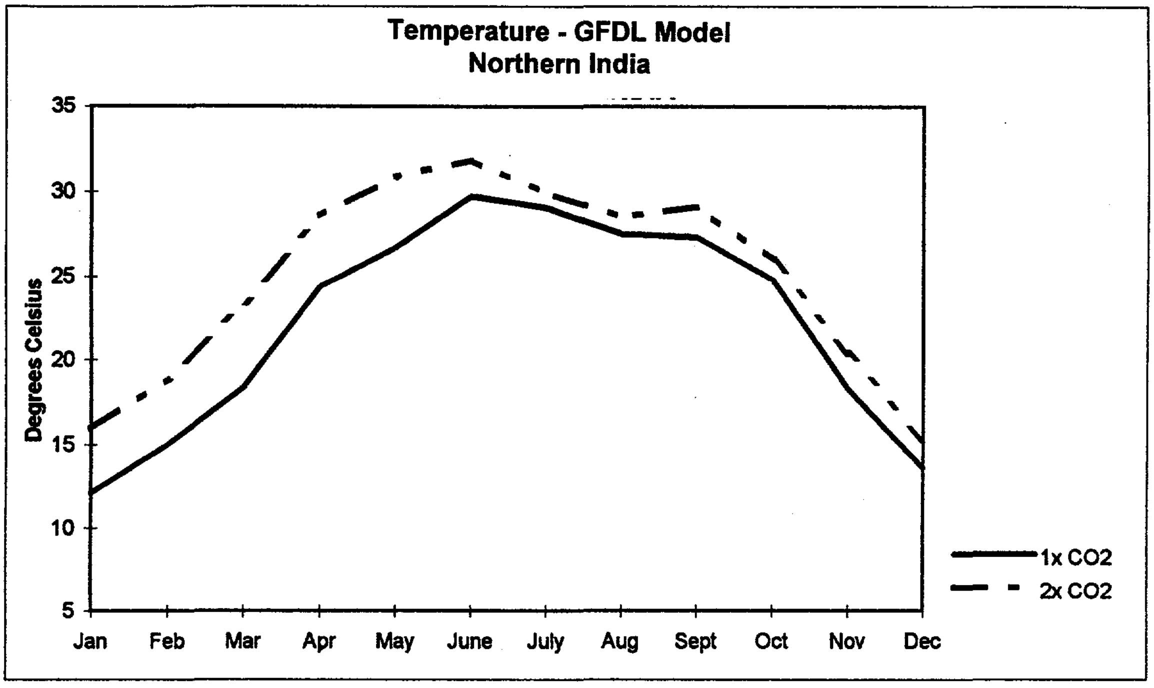


Figure 3A.6: GFDL projections for northern India



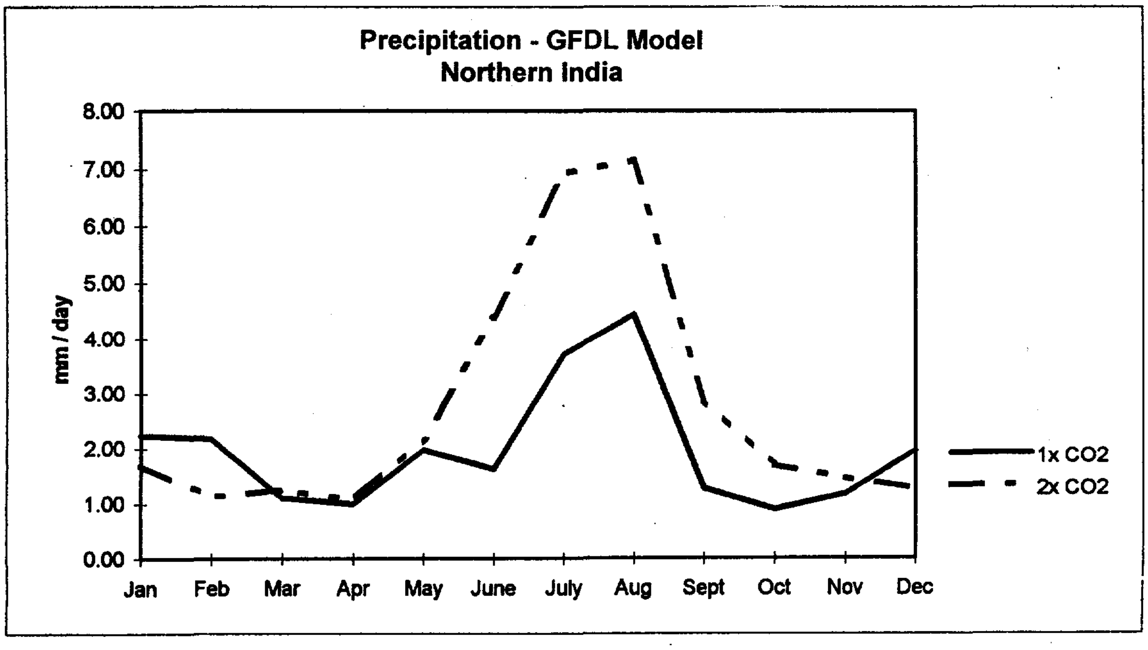


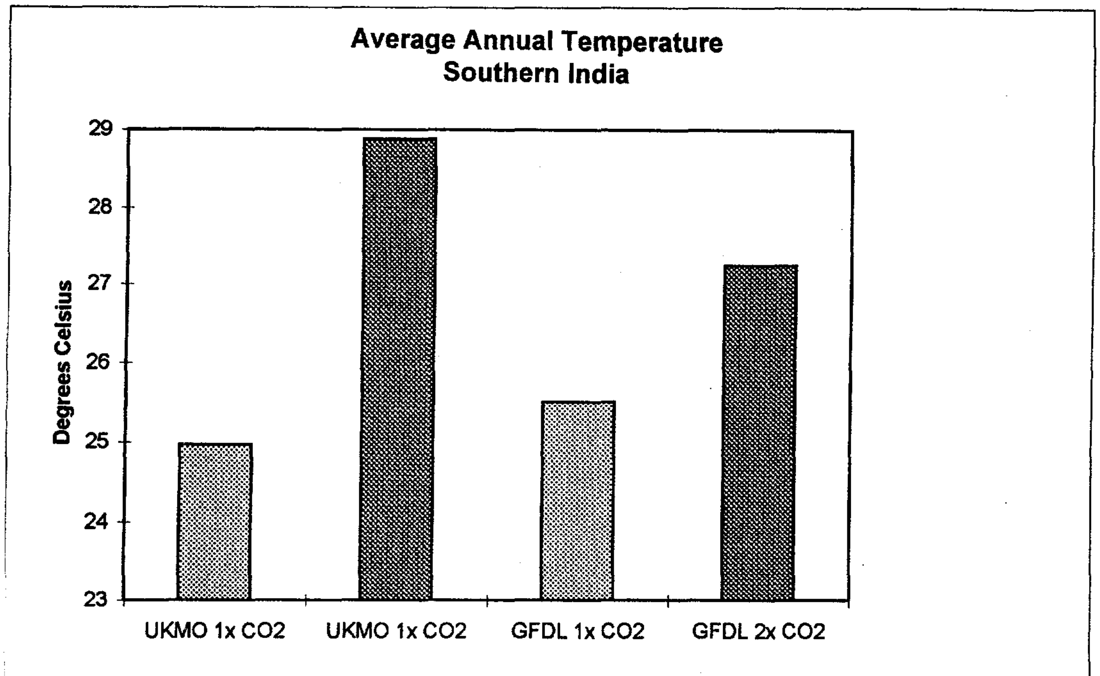
Table 3A.1: UKMO model - northern India

UKMO MODEL - NORTHERN INDIA									
	Temperature (C)			*Precip (mm/day)*			*Solar Rad (W/m2)*		
	1x CO2	2x CO2	Difference	1x CO2	2x CO2	Difference	1x CO2	2x CO2	Ratio
Annual Avg.	**17.98**	**23.25**	**5.28**	**1.64**	**2.03**	**1.28**	**246.76**	**251.02**	**1.036**
Jan Avg	5.90	12.31	**6.42**	1.40	1.20	**0.77**	174.22	185.56	**1.083**
Feb Avg	9.17	15.06	**5.90**	0.92	1.12	**1.04**	219.44	227.11	**1.046**
Mar Avg	15.31	21.06	**5.74**	1.40	1.37	**1.01**	249.11	258.78	**1.072**
Apr Avg	19.57	24.73	**5.15**	1.56	1.94	**1.39**	280.56	287.89	**1.059**
May Avg	23.01	28.48	**5.47**	1.78	2.41	**1.48**	308.56	312.33	**1.022**
June Avg	26.23	31.77	**5.52**	1.71	2.34	**1.54**	329.11	325.44	**0.990**
July Avg	28.71	33.19	**4.45**	1.46	2.83	**2.07**	306.33	297.67	**0.980**
Aug Avg	26.06	29.34	**3.29**	2.60	3.59	**1.38**	267.67	262.44	**0.979**
Sept Avg	23.33	27.38	**4.06**	1.80	2.43	**1.30**	266.33	262.78	**0.994**
Oct Avg	18.38	24.00	**5.63**	1.68	1.94	**1.71**	232.44	237.78	**1.033**
Nov Avg	12.28	18.01	**5.73**	1.71	1.66	**0.90**	172.78	185.22	**1.077**
Dec Avg	7.76	13.73	**5.98**	1.70	1.52	**0.80**	154.56	169.22	**1.077**
1st Quarter (JFM)	10.13	16.14	**6.02**	1.24	1.23	**0.94**	214.26	223.81	**1.067**
2nd Quarter (AMJ)	22.94	28.33	**5.38**	1.68	2.23	**1.47**	306.07	308.56	**1.024**
3rd Quarter (JAS)	26.03	29.97	**3.93**	1.95	2.95	**1.58**	280.11	274.30	**0.984**
4th Quarter (OND)	12.80	18.58	**5.78**	1.70	1.71	**1.14**	186.59	197.41	**1.062**

Table 3A.2: GFDL model northern India

GFDL MODEL - NORTHERN INDIA									
	Temperature (C)			*Precip (mm/day)*			*Solar Rad (W/m2)*		
	1x CO2	2x CO2	Difference	1x CO2	2x CO2	Difference	1x CO2	2x CO2	Ratio
Annual Avg.	**22.25**	**24.91**	**2.65**	**1.97**	**2.76**	**1.60**	**171.99**	**166.13**	**0.976**
Jan	12.13	15.98	**3.84**	2.24	1.69	**0.73**	121.50	127.50	**1.046**
Feb	15.00	18.89	**3.88**	2.18	1.14	**0.53**	144.25	156.75	**1.094**
Mar	18.39	23.35	**4.96**	1.11	1.26	**1.20**	187.63	185.25	**0.989**
Apr	24.40	28.59	**4.18**	1.00	1.09	**1.20**	209.25	210.00	**1.005**
May	26.74	30.89	**4.16**	1.99	2.19	**0.98**	208.25	205.25	**0.984**
June	29.75	31.88	**2.13**	1.64	4.39	**2.68**	214.00	193.13	**0.901**
July	29.05	29.94	**0.90**	3.73	6.94	**2.68**	192.38	173.25	**0.900**
Aug	27.53	28.54	**1.01**	4.45	7.15	**1.62**	176.13	160.13	**0.914**
Sept	27.35	29.15	**1.80**	1.29	2.89	**3.08**	187.13	168.25	**0.900**
Oct	24.81	26.05	**1.23**	0.90	1.70	**2.60**	168.38	154.88	**0.923**
Nov	18.31	20.38	**2.06**	1.18	1.48	**1.30**	139.25	133.63	**0.964**
Dec	13.58	15.26	**1.68**	1.98	1.28	**0.66**	115.75	125.50	**1.095**
1st Quarter (JFM)	15.17	19.40	**4.23**	1.84	1.36	**0.82**	151.13	156.50	**1.043**
2nd Quarter (AMJ)	26.96	30.45	**3.49**	1.54	2.55	**1.62**	210.50	202.79	**0.963**
3rd Quarter (JAS)	27.98	29.21	**1.24**	3.15	5.66	**2.46**	185.21	167.21	**0.905**
4th Quarter (OND)	18.90	20.56	**1.66**	1.35	1.48	**1.52**	141.13	138.00	**0.994**

Figure 3A.7: Annual average temperature and precipitation projections for southern India for two GCMs



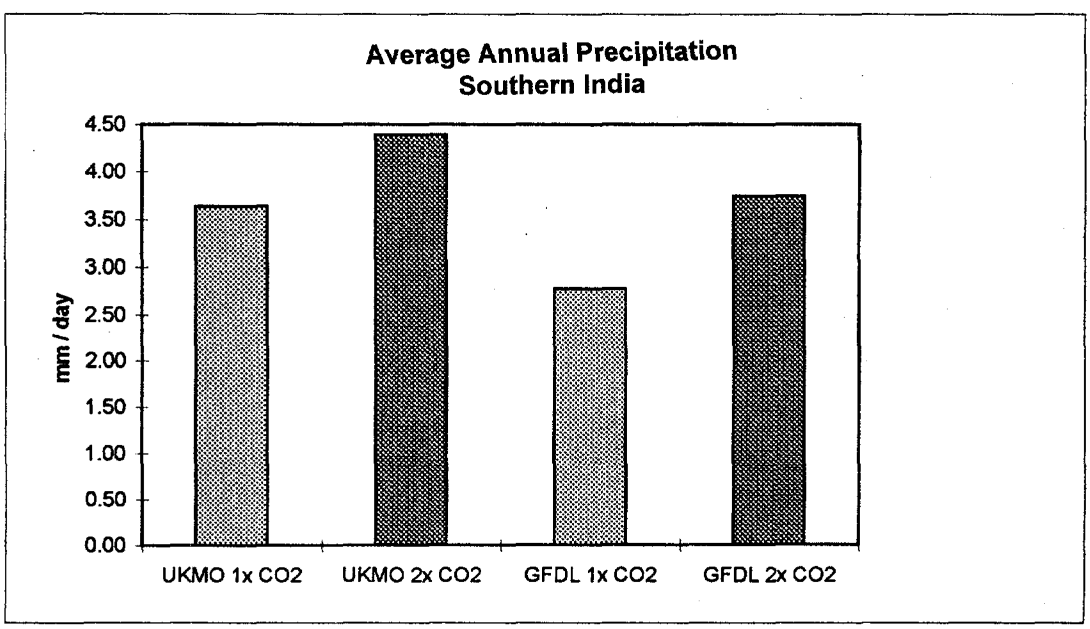
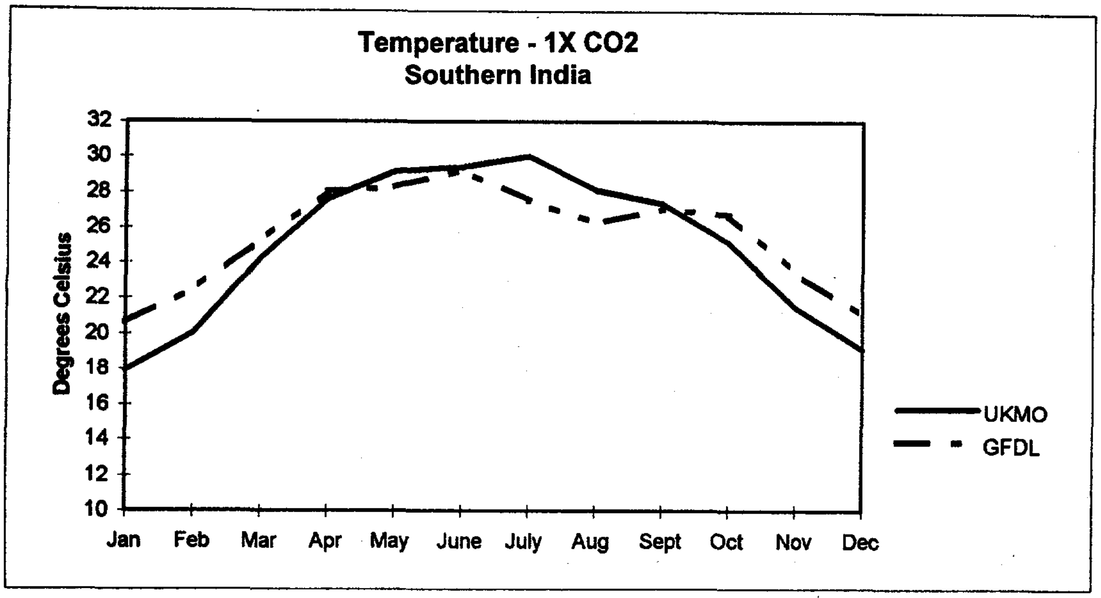


Figure 3A.8: Temperature projections under two scenarios for southern India



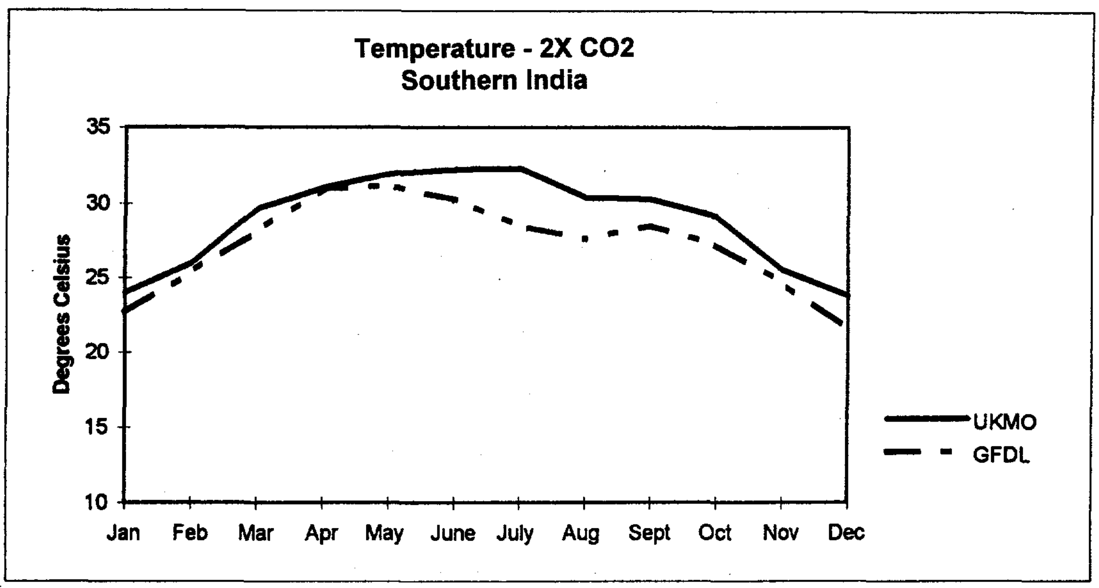
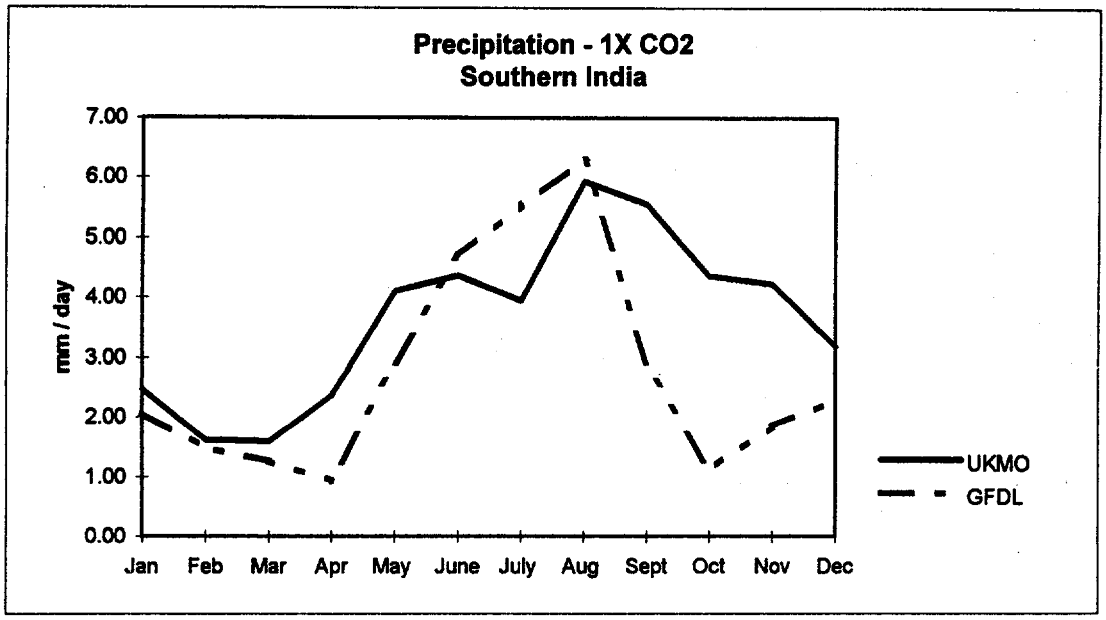


Figure 3A.9: Precipitation projections under two scenarios for southern India



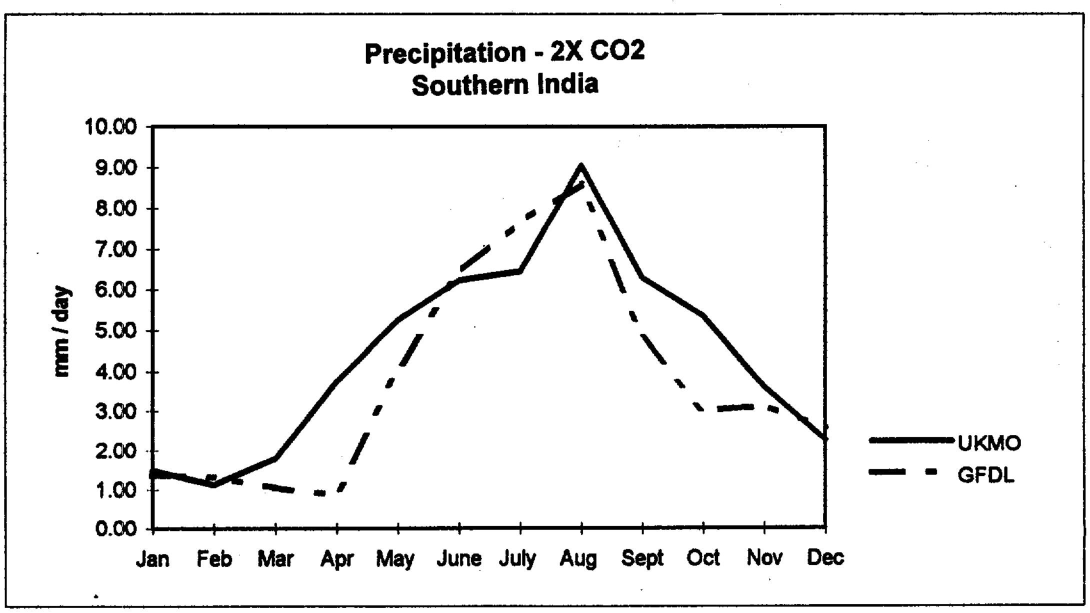
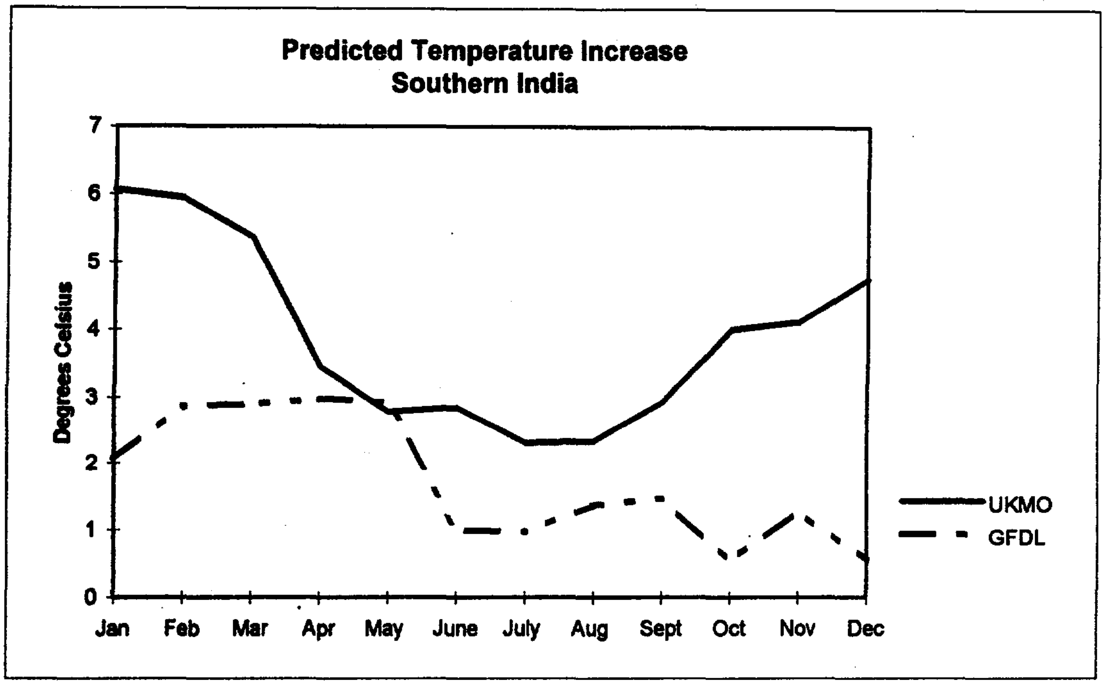


Figure 3A.10: Projected increases in temperature and precipitation under two GCMs, by month, for southern India



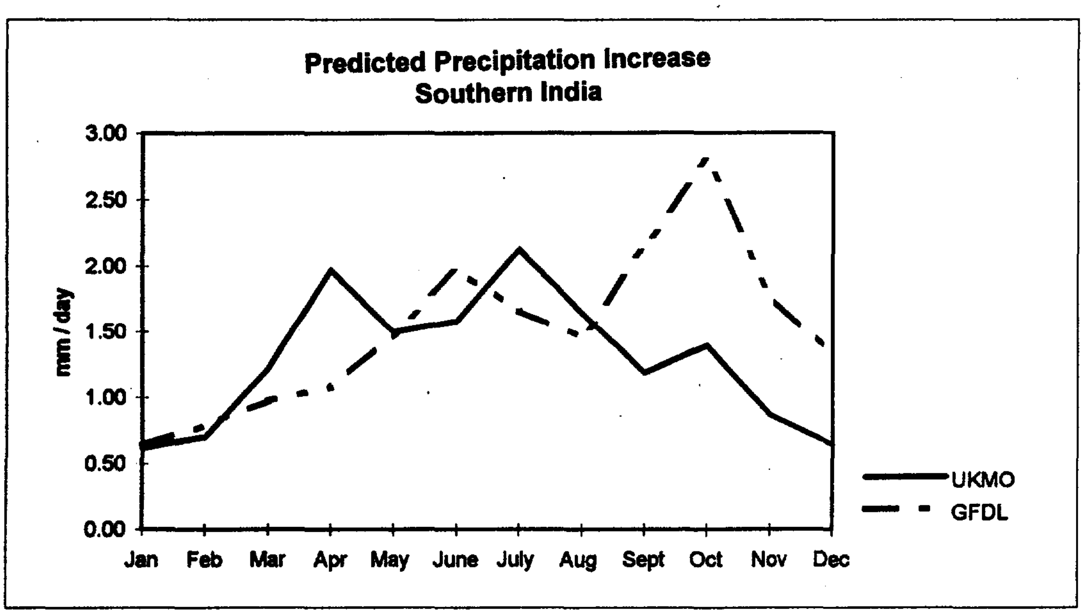
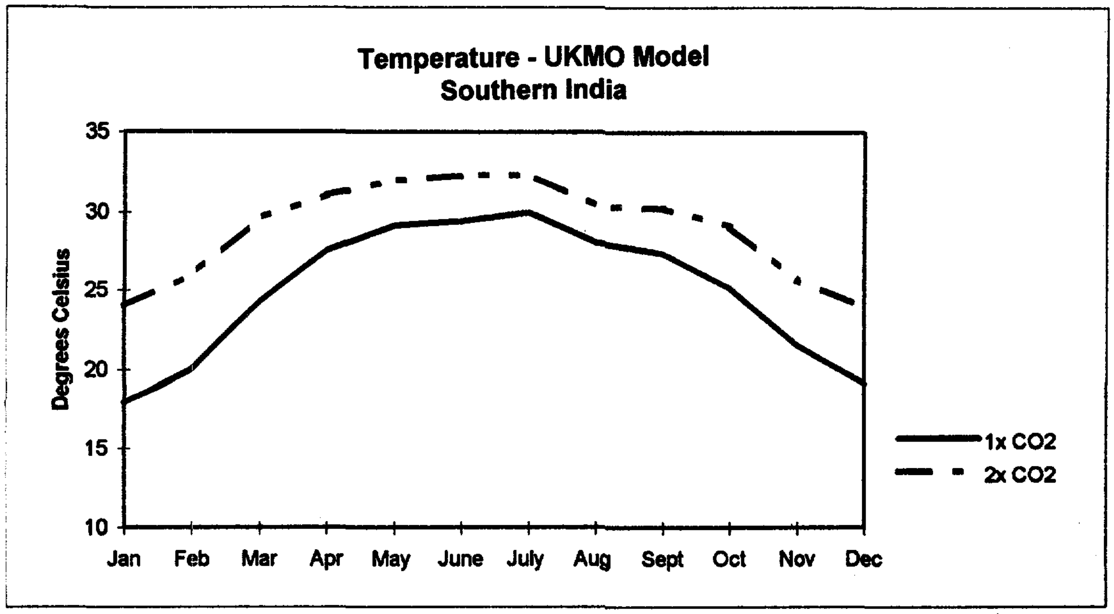


Figure 3A.11: UKMO projections for southern India



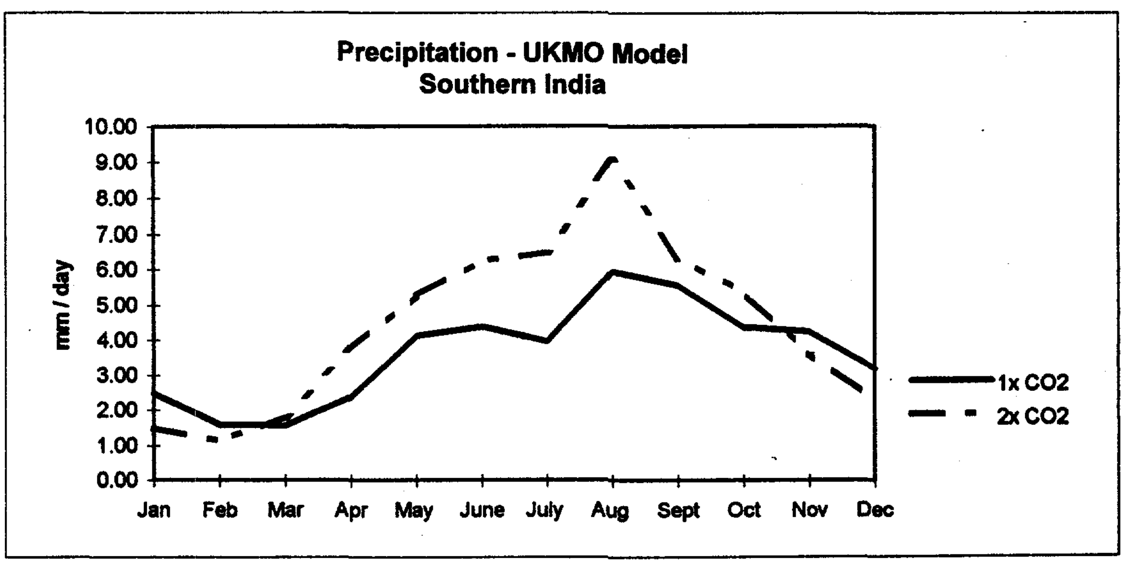
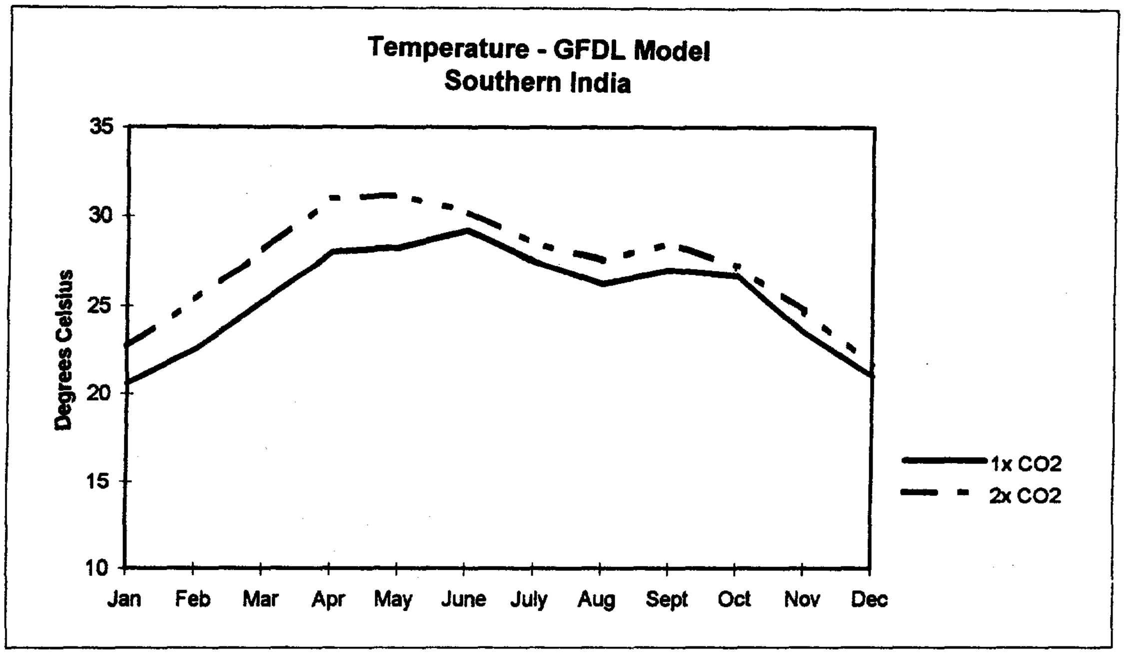


Figure 3A.12: GFDL projections for southern India



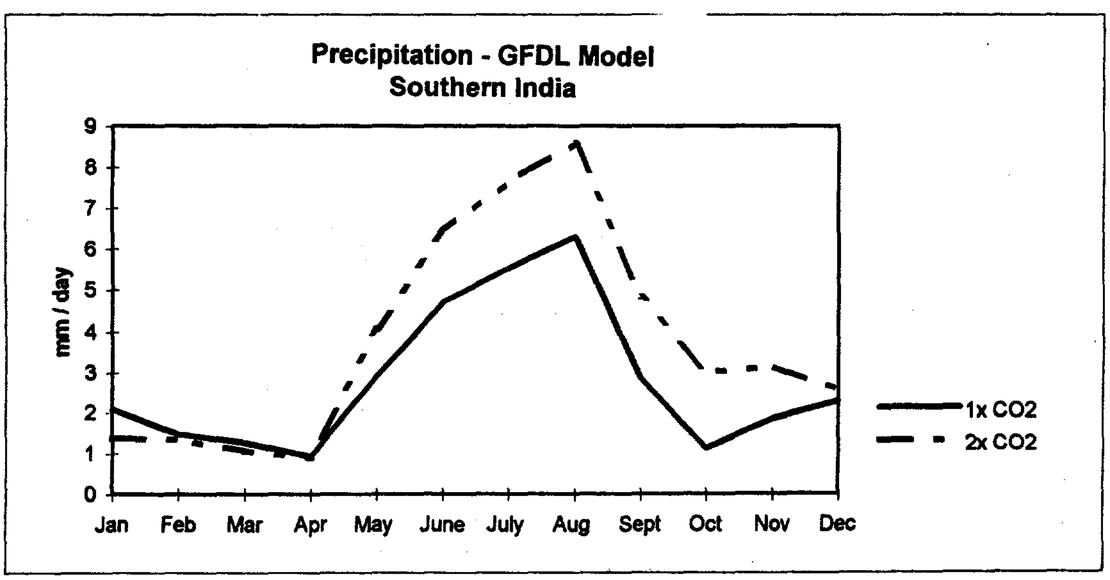


Table 3A.3: UKMO model - southern India

UKMO MODEL - SOUTHERN INDIA									
	Temperature (C)			*Precip (mm/day)*			*Solar Rad (W/m2)*		
	1x CO2	2x CO2	Difference	1x CO2	2x CO2	Difference	1x CO2	2x CO2	Ratio
Annual Avg.	**24.96**	**28.88**	**3.91**	**3.63**	**4.39**	**1.29**	**250.44**	**250.91**	**1.013**
Jan Avg	17.94	23.99	**6.07**	2.46	1.49	**0.62**	196.00	209.13	**1.073**
Feb Avg	20.04	25.98	**5.95**	1.61	1.14	**0.70**	242.63	252.38	**1.043**
Mar Avg	24.26	29.64	**5.36**	1.58	1.80	**1.22**	284.75	286.50	**1.006**
Apr Avg	27.58	31.03	**3.45**	2.36	3.75	**1.97**	298.88	289.75	**0.970**
May Avg	29.15	31.95	**2.78**	4.10	5.26	**1.50**	293.75	289.00	**0.990**
June Avg	29.40	32.25	**2.84**	4.36	6.24	**1.59**	295.25	280.13	**0.950**
July Avg	30.00	32.33	**2.31**	3.94	6.46	**2.13**	283.25	260.25	**0.930**
Aug Avg	28.10	30.43	**2.34**	5.93	9.05	**1.64**	247.38	244.25	**0.995**
Sept Avg	27.35	30.28	**2.93**	5.54	6.30	**1.19**	259.75	263.88	**1.021**
Oct Avg	25.11	29.14	**4.02**	4.35	5.36	**1.40**	236.75	240.75	**1.016**
Nov Avg	21.50	25.65	**4.14**	4.21	3.61	**0.87**	189.88	202.38	**1.069**
Dec Avg	19.15	23.93	**4.77**	3.18	2.26	**0.64**	177.00	192.50	**1.093**
1st Quarter (JFM)	20.75	26.53	**5.79**	1.88	1.48	**0.85**	241.13	249.33	**1.040**
2nd Quarter (AMJ)	28.71	31.74	**3.02**	3.61	5.08	**1.69**	295.96	286.29	**0.970**
3rd Quarter (JAS)	28.48	31.01	**2.53**	5.13	7.27	**1.65**	263.46	256.13	**0.982**
4th Quarter (OND)	21.92	26.24	**4.31**	3.91	3.75	**0.97**	201.21	211.88	**1.059**

Table 3A.4: FGDL model - southern India

GFDL MODEL - SOUTHERN INDIA									
	Temperature (C)			*Precip (mm/day)*			*Solar Rad (W/m2)*		
	1x CO2	2x CO2	**Difference**	1x CO2	2x CO2	**Difference**	1x CO2	2x CO2	**Ratio**
Annual Avg.	**25.50**	**27.25**	**1.74**	**2.77**	**3.75**	**1.51**	**186.61**	**179.04**	**0.963**
Jan	20.59	22.64	**2.07**	2.07	1.39	**0.63**	156.57	166.14	**1.069**
Feb	22.50	25.37	**2.87**	1.47	1.33	**0.79**	185.29	193.71	**1.043**
Mar	25.29	28.17	**2.89**	1.26	1.06	**0.98**	216.00	221.86	**1.031**
Apr	28.01	30.99	**2.98**	0.93	0.89	**1.08**	235.57	237.14	**1.004**
May	28.29	31.16	**2.91**	2.91	4.07	**1.48**	214.00	210.71	**0.987**
June	29.23	30.24	**0.99**	4.70	6.44	**1.98**	197.86	177.14	**0.911**
July	27.51	28.50	**0.97**	5.53	7.67	**1.66**	179.14	162.86	**0.921**
Aug	26.24	27.61	**1.37**	6.30	8.60	**1.46**	163.71	152.29	**0.936**
Sept	27.06	28.53	**1.48**	2.86	4.81	**2.15**	183.71	166.71	**0.916**
Oct	26.73	27.27	**0.53**	1.11	3.00	**2.80**	194.14	167.00	**0.861**
Nov	23.51	24.79	**1.28**	1.84	3.13	**1.77**	165.86	149.14	**0.897**
Dec	21.10	21.67	**0.56**	2.27	2.56	**1.32**	147.43	149.14	**0.983**
1st Quarter (JFM)	22.79	25.40	**2.61**	1.60	1.26	**0.80**	185.95	193.90	**1.048**
2nd Quarter (AMJ)	28.51	30.80	**2.29**	2.85	3.80	**1.51**	215.81	208.33	**0.968**
3rd Quarter (JAS)	26.94	28.21	**1.27**	4.90	7.03	**1.76**	175.52	160.62	**0.924**
4th Quarter (OND)	23.78	24.58	**0.79**	1.74	2.90	**1.96**	169.14	155.10	**0.914**

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4 THE CLIMATE SENSITIVITY OF INDIAN AGRICULTURE

Apurva Sanghi, Robert Mendelsohn and Ariel Dinar

INTRODUCTION

CLIMATE CHANGE AND AGRICULTURE

Since recognition of the potential for future climate change (IPCC, 1990), efforts have been underway to estimate the economic impact of projected changes in climate on important sectors such as agriculture. Most impact studies have focused on agriculture in the developed world (Callway et al., 1982; Adams et al., 1988, U.S. EPA, 1989, Easterling et al., 1993; Adams et al., 1996). Few of these studies, however, fully account for farmer-adaptation to changing climates. Some studies do allow changes in fertilizer application, irrigation, or cultivars, but adaptation is limited at best. A recent study looks at farmer-adapted responses to climate change in the agricultural sector as a whole in the United States (Mendelsohn et al., 1994).

Given the inherent global nature of the problem, it is essential to discern the impact of climate change on agriculture in developing countries as well. This is especially important for countries where agriculture is a key component of GDP, and which lie in tropical and sub-tropical zones likely to be adversely affected by climate change (IPCC, 1990b; NAS, 1992). Two such developing countries are Brazil and India, with large land masses, differing climate zones, and varying cropping patterns. Agriculture constituted 30% of 1994 Indian GNP, and 10% of 1994 Brazilian GNP (World Bank, 1996).

This paper provides the first detailed estimates of the impact of potential climate change on the agricultural sector in India.[1] The analysis computes the impacts of changes in temperature and precipitation on agricultural net revenue per cropped hectare. We utilize district-level agricultural, climate, and edaphic data for 271 districts, for the period 1966-1986, to examine farmer-adapted responses to climate variations across the country. A wide variety of crops, including cereals, pulses, oilseeds, fibre crops, and other non-food grain crops such as sugarcane and tobacco, are considered.

TWO APPROACHES

Two distinct approaches have emerged in the literature to estimate the impact of climate change on agricultural activity: the traditional "Production Function" approach and, more recently, the "Ricardian" approach. The production function approach takes an underlying production function and varies the relevant environmental input variables to estimate the impact of these inputs on production yield (Callway et al., 1982; Decker et al., 1986; Adams et al., 1988,

[1] A recent study does examine the impact of climate change on agriculture in both developed and developing countries (Rosenzweig and Parry, 1993). However, the focus is primarily on food grains. Tropical and sub-tropical crops that may benefit from warming are not studied. This exclusion of less heat-sensitive, warmer weather crops will tend to overstate damages.

1990; Adams, 1989; Rind et al., 1990; Rosenzweig and Parry, 1993). The production function approach is attractive in its close collaboration with agronomic science. However, although this approach isolates the impact of environmental change, it does not fully account for the myriad of adaptations that farmers may make in response to varying environmental conditions. Thus, the traditional production function approach may have an inherent bias in that it tends to overestimate the damage from climate change by failing to incorporate economic substitutions by farmers as environmental conditions change.

The Ricardian approach, instead of looking at the yields of specific crops, examines how climate in different places affects the *net rent* or *value* of farmland, (Mendelsohn et al., 1994). This approach takes into account both the direct impacts of climate on yields of different crops as well as the indirect substitution to other activities, introduction of new land uses, and other potential adaptations to different climates.

Part 2 presents the production-function and Ricardian frameworks. Part 3 outlines data sources, definitions, and empirical specifications. Part 4 presents the empirical results and addresses robustness issues. Part 5 analyzes, and interprets in detail, the climate coefficients and the seasonal and regional impacts. Part 6 focuses on implications for potential global warming. Part 7 concludes, and outlines policy implications and future work.

THE ECONOMIC FRAMEWORK

THE PRODUCTION FUNCTION APPROACH

The agronomic production function approach begins with the basic relationship between climate and crop production. Through experiments, agronomists have calibrated models which predict the yield of specific crops depending on weather patterns. These simulation models have historically been used to predict changes in yields for specific crops (Adams et al. 1989, Rosenzweig and Parry 1993). The outcome from these simulations is then incorporated into an economic model of farmer behavior, which in turn leads to a partial equilibrium model of the farm sector. The production function approach is closely linked to agronomic science and hydrological conditions. It is also the only current method capable of including carbon dioxide fertilization (provided appropriate agronomic models) in the analysis.[2]

The production function model is a structural model which predicts two basic phenomenon: yields (Q_i) and crop shares (H_i). Based on previous research (e.g., Rosenzweig and Iglesias 1994) the yield per hectare of each crop is likely to be a function of climate, soils, and other inputs.

For a set of well-behaved production functions,

$$(3)\ Q_i = Q_i\,(\mathbf{K}_i, \mathbf{E}), \qquad i = 1,..,n$$

[2] Higher concentrations of CO_2 in the atmosphere will spur plant growth as carbon is a plant nutrient (Kimball, 1982, Strain and Cure, 1985, Wittwer, 1986). IPCC states that "...studies carried out on small-scale experimental stands of vegetation, under optimal conditions of water and nutrient supply, suggest potential increases in photosynthesis of 20% to 40% when CO_2 is doubled" (IPCC, 1994, p.18).

where, $\mathbf{K}_i = [K_{i1},\ldots K_{ij},\ldots K_{iJ}]$ is a vector of all purchased inputs in the production of good i; K_{ij} is the purchased input j ($j = 1,\ldots J$) in the production of good i, and $\mathbf{E}=[E_1,\ldots E_m,\ldots E_M]$ is a vector of exogenous environmental inputs such as temperature, precipitation, and soils which is common to a production site.

By comparing the yields in different locations, one can estimate the actual response of yields to climate:

$$(4) \qquad Q_i = \hat{Q}_i(\mathbf{K}_i, \mathbf{E}) + u_{1i}$$

where $\hat{Q}_i$ is the predicted yield for crop i, and u_{1i} an error term.

The mix or the frequency of any crop being planted is the result of the relative profitability of each crop and aggregate constraints such as water availability. The share of a given crop can be modeled as:

$$(5) \qquad H_i = H_i(\mathbf{E}, \mathbf{Z}, Q_i) + u_{2i}$$

where u_{2i} is an error term.

The fraction of hectares of each crop (H_i) in an area is expected to be a function of climate, market access ($\mathbf{Z}$), and crop yields per hectare. Because Q_i includes the error terms u_{1i}, the predicted values of Q_i should be used in the crop share model. For a given farm, assuming profit maximizing farmers, the objective is:

$$(6) \qquad \max N = \sum_i H_i \cdot \left(P_i \cdot Q_i - \sum_j w_j \cdot K_{ij} \right)$$

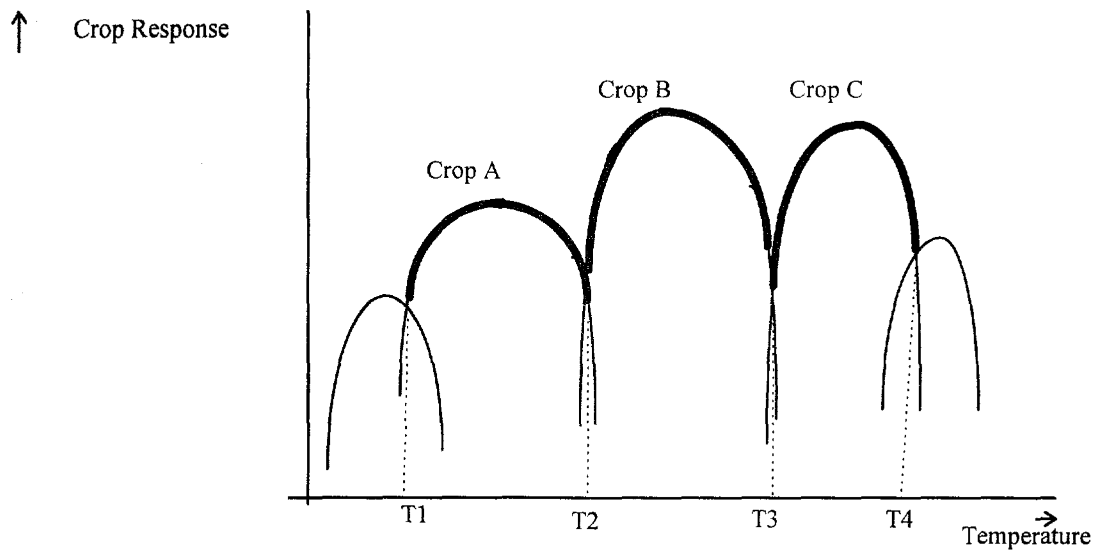
subject to the physical conditions facing the farm (soil, climate, water). Where N is the per unit of land net income as estimated by the empirical production function approach, H_i is the share of crop i, P_i is market price for crop i, K_{ij} is the amount of input j used on crop i, and w_j is the unit cost of input j. Thus, by estimating the profit maximizing level of inputs and yields for each crop, one could predict the net revenue from each crop. Combining this information with the predicted crop mix, one could estimate net revenues per hectare in each region. Aggregating net impacts across locations would then yield an aggregate net impact.

THE RICARDIAN METHODOLOGY

The main drawback of the production function approach is its weakness in modeling the myriad of adjustments that farmers make in response to varying environmental conditions. Farmers are likely to respond to changing climate and other environmental factors by varying, among other things, the crop mix, planting and harvest dates, irrigation scheduling, and application of fertilizers and pesticides, thereby mitigating potential harmful effects of climate change.

Consider Figure 4.1 which plots response of more than one crop against temperature. As the figure demonstrates, the optimum range to grow crop A is [T1-T2]. As temperature increases, farmers will substitute crop A for crop B which prefers warmer temperatures (optimal range [T2-T3]). The same argument carries over to crops B and C: for even hotter temperatures, it will be optimal to switch from crop B to C in the temperature range [T3-T4]. Thus the true sensitivity of crop response to temperature change is the *envelope* (value function) of the individual crop (structural) responses as is depicted by the solid curve in Figure 4.1. Ignoring adaptation would clearly overstate damages.

Figure 4.1: Envelope crop response curves to changes in temperature



Adaptations, however, are costly, and these costs are economic damages. However, since adaptations are voluntary, farmers will choose to undertake them only if they are beneficial. Thus, to fully take into account both the costs and benefits of adaptation, the relevant dependent variable should be *net revenues* or *land values* (capitalized net revenues), and not yields. The Ricardian approach, therefore, measures damages as reductions in net revenues or land values.

Assume a set of well-behaved production functions of the form:

(7) $\quad Q_i = Q_i\,(\mathbf{K}_i\,,\mathbf{E}), \qquad i = 1,..,n$

where, as before, $\mathbf{K}_i = [\ K_{i1},\ldots K_{ij},\ldots K_{iJ}\ ]$ is a vector of all purchased inputs in the production of good i; K_{ij} is the purchased input j (j = 1,...J) in the production of good i, and $\mathbf{E} = [\ E_1,\ldots E_m,\ldots E_M]$ is a vector of exogenous environmental inputs such as temperature, precipitation, and soils which is common to a production site.

Given a set of factor prices w_j for K_j, $\mathbf{E}$, and Q, cost minimization leads to a cost function:

(8) $C_i = C_i(Q_i ,\mathbf{w}, \mathbf{E})$

where C_i is the cost of production of good i and $\mathbf{w} = [w_1,\ldots w_i,\ldots w_J]$ is the vector of factor prices.

Assume a set of utility maximizing consumers with well behaved utility functions and linear budget constraints who take prices as given. This leads to a system of inverse demand functions for outputs i =1,...,n:

(9) $P_i = D^{-1}(Q_1,\ldots Q_i,\ldots,Q_n, Y)$

where P_i and Q_i are respectively the price and quantity of good i and Y is the aggregate income.

Given market prices, profit maximization on a given site yields:

$$(10) \quad \max_{Q_i} \; P_iQ_i - C_{i\text{-}}(Q_i,\mathbf{w},\mathbf{E}) - p_L L_i$$

where p_L is the annual cost or rent of land at that site and $C_{i\text{-}}()$ is the cost function of all purchased inputs other than land. $C_{i\text{-}}()$ is defined as $C_i + p_L L_i$

Perfect competition in the land market will drive profits to zero:

$$(11) \quad P_iQ_i^* - C_{i\text{-}}^*(Q_i^*,\mathbf{w},\mathbf{E}) - p_L L_i^* = 0$$

If use i is the best use for the land given E and R, the observed market rent on the land will be equal to the annual net profits from the production of good i. Solving (5) for p_L gives land rent per hectare to be equal to net revenue per hectare:

$$(12) \quad p_L = [P_iQ_i^* - C_{i\text{-}}^*(Q_i^*,\mathbf{w},\mathbf{E})] / L_i$$

The present value of the stream of current and future revenues gives land value:

$$(13) \quad V_L = \int_0^\infty p_L e^{-rt}dt \int_0^\infty [P_iQ_i - C_{i-}(Q_i,\mathbf{w},\mathbf{E})]e^{-rt} / L_i dt$$

The issue to be analyzed is the impact of exogenous changes in environmental variables on net economic welfare. Consider an environmental change from the environmental state A to B, which leads environmental inputs to change from $\mathbf{E}_A$ to $\mathbf{E}_B$. The change in annual welfare from this environmental change is given by:

$$\Delta W = W(\mathbf{E_B}) - W(\mathbf{E_A}) = \int_0^{Q_B} \Sigma D^{-1}(Q_i)dQ_i - \Sigma C_{i\text{-}}(Q_i, \mathbf{w}, \mathbf{E_A}) - \int_0^{Q_A} \Sigma D^{-1}(Q_i)dQ_i - \Sigma C_{i\text{-}}(Q_i, \mathbf{w}, \mathbf{E_B})$$

If market prices are unchanged as a result of the change in **E**, then the above equation reduces to:

$$(14) \qquad \Delta W = W(\mathbf{E_B}) - W(\mathbf{E_A}) = \mathbf{PQ_B} - \Sigma C_{i\text{-}}(Q_i, \mathbf{w}, \mathbf{E_A}) - [\mathbf{PQ_A} - \Sigma C_{i\text{-}}(Q_i, \mathbf{w}, \mathbf{E_B})]$$

Substituting (12) into (14) gives:

$$(15) \qquad \Delta W = W(\mathbf{E_B}) - W(\mathbf{E_A}) = \sum_i (p_{LB} L_B - p_{LA} L_A)$$

where p_{LA} and L_A are at $\mathbf{E_A}$ and p_{LB} and L_B are at $\mathbf{E_B}$.
The present value of this welfare change is thus:

$$(16) \qquad \int_0^{\infty} \Delta W e^{-rt} dt = \sum_i (V_{LB} L_B - V_{LA} L_A)$$

The Ricardian model takes the form of either (12) or (16) depending on whether the dependent variable is annual net revenues or capitalized net revenues (farm values). The value of the change in the environmental variable is captured exactly by the change in land values across differing environmental conditions. Cross-sectional observations, where normal climate and edaphic factors vary, can hence be utilized to estimate farmer-adapted climate impacts on production and land rents.

Due to imperfect land markets and weak documentation of agricultural farm values in India, in this paper we estimate (12), using annual net revenues as the independent variable (Sanghi, 1997 estimates a version of (16) for Brazil using agricultural farm values as the dependent variable).

The Ricardian approach is most reliable for estimating impacts of small changes in climate because of the assumption of unchanged relative crop prices. If relative prices change as a result of the impact of climate change on aggregate supply, the Ricardian analysis underestimates or overestimates the impacts, depending on whether the supply of that commodity increases or decreases. However, partial equilibrium welfare estimates provide a reasonable approximation of welfare changes estimated from general equilibrium models (Kokoski and Smith, 1987; Mendelsohn et al., 1996). Though not explicitly modeled in this paper, it is reasonable to assume that, due to moderating effects of international trade, aggregate world supply will not change by much. Therefore, the Ricardian estimates provide reliable measures of changes in economic welfare.

Since the analysis makes forecasts based on current farming practices, it does not capture future changes affecting agriculture such as technical change and carbon dioxide fertilization: potentially increased plant growth from higher concentrations of CO_2. Even though a crucial assumption made in CO_2 fertilization is that all other inputs are applied at an optimal level, ignoring CO_2 fertilization may overestimate damages and underestimate gains.

COMBINING THE TWO APPROACHES

In principle, estimates from the Ricardian and production function approaches would yield identical estimates of farm net revenue as a function of climate, from which welfare estimates could be made from simulating different climate outcomes. As mentioned earlier, the agronomic production function approach explains differences in yields on the basis of varying environmental conditions. These yield response functions are then incorporated in economic models, giving changes in income. The Ricardian approach directly explains differences in income. However, in practice, due to limitations in fully accounting for adaptation, the production function approach tends to overestimate damages. Nevertheless, the two models can be used to cross check each other, as the empirical yield models by crops can provide some insight into the reduced-form envelope function of the Ricardian approach.

We would like to have estimated the underlying production functions for the individual crops (that form the envelope in Figure 4. 1), and then compute changes in net income employing the production function approach as described earlier. Applying the production function approach would, obviously, require estimating the production function with its appropriate inputs. However, no crop-specific inputs are reported in the censuses. This poses a problem in estimating the crop-specific production function.[3] Any estimation of crop-specific production functions solely on the basis of climate and edaphic variables will be biased and inaccurate. For this reason, welfare estimates are made utilizing the Ricardian climate coefficients. The production function approach is restricted to demonstrating that climate variables have a significant effect on district-level production yields. These estimates are reported in Appendix A.

DEVELOPING COUNTRY MODIFICATIONS

Given differences in agricultural sectors in developing and developed countries, methodologies used to date to estimate climate change impacts in developed countries have to be modified. This section highlights some of the major differences between developed and developing countries' agricultural sectors, which are taken into account in the methodology utilized in this analysis.

(i) A key characteristic of developing country agricultural sectors is the large share of non-hired household labor in agriculture. Given the absence of formal markets for self-employed/household labor, ignoring non-hired labor underestimates input costs, and hence overestimates net revenues, the key dependent variable. To account for household/non-hired labor, we use as a proxy the number of cultivators (self-employed males who list their primary job classification as cultivators), and include it on the right hand side of the regression equation. Doing this enables us to compute an implicit shadow wage for self-employed labor.

(ii) Prices of crucial inputs are often controlled by developing country governments, as is the case in India. For example, tractor prices do not vary across India for the

[3] We tried two procedures to allocate inputs to crops. First, inputs were allocated according to the area planted under each crop. However, this method assumes that inputs are in proportion to planted area which is a troublesome assumption in itself. Second, we tried using the cost-of-cultivation data (crop budgets) to estimate crop-specific inputs. However, the cost of cultivation data is at the state level, and we run into the same problem of arbitrarily allocating state-level inputs to the district level.

period of our data sample. There is minimal cross-sectional variation in official bullock prices as well. This presents a problem in obtaining accurate rental costs of these inputs, which is crucial for the calculation of net revenues. Therefore, though official prices for bullocks and tractors exist, due to little or no cross-sectional variation in these prices, they are not used to compute the rental cost of these inputs. Cross-sectional variation in the quantities of these inputs are exploited to compute the rental prices. The number of bullocks and tractors (on a per hectare basis) is therefore included on the right hand side of the climate regressions in order to compute the shadow rental costs.

(iii) An issue specific to India is the Green Revolution for the time period covered by the data set. The Green Revolution refers to the period 1967-1973 (mainly in Punjab, Haryana, and Western U.P.) when high yielding variety (HYV) seeds were imported from abroad. Use of these seeds and accompanying inputs spread to the rest of the country by the mid- to late- 1970s. The fraction of area planted to HYV crops (rice, wheat, maize, jowar, and bajra) is used as a proxy to control for cross-sectional discrepancies in the adoption of the Green Revolution.

(iv) Census data, though covering a spectrum of income ranges and farming practices, does not capture subsistence farming to the degree that it is practiced in particular countries. Due to reduced substitutability to other activities, subsistence agriculture could be most vulnerable to warming. Given data limitations, however, we do not address the impact of climate change on subsistence agriculture in this analysis. However, as highlighted in the conclusions, reasonable inferences can be drawn about the vulnerability of subsistence farming to climate change.

DATA AND EMPIRICAL SPECIFICATIONS

UNITS OF ANALYSIS

The units of observations for this analysis are 271 districts in thirteen Indian states for the period 1966-1986 (Appendix B describes the economic variables in complete detail, including the modifications made to the original data set).[4] Briefly, the data includes area irrigated, area planted, production yields, and farm harvest price for each of the following major crops: bajra, jowar, maize, rice and wheat; and area planted, production, and farm harvest price for the following minor crops: barley, cotton, groundnut, gram, jute, other pulses, potato, ragi, rapeseed, sesamum, soybeans, sugar, sunflower, tobacco, and tur. Variable and other inputs such as agricultural labor, cultivators, wages, factory earnings, literacy rates and rural population, are also available at the district level. Quantities of nitrogen, phosphorous, and potassium fertilizer and their prices are included. Information on bullocks and tractors is included.

[4] Most of the agricultural data has been collected by James McKinsey and Robert Evenson of Yale University from various Indian publications. Although data is available from 1955 through 1988, not all variables are measured each year. Various corrections and modifications made to this original data set are listed in Appendix C.

THE DEPENDENT VARIABLE: NET REVENUE PER CROPPED HECTARE

From the above data, for each of the 20 years, district-level net revenues are calculated as the value of production of major and minor crops less the expenditure on fertilizer and hired labor. The total cropped area is defined as the sum of the cropped areas for the thirteen crops including area planted under the High Yielding Varieties (HYVs) of the 5 major crops. From this, for district k in year y, the net revenue per cropped hectare is calculated to be:

$$(17)\qquad NREVHA^{k}=\sum_{i=1}^{20}\ [(p_i^{k}\cdot q_i^{k})-(pN^{k}\cdot qN^{k}+pP^{k}\cdot qP^{k}+pK^{k}\cdot qK^{k})-(w^{k}\cdot L^{k}\cdot days^{k})]/Totarea^{k}$$

where k=1...271, and
pi=farm harvest price of crop i,
qi=yield of crop i,
pN, pP, and pK=prices of nitrogen, phosphorous, and potassium respectively,
qN, qP, and qK=quantities of nitrogen, phosphorous, and potassium respectively,
w=labor cost of hired labor,
L=number of rural males whose primary job classification is agricultural labor,
days=average number of days worked in the state by farm workers, and
$Totarea=\sum_{i=1}^{20} Ai$, where Ai is the area planted to crop i (including HYVs).

The appropriate prices for the purpose of this study are farm harvest prices (as opposed to retail or wholesale prices), as these are the prices that farmers use to form their expectations. All prices and wages are deflated using the agricultural GDP deflator, and are in constant 1980 Rupees (*Source*: Agricultural Statistics (1996), Center for Monitoring Indian Economy, Mumbai, India). Since we are interested in the effect of climate on agricultural value, multiple-cropping (growing more than one crop per year, per hectare) should be, and is, taken into account in the computation of net revenue per hectare. Revenue from multiple crops is therefore included in (17), and so is the area planted under the multiple crops in the construction of the total area variable (the variable *Totarea* is thus the total gross cropped area). Figure 4.2 presents the 20-year average of net revenues per hectare for the 271 districts. From Figure 4.2, it is apparent that the high value districts are the agriculturally rich regions of Punjab, Haryana, Western Uttar Pradesh, and the eastern and coastal plains. The desert region of Rajasthan, together with sections of Bihar and Central India are among the least valuable agricultural regions.

CLIMATE VARIABLES: ESTIMATING A CLIMATE SURFACE

The appropriate climate variables for this study are the "normal" climate variables--30-year averages of temperatures and precipitation observed over the period 1930-1960, that farmers have adapted to (Appendix C provides a complete summary of data sources and the variables used in the study). The climate variables are made available by the Food and Agricultural

Organization (FAO) climate data bank.(FAO Irrigation and Drainage Paper, 1990)[5] This data corresponds to 160 weather stations across India. Table 14 shows the locations of these weather stations. We use 8 climate variables: normal temperatures(°C) and rainfalls(mm) for the months of April, July, October, and January. These four months correspond to various seasons affecting agricultural activity in India. April, one of the hottest months, is the sowing season for summer crops. July is the post-monsoon, growing season for summer crops. October is both the harvesting season for summer crops and the sowing season for winter crops. January, the winter season, is the growing season for winter crops.

The climate variables are available only for 160 weather stations located throughout India whereas there are 271 districts used in this study[6]. The assignment of climate variables to districts presents a methodological problem. A *climate surface* for each district is estimated by running a weighted regression across all the weather stations within a 600 miles radius (Mendelsohn et al. 1994, Sanghi 1997)[7]. Stations closer to a given district are assumed to contain more information about that district's climate, so the weight in the regressions is the inverse of the square root of a station's distance to the geographical center of the district. The dependent variables are the 4 monthly normal temperatures and rainfalls for the 30 year period (1930-1960). There are 14 exogenous variables: latitude, longitude, altitude, distance from nearest shoreline, and the corresponding square and interaction terms. The square and interaction terms are included in order to capture the non-linear impacts of the predicting variables on temperature and precipitation. A separate regression for temperatures and precipitation is estimated for each district. This leads to a total of $4 \cdot 2 \cdot 271$=2,168 regressions. The predicted temperatures and precipitation values for the geographic center of the districts from this estimation procedure are the independent climate variables used in the net-revenue regressions. Table 4.1 and 4.2 show a sample prediction and the variables used for one such district.

5 Normal climate variables are treated as the expected climate variables perceived by agents in the land market. it is true that in any given year, current weather may depart from normal weather, but this is not expected to influence land value assessments. Furthermore, the fact that the climate observations are for a different time period (1930-1960) than the agricultural data (1966-1986) is not of great concern. It is highly unlikely that long-run climate would have changed over these two time periods in India.

6 The International Irrigation Management Institute in conjunction with Utah State University is currently in the process of compiling a data base entitled The World Water and Climate Atlas for Agriculture. This data base will contain agricultural climate data from 1961 to 1990 from 56,000 weather stations around the world. Thus it will allow researchers to extract moisture and temperature data for an area as small as one square mile. The data base is expected to be available by the end of 1997 (Source: "To find Favorable Farm Climate, a World Map on the Web", *The New York Times*, Monday, March 17, 1997, pp.A4).

7 The choice of a 600 miles radius is arbitrary. Various other radii were tried, and the 600 miles radius was chosen because it gave the best predictions.

Table 4.1: Sample district temperature interpolation (Balangir, Orissa)

Independent Variables	January	April	July	October
Intercept	151.1593*	-68.0129	-9.856891	83.18637*
Altitude	-0.005168	0.013347	-0.004617	-0.004241
Latitude	-0.766564	3.84038*	0.264911	1.101181*
Longitude	-2.696666*	1.611728	0.947104	-1.566711
Distance to sea	0.010457*	-0.013597*	-0.010795*	0.001797*
Latitude x longitude	0.023047	-0.046967*	-0.030338*	-0.020315*
Latitude x altitude	-0.000221	5.47E-05	0.000286	-0.000265
Altitude x longitude	6.65E-05	-0.000174	-6.78E-05	5.2E-05
Altitude squared	-3.74E-07	-1.84E-06	-6.88E-07	3.83E-07
Latitude squared	-0.046296*	0.001907	0.057357*	0.012604
Longitude squared	0.01304*	-0.005018	-0.002563	0.011773*
Distance to sea squared	-5.12E-06	1.16E-05	9.05E-06	3.04E-08
Distance x altitude	1.17E-06	-1.6E-05*	-7.1E-06*	-2.53E-06
Distance x latitude	0.000424	-0.002148*	-0.000976	-0.000382
Distance x longitude	-0.000198*	0.000771*	0.000361*	8.5E-05
Adjusted R^2	0.9677	0.8092	0.9341	0.9594
Number of observations	89	89	89	89

*Statistically significant at the 5% level

Table 4.2: Sample district precipitation interpolation (Balangir, Orissa)

Independent Variables	January	April	July	October
Intercept	-1131.132*	16109*	33765*	7654.415*
Altitude	0.000724	-3.308682*	-10.55509*	-1.728379*
Latitude	-17.98414*	-24.74181	22.79569	-66.6389
Longitude	31.81625*	-382.4105*	-814.4482*	-166.846*
Distance to sea	-0.065703	0.004876	0.452735	0.199759
Latitude x longitude	0.227047	0.740002	2.441275	1.264743
Latitude x altitude	0.005453*	-0.035691*	-0.070136*	-0.013196
Altitude x longitude	-0.001181	0.047875*	0.139321*	0.021904*
Altitude squared	-2.15E-05*	4.31E-05	0.000164	6.85E-05*
Latitude squared	0.00061	-1.038216	-5.567335*	-1.532406*
Longitude squared	-0.219904*	2.222974*	4.613648*	0.903091*
Distance to sea squared	5.26E-05	-0.000622*	-0.002626*	-0.000492
Distance x altitude	4.4E-05	0.000825*	0.003553	-0.000813*
Distance x latitude	0.00048	0.063412*	0.18034*	0.111812*
Distance x longitude	0.000318	-0.015192*	-0.043508	-0.033832*
Adjusted R^2	0.7122	0.8887	0.8027	0.8527
Number of observations	87	89	89	89

*Statistically significant at the 5% level

To assess the reliability of the above spatial statistical approach in predicting district level average climate, we predicted the climate for each of the 160 weather stations by dropping the weather station and predicting its climate employing the above approach, and then comparing it to the actual measurements for each station. We are able to predict temperatures between 93% to 97% of actual weather station temperatures, and precipitation between 70% to 96% of actual weather station precipitation. Thus, this method is reasonable for the purposes of predicting district-level climate variables.

It is important to note that the accuracy of this procedure increases with both the number and spatial distribution of data points (weather stations) as well as the number of years that the data set covers.[8] Figures 4.3 through 4.10 show the spatial distribution of the predicted temperature and precipitation for the 271 districts from this procedure, in January, April, July and October.

[8] There exists another data set available from the Indian Meteorological Department (IMD, Pune, India) that contains climate and weather data from 1960-1980 (for the prohibitively expensive sum of U.S. $14,500). However, the IMD data set contains information from only 120 weather stations as opposed to 160 weather stations in the FAO set. Furthermore, the IMD data set covers only a 20 year period compared to the 30 year period in the FAO set. The FAO data set is, therefore, likely to yield more accurate district-level climate predictions.

Figure 4.2: District-level net revenues per hectare

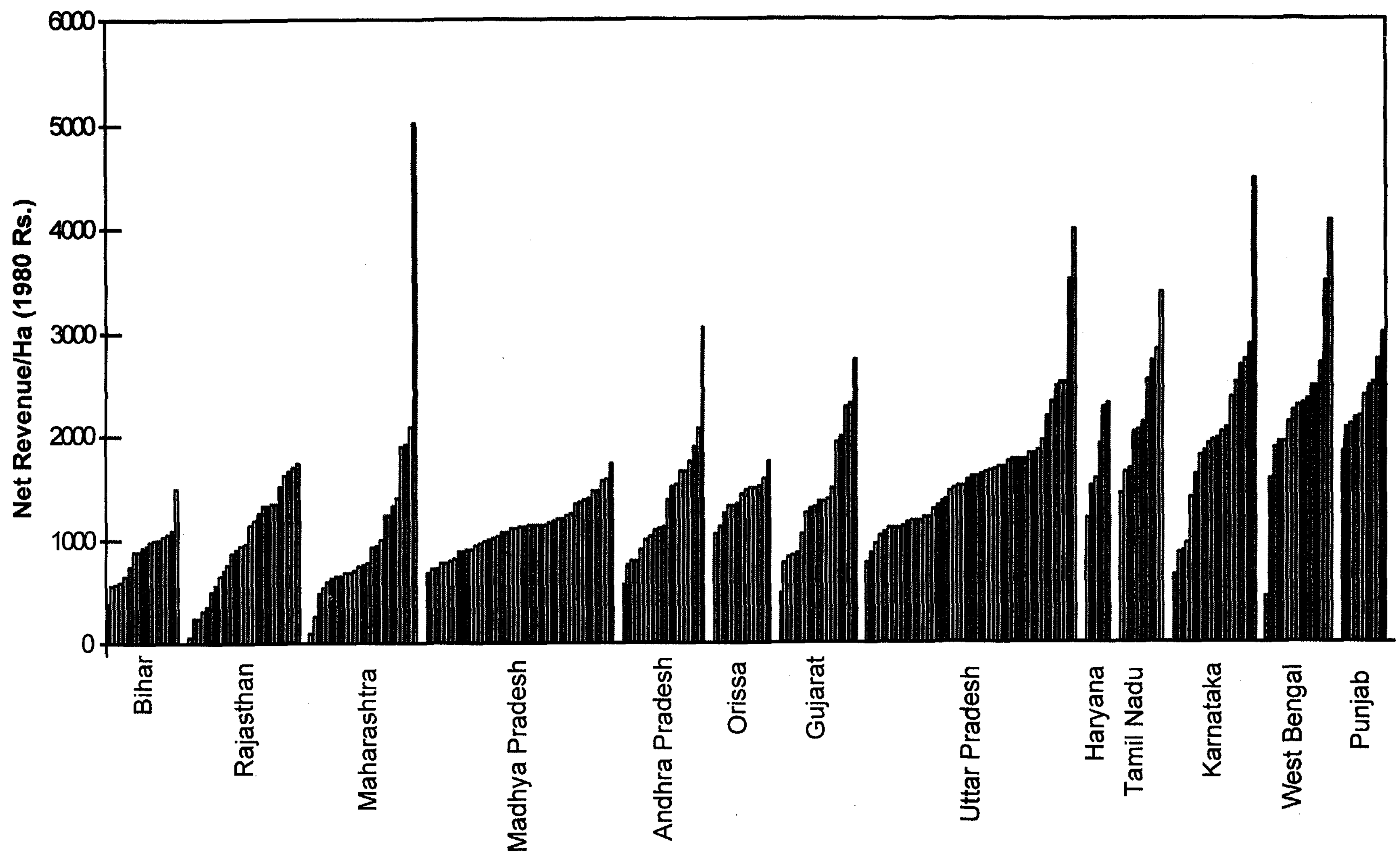
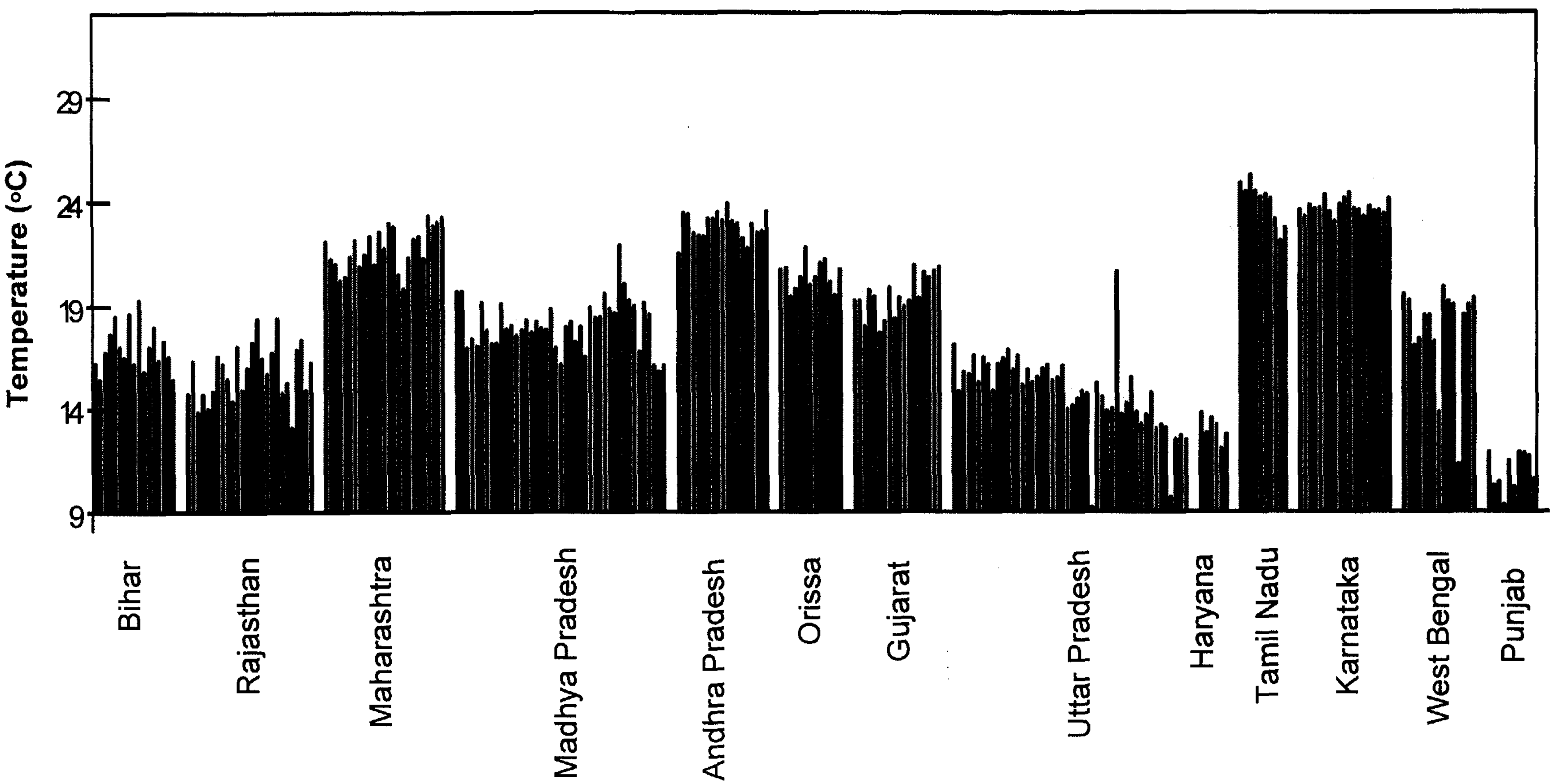


Figure 4.3: District temperature January (°C)



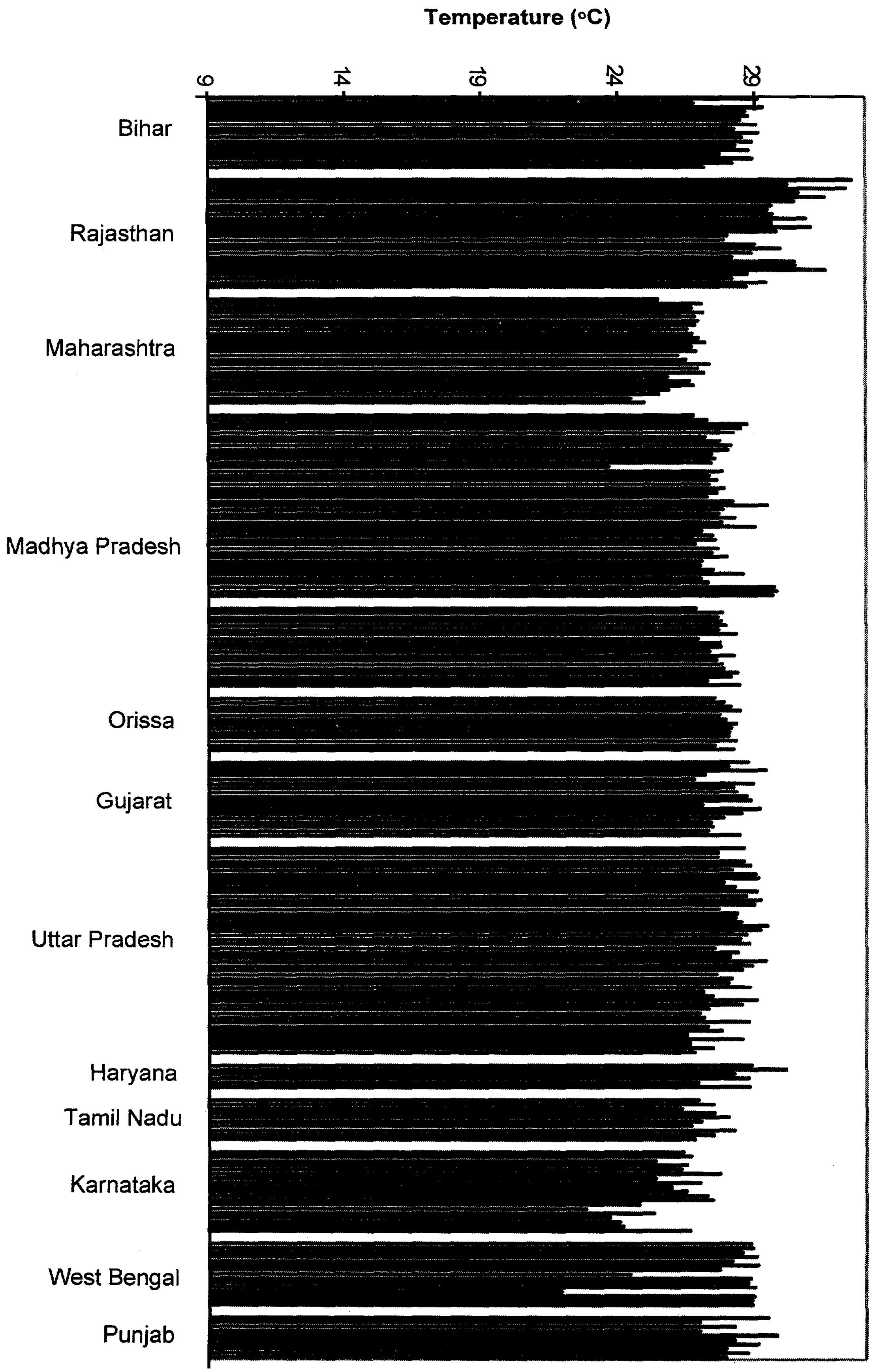


Figure 4.4: District temperature April (°C)

Figure 4.5: District temperature July (°C)

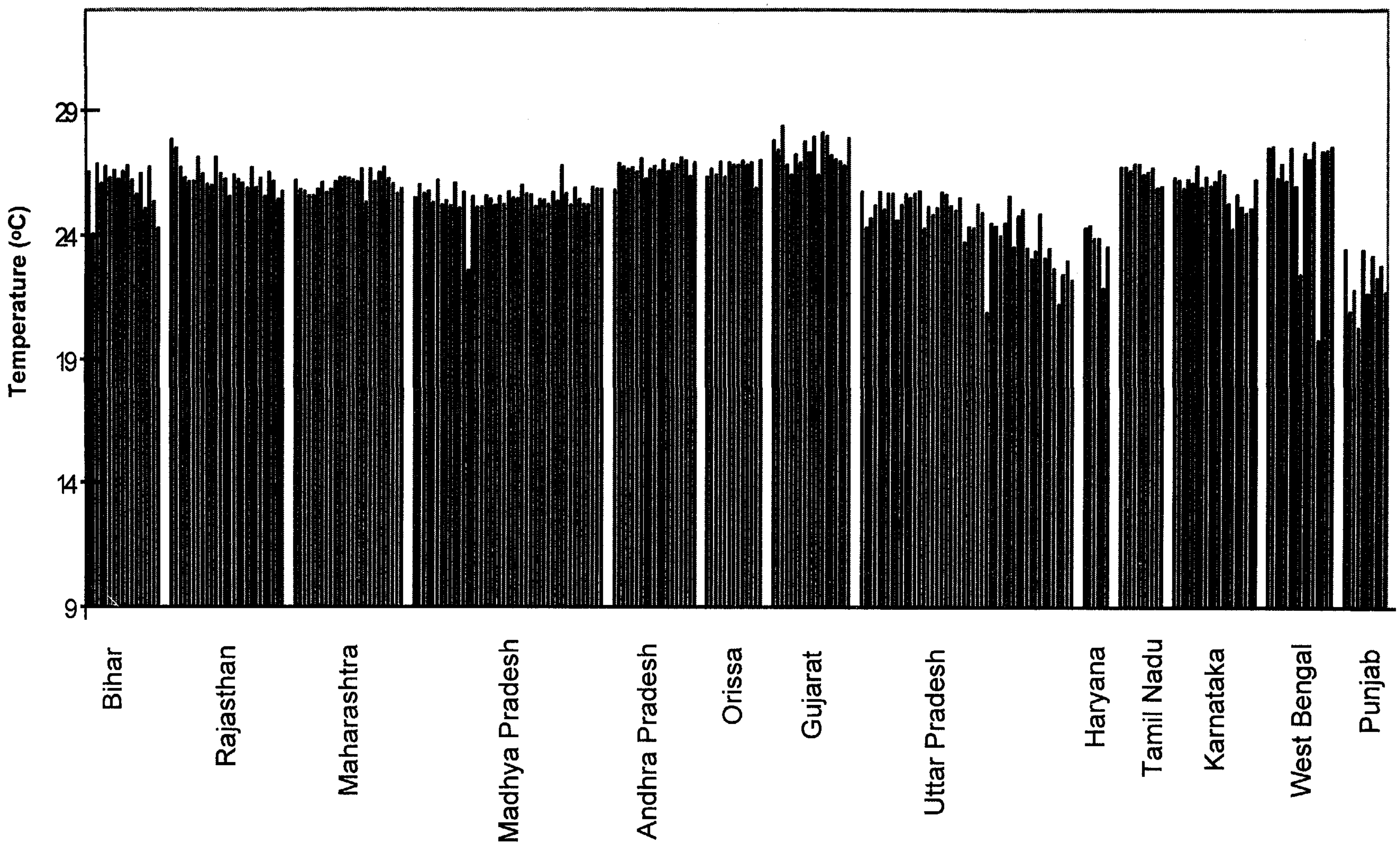


Figure 4.6: District temperature October (°C)

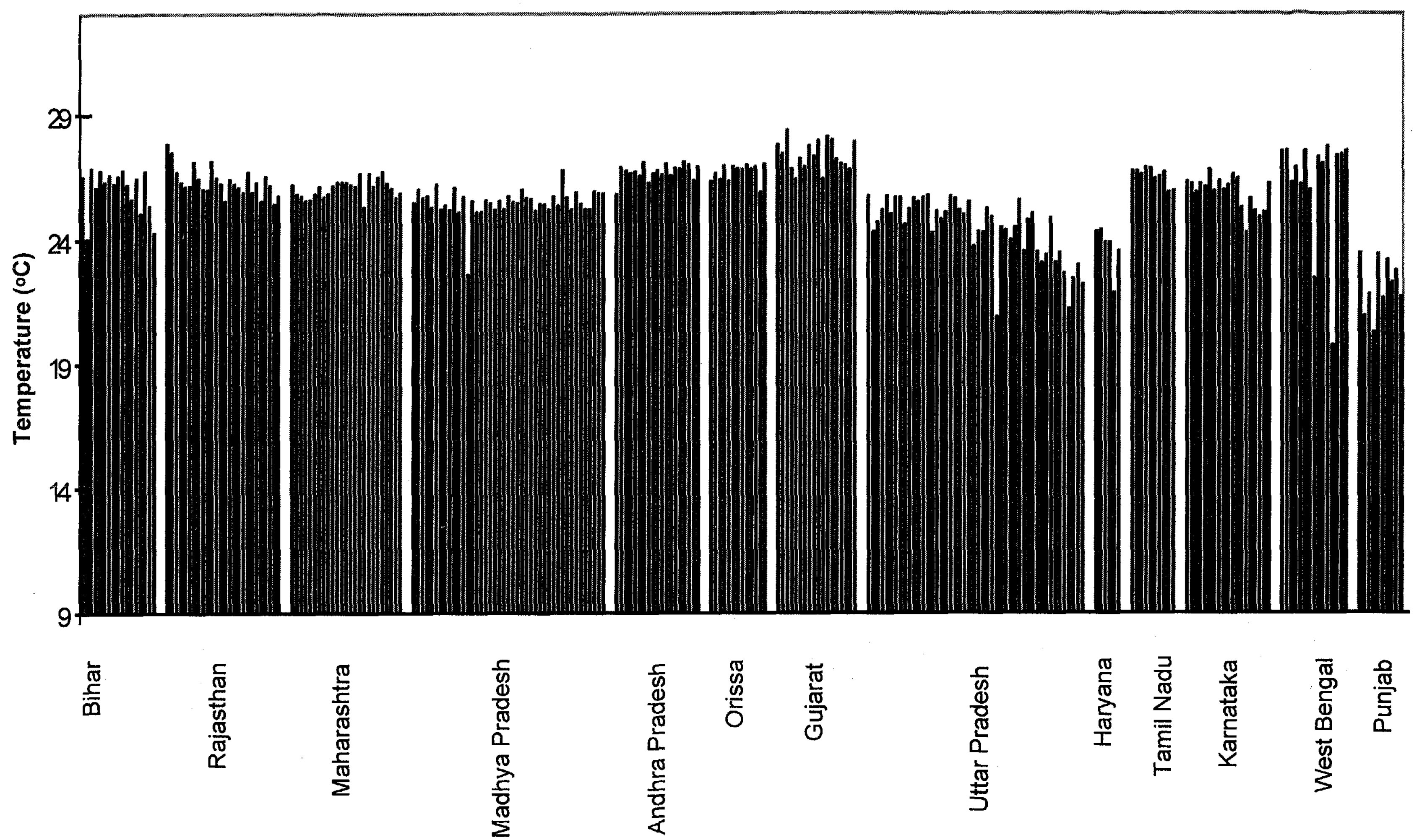


Figure 4.7: District rainfall January (mm)

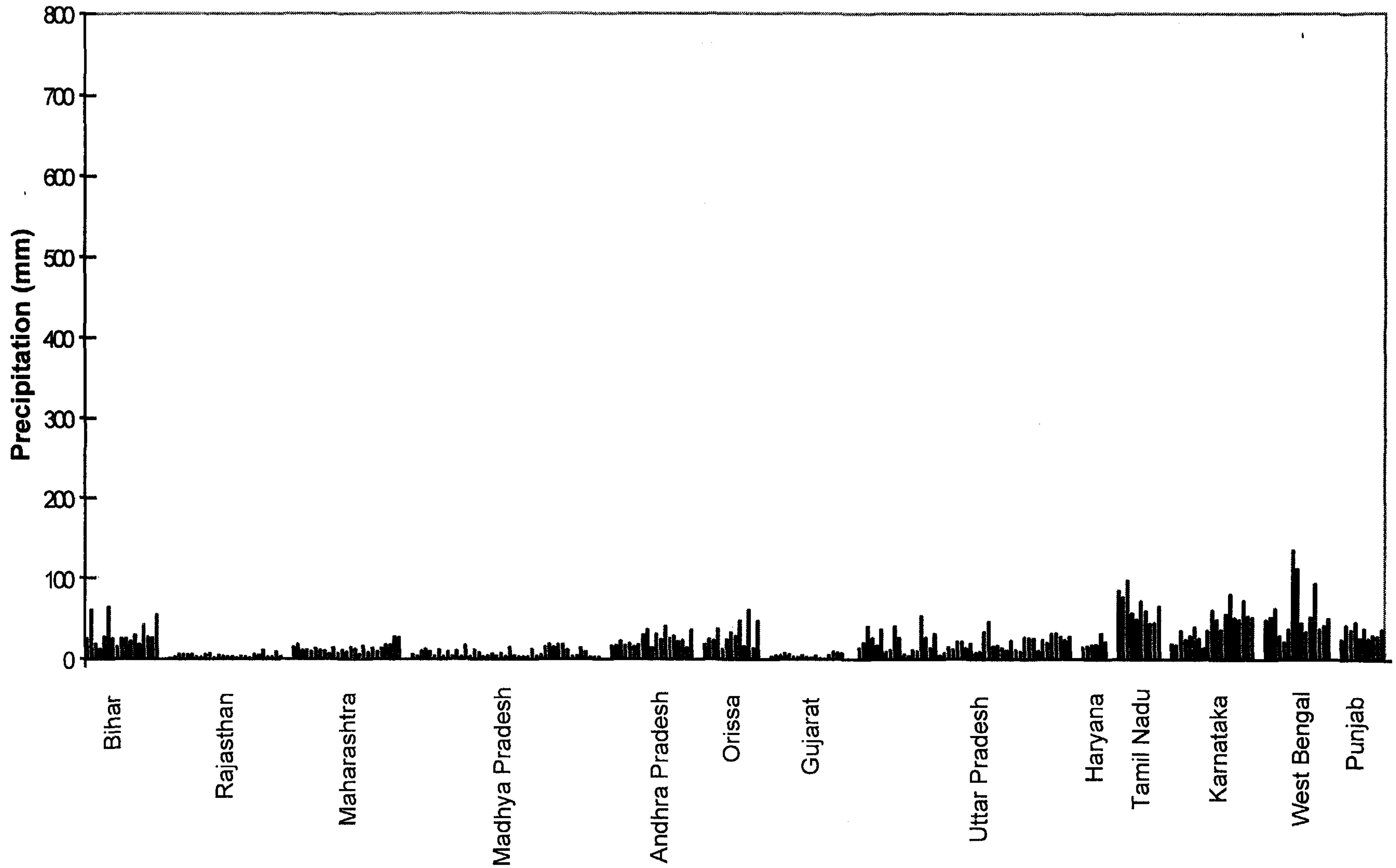


Figure 4.8: District rainfall April (mm)

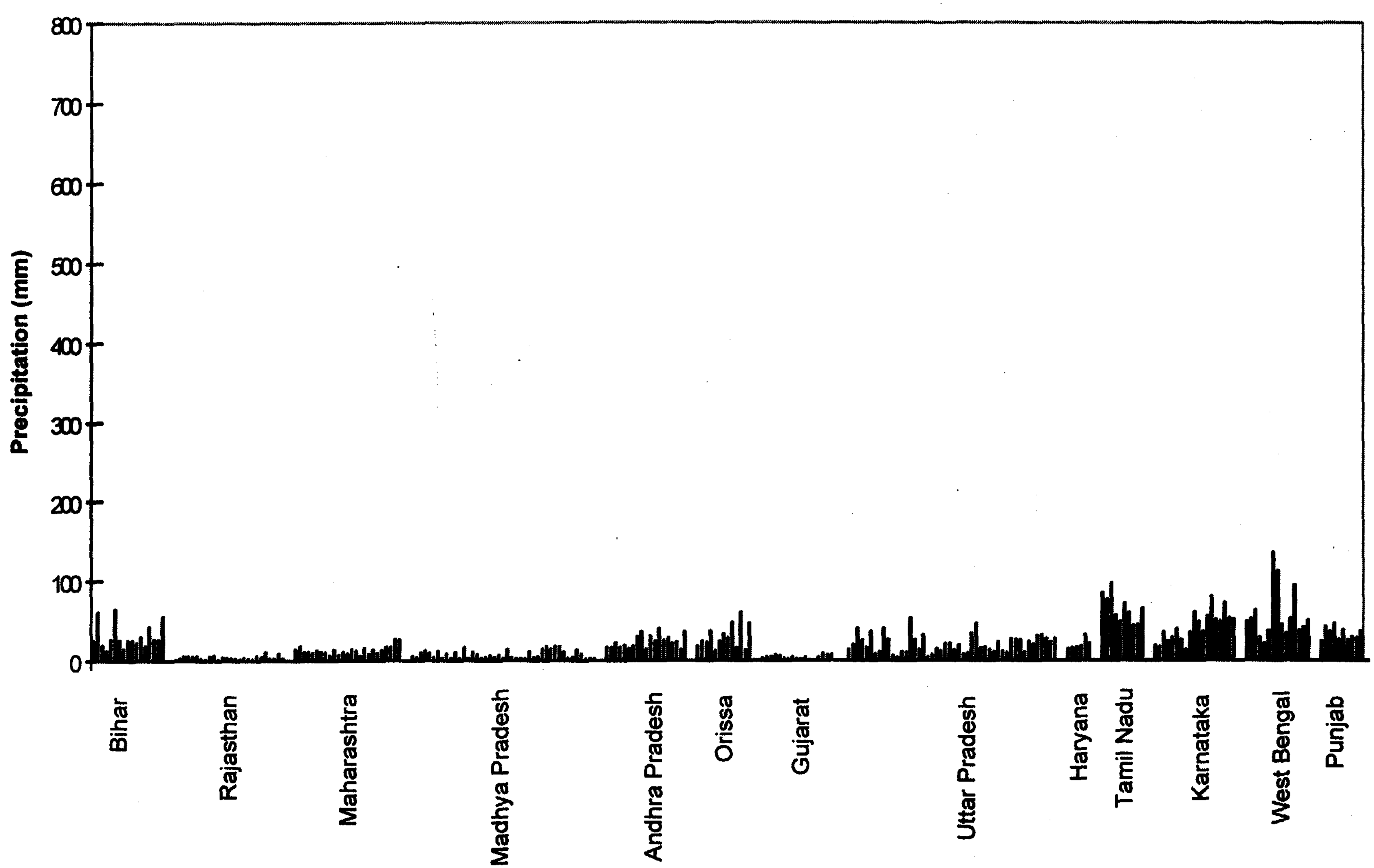


Figure 4.9: District rainfall July (mm)

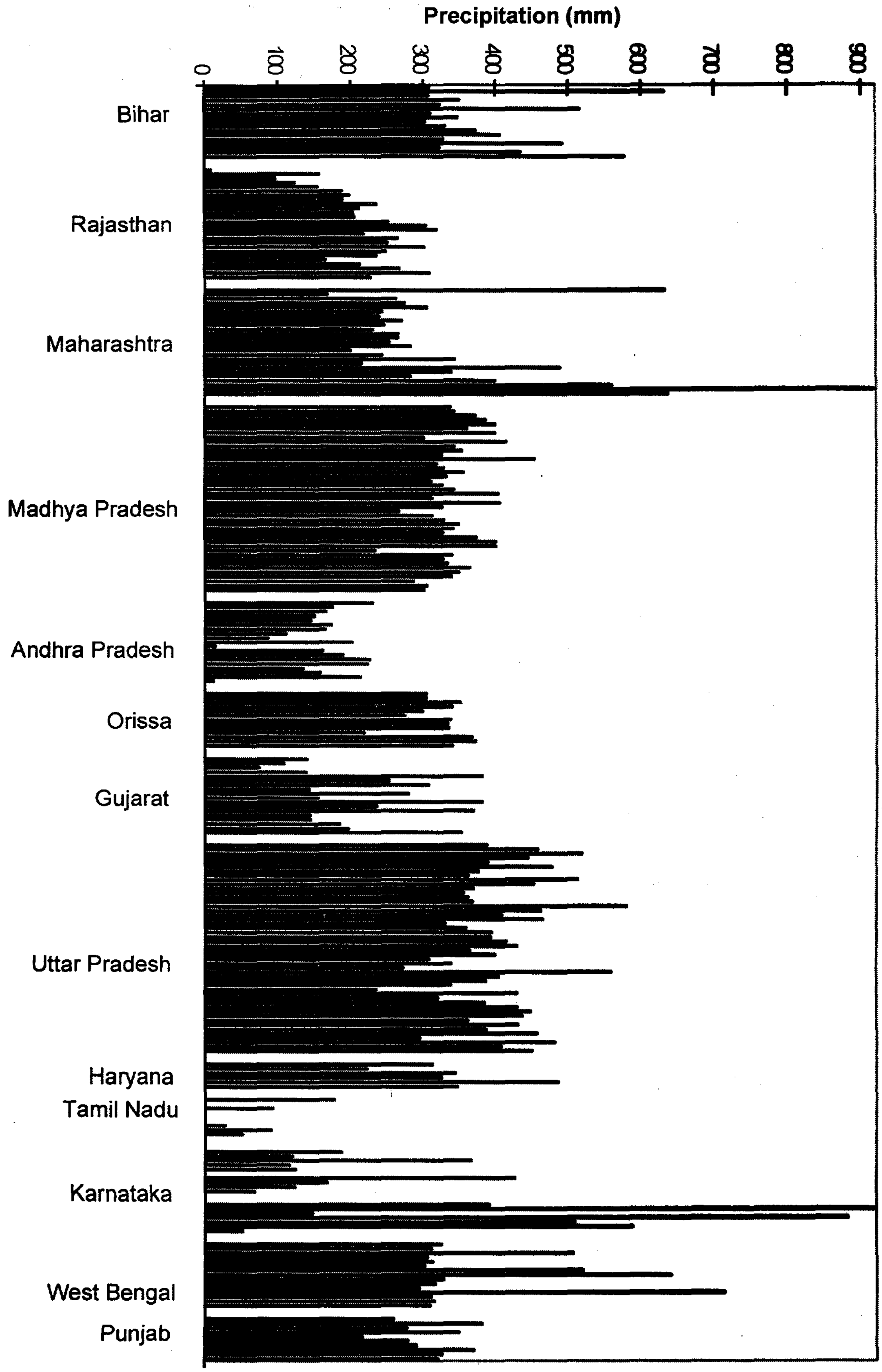
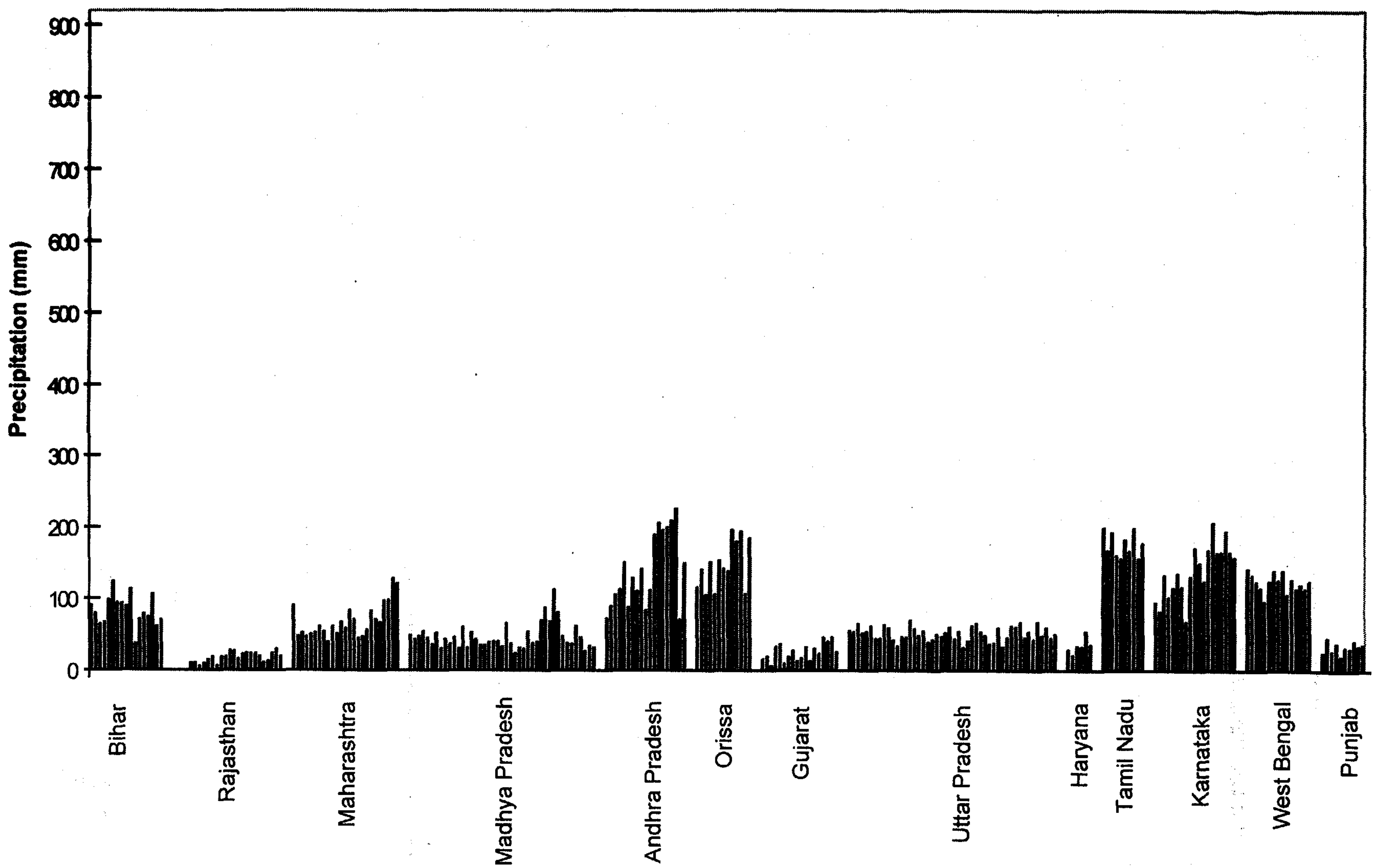


Figure 4.10: District rainfall October (mm)



EDAPHIC AND OTHER CONTROL VARIABLES

Edaphic variables (soil slope, type, texture, top soil depth) vary significantly over the districts, and hence need to be controlled for in order to isolate climate from other effects. Appendix D details the edaphic variables. Care is taken not to include soil variables that might be "hidden climate indicators" i.e. variables that may be correlated to temperature and precipitation, such as the Storie Index C, which in part is based on climatic variables. Population density and literacy rates are also included to control for urban influences on agricultural rent. District latitude and mean altitude can be considered as proxies for day length and the diurnal cycle respectively.

EMPIRICAL RESULTS

RICARDIAN CLIMATE REGRESSIONS

The data is pooled and district level net revenues per hectare are regressed on climate, edaphic, geographic and control variables as defined above to estimate the best-use value function across different districts. Yearly dummies are used to control for year to year variations in weather, prices, and other variables affecting agriculture over the 20 year period. The regression results are presented in Table 4.3.

The independent variables include the linear and quadratic temperature and precipitation terms for the four seasonal months; the four corresponding rainfall-temperature interaction terms; edaphic and geographic variables (soil type, slope, and latitude); shadow inputs (bullocks, tractors, and self-employed labor); and other control variables (fraction of area planted under HYV, population density, and literacy proportion). The quadratic and interaction climate terms are included to capture second-order effects of climate on crop yields (and hence net revenues). The signs and magnitudes of the higher order terms determine if the response function is U-shaped or hill- shaped. Each observation is weighted by the area in cropland in each district (acreage weights).[9] The linear, quadratic, and interaction climate terms are demeaned.

In the preliminary runs, altitude was included to control for the diurnal cycle. However, district-level altitude is highly correlated with district-level October temperature and thus turns out to be a hidden indicator of climate. For this reason, altitude is excluded from the final regressions.

The soil variables used in the final analysis are district-level soil types and top soils. In earlier runs, all the soil types, and other soil variables such as soil PH and soil slopes were used, but were found to be highly (statistically) insignificant. Soil types and top soils that had coefficients of similar magnitude and signs were combined for ease of handling.

[9] The justification for using acreage weights is that the data are at the district, and not at the farm level. Larger districts include more farms, resulting in lower measurement errors. Since the aim is to treat farms (not districts) as having comparable information, larger districts are given a higher weight.

Table 4.3: Results of pooled analysis

Independent Variable	Parameter	Independent Variable	Parameter	Independent Variable	Parameter
Intercept	4659.3 (8.92)	(Apr rain)x(Apr temp)	8.21 (11.59)	dmyr68	291.85 (5.37)
Jan temperature	-132.67 (-3.38)	(Jul rain)x(Jul temp)	-0.21 (-1.97)	dmyr69	288.73 (5.38)
April temperature	-371.74 (-16.71)	(Oct rain)x(Oct temp)	3.01 (5.83)	dmyr70	410.9 (7.75)
July temperature	-103.26 (-2.84)	Soil 1	193.55 (9.28)	dmyr71	365.48 (6.93)
October temperature	486 (7.35)	Soil 2	221.68 (8.59)	dmyr72	354.38 (6.74)
Jan temperature square	-39.25 (-11.4)	Soil 3	-153.56 (-4.39)	dmyr73	611.14 (11.8)
April temperature square	80.34 (12.48)	Soil 4	13.31 (0.41)	dmyr74	562.95 (10.77)
July temperature square	35.02 (4.62)	Soil 5	-10.06 (-0.22)	dmyr75	519.47 (10.07)
October temperature square	-68.08 (-6.77)	Soil 6	81.32 (1.56)	dmyr76	350.85 (6.77)
Jan precipitation	18.53 (6.11)	Cultivators/ha	-26.95 (-0.78)	dmyr77	430.96 (8.4)
April precipitation	-14.38 (-8)	Bulls/ha	49.73 (1.16)	dmyr78	337.96 (6.61)
July precipitation	-0.41 (-2.11)	Tractors/ha	28681 (8.98)	dmyr80	329.72 (6.46)
October precipitation	2.28 (2.23)	Population Density	13.55 (2.16)	dmyr81	206.03 (4.06)
January precipitation square	-0.16 (-1.57)	Literacy	769.94 (6.85)	dmyr82	160.51 (3.13)
April precipitation square	0.28 (10.58)	Fraction of area under HY.V	137.31 (1.87)	dmyr83	307.47 (6.05)
July precipitation square	0.01 (3.89)	Latitude	-174.43 (-7.83)	dmyr84	155.17 (2.96)
October precipitation square	-0.04 (-7.34)	dmyr66	376.62 (6.77)	dmyr85	79.72 (1.52)
(Jan rain)x(Jan temp)	-3.62 (-4.57)	dmyr67	541.24 (9.92)	dmyr86	-12.08 (-0.23)

Note:
Dependent Variable: Net revenue per hectare
Number of Observations: 5690
Adj R^2 =0.44
Weight=Gross cropped area
( )=t-value

INTERPRETATION OF CONTROL VARIABLES AND ROBUSTNESS ISSUES

Inclusion of interaction terms in the regression precludes the direct interpretation of the climate coefficients estimated in the regression[10]. The discussion and interpretation of the climate coefficients is therefore investigated in detail in the next section. This section examines the coefficients on the control variables, and emphasizes some robustness issues.

The control variables in the pooled regression behave as expected. The dummy year excluded was for 1979. Net revenues per hectare were the lowest for 1979 relative to other years. The yearly dummies included in the regression capture this effect and are thereby significantly positive. Population density and literacy have a positive impact on net revenues as expected, because of proximity to markets and other urban influences. The coefficient on the number of cultivators, though statistically insignificant, has a negative impact on net revenues. This can be interpreted as farms' constraints on hiring more efficient farm labor especially during peak seasons. The shadow price of both bullocks and tractors is positive, tractors contributing significantly more than bullocks. The coefficient on fraction of area under HYV is positive, reflecting the positive effect on net revenues through increased productivity as a result of the Green Revolution.

As a robustness check, the model was estimated using two other procedures. Since we are interested in the long-run impact of climate on net revenues, one approach is to regress averaged district-level net revenues per hectare on the average of the independent variables over the 20 year time period. Another is to estimate the model independently for each year over the 20 year period (1966-1986). Regression coefficients from these procedures alongwith the relevant estimates from the pooled regression in Table 4.3 are presented in Table 4.4.

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[10] If $y=a(x-x_m)^2+b(x-x_m)+e$, then the coefficient 'b' of the linear term reflects the marginal value of the variable x evaluated at its mean x_m, while the quadratic term reflects the change in the marginal effects as one moves away from the mean. However, if $y=a(x-x_m)^2+b(x-x_m)+c(x-x_m).(z-z_m)+e$, then the marginal value of x evaluated at its mean is $b+c(z-z_m)$.

Table 4.4: Comparison of pooled, averaged, and repeated cross-sectional regression results

	Pool	Average	1966	1967	1968	1969	1970	1971	1972	1973	1974
Intercept	4659.3 (8.92)	5386.38 (2.8)	3064.57 (1.31)	6635.49 (2.95)	3310.29 (1.53)	5309.92 (2.76)	6335.23 (2.96)	9761.61 (4.22)	8148.08 (3.7)	9364.17 (4.27)	7700.53 (3.4)
Jan temperature	-132.67 (-3.38)	-185.4 (-1.28)	-356.83 (-2.01)	-361.33 (-2.13)	-338.35 (-2.08)	-383.58 (-2.63)	-350.78 (-2.18)	-427.77 (-2.45)	-564.03 (-3.38)	-253.95 (-1.54)	-377.78 (-2.19)
April temperature	-371.74 (-16.71)	-304.76 (-3.61)	-36.19 (-0.35)	-160.44 (-1.6)	-48.31 (-0.5)	-111.16 (-1.28)	-227.26 (-2.35)	-319.49 (-3.05)	-79.54 (-0.81)	-389.39 (-3.94)	-165.12 (-1.6)
July temperature	-103.26 (-2.84)	-123.96 (-0.92)	-374.71 (-2.39)	-263.84 (-1.74)	-349.65 (-2.41)	-307.61 (-2.34)	-164.82 (-1.14)	-80.88 (-0.51)	-161.47 (-1.06)	-83.21 (-0.55)	-196.32 (-1.22)
October temperature	486 (7.35)	504.5 (2.06)	718.68 (2.48)	770.08 (2.77)	515.84 (1.94)	568.17 (2.37)	478.89 (1.79)	505.77 (1.73)	370.72 (1.33)	504.6 (1.82)	467.94 (1.61)
Jan temperature square	-39.25 (-11.4)	-39.36 (-3.1)	-11.07 (-0.72)	-37.64 (-2.55)	-11.71 (-0.83)	-20.68 (-1.64)	-27.12 (-1.93)	-48.51 (-3.17)	-30.04 (-2.06)	-69.03 (-4.79)	-53.25 (-3.49)
April temperature square	80.34 (12.48)	80.94 (3.41)	67.42 (2.31)	60.81 (2.17)	72.47 (2.74)	84.57 (3.56)	74.39 (2.8)	80.32 (2.79)	86.12 (3.16)	58.62 (2.14)	85.84 (3.05)
July temperature square	35.02 (4.62)	42.18 (1.51)	31.68 (0.94)	34.83 (1.08)	35.09 (1.13)	24.48 (0.88)	13.89 (0.45)	37.89 (1.12)	22.49 (0.69)	58.28 (1.81)	74.1 (2.21)
October temperature square	-68.08 (-6.77)	-60.48 (-1.63)	-59.87 (-1.31)	-57.32 (-1.32)	-37.77 (-0.91)	-46.87 (-1.26)	-4.37 (-0.11)	-32.64 (-0.72)	-63.11 (-1.47)	-51.38 (-1.19)	-103.8 (-2.34)
Jan precipitation	18.53 (6.11)	16.48 (1.47)	18.44 (1.39)	20.9 (1.64)	2.39 (0.19)	13.4 (1.21)	-3.89 (-0.32)	-1.7 (-0.13)	-5.49 (-0.43)	16.63 (1.3)	2.62 (0.2)
April precipitation	-14.38 (-8)	-16.57 (-2.49)	-12.74 (-1.59)	-8.31 (-1.1)	-13.77 (-1.9)	-19.21 (-2.96)	-19.52 (-2.65)	-19.95 (-2.46)	-22.25 (-2.9)	-7.57 (-1)	-14.65 (-1.9)
July precipitation	-0.41 (-2.11)	-0.01 (-0.01)	0.03 (0.04)	0.34 (0.4)	0.46 (0.56)	-0.01 (-0.02)	0.55 (0.68)	0.72 (0.82)	0.52 (0.62)	-1.23 (-1.5)	-0.88 (-1.03)
October precipitation	2.28 (2.23)	3.41 (0.9)	9.3 (1.99)	1.36 (0.31)	11.4 (2.66)	7.54 (1.99)	8.38 (1.95)	3.45 (0.73)	12.55 (2.81)	-1.74 (-0.4)	3.35 (0.74)
January precipitation square	-0.16 (-1.57)	-0.2 (-0.54)	0.04 (0.08)	-0.27 (-0.63)	-0.29 (-0.71)	-0.42 (-1.14)	-0.25 (-0.61)	-0.36 (-0.81)	0.51 (1.19)	-0.38 (-0.89)	0.4 (0.89)
April precipitation square	0.28 (10.58)	0.32 (3.22)	0.28 (2.45)	0.17 (1.48)	0.34 (3.13)	0.46 (4.8)	0.44 (4.04)	0.33 (2.78)	0.37 (3.29)	0.2 (1.73)	0.23 (2.02)
July precipitation square	0.01 (3.89)	0.01 (1.33)	0.01 (1.3)	0.01 (-0.05)	0.01 (0.99)	0.01 (0.61)	0.01 (1.52)	0.01 (1.13)	0.01 (2.43)	0.01 (0.35)	0.01 (1.13)
October precipitation square	-0.04 (-7.34)	-0.04 (-2.29)	-0.01 (-0.55)	-0.03 (-1.49)	-0.04 (-1.73)	-0.05 (-2.51)	-0.04 (-2.04)	-0.04 (-1.7)	-0.05 (-2.1)	-0.03 (-1.51)	-0.05 (-2.16)
(Jan rain)x(Jan temp)	-3.62 (-4.57)	-3.58 (-1.23)	-3.13 (-0.89)	-7.92 (-2.37)	-3.42 (-1.07)	-3.36 (-1.17)	-2.28 (-0.7)	-5.3 (-1.5)	0.15 (0.04)	-9.56 (-2.89)	-4.65 (-1.35)
(Apr rain)x(Apr temp)	8.21 (11.59)	8.31 (3.2)	6.91 (2.2)	3.99 (1.32)	9.05 (3.17)	10.31 (4.02)	11.59 (4.01)	7.84 (2.49)	10.83 (3.59)	5.55 (1.85)	6.32 (2.06)

Table 4.4 Comparison of pooled, averaged, and repeated cross-sectional regression results (cont.)

	Pool	Average	1966	1967	1968	1969	1970	1971	1972	1973	1974
(Jul rain)x(Jul temp)	-0.21 (-1.97)	-0.02 (-0.05)	0.09 (0.18)	-0.45 (-0.97)	0.1 (0.23)	-0.07 (-0.18)	0.12 (0.26)	0.05 (0.11)	0.11 (0.24)	-0.57 (-1.25)	-0.36 (-0.77)
(Oct rain)x(Oct temp)	3.01 (5.83)	2.86 (1.51)	0.09 (0.04)	4.46 (2.05)	-0.23 (-0.11)	1.42 (0.76)	0.32 (0.15)	4.25 (1.84)	2.88 (1.3)	4.61 (2.11)	6.81 (3.01)
Soil 1	193.55 (9.28)	168.83 (2.2)	192.2 (2.11)	188.08 (2.15)	261 (3.14)	222.31 (2.96)	209.09 (2.49)	309.05 (3.35)	263.72 (3)	143.34 (1.64)	187.34 (2.08)
Soil 2	221.68 (8.59)	211.28 (2.23)	256.5 (2.23)	250.56 (2.28)	240.55 (2.31)	188.33 (2.01)	292.26 (2.76)	268.03 (2.31)	117.9 (1.06)	173.2 (1.57)	50.55 (0.45)
Soil 3	-153.56 (-4.39)	-115.86 (-0.9)	-304.82 (-2.01)	-143.43 (-0.99)	-120.49 (-0.85)	-113.44 (-0.91)	-45.41 (-0.32)	-29.3 (-0.19)	-219.07 (-1.49)	-173.48 (-1.18)	-285.7 (-1.87)
Soil 4	13.31 (0.41)	47.82 (0.4)	-127.55 (-0.85)	51.14 (0.37)	23.03 (0.18)	-136.93 (-1.17)	-88.79 (-0.67)	-236.58 (-1.64)	-358.31 (-2.56)	-237.59 (-1.73)	-247.31 (-1.75)
Soil 5	-10.06 (-0.22)	-7.64 (-0.05)	47.15 (0.23)	98.34 (0.49)	138.92 (0.72)	71.49 (0.42)	-116.65 (-0.62)	26.83 (0.13)	-55.42 (-0.28)	69.69 (0.35)	5.91 (0.03)
Soil 6	81.32 (1.56)	70.31 (0.37)	39.17 (0.17)	162.05 (0.72)	87.01 (0.41)	-24.82 (-0.13)	-139.95 (-0.66)	99.07 (0.43)	49.89 (0.22)	240.32 (1.09)	223.95 (0.96)
Cultivators/hectare	-26.95 (-0.78)	79.33 (0.56)	546.47 (2.75)	410.41 (2.29)	140 (0.91)	78.1 (0.62)	33.73 (0.26)	166.55 (1.32)	230.85 (1.8)	256.61 (1.84)	338.91 (2.29)
Bulls/hectare	49.73 (1.16)	-77.13 (-0.44)	-416.33 (-1.76)	-79.06 (-0.34)	125.05 (0.63)	75.13 (0.45)	73.43 (0.43)	89.12 (0.53)	24.74 (0.17)	183.93 (1.17)	-58.93 (-0.37)
Tractors/hectare	28681 (8.98)	62670 (3.44)	400742 (4.16)	273264 (3.47)	168561 (2.9)	98942 (2.34)	103381 (2.36)	90520 (2.15)	80406 (2.25)	111999 (3.26)	59625 (1.92)
Population Density	13.55 (2.16)	9.15 (0.39)	2.53 (0.08)	44.93 (1.44)	-4.34 (-0.14)	30.99 (1.21)	13.66 (0.45)	15.73 (0.48)	7.25 (0.25)	58.4 (2.03)	44.68 (1.58)
Literacy	769.94 (6.85)	529.15 (1.22)	305.57 (0.56)	-672.36 (-1.24)	250.32 (0.48)	464.41 (1.01)	-93.99 (-0.18)	19.56 (0.04)	561.09 (1.06)	-123.79 (-0.24)	167.04 (0.32)
Fraction of area under HYV	137.31 (1.87)	474.81 (1.25)	1018.66 (0.33)	447.68 (0.39)	899.19 (1.05)	314.94 (0.81)	859.14 (1.49)	640.82 (1.17)	364.1 (0.76)	295.99 (0.7)	1308.36 (3.45)
Latitude	-174.43 (-7.83)	-195.29 (-2.38)	-107 (-1.07)	-245.21 (-2.55)	-124.81 (-1.35)	-203.51 (-2.47)	-226.59 (-2.47)	-388.01 (-3.91)	-320.41 (-3.39)	-354.22 (-3.77)	-297.46 (-3.06)
Adj, R-square	0.44	0.51	0.49	0.52	0.53	0.50	0.48	0.49	0.55	0.54	0.50
Number of Observations	5690	270	270	270	270	270	270	270	270	270	270

Table 4.4: Comparison of pooled, averaged, and repeated cross-sectional regression results (cont.)

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Intercept	190.96 (0.08)	6784.76 (2.98)	8600.45 (4.29)	2056.72 (0.99)	4533.7 (2.25)	7455.42 (3.07)	4324.81 (2.05)	1699.56 (0.8)	6512.18 (2.9)	4650.96 (1.79)	5052.68 (1.94)	2593.47 (0.87)
Jan temperature	189.32 (1.01)	-33.22 (-0.19)	-58.44 (-0.38)	395.25 (2.49)	91.95 (0.6)	-246.98 (-1.38)	-44.58 (-0.28)	72.27 (0.46)	-129.52 (-0.76)	-307.03 (-1.56)	-364.32 (-1.83)	8.29 (0.04)
April temperature	-372.88 (-3.45)	-411.2 (-4.08)	-454.46 (-5.16)	-619.19 (-6.77)	-500.66 (-5.5)	-406.78 (-3.89)	-313.99 (-3.43)	-359.66 (-3.94)	-364.25 (-3.7)	-370.73 (-3.33)	-208.23 (-1.85)	-495 (-3.92)
July temperature	36.26 (0.21)	132.15 (0.82)	150.98 (1.06)	375.66 (2.54)	98.62 (0.68)	-175.82 (-1.05)	-100.07 (-0.68)	-32.49 (-0.22)	75.64 (0.48)	-500.45 (-2.73)	-413.61 (-2.23)	-193.93 (-0.93)
October temperature	-52.15 (-0.16)	316.09 (1.07)	305.14 (1.17)	-29.84 (-0.11)	313.58 (1.2)	769.38 (2.56)	535.69 (2.01)	347.65 (1.3)	460.4 (1.6)	1238.26 (3.72)	827.35 (2.47)	610.98 (1.63)
Jan temperature square	-24.29 (-1.48)	-52.18 (-3.47)	-73.32 (-5.5)	-40.2 (-2.91)	-49.21 (-3.67)	-50.49 (-3.08)	-28.33 (-2.02)	-26.43 (-1.84)	-54.7 (-3.68)	-30.71 (-1.8)	-30.44 (-1.76)	-36.98 (-1.87)
April temperature square	57.65 (1.89)	55.5 (1.98)	117.04 (4.69)	67.76 (2.6)	50.12 (1.99)	86.48 (2.95)	65.08 (2.52)	54.95 (2.12)	94.15 (3.41)	98.76 (3.1)	112.57 (3.5)	110.56 (3.09)
July temperature square	-31.29 (-0.86)	51.41 (1.53)	50.53 (1.71)	29.9 (0.99)	33.25 (1.13)	69.2 (1.99)	32.99 (1.1)	16.73 (0.55)	7.64 (0.24)	87.06 (2.34)	77.45 (2.08)	75.36 (1.8)
October temperature square	-49.8 (-1.04)	-45.93 (-1.05)	-98.71 (-2.53)	0.63 (0.02)	-31.94 (-0.82)	-100.03 (-2.18)	-38.56 (-0.96)	-33.18 (-0.83)	-17.63 (-0.41)	-78.45 (-1.56)	-147.24 (-2.91)	-101.35 (-1.77)
Jan precipitation	6.66 (0.45)	19.94 (1.48)	26.5 (2.22)	23.53 (1.92)	11.86 (0.99)	31.92 (2.31)	27.39 (2.26)	23.62 (1.95)	16.49 (1.27)	35.65 (2.36)	37.54 (2.47)	47.77 (2.81)
April precipitation	-17.72 (-2.08)	-12.32 (-1.56)	-6.33 (-0.9)	-22.96 (-3.16)	-1.92 (-0.27)	-23.7 (-2.9)	-17.91 (-2.45)	-21.26 (-2.9)	-13.65 (-1.72)	-16.7 (-1.82)	-21.95 (-2.39)	-31.37 (-3.05)
July precipitation	-1.62 (-1.74)	-0.3 (-0.36)	-0.51 (-0.68)	0.36 (0.46)	-0.5 (-0.65)	0.55 (0.63)	0.55 (0.72)	-0.02 (-0.03)	0.59 (0.7)	-0.22 (-0.23)	-0.86 (-0.89)	0.04 (0.04)
October precipitation	6.1 (1.25)	-3.97 (-0.87)	-5.42 (-1.34)	-0.59 (-0.14)	-6.68 (-1.64)	0.4 (0.09)	-0.44 (-0.11)	3.38 (0.82)	5.6 (1.29)	0.33 (0.07)	6.34 (1.25)	8.3 (1.49)
January precipitation square	-0.1 (-0.2)	0.43 (0.95)	-0.18 (-0.44)	-0.24 (-0.58)	-0.06 (-0.15)	-0.43 (-0.91)	-0.18 (-0.42)	-0.61 (-1.44)	-0.64 (-1.42)	-0.27 (-0.51)	0 (-0.01)	-0.24 (-0.4)
April precipitation square	0.3 (2.34)	0.24 (2.05)	0.29 (2.77)	0.36 (3.29)	0.14 (1.31)	0.35 (2.86)	0.32 (2.96)	0.3 (2.75)	0.39 (3.25)	0.41 (3.04)	0.35 (2.61)	0.4 (2.7)
July precipitation square	0.01 (-0.66)	0.01 (0.23)	0.01 (-0.55)	0.01 (1.2)	0.01 (-0.01)	0.01 (1.33)	0.01 (0.68)	0.01 (1.34)	0.01 (0.67)	0.01 (1.95)	0.01 (2.19)	0.01 (2.82)
October precipitation square	-0.01 (-0.5)	-0.05 (-2.16)	-0.03 (-1.38)	-0.02 (-0.93)	-0.05 (-2.52)	-0.04 (-1.77)	-0.03 (-1.42)	-0.05 (-2.17)	-0.08 (-3.64)	-0.08 (-3.05)	-0.06 (-2.24)	-0.04 (-1.34)
(Jan rain)x(Jan temp)	-1.67 (-0.44)	-2.42 (-0.7)	-5.32 (-1.73)	0.93 (0.29)	-3.68 (-1.19)	-7.82 (-2.14)	-2.73 (-0.86)	-3.27 (-1.01)	-4.95 (-1.45)	-1.56 (-0.39)	-0.59 (-0.15)	0.1 (0.02)
(Apr rain)x(Apr temp)	9.44 (2.84)	3.68 (1.19)	9.24 (3.36)	8.47 (2.96)	4.47 (1.6)	7.18 (2.24)	6.96 (2.45)	6.71 (2.33)	11.43 (3.72)	9.12 (2.59)	9.02 (2.53)	12.37 (3.12)

Table 4.4: Comparison of pooled, averaged, and repeated cross-sectional regression results (cont.)

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
(Jul rain)x(Jul temp)	-1.33	-0.35	-0.44	0.38	-0.37	0.2	-0.15	-0.1	-0.42	0.43	0.26	1.14
	(-2.62)	(-0.74)	(-1.06)	(0.89)	(-0.87)	(0.41)	(-0.36)	(-0.23)	(-0.9)	(0.8)	(0.49)	(1.89)
(Oct rain)x(Oct temp)	-1.24	4.84	2.96	-0.07	4.69	3.88	2.43	1.7	2.3	7.19	5.63	-0.21
	(-0.51)	(2.14)	(1.47)	(-0.04)	(2.31)	(1.66)	(1.18)	(0.82)	(1.04)	(2.78)	(2.15)	(-0.07)
Soil 1	86.23	9.13	-15.44	124.02	1.69	56.19	166.85	210.15	225.71	225.24	209.87	177.1
	(0.87)	(0.1)	(-0.19)	(1.47)	(0.02)	(0.59)	(1.96)	(2.45)	(2.46)	(2.11)	(1.95)	(1.46)
Soil 2	232.71	41.41	127.82	72.12	83.05	220.41	181.09	207.17	341.24	178.66	250.92	271.13
	(1.87)	(0.36)	(1.24)	(0.69)	(0.83)	(1.89)	(1.76)	(2.02)	(3.1)	(1.41)	(1.98)	(1.91)
Soil 3	-42.86	-107.32	-151.86	-85.35	-178.89	-239.77	-143.78	-94.82	-40.93	-205.47	-159.72	-180.79
	(-0.26)	(-0.7)	(-1.1)	(-0.6)	(-1.29)	(-1.49)	(-1.02)	(-0.66)	(-0.27)	(-1.17)	(-0.9)	(-0.91)
Soil 4	82.43	261.72	137.27	114.14	181.99	36.37	95.4	147.11	285.6	244.41	271.74	269.3
	(0.53)	(1.83)	(1.1)	(0.87)	(1.45)	(0.25)	(0.74)	(1.11)	(2.05)	(1.5)	(1.67)	(1.47)
Soil 5	202.05	-30.56	-61.57	-32.9	-24.25	-9.29	-29.33	4.45	49.89	-41.42	-200.1	-46.01
	(0.92)	(-0.15)	(-0.34)	(-0.17)	(-0.14)	(-0.05)	(-0.17)	(0.03)	(0.27)	(-0.18)	(-0.86)	(-0.17)
Soil 6	300.54	175.23	128.36	170.53	48.65	58.48	-16.71	101.62	64.58	89.56	-82.1	43.05
	(1.22)	(0.76)	(0.62)	(0.8)	(0.25)	(0.26)	(-0.08)	(0.52)	(0.3)	(0.34)	(-0.31)	(0.14)
Cultivators/hectare	-171.81	-132.78	243.58	-37.73	38.81	-36.14	112.71	-97.21	-40.98	-266.96	-146.77	-275.17
	(-0.95)	(-0.8)	(1.54)	(-0.23)	(0.24)	(-0.2)	(0.69)	(-0.62)	(-0.25)	(-1.64)	(-0.93)	(-1.72)
Bulls/hectare	933.06	-105.19	-51.81	114.27	-265.64	39.24	-215.59	-169.39	-543.36	-390.8	-459.34	-364.42
	(4.66)	(-0.58)	(-0.3)	(0.61)	(-1.49)	(0.18)	(-1.08)	(-0.9)	(-2.46)	(-1.64)	(-1.93)	(-1.45)
Tractors/hectare	19790	59948	59400	28455	39529	68137	53559	35719	28826	27208	26635	42931
	(0.61)	(2.25)	(2.67)	(1.42)	(2.37)	(4.04)	(3.98)	(3.03)	(2.45)	(2.46)	(2.58)	(4.06)
Population Density	24.15	44.58	20.43	-22.46	19.71	8.58	-8.63	22.74	-29.5	14.33	4.57	-34.94
	(0.79)	(1.57)	(0.84)	(-0.8)	(0.8)	(0.31)	(-0.36)	(0.95)	(-1.22)	(0.55)	(0.17)	(-1.22)
Literacy	1219.15	667.11	606.06	1101.6	663.49	914.05	188.98	521.63	685.16	802.45	754.32	893.68
	(2.14)	(1.28)	(1.32)	(2.38)	(1.52)	(1.85)	(0.44)	(1.23)	(1.52)	(1.56)	(1.49)	(1.63)
Fraction of area under HYV	830.83	1336.02	966.13	994.4	622.34	-111.39	551.4	199.56	-25.01	-204.87	-166.9	-248.03
	(2)	(3.57)	(3.24)	(3.17)	(2.04)	(-0.33)	(1.93)	(0.73)	(-0.09)	(-0.73)	(-0.61)	(-0.82)
Latitude	11.93	-256.49	-324.18	-48.92	-156.27	-284.42	-149.65	-31.55	-215.29	-156.36	-169.79	-60.09
	(0.11)	(-2.64)	(-3.77)	(-0.55)	(-1.81)	(-2.74)	(-1.67)	(-0.35)	(-2.24)	(-1.41)	(-1.53)	(-0.47)
Adj, R-square	0.40	0.50	0.56	0.54	0.48	0.43	0.46	0.43	0.45	0.46	0.44	0.44
Number of Observations	270	270	270	270	270	270	270	270	270	270	270	270

Comparing the coefficients row by row, it is readily observed that the model is remarkably robust across all three econometric procedures. The climate coefficients retain their signs (though their magnitude varies), with very few exceptions. Some of the climate coefficients change signs in some years. For example, though January temperature coefficients are for the most part negative, they are positive in 1975, 1978, 1979, and 1982. This is most likely due to the effect of weather on annual net revenues. Coefficients on the control variables are also markedly stable. The coefficient on fraction of area under HYV is positive and significant for the 1974-1979 period, the period when the Green Revolution was at its peak. Since the yearly dummies in the pooled regression control for weather and other distortions, we base the impacts in this analysis, on the regression coefficients from the pooled version.[11]

SIMULATION OF IMPACTS AND INTERPRETATION OF CLIMATE COEFFICIENTS

SIMULATION OF NET REVENUE PER HECTARE

As the regression results indicate, climate has a highly non-linear and significant impact on net revenues. The quadratic and interaction climate terms are significant, capturing underlying nonlinearities. As mentioned in the previous section, even though the climate variables are demeaned, the interaction terms make the interpretation of the marginal effects at the mean slightly complicated. We thereby compute total, and partial temperature and precipitation effects by season, for a +2°C rise in temperature and a +7% increase in rainfall.

The change in the dependent variable (agricultural net revenues per hectare) is simulated utilizing estimated regression coefficients from the pooled analysis (Table 4.3) for each of the 271 districts for the 1966-1986 period. District level changes in net revenue per hectare are then aggregated to get a measure of the net impact for the country as a whole. The change in net revenue per hectare of a given climate scenario in year y is given by:

$$(18) \quad GW^{y} = \sum_{d=1}^{271} [nrevha_d^y(T_d + \Delta T_{cs}, P_d + \Delta P_{cs}) - nrevha_d^y(T_d, P_d)]$$

where:

$y=1966\ldots1986$,

(T_d, P_d) describes the climate (temperature and precipitation) for district d,

$(T_d + \Delta T_{cs}, P_d + \Delta P_{cs})$ describes the new climate under a simulated climate scenario,

$nrevha_d^y(T_d, P_d)$ = predicted value of the net revenue per hectare for district d in year y,

$nrevha_d^y(T_d + \Delta T_{cs}, P_d + \Delta P_{cs})$ = forecasted value of net revenues under a climate scenario for district d and year y[12]

Yearly changes in the net revenue per hectare are correspondingly averaged over the 20 year period (1966-86) to yield an average net impact.

[11] Impacts from the averaged procedure are very similar to those from the pooled one.

[12] If the resulting loss from a climate change for any individual district was more than that district's (predicted) net revenue, then the loss was limited to its current net revenue.

(b) Seasonal Temperature and Precipitation Effects

The change in net revenue per hectare is calculated for the benchmark warming scenario of a +2.0°C rise in mean temperature and a +7% increase in mean precipitation levels for each of the four months (IPCC, 1996).[13] Table 4.5 presents these impacts by season.

Table 4.4: Change in net revenue per hectare (1980 Rs.) seasonal temperature and precipitation effects

	January	April	July	October	**Total**
Temperature Effects (+2.0°C)	-408.1	-414.1	-66.4	+699.7	-207.9
Precipitation Effects (+7%)	+28.6	-13.7	+0.30	-0.80	+14.4

Note: Average net revenue per hectare (in 1980 Rs.)=1424.7

Overall, a rise in temperatures is harmful, reducing net revenue per hectare, whereas an increase in precipitation levels is beneficial, increasing net revenue per hectare. However, net revenues are much more sensitive to temperatures than to precipitation. Consequently, the negative temperature effects exceed the positive precipitation effects, leading to an overall reduction in net revenue per hectare.

As observed from the table, there is significant *seasonal variation* in both temperature and precipitation effects. Seasonal impacts of a +2.0°C rise in temperature are as follows: The change in net revenue per hectare in October, the post-summer harvesting season and the planting season for winter crops, is positive. However, the change in net revenue per hectare is negative in January, the winter growing season; in April, the summer planting season; and in July, the post-monsoon summer growing season. April and January effects are the most negative, and outweigh the beneficial October effect, leading to an overall reduction in net revenues per hectare.

October temperature effects may be positive because warmer temperatures during this harvesting season may facilitate the ripening process and ensure optimal crop production. This finding is consistent with the U.S. and Brazilian results (Mendelsohn et al., 1994; Sanghi, 1997). Negative January temperature effects could be the result of heat sensitivity of winter crops (such as wheat and winter maize) to even incremental increases in temperature.[14] Furthermore, because of the shorter hibernation period as a result of a warmer winter, there can be an increased incidence of pests and insects such as rice stemborers, leaf and plant hoppers, blast, and tungro. Such infestation has a damaging impact on agricultural activity.[15] This finding is also consistent with U.S. and Brazilian results mentioned above. Negative April and July temperature effects

[13] The partial effect of, say, January temperatures, is calculated by simulating an increase in January temperature only, holding all else constant in equation (18).

[14] This finding is consistent with detailed studies on wheat production in India (Rosenzweig and Parry, 1993; Rao and Sinha, 1994).

[15] A pioneering global study by Cramer (1967) estimates losses due to insects and pests to be as high as 34.4% of potential production before harvest. Way (1976) quantifies actual pest losses to the order of 35% reduction of the total rice crop in India. Later studies report loss estimates of 23.7% and 18.3% of potential production in East and Southeast Asia, and in the Central Luzon region of the Philippines (Ahrens et al.,1983; Litsinger et al., 1987).

are, in all probability, the result of increased heat stress during already hot planting and growing seasons.

Although minor relative to temperature effects, there is notable seasonal variation in precipitation effects as well. The January effect is the most positive, reflecting the potential benefit of increased moisture to winter crops. The April effect is the most negative, perhaps because higher rainfall during this planting season could adversely affect seedling establishment and growth. The October effect is mildly negative, indicating that increased rainfall during harvesting is likely to be harmful. The impact of increased precipitation in July is marginal, since most of the country receives ample rainfall during this time.

REGIONAL DISTRIBUTION OF SEASONAL IMPACTS

Given the broad effects outlined above, the *regional variations* in temperature and precipitation impacts in each season are now discussed. Figures 4.11-4.14 exhibits the change in net revenue per hectare regionally and seasonally from a uniform increase of +2.0°C temperature across the four months. As seen from the figure, although the temperature increase is uniform, the spatial distribution of impacts is not.

In the (winter) month of January, the relatively warm Southern-Central peninsula is the most negatively impacted from the temperature increase. Cooler northern districts of Punjab, Haryana, and Western Uttar Pradesh benefit from warming. This could be because these regions can shift to higher (warmer) value activities, which the Southern-Central peninsula may not be able to, since it is much warmer. April effects are the most negative for the cooler regions of Punjab, Haryana, and western Uttar Pradesh, the main temperate wheat growing area of India. This probably reflects the affinity of wheat for cooler temperatures. A counter-intuitive result is that in April, the hottest districts (in the Central-Southern peninsula) show a gain. This could be because these are the regions that primarily grow jowar and bajra, which are both heat loving crops. However, since these are low value activities (compared to rice, wheat, and maize), the overall loss in net revenue is still negative from an increase in April temperatures. The distribution of July temperature effects is mostly neutral. The distribution of October temperature effects is almost uniformly beneficial, since a warmer harvesting season is expected to facilitate expeditious (summer) crop harvesting.

The regional distribution of the partial temperature (+2.0°C) and precipitation (+7%) effects are portrayed in Figures 4.11-4.14. The combined net impact (+2.0°C and +7%P) is portrayed in Figure 4.15. From a comparison of Figures 4.11-4.14 and 4.15-4.16, it can be seen that the minor precipitation effects do not alter the spatial patterns of the overall regional impacts. Therefore, overall regional impacts shown in Figures 15-16 are mainly a function of the regional temperature effects shown in Figures 4.11-4.14.

Figure 4.11: District level January temperature effects +2°C (1980 Rs.)

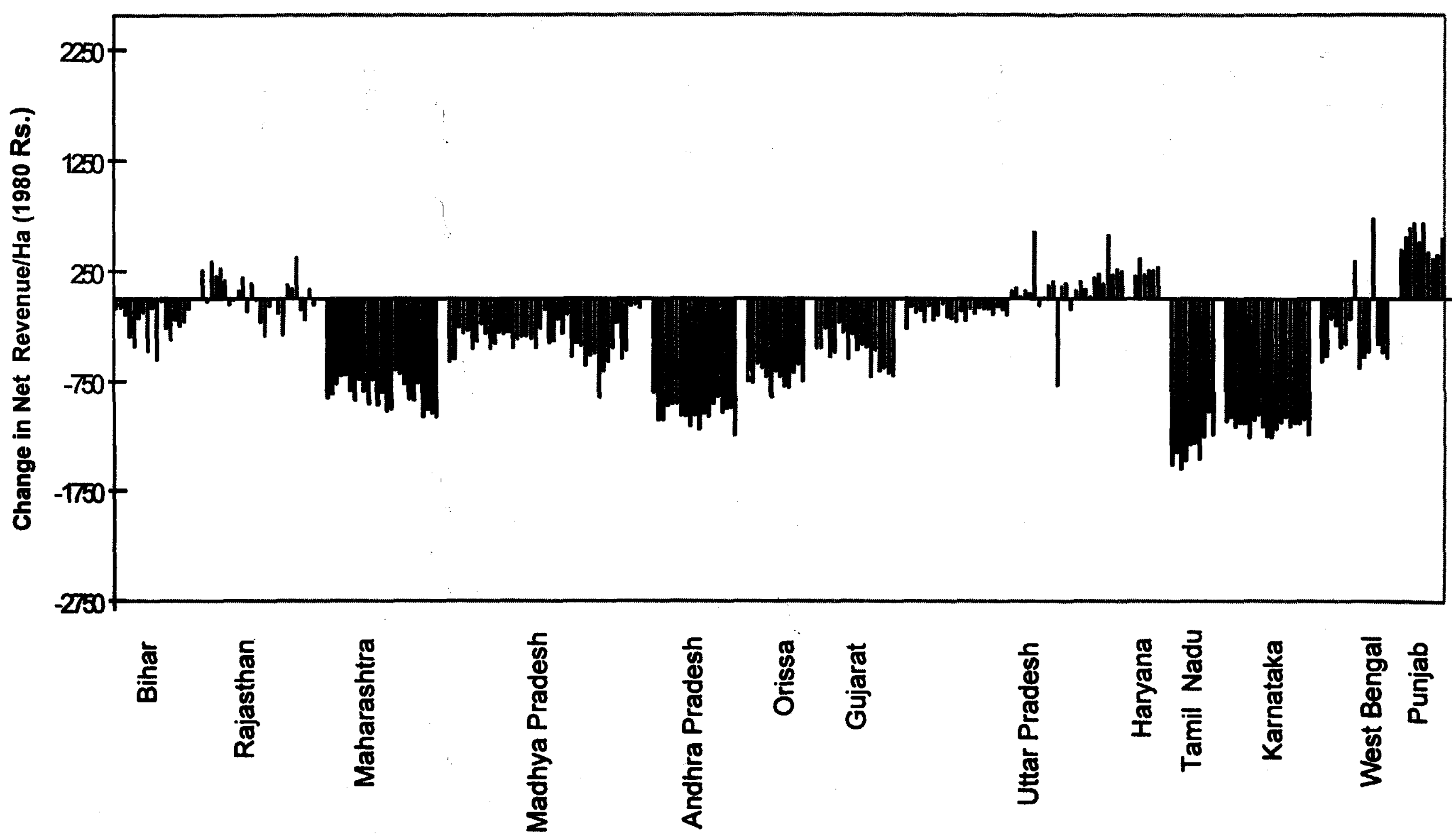


Figure 4.12: District level April temperature effects +2°C (1980 Rs.)

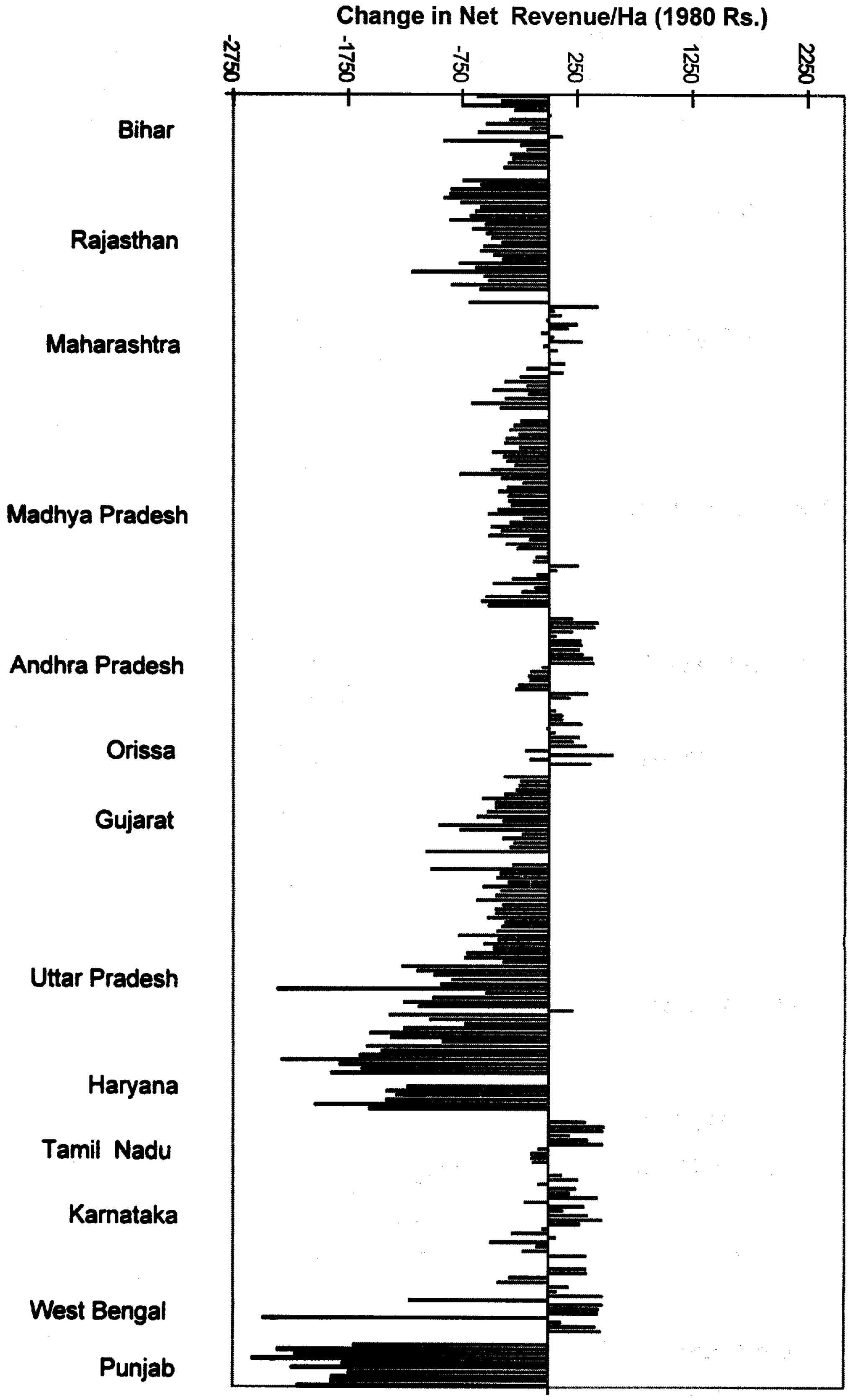


Figure 4.13: District level July temperature effects +2°C (1980 Rs.)

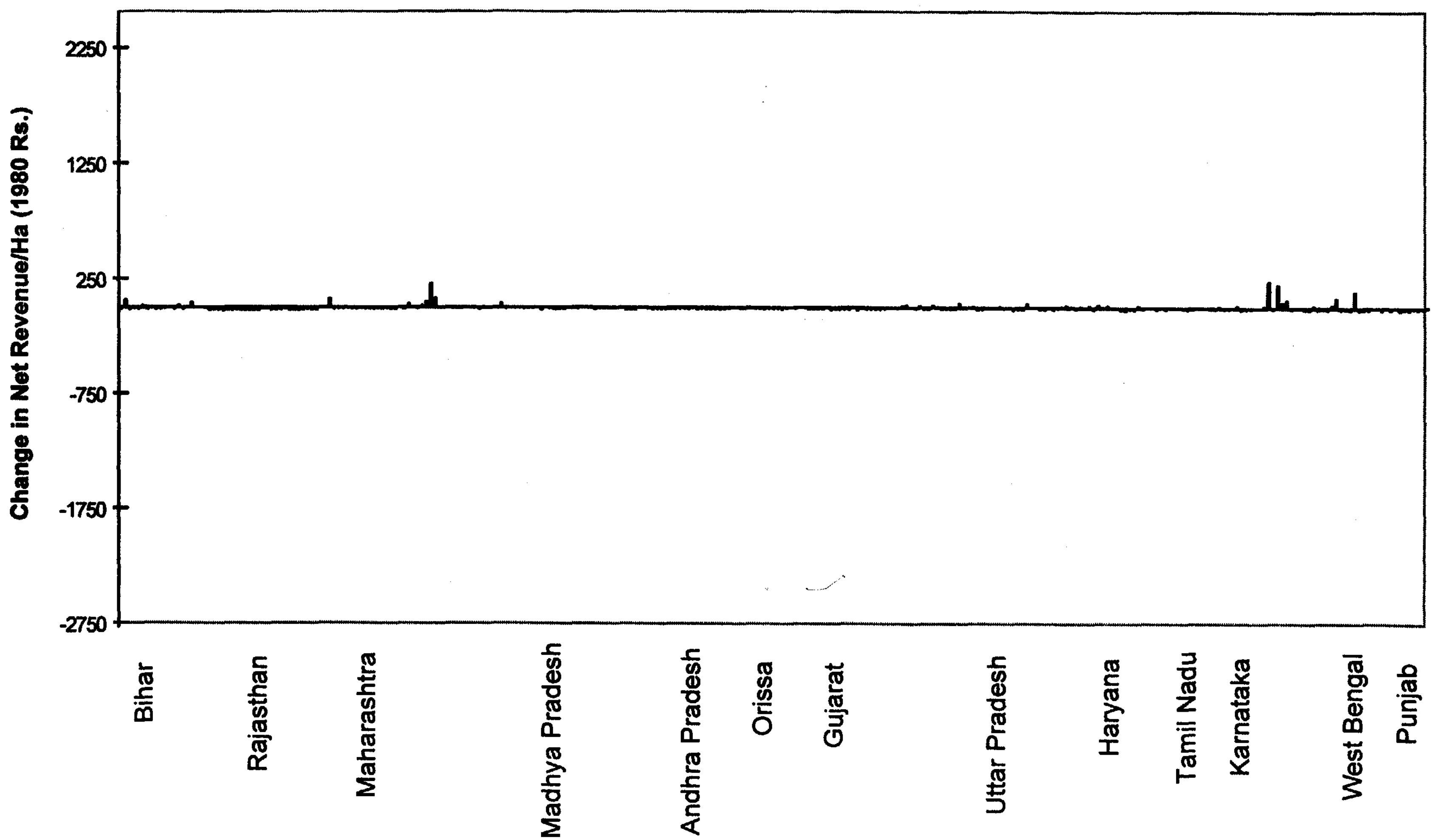


Figure 4.14: District level October temperature effects +2°C (1980 Rs.)

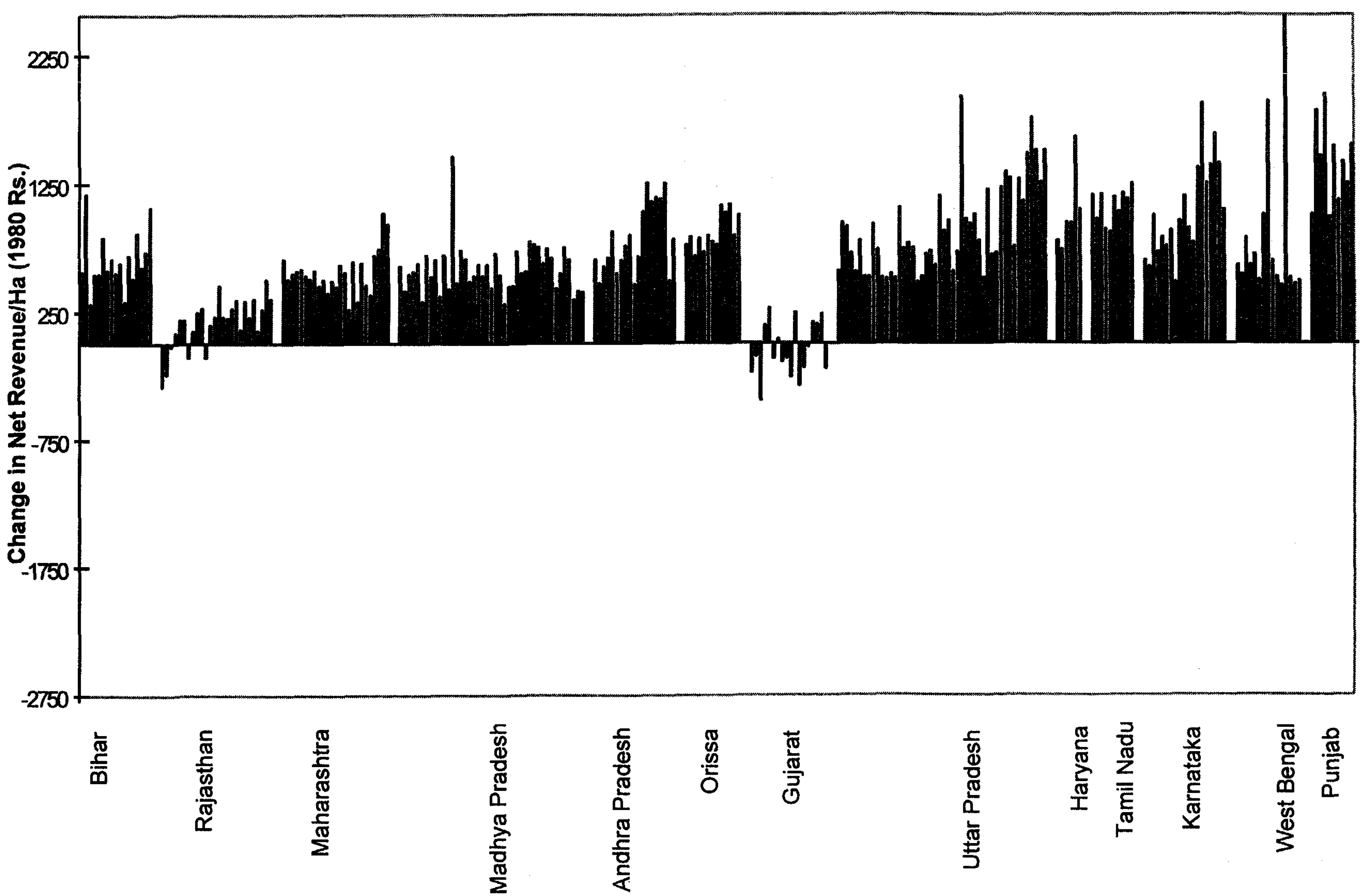


Figure 4.15: District level partial precipitation (+7%) effect (1980 Rs.)

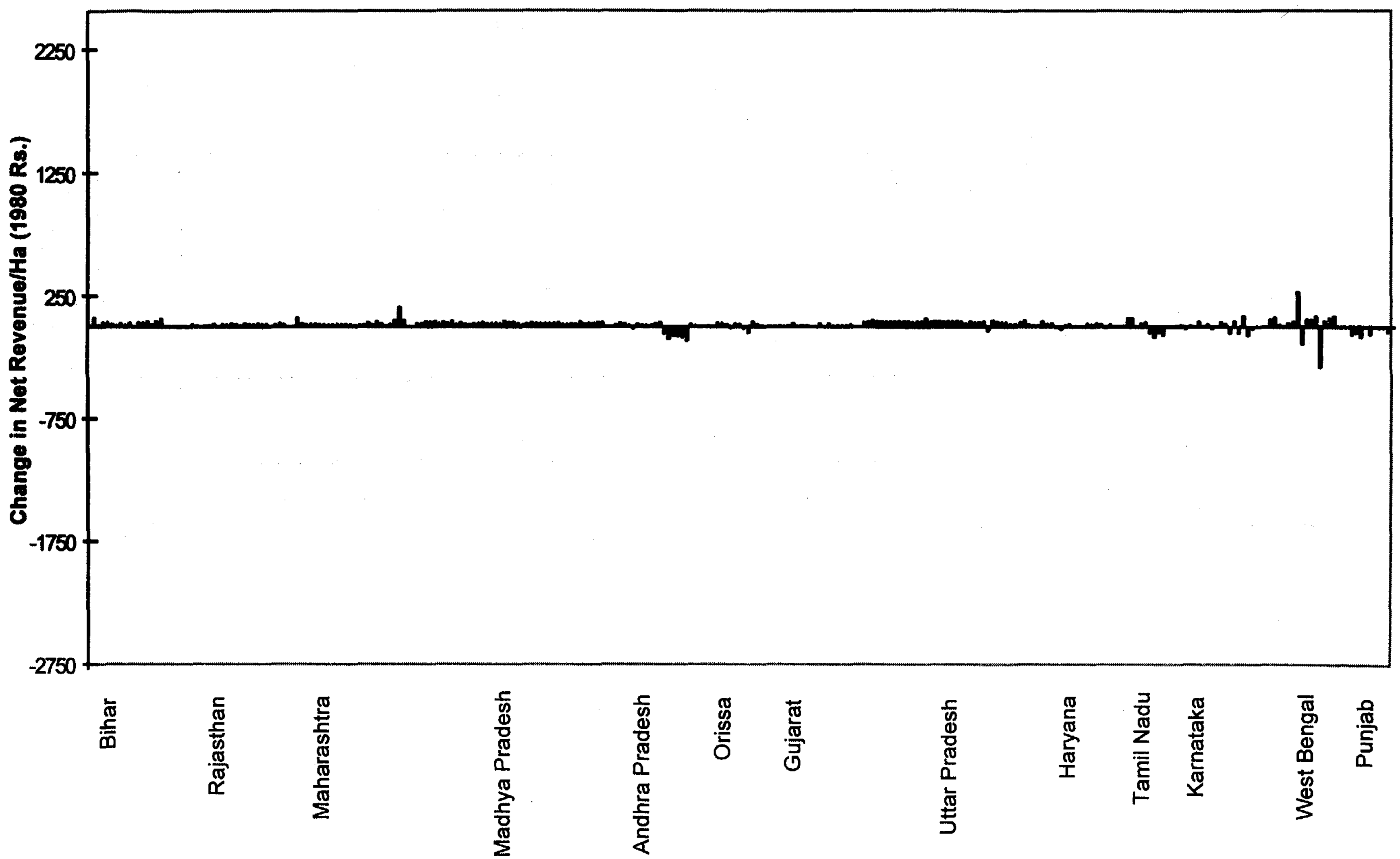


Figure 4.16: District level partial temperature (+2%) effect (1980 Rs.)

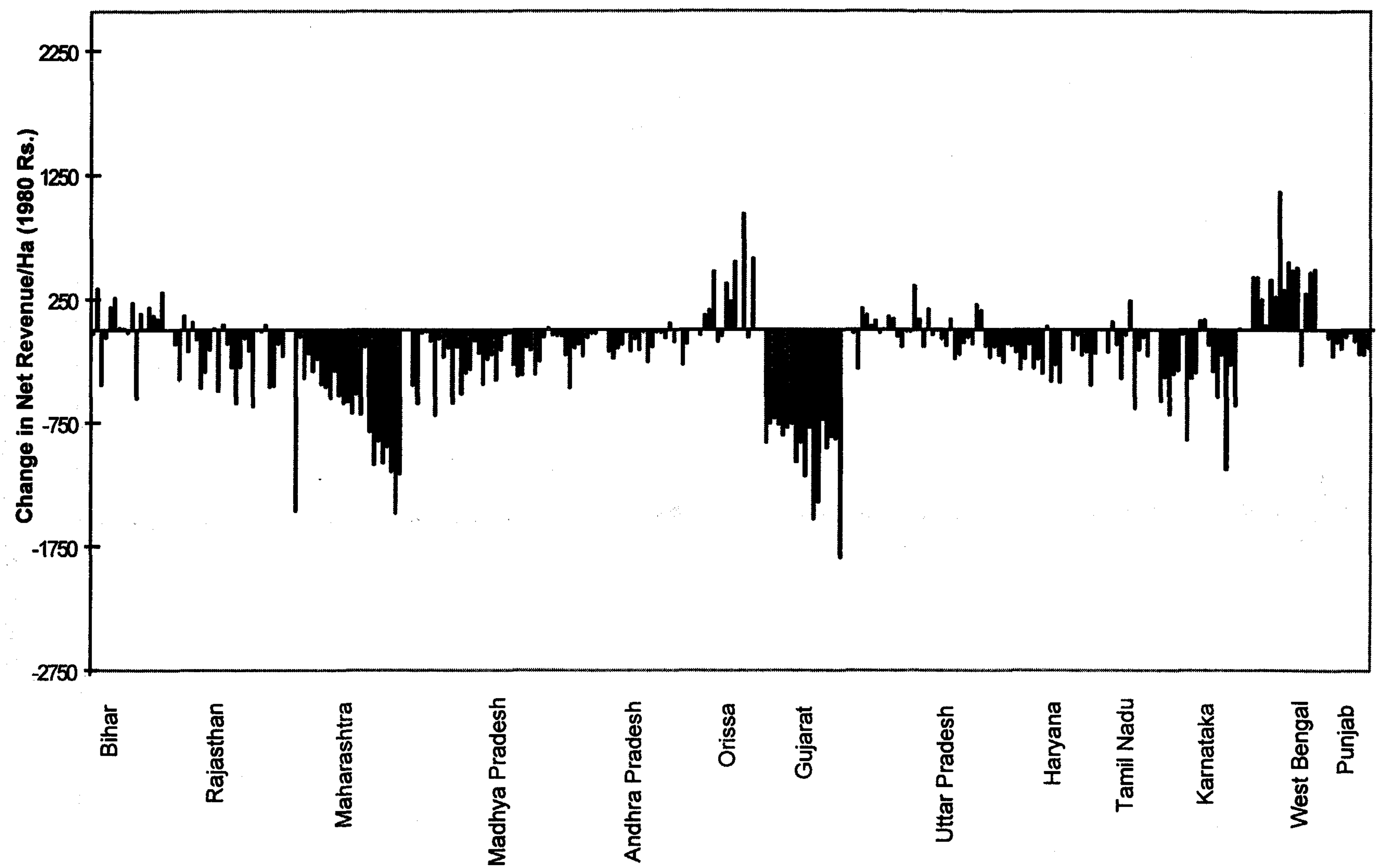
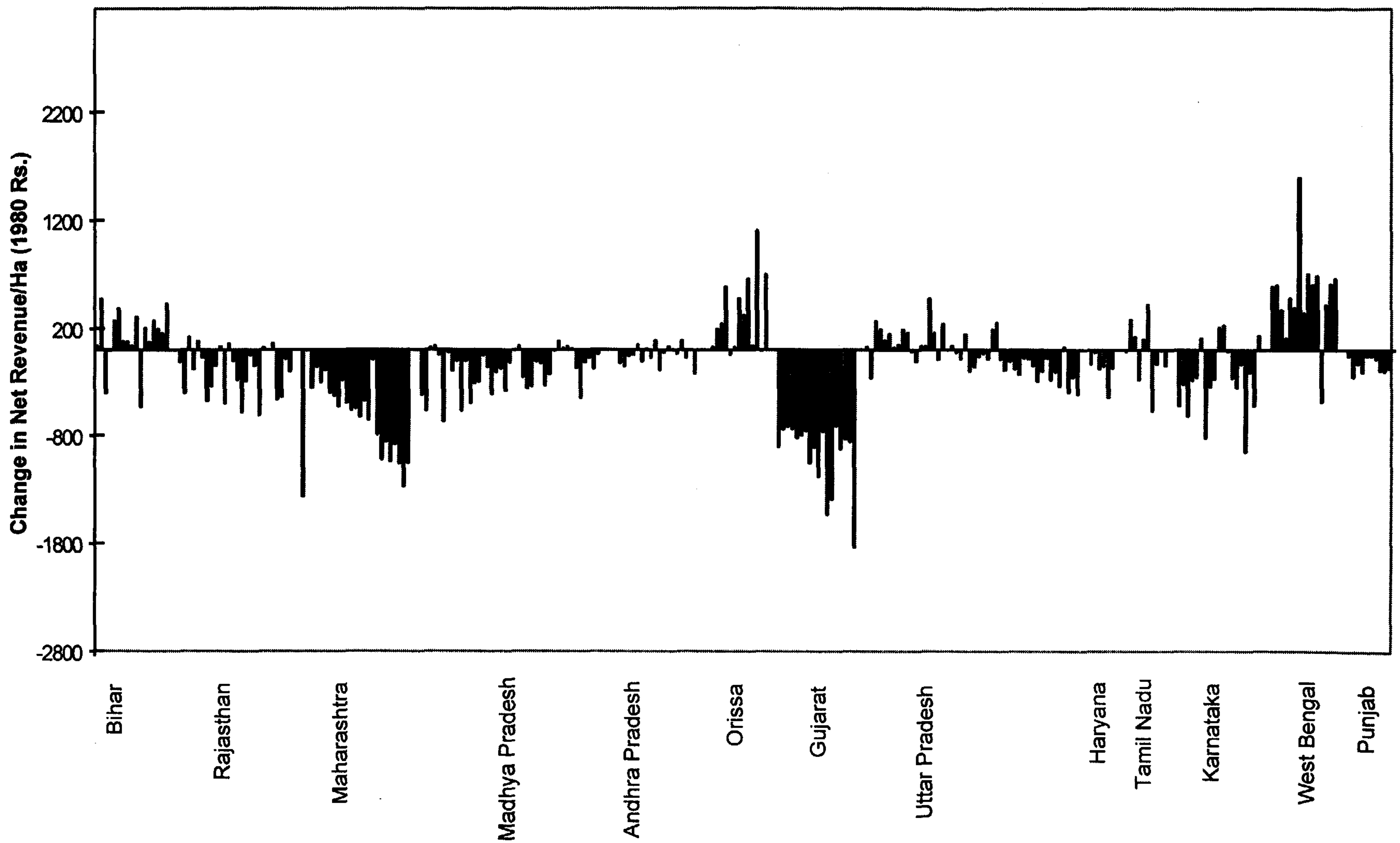


Figure 4.17: District level bench mark warming (+2°C;+7%) effect (1980 Rs.)



OVERALL REGIONAL IMPACTS

Displaying the spatial temperature effects provides useful insights into overall regional impacts displayed in Figures 4.15 and 4.16. Aggregating the temperature effects in Figures 4.11-4.14, it is readily observed that the coastal and inland regions of Gujurat, Maharashtra, and Karnataka are most adversely affected as the harmful January and April effects overcome the beneficial October and (mildly positive) July effects. The high value wheat (winter crop) growing regions of Punjab, Haryana, and Western Uttar Pradesh are also damaged, but not as much as the western districts, because of potential substitution to higher value activities (such as summer rice, for example) in currently cooler regions. The agriculturally low value, hot and dry districts of Rajasthan and Central India are also negatively impacted. However, not all warming is harmful. Eastern districts of Andhra Pradesh, Orissa and West Bengal benefit mildly from warming. Overall, the net impact for the country is negative.

IMPLICATIONS FOR GLOBAL WARMING

The above findings have implications for potential impact of global warming on Indian agriculture. As described in Section 5, the regression coefficients are applied to forecast changes in aggregate net revenues $(\text{net revenue per hectare} \cdot \text{total cropped area})$ for selected climate scenarios. Given the inherent uncertainty in predicting precise country forecasts, we consider a range of climate scenarios, including IPCC's best-guess estimate of a 2.0°C rise in temperature and a 7% increase in rainfall (IPCC, 1996). Although forecasts for India employing General Circulation Models (GCMs) were made for this project, they are believed to be too high in their general projections, especially for rainfall (Lonergan, 1998). For a benchmark doubling of carbon from pre-industrial levels (expected to occur sometime in the next century), these models predict as much as a +288% increase in precipitation levels for the month of October in Southern India, and as high as a +6.42°C rise in winter temperatures for Northern India. One GCM even predicts the monsoon at the wrong time of the year. For these reasons, GCM forecasts are not used to compute impacts. Though the impacts from uniform warming scenarios shown below include all farmer adaptations, they do not consider (damage reducing) CO_2 fertilization effects.

In order to express the impact on the 1994 Indian economy in 1996 US dollars, net impacts were converted from 1980 Rupees to 1990 U.S. dollars by using official exchange rates (*Source*: International Financial Statistics Yearbook, International Monetary Fund, Washington D.C.,1996). Net impacts were then converted to 1996 U.S dollars using a GDP deflator (*Source*: Budget of the United States Government, Historical Tables, Fiscal Year 1998). Table 5.6 shows the impacts for a range of climate scenarios in 1996 U.S. dollars, and as a percentage change in net revenues.

For benchmark warming, the losses are a 12.3% reduction in net revenues. The response function with respect to temperature is hill-shaped, with higher temperatures reducing net revenues. Although increased precipitation has a moderating impact on temperature effects, overall losses continue to be dominated by negative temperature effects.

Compared to impacts forecasted for India by calibrating U.S. climate response functions (0.31% loss GDP for the (+2.5°C, +7%mm) scenario in Mendelsohn, 1996), the losses calculated here are much higher (12.3% reduction in net revenues, the relevant dependent variable, for the (+2.0°C, +7%mm) scenario). This difference makes evident potential errors in using climate response functions from one region to make forecasts about others, given fundamental economic, technological, and ecological differences, including key differences in adaptability of agricultural systems. To quantify these differences, as a future project, we plan to use calibrated response functions from Brazil, India, and the U.S. to estimate impacts for each of these countries from response functions derived from the other two.

Table 4.5: Impacts in 1996 billion dollars

Impacts	+0.0°C	+1.0°C	+2.0°C	+3.5°C
+0%	0	-1.06 (-8.76)	-1.94 (16.03)	-2.54 (-21)
+7%	+0.13 (+1.07)	-0.77 (-6.36)	-1.49 (-12.30)	-1.91 (-15.78)
+14%	+0.27 (+2.23)	-0.46 (-3.80)	-1.03 (-8.51)	-1.25 (-10.33)

Note: Total net revenue in 1996 billion $ = 12.10.
Numbers in parentheses are % change in net revenue.

CONCLUSIONS AND POLICY IMPLICATIONS

This report provides the first detailed estimates of the impact of climate change on India's agricultural sector. The analysis utilizes the Ricardian methodology that captures farmer adaptation to varying environmental factors. The methodology is modified to take into account key differences between agricultural sectors in developed and developing countries.

We analyze data from 271 districts for the period 1966-1986 to examine the farmer-adapted responses to climate variations across the country. A wide variety of crops that include cereals, pulses, oilseeds, fibre crops, and other non-food grain crops such as sugarcane and tobacco are considered. Using a pooled analysis, district-level net revenues per hectare are regressed on climate, edaphic, geographic and control variables to estimate a best-use value function across different districts. Yearly dummies are used to control for annual variations in weather, prices, and other factors affecting agriculture over the 20-year period. The pattern of estimated climate coefficients is remarkably robust and consistent over three econometric specifications, one of which includes twenty independent cross-sections (Table 4.4).

Findings indicate that climate change will have a overall negative impact on Indian agriculture, with varying seasonal and regional implications. Applying IPCC's uniform benchmark warming scenario of +2.0°C rise in mean temperature and a +7% increase in mean precipitation levels, we calculate the impact to be a 12.3% reduction in net revenues for the country as a whole (Table 4.6). We also compute separately the effects of the rise in temperature (+2.0°C), as well as the rise in precipitation (+7%). We find that a rise in temperature is damaging, whereas an increase in precipitation levels is beneficial. However, the positive precipitation effect is dwarfed by the negative temperature effect (Figures 4.15-4.16). These temperature and precipitation effects are further broken down into seasonal and regional impacts.

Seasonal impacts (Table 4.5) of a +2.0°C rise in temperature are as follows: The change in net revenues per hectare in October, the post-summer harvesting season and the planting season for winter crops, is positive. However, the change in net revenues per hectare is negative in January, the winter growing season; in April, the summer planting season; and in July, the post-monsoon summer growing season. April and January effects are the most negative, and outweigh the beneficial October effect, leading to an overall reduction in net revenues per hectare.

October temperature effects may be positive because warmer temperatures during this harvesting season may facilitate the ripening process and ensure optimal crop production. Negative January temperature effects could be the result of heat sensitivity of winter crops (such as wheat and winter maize) to even incremental increases in temperature, as well as potential crop losses from a higher incidence of pest infestations. Negative April and July temperature effects are, in all probability, the result of increased heat stress during already hot planting and growing seasons.

Although minor, the seasonal impacts of a 7% increase in precipitation levels (Table 4.5) are as follows: the January effect is the most positive, reflecting the potential benefit of increased moisture to winter crops. The April effect is the most negative, perhaps because higher rainfall during this planting season could adversely affect seedling establishment and growth. The October effect is mildly negative, indicating that increased rainfall during harvesting is likely to be harmful. The impact of increased precipitation in July is marginal, since most of the country receives ample rainfall during this time.

There is significant regional variation in the impacts from a +2.0°C rise in mean temperature and a +7% increase in mean precipitation levels (Figure 4.17). Coastal and inland regions of Gujurat, Maharashtra, and Karnataka are most negatively affected. High-value agricultural regions of Punjab, Haryana, and Western Uttar Pradesh show a small loss. The magnitude of the small losses in these regions suggests that agriculture will shift to potentially more valuable summer crops. The agriculturally low value, hot and dry districts of Rajasthan and Central India are negatively impacted. However, not all warming is harmful. Eastern districts of Andhra Pradesh, Orissa and West Bengal benefit mildly from warming.

Policy implications arising from the findings in the paper include the need to develop increased heat tolerance in high-value temperature sensitive crops. Furthermore, minimizing run-offs to capture benefits from increased rainfall will be a beneficial strategy, particularly for winter crops. The potential for increased pest infestations as a result of warmer winter climates calls for research into mitigation strategies. Finally, since the potential to substitute to other activities is lower, subsistence farming (not included in this analysis) is likely to be as, if not more, adversely affected as the commercial sector by warming. Thus, appropriate mitigation strategies, such as technical and financial support, may need to be in place.

Multilateral efforts to contain and mitigate potential global warming are already underway at the international level. It remains to be seen whether the Framework Convention on Climate Change (FCCC), the international treaty on climate change, will be successful in realizing its objective of getting nations to voluntarily restrict their greenhouse gas emissions at 1990 levels by the turn of the century. While the analysis in this paper may be broadly applicable to some countries in South Asia with comparable agricultural sectors, detailed research on the impact of climate change on agriculture in other developing countries is required. Furthermore, research on other climate sensitive sectors such as energy and forestry will be necessary to unmask more fully the economic impacts of possible climate change in developing countries.

APPENDIX A: PRODUCTION FUNCTION ESTIMATES

This Appendix reports the regression results of estimating an (incomplete) production function for the five major Indian crops: rice, wheat, maize, jowar, and bajra. For each crop, three different specifications were tried: linear-quadratic, log-linear, and log-log. Regression results from the specification that gave the best fit are reported below in Tables 4A.1-4A.5. Observations were pooled for the period 1966--1986 for all the regressions with 1979 as the reference year. As was the case in the net revenues regressions, soil types and top soils that had coefficients of similar magnitude and signs in preliminary runs were combined for ease of handling. The results below indicate that climate has a significant and non-linear impact on crop yields.

Table 4A.1: Yield regressions for rice

Independent Variable	Parameter	Independent Variable	Parameter
Intercept	1.62 (4.58)	dmyr69	0.24 (5.83)
Jan temperature	0.17 (17.09)	dmyr70	0.34 (8.35)
April temperature	-0.22 (-25.26)	dmyr71	0.31 (7.58)
July temperature	0.24 (14.22)	dmyr72	0.06 (1.35)
October temperature	-0.21 (-11.59)	dmyr73	0.4 (9.82)
Jan precipitation	-0.01 (-4.08)	dmyr74	0.19 (4.53)
April precipitation	0.01 (1.55)	dmyr75	0.49 (12.02)
July precipitation	-0.01 (-9.35)	dmyr76	0.41 (10.05)
October precipitation	0.01 (3.85)	dmyr77	0.56 (13.78)
Soil 1	0.17 (10.77)	dmyr78	0.56 (13.92)
Soil 2	-0.16 (-5.46)	dmyr80	0.56 (13.89)
Soil 3	-0.04 (-1.23)	dmyr81	0.56 (13.74)
Soil 4	0.05 (1.46)	dmyr82	0.45 (11.08)
dmyr66	-0.09 (-2.05)	dmyr83	0.67 (16.78)
dmyr67	0.19 (4.56)	dmyr84	0.59 (14.36)
dmyr68	0.12 (2.98)	dmyr85	0.6 (14.8)
		dmyr86	0.51 (12.38)

Note: Adjusted R square = 0.45
Number of Observations=5390
Dependent Variable=log(yield per hectare_rice)
()= t-value

Table 4A.2: Yield regressions for wheat

Independent Variable	Parameter ($x10^5$)	Independent Variable	Parameter ($x10^5$)
Intercept	694882.1 (2.07)	Soil 5	-19754.5 (-5.26)
Jan temperature	-81876.7 (-9.35)	dmyr66	-37135.9 (-8.5)
April temperature	35090.9 (1.97)	dmyr67	-20893.9 (-4.82)
July temperature	149178.9 (8.36)	dmyr68	-16309.4 (-3.74)
October temperature	-194300 (-5.47)	dmyr69	-12820.5 (-2.96)
Jan temperature square	1762.1 (8.93)	dmyr70	-600.4 (-0.14)
April temperature square	-705.3 (-2.37)	dmyr71	4188 (0.97)
July temperature square	-2853 (-9.01)	dmyr72	-4093 (-0.95)
October temperature square	4404.1 (6.65)	dmyr73	-9210.5 (-2.15)
Jan precipitation	-109.9 (-0.4)	dmyr74	5072.2 (1.17)
April precipitation	829.6 (4.71)	dmyr75	17586.5 (4.1)
July precipitation	242.6 (10.91)	dmyr76	9986.9 (2.31)
October precipitation	-58.9 (-0.63)	dmyr77	18958.8 (4.43)
January precipitation square	-29.6 (-5.72)	dmyr78	20992.7 (4.92)
April precipitation square	-9.06 (-6.37)	dmyr80	13356.9 (3.13)
July precipitation square	-0.28 (-9.29)	dmyr81	20010.1 (4.72)
October precipitation square	-1.3 (-3.52)	dmyr82	31862.7 (7.47)
Soil 1	23374 (12.18)	dmyr83	42895.6 (10.19)
Soil 2	-7786.6 (-4.03)	dmyr84	42226.8 (9.79)
Soil 3	-16028.7 (-3.8)	dmyr85	49152.4 (11.41)
Soil 4	-14778.5 (-4.51)	dmyr86	45549.6 (10.53)

Note: Adjusted R square = 0.58
Number of Observations=5690
Dependent Variable=log(yield per hectare_wheat)
()= t-value

Table 4A.3: Yield regressions for maize

Independent Variable	Parameter	Independent Variable	Parameter
Intercept	6.62 (7.76)	dmyr69	-0.12 (-2.67)
log(Jan temperature)	2.71 (12.89)	dmyr70	0.14 (3.13)
log(April temperature)	-3.67 (-11.65)	dmyr71	-0.28 (-6.17)
log(July temperature)	5.18 (11.15)	dmyr72	-0.02 (-0.45)
log(October temperature)	-5.86 (-11.4)	dmyr73	-0.1 (-2.12)
log(Jan precipitation)	-0.16 (-13.51)	dmyr74	-0.16 (-3.48)
log(April precipitation)	0.04 (4.13)	dmyr75	0.1 (2.21)
log(July precipitation)	0.01 (2.32)	dmyr76	0.08 (1.65)
log(October precipitation)	-0.02 (-0.94)	dmyr77	0.01 (0.19)
Soil 1	-0.01 (-0.16)	dmyr78	0.08 (1.86)
Soil 2	-0.04 (-1.3)	dmyr80	0.08 (1.76)
Soil 3	-0.08 (-1.47)	dmyr81	0.17 (3.8)
Soil 4	0.02 (0.4)	dmyr82	0.16 (3.49)
dmyr66	-0.09 (-1.97)	dmyr83	0.31 (6.96)
dmyr67	-0.01 (-0.21)	dmyr84	0.31 (6.92)
dmyr68	-0.18 (-3.84)	dmyr85	0.17 (3.66)
		dmyr86	0.16 (3.55)

Note: Adjusted R square = 0.25
Number of Observations=5138
Dependent Variable=log(yield per hectare_maize)
()= t-value

Table 4A.4: Yield regressions for jowar

Independent Variable	Parameter	Independent Variable	Parameter
Intercept	-2.45 (-4.61)	dmyr69	-0.01 (-0.23)
Jan temperature	0.09 (6.11)	dmyr70	0.03 (0.51)
April temperature	0.06 (4.51)	dmyr71	-0.14 (-2.44)
July temperature	0.01 (0.03)	dmyr72	-0.10 (-1.78)
October temperature	-0.08 (-3.43)	dmyr73	0.08 (1.51)
Jan precipitation	0.02 (9.67)	dmyr74	0.07 (1.27)
April precipitation	0.01 (3.24)	dmyr75	0.11 (2.04)
July precipitation	0.01 (8.44)	dmyr76	0.17 (3.02)
October precipitation	-0.01 (-0.35)	dmyr77	0.22 (3.99)
Soil 1	0.01 (0.36)	dmyr78	0.23 (4.1)
Soil 2	-0.19 (-8.02)	dmyr80	0.12 (2.08)
Soil 3	-0.59 (-11.62)	dmyr81	0.25 (4.55)
Soil 4	-0.15 (-3.83)	dmyr82	0.14 (2.51)
Soil 5	-0.11 (-2.34)	dmyr83	0.37 (6.73)
dmyr66	-0.10 (-1.79)	dmyr84	0.41 (7.27)
dmyr67	0.01 (0.25)	dmyr85	0.16 (2.89)
dmyr68	-0.10 (-1.81)	dmyr86	0.15 (2.68)

Note: Adjusted R square = 0.29
Number of Observations=4663
Dependent Variable=log(yield per hectare_jowar)
()= t-value

Table 4A.5: Yield regressions for bajra

Independent Variable	Parameter	Independent Variable	Parameter
Intercept	-13.78 (-4.1)	Soil 5	-0.01 (-0.06)
Jan temperature	0.27 (2.7)	dmyr66	0.04 (0.78)
April temperature	-0.58 (-2.81)	dmyr67	0.03 (0.48)
July temperature	0.77 (4.14)	dmyr68	-0.01 (-0.07)
October temperature	0.79 (1.85)	dmyr69	0.08 (1.48)
Jan temperature square	0.01 (-1.93)	dmyr70	0.29 (5.48)
April temperature square	0.01 (2.16)	dmyr71	0.04 (0.72)
July temperature square	-0.01 (-3.92)	dmyr72	0.03 (0.48)
October temperature square	-0.02 (-1.95)	dmyr73	0.12 (2.24)
Jan precipitation	0.02 (5.3)	dmyr74	0.04 (0.74)
April precipitation	-0.01 (-2.45)	dmyr75	0.12 (2.27)
July precipitation	-0.01 (-3.41)	dmyr76	0.16 (3.09)
October precipitation	-0.01 (-4.23)	dmyr77	0.12 (2.29)
January precipitation square	-0.01 (-1.11)	dmyr78	0.12 (2.26)
April precipitation square	-0.01 (-1.01)	dmyr80	0.10 (1.81)
July precipitation square	0.01 (2.38)	dmyr81	0.10 (1.86)
October precipitation square	0.01 (3.96)	dmyr82	0.07 (1.32)
Soil 1	0.01 (0.41)	dmyr83	0.18 (3.37)
Soil 2	-0.05 (-1.69)	dmyr84	0.17 (3.27)
Soil 3	-0.05 (-1.05)	dmyr85	0.08 (1.46)
Soil 4	-0.15 (-6.31)	dmyr86	0.13 (2.39)

Note: Adjusted R square = 0.10
Number of Observations=5690
Dependent Variable=yield per hectare_bajra
()= t-value

APPENDIX B: VARIABLES IN THE ORIGINAL DATA SET

The original data set was created by James McKinsey and Robert Evenson between 1980 and 1990, and has been used in numerous studies of production and productivity in Indian agriculture. The data set contains observations for each of the variables for the agricultural years 1957/58 through 1987/87. The agricultural year 1957/58 is denoted by 1957. Unless noted, all variables are expressed as annual flows or average annual stocks or average annual levels.

This appendix describes in detail the economic variables used in the study as described in the original data set. The next appendix describes the errors that were discovered and corrected for in the original data set.

DATA SOURCE ABBREVIATIONS:

API:	Agricultural Prices in India.
APPCI:	Area and Production of Principal Crops in India, GOI.
ASI:	Agricultural Situation in India.
AWI:	Agricultural Wages in India.
BFS:	Bulletin of Food Statistics.
BRS:	Basic Road Statistics.
CSRS:	Crop and Season Reports of the various States.
CTOI:	Climatological Tables of Observatories in India.
DCD:	Department of Community Development.
DES:	Directorate of Economics and Statistics.
DOM:	Directorate of Marketing.
EPW:	Economic and Political Weekly.
FAI:	Fertilizer Association of India.
FHPPI:	Farm Harvest Prices of Principal crops in India.
FS:	Fertilizer Statistics (published by FAI).
GOI:	Government of India.
IAS:	Indian Agricultural Statistics.
ICAR:	Indian Council of Agriculture and Research.
ICRISAT:	International Crop Research Institute...
ISA:	Indian Science Abstracts.
JIW:	Journal of Income and Wealth.

LS: Livestock Census.

MOA: Ministry of Agriculture.

PSA: Primary Census Abstract (reprinted in SAS).

SAS: Statistical Abstracts of India.

WB: World Bank.

Table 4B.1: Description of variables in the data set

Variables	Source(s)	Available by				Interpolated/
		Month	Year	District	State	Constructed
(1) ***Coverage***						
State	-	-	-	-	-	-
District	-	-	-	-	-	-
Year	-	-	-	-	-	-
(2) ***Outputs***						
Ax, Ay ('000 ha) x=major crops y=minor crops	APPCI ('54-'70); SAS; CSRS; ASI('70s-'80s)	No	Yes	Yes	Yes	No
Qx, Qy ('000 tons)	"	"	"	Yes	Yes	No
Px, Py (Rs/quintal)	FHPPI (DES)	"	"	Yes	Yes	No
Ix ('000 ha)	SAS; CSRS; ICRISAT	"	"	Yes	Yes	No
HYVx ('000 ha)	"	"	"	Yes	Yes	No
(3) ***Variable Inputs***						
RURPOP	PSA; SAS; Census ('51, '61, '71, '81)	No	Yes	Yes	Yes	No
AGLABOR	"	"	"	Yes	Yes	Inter.
CULTIVAT	"	"	"	Yes	Yes	Inter.
QLABOR	"	"	"	?	Yes	Const.
WAGE	AWI (DES)	Yes	"	Yes	Yes	No
NITRO_TP P205_TP (Rs/ton) K20_TP	FS	"	"	Yes	Yes	Const.

Table 4B.1: Description of variables in the data set (cont.)

Variables	Source(S)	Available By				Interpolated/ Constructed
		Month	Year	District	State	
QBULLOCK	LS (1&2) ('56, '61, '66, '72, '77);	"	"	Yes	Yes	Inter.
QTRACTOR	"	"	"	Yes	Yes	Inter.
PBULLOCK	API (DES)	"	"	Yes	Yes	Const.
PTRACTOR	"	"	"	Yes	Yes	Const.
(4) ***Other Inputs***						
Literacy	PSA; SAS; Census ('51, '61, '71, '81)	No	Yes	Yes	Yes	Inter.
Population Density	PSA; SAS; Census ('51, '61, '71, '81)	No	Yes	Yes	Yes	Inter.

Note: "Intermediate" variables have been omitted from this table.

The data set covers 271 districts within thirteen states of India. Table 4B.2 lists the districts and states:

Table 4B.2: Districts in the data set

District	State	District	State
24 Parganas	West Bengal	Basti	Uttar Pradesh
Adilabad	Andhra Pradesh	Bathinda	Punjab
Agra	Uttar Pradesh	Belgaum	Karnataka
Ahmadnagar	Maharashtra	Bellary	Karnataka
Ahmedabad	Gujarat	Betul	Madhya Pradesh
Ajmer	Rajasthan	Bhagalpur	Bihar
Akola	Maharashtra	Bhandara	Maharashtra
Aligarh	Uttar Pradesh	Bharatpur	Rajasthan
Allahabad	Uttar Pradesh	Bharuch	Gujarat
Alwar	Rajasthan	Bhavnagar	Gujarat
Ambala	Haryana	Bhilwara	Rajasthan
Amravati	Maharashtra	Bhind	Madhya Pradesh
Amreli	Gujarat	Bid	Maharashtra
Amritsar	Punjab	Bidar	Karnataka
Anantapur	Andhra Pradesh	Bijapur	Karnataka
Aurangabad	Maharashtra	Bijnor	Uttar Pradesh
Azamgarh	Uttar Pradesh	Bikaner	Rajasthan
Bahraich	Uttar Pradesh	Bilaspur	Madhya Pradesh
Balaghat	Madhya Pradesh	Birbhum	West Bengal
Balangir	Orissa	Budaun	Uttar Pradesh
Baleshwar	Orissa	Bulandshahr	Uttar Pradesh
Ballia	Uttar Pradesh	Buldana	Maharashtra
Banas-Kantha	Gujarat	Bundi	Rajasthan
Banda	Uttar Pradesh	Champaran	Bihar
Banglore	Karnataka	Chandrapur	Maharashtra
Bankura	West Bengal	Chengalpattu	Tamil Nadu
Banswara	Rajasthan	Chhatapur	Madhya Pradesh
Barabanki	Uttar Pradesh	Chhindwara	Madhya Pradesh
Barddhaman	West Bengal	Chikmagalur	Karnataka
Bareilly	Uttar Pradesh	Chitradurga	Karnataka
Barmer	Rajasthan	Chittaurgarh	Rajasthan
Bastar	Madhya Pradesh	Chittoor	Andhra Pradesh

(cont.)

Table 4B.2: Districts in the data set (cont.)

District	State	District	State
Churu	Rajasthan	Hoshangabad	Madhya Pradesh
Coimbatore	Tamil Nadu	Hoshiarpur	Punjab
Cuddapah	Andhra Pradesh	Hugli	West Bengal
Cuttack	Orissa	Hyderabad	Andhra Pradesh
Dakshin Kannad	Karnataka	Indore	Madhya Pradesh
Damoh	Madhya Pradesh	Jabalpur	Madhya Pradesh
Darbhanga	Bihar	Jaipur	Rajasthan
Darjiling	West Bengal	Jaisalmer	Rajasthan
Datia	Madhya Pradesh	Jalandhar	Punjab
Dehradun	Uttar Pradesh	Jalaun	Uttar Pradesh
Deoria	Uttar Pradesh	Jalgaon	Maharashtra
Dewas	Madhya Pradesh	Jalor	Rajasthan
Dhanbad	Bihar	Jalpaiguri	West Bengal
Dhar	Madhya Pradesh	Jamnagar	Gujarat
Dharwad	Karnataka	Jaunpur	Uttar Pradesh
Dhenkanal	Orissa	Jhabua	Madhya Pradesh
Dhule	Maharashtra	Jhalawar	Rajasthan
Dumka	Bihar	Jhansi	Uttar Pradesh
Dungarpur	Rajasthan	Jhunjhunun	Rajasthan
Durg	Madhya Pradesh	Jodhpur	Rajasthan
East Godavari	Andhra Pradesh	Junagarh	Gujarat
East Nimar	Madhya Pradesh	Kachchh	Gujarat
Etah	Uttar Pradesh	Kalahandi	Orissa
Etawah	Uttar Pradesh	Kanniyakumari	Tamil Nadu
Faizabad	Uttar Pradesh	Kanpur	Uttar Pradesh
Farrukhabad	Uttar Pradesh	Kapurthala	Punjab
Fatehpur	Uttar Pradesh	Karimnagar	Andhra Pradesh
Firozpur	Punjab	Karnal	Haryana
Ganganagar	Rajasthan	Kendujhar	Orissa
Ganjam	Orissa	Khammam	Andhra Pradesh
Gaya	Bihar	Kheda	Gujarat
Ghazipur	Uttar Pradesh	Kheri	Uttar Pradesh
Gonda	Uttar Pradesh	Koch-Bihar	West Bengal
Gorakhpur	Uttar Pradesh	Kodagu	Karnataka
Gulbarga	Karnataka	Kolar	Karnataka
Guna	Madhya Pradesh	Kolhapur	Maharashtra
Guntur	Andhra Pradesh	Koraput	Orissa
Gurdaspur	Punjab	Kota	Rajasthan
Gurgaon	Haryana	Krishna	Andhra Pradesh
Gwalior	Madhya Pradesh	Kurnool	Andhra Pradesh
Hamirpur	Uttar Pradesh	Lucknow	Uttar Pradesh
Haora	Wes Bengal	Ludhiana	Punjab
Hardoi	Uttar Pradesh	Madurai	Tamil Nadu
Hassan	Karnataka	Mahbubnagar	Andhra Pradesh
Hazaribag	Bihar	Mahendragarh	Haryana

(cont.)

Table 4B.2: Districts in the data set (cont.)

District	State	District	State
Hissar	Haryana	Mahesana	Gujarat
Hoshangabad	Madhya Pradesh	Mainpuri	Uttar Pradesh
Maldah	West Bengal	Raisen	Madhya Pradesh
Mandla	Madhya Pradesh	Rajgarh	Madhya Pradesh
Mandsaur	Madhya Pradesh	Rajkot	Gujarat
Mandya	Karnataka	Ramanathapuram	Tamil Nadu
Mathura	Uttar Pradesh	Rampur	Uttar Pradesh
Mayurbhanj	Orissa	Ranchi	Bihar
Medak	Andhra Pradesh	Ratlam	Madhya Pradesh
Medinipur	West Bengal	Ratnagiri	Maharashtra
Meerut	Uttar Pradesh	Rewa	Madhya Pradesh
Mirzapur	Uttar Pradesh	Rohtak	Haryana
Moradabad	Uttar Pradesh	Sabar-Kantha	Gujarat
Morena	Madhya Pradesh	Sagar	Madhya Pradesh
Munger	Bihar	Saharanpur	Uttar Pradesh
Murshidabad	West Bengal	Saharsa	Bihar
Muzaffarnagar	Uttar Pradesh	Salem	Tamil Nadu
Muzzaffarpur	Bihar	Sambalpur	Orissa
Mysore	Karnataka	Sangli	Maharashtra
Nadia	West Bengal	Sangrur	Punjab
Nagaur	Rajasthan	Saran	Bihar
Nagpur	Maharashtra	Satara	Maharashtra
Nainital	Uttar Pradesh	Satna	Madhya Pradesh
Nalgonda	Andhra Pradesh	Sawai Madhopur	Rajasthan
Nanded	Maharashtra	Sehore	Madhya Pradesh
Narsimhapur	Madhya Pradesh	Seoni	Madhya Pradesh
Nashik	Maharashtra	Shahabad	Bihar
Nellore	Andhra Pradesh	Shahdol	Madhya Pradesh
Nilgiri	Tamil Nadu	Shahjahanpur	Uttar Pradesh
Nizamabad	Andhra Pradesh	Shajapur	Madhya Pradesh
North Arcot	Tamil Nadu	Shimoga	Karnataka
Osmanabad	Maharashtra	Shivpuri	Madhya Pradesh
Palamu	Bihar	Sidhi	Madhya Pradesh
Pali	Rajasthan	Sikar	Rajasthan
Panch-Mahals	Gujarat	Singhbhum	Bihar
Panna	Madhya Pradesh	Sirohi	Rajasthan
Parbhani	Maharashtra	Sitapur	Uttar Pradesh
Patiala	Punjab	Solapur	Maharashtra
Patna	Bihar	South Arcot	Tamil Nadu
Phulabani	Orissa	Srikakulam	Andhra Pradesh
Pilibhit	Uttar Pradesh	Sultanpur	Uttar Pradesh
Pratapgarh	Uttar Pradesh	Sundargarh	Orissa
Pune	Maharashtra	Surat	Gujarat
Puri	Orissa	Surendranagar	Gujarat
Purnea	Bihar	Surguja	Madhya Pradesh

(cont.)

Table 4.B.2: Districts in the data set (cont.)

District	State
Puruliya	West Bengal
Rae-Bareli	Uttar Pradesh
Raichur	Karnataka
Raigarh	Madhya Pradesh
Raigarh	Maharashtra
Thane	Maharashtra
Thanjavur	Tamil Nadu
The-Dangs	Gujarat
Tikamgarh	Madhya Pradesh
Tiruchchirappalli	Tamil Nadu
Tirunelveli-Kattabo	Tamil Nadu
Tonk	Rajasthan
Tumkur	Karnataka
Udaipur	Rajasthan
Ujjain	Madhya Pradesh
Unnao	Uttar Pradesh
Uttar Kannad	Karnataka
Vadodara	Gujarat
Valsad	Gujarat
Varanasi	Uttar Pradesh
Vidisha	Madhya Pradesh
Visakhapatnam	Andhra Pradesh
Warangal	Andhra Pradesh
Wardha	Maharashtra
West Dinajpur	West Bengal
West Nimar	Madhya Pradesh
Yavatmal	Maharashtra

Definitions Of Variables:

(1) *Coverage:*

STATE= 2 digit state code
DISTRICT= 2 digit district code
YEAR=Years used in the data set (1956/57--1987/88)

Kerala and Assam are the major agricultural states absent from the data set. Also absent, but less important agriculturally, are the minor states and Union Territories in the Northeastern part of India, as well as the far-northern states of Himachal Pradesh and Jammu & Kashmir.

The 271 districts and 13 states constitute the three primary northern wheat and northern rice producing states (Haryana, Punjab, Uttar Pradesh), two northwestern bajra-producing states (Gujarat and Rajasthan), three Eastern states (Bihar, Orissa, and West Bengal), and the Semi-Arid Tropics States as specified by ICRISAT.

Any changes occurring in district boundaries have been accounted for. Original district boundaries have been preserved by consolidating new districts into their 'parent' districts (which is why the actual number of modern-day districts is considerably larger than 271). These changes have occurred, for example, because of the division of the former Punjab into Punjab, Haryana and Himachal Pradesh; the division of some districts into two or more smaller districts in many states (especially in Bihar); or the transfer of parts of one district to another. Using district latitudes and longitudes, the distance of a district's center to the nearest shoreline was calculated by using Geographical Information Systems software (MAPINFO).

(2) *Outputs:*

x= major crops: BAJRA, JOWAR, MAIZE, RICE, WHEAT
y=minor crops: BAR (barley), COTN (cotton), GNUT (groundnut), GRAM, JUTE, OPULS (other pulses), POTAT (potato), RAGI, TUR, RMSEED (rapeseed and mustard), SESA (sesame), SOY, SUGAR, SUNFL, TOBAC (tobacco)
Ax, Ay=Area Planted ('000 ha)
Qx, Qy=Production ('000 tons)
Px,Py=Farm Harvest Price (Rs/quintal)
Ix=Area irrigated under the crop x ('000 ha)
HYVx=Area planted to HYV of crop x ('000 ha)

(3) *Variable Inputs:*

AGLABOR=Number of rural males whose primary job classification is agricultural labor
CULTIVAT=Number of rural males whose primary job classification is cultivation (note: both AGLABOR and CULTIVAT are stock variables).
QLABOR=Wtd. sum of AGLABOR and CULTIVAT=(AGLABOR+CULTIVAT)*(# of days worked in the state by farm workers)
WAGE=Wtd. (by month) annual labor cost. Wages of a male ploughman were recorded; if not available then wages of a male field laborer or male "Other Agricultural Labor" were selected. June and August were weighted more heavily than other months because of the high intensity of field work during those months.
NITRO-TP; P205-TP; K20-TP=Prices of fertilizers (nitrogen, phosphorus and potassium) in Rs/ton. Prices of fertilizers are strictly controlled by the GOI, so the only cross- section price variation arises from the cost of transportation from the railhead to the field. Prices are based on reported maximum sale prices of common fertilizer compounds adjusted for the proportion of the nutrient present in each compound.
QBULLOCK=Number of castrated (male) cattle over the age of 3 years which are used in rural areas for work only.
QTRACTOR=Number of four-wheel machines (not tracked or walk behind two-wheeled ones).
PBULLOCK=(0.5)*(bullock price). The 0.5 represents the substantial annual flow of expenses entailed in breeding, raising and feeding bullocks, as well as the necessary rate of return on their ownership.
PTRACTOR=Average tractor prices (controlling for depreciation) using the prices of Eicher 24-HP tractors and Escort tractors.

(4) *Other Variables:*

LITERACY= Proportion of rural males who are classified as literate (defined as "the ability to read and write in any language"). Census enumerators, beginning with the 1971 census, were required to observe each individual's ability to read and write before classifying him or her to be literate. As is true for all census variables, values for the inter-censal years were obtained by linear interpolation. Literacy rates change so slowly and so regularly that this procedure seems amply justified.

POPDEN=Population Density was calculated by dividing the population as per the population censuses by the area in each district. Like the LITERACY variable, values for the inter-censal variables were linearly interpolated.

APPENDIX C: ERRORS IN ORIGINAL DATA SET

Over the course of the project, various errors were discovered in the original data set and corrected for. Presented below is a list of errors corrected for, to caution researchers who have/are using the original data set.

Some of the errors are huge, and can substantially modify the results. For example, the price of sugar in 1980 is entered as Rs.71693.96, whereas the actual price is Rs. 380.86. Various such errors were discovered and amended. Other errors include mistakes in appropriate transformation of units. For example, for 1984 onwards, cotton production is reported in '000 bales but the price of cotton is reported in Rs./ton. In most cases, the errors were rectified by tallying them with the original census variables. In a small number of cases, the errors were approximated by using information from neighboring years or districts.

1) ABARLEY: Area planted under barley for districts in Madhya Pradesh for the years 1966-1983 was missing in the original data set.
2) QBARLEY: Barley production for districts in Madhya Pradesh for the years 1966-1983 was missing in the original data set.
3) APOTATO: Area planted under potato for districts in Madhya Pradesh for the years 1966-1983 was missing in the original data set.
4) QPOTATO: Potato production for districts in Madhya Pradesh for the years 1966-1983 was missing in the original data set.
5) ATUR: With the exception of Bihar and Orissa, area planted under tur is missing for 17 year period (1966-1983) in the original data set.
6) QTUR: With the exception of Bihar and Orissa, production of tur is missing for the17 year period (1966-1983) in the original data set.
7) PTUR: With the exception of Bihar and Orissa, price of tur is missing for the 17 year period (1966-1983) in the original data set.
8) ATUR: For the 20 year period 1966-1986, the variable ATUR is incorrectly recorded for the state of Orissa
9) QJUTE: For all the districts in the data set, and for all the years, the quantity of jute is recorded is recorded incorrectly.
10) For the year 1966, the following variables have been recorded incorrectly in the following districts:

District	Variable
All districts in Orissa	agram
Dhar	qrice
Thane	agnut
Thane	qgnut
Banglore	qjowar
Banglore	ajowar
Kolar	qjowar
Farrukhabad	apotato
Kota	arice
Jhalawar	qrice

11) ARICE: For the year 1969 area planted under rice has been recorded incorrectly for Kota.

12) In 1972, the following variables are recorded incorrectly in the original data set.

District	Variable
Ludhiana	ptobac
Jalor	pwheat

13) In 1974, the following variables are recorded incorrectly in the data set.

District	Variable
South Arcot	psesamum
Banas-Kantha	qsesamum

14) In 1976, the following variables are recorded incorrectly in the data set.

District	Variable
Anantpur	qrice
Bidar	other pulses
Faizabad	qsesamum

15) In 1978, the following variables are recorded incorrectly in the data set:

District	Variable
Hoshangabad	pcotton
Mahendragarh	qjowar

16) In 1979, the following variables were recorded incorrectly:

District	Variable
All districts in Gujurat	agram
Datia	qrice
Bhatinda	awheat
Sangrur	awheat
Patiala	awheat
Banas-Kantha	abarley
Banas-Kantha	qbarley
Kachchh	qbarley
Kachchh	abarley
Mahensa	abarley
Mahensa	qbarley
Ahembdabad	abarley
Ahembdabad	qbarley

17) In 1980, the following variables were recorded incorrectly:

District	Variable
All districts in Gujurat	agram
Champaran	psugar
Adilabad	qwheat
Chikmagalur	abajra
Chikmagalur	qbajra
Banas-Kantha	abarley
Banas-Kantha	qbarley
Kachchh	abarley
Kachchh	qbarley
Mahensa	abarley
Mahensa	qbarley
Ahembdabad	abarley
Ahembdabad	qbarley

18) In 1981, the following variables were recorded incorrectly:

District	Variable
All districts in Gujurat	agram
All districts in Bihar	armseed
All districts in Bihar	qrmseed
Agra	agram
Banas-Kantha	abarley
Kachchh	abarley
Mahensa	abarley
Ahembdabad	abarley
Banas-Kantha	qbarley
Kachchh	qbarley
Mahensa	qbarley
Ahembdabad	qbarley

19) In 1982, the following variables were recorded incorrectly:

District	Variable
Banas-Kantha	abarley
Kachchh	abarley
Mahensa	abarley
Ahembdabad	abarley
Banas-Kantha	qbarley
Kachchh	qbarley
Mahensa	qbarley
Ahembdabad	qbarley

20) In 1983, the following variables were recorded incorrectly:

District	Variable
Banas-Kantha	abarley
Kachchh	abarley
Mahensa	abarley
Ahembdabad	abarley
Banas-Kantha	qbarley
Kachchh	qbarley
Mahensa	qbarley
Ahembdabad	qbarley

21) In 1984, the following variables were recorded incorrectly:

District	Variable
Nellore	hyvrice
South Arcot	qrice
all districts	qcotton

22) QCOTTON: For years >=1984, production of cotton has been recorded incorrectly.

23) In 1985, the price of gram is recorded incorrectly in the original data set for Bankura (West Bengal).

APPENDIX D: CLIMATE VARIABLES

Climate variables are made available from the Food and Agricultural Organization (FAO). The climate variables come from 160 weather stations well scattered across India (Table 4D.1). The climatological data includes monthly maximum and minimum temperature, mean daily relative humidity, sunshine hours, windspeed, precipitation and calculated values for reference evapotranspiration and effective rainfall.

Table (4D.1) presents an alphabetical list of weather stations with their geographical coordinates.

Table 4D.1: List of weather stations

Station	District	State / Union Territory	Altitude (m)	Latitude (°,/)	Longitude (°,/)
Agra	Agra	Uttar Pradesh	169	27.1	78.02
Ahmadabad	Ahmadabad	Gujarat	55	23.04	72.38
Ahmadnagar	Ahmadnagar	Maharashtra	657	19.05	74.48
Ajmer	Ajmer	Rajasthan	486	26.27	74.37
Akola	Akola	Maharashtra	282	20.42	77.02
Alibag	Raigarh	Maharashtra	7	18.38	72.52
Aligarh	Aligarh	Uttar Pradesh	187	27.53	78.04
Allababad	Allahabad	Uttar Pradesh	98	25.27	81.44
Ambala	Ambala	Haryana	272	30.23	76.46
Amini	(N/A)	(Island)	4	11.07	72.44
Amraoti	Amravati	Maharashtra	370	20.56	77.47
Amritsar	Amritsar	Punjab	234	31.38	74.52
Angul	Dhenkanal	Orissa	139	20.5	85.06
Asansol	Barddhaman	West Bengal	126	23.41	86.58
Aurangabad	Aurangabad	Maharashtra	581	19.53	75.2
Bahraich	Bahraich	Uttar Pradesh	124	27.34	81.36
Balasore	Baleshwar	Orissa	20	21.31	86.56
Balehonnur	Chikmagalur	Karnataka	889	13.22	75.27
Bangalore	Banglore	Karnataka	921	12.58	77.35
Bareilly	Bareilly	Uttar Pradesh	173	28.22	79.24
Barmer	Barmer	Rajasthan	194	25.45	71.23
Baroda	Vadodara	Gujarat	34	22.18	73.15
Belgaum	Belgaum	Karnataka	753	15.51	74.32
Bellary	Bellary	Karnataka	449	15.09	76.51
Berhampore	Murshidabad	West Bengal	19	24.08	88.16
Bhaunagar (Aero)	Bhavnagar	Gujarat	11	21.45	72.11
Bhopal (Bairagarh)	Sehore	Madhya Pradesh	523	23.17	77.21
Bhuj (Rudramata)	Kachchh	Gujarat	80	23.15	69.4
Bidar	Bidar	Karnataka	664	17.55	77.32
Bijapur	Bijapur	Karnataka	594	16.49	75.43
Bikaner	Bikaner	Rajasthan	224	28	73.18
Bombay	Greater Bombay	Maharashtra	11	18.54	72.49
Burdwan	Barddhaman	West Bengal	32	23.14	87.51
Calcutta (Dum Dum)	24 Parganas	West Bengal	6	22.39	88.26
Chaibasa	Singhbhum	Bihar	226	22.33	85.49

Table 4D.1: List of weather stations (cont.)

Station	District	State / Union Territory	Altitude (m)	Latitude (°,/)	Longitude (°,/)
Chandbali	Baleshwar	Orissa	6	20.47	86.44
Chandrapur	Chandrapur	Maharashtra	193	19.58	79.18
Cherrapunji	(N/A)	Assam	1313	25.15	91.44
Chitradurga	Chitradurga	Karnataka	733	14.14	76.26
Cochin	Ernakulam	Kerela	3	9.58	76.14
Coimbatore	Coimbatore	Tamil Nadu	409	11	78.58
Coonoor	Nilgiri	Tamil Nadu	1747	11.21	76.48
Cuddalore	South Arcot	Tamil Nadu	12	11.46	79.46
Cuddapah	Cuddapah	Andhra Pradesh	130	14.29	78.5
Cuttack	Cuttack	Orissa	27	20.28	85.56
Daltonganj	Palamu	Bihar	221	24.03	84.04
Darbhanga	Darbhanga	Bihar	49	26.1	85.54
Darjeeling	Darjiling	West Bengal	2127	27.03	88.16
Dehra Dun	Dehradun	Uttar Pradesh	682	30.19	78.02
Dhambad	Dhanbad	Bihar	257	23.47	86.26
Dhubri	(N/A)	Assam	35	26.01	89.58
Dibrugarh	(N/A)	Assam	110	27.29	95.01
Dohad	Panch-Mahals	Gujarat	333	22.5	74.16
Dumka	Dumka	Bihar	149	24.16	87.15
Dwarka	Jamnagar	Gujarat	11	22.22	69.05
Fatehpor	Fatehpur	Uttar Pradesh	114	25.56	80.5
Gadag	Dharwad	Karnataka	650	15.25	75.38
Ganganagar	Ganganagar	Rajasthan	177	29.55	73.53
Gauhati	(N/A)	Assam	54	26.06	91.35
Gaya	Gaya	Bihar	116	24.45	84.57
Gonda	Gonda	Uttar Pradesh	110	27.08	81.58
Gopalpur	Ganjam	Orissa	17	19.16	84.53
Gorakhpur	Gorakhpur	Uttar Pradesh	77	26.45	83.22
Gulbarga	Gulbarga	Karnataka	458	17.21	76.51
Guna	Guna	Madhya Pradesh	478	24.39	77.19
Gwalior	Gwalior	Madhya Pradesh	207	26.14	78.15
Hanamkonda	Adilabad	Andhra Pradesh	269	19.01	79.34
Hassan	Hassan	Karnataka	960	13	76.09
Hazaribagh	Hazaribag	Bihar	611	23.59	85.22
Hissar	Hissar	Haryana	221	29.1	75.44
Honavar	Uttar_Kannad	Karnataka	29	14.17	74.27
Hoshangabad	Sehore	Madhya Pradesh	302	22.46	77.46
Hyderabad	Hyderabad	Andhra Pradesh	545	17.27	78.28
Indore	Indore	Madhya Pradesh	567	22.43	75.48
Jabalpur	Jabalpur	Madhya Pradesh	393	23.12	79.57
Jagdalpur	Bastar	Madhya Pradesh	553	19.05	82.02
Jaipur (Sanganer)	Jaipur	Rajasthan	390	26.49	75.48
Jalgaon	Jalgaon	Maharashtra	201	21.03	75.34
Jalpaiguri	Jalpaiguri	West Bengal	83	26.32	88.43
Jammu	(N/A)	Jammu & Kashmir	366	32.4	74.5
Jamnagar (Aero)	Jamnagar	Gujarat	20	22.27	70.02
Jamshedpur	Singhbhum	Bihar	129	22.49	86.11

Table 4D.1: List of weather stations (cont.)

Station	District	State / Union Territory	Altitude (m)	Latitude (°,/)	Longitude (°,/)
Jhalawar	Jhalawar	Rajasthan	321	24.32	76.1
Jhansi	Jhansi	Uttar Pradesh	251	25.27	78.35
Jodhpur	Jodhpur	Rajasthan	224	26.18	73.01
Kakinada	East Godavari	Andhra Pradesh	8	16.57	82.14
Kalimpong	Darjiling	West Bengal	1209	27.04	88.28
Kalingapatam	Srikakulam	Andhra Pradesh	6	18.2	84.08
Kanker	Bastar	Madhya Pradesh	402	20.16	81.29
Kanpur Air Fld	Kanpur	Uttar Pradesh	126	26.26	80.22
Khandwa	East Nimar	Madhya Pradesh	318	21.5	76.22
Kodaikanal	Madurai	Tamil Nadu	2343	10.14	77.28
Kota	Kota	Rajasthan	257	25.11	75.51
Kozhikode (Calicut)	(N/A)	Kerela	5	11.15	75.47
Krishnanagar	Nadia	West Bengal	15	23.24	88.31
Kurnool	Kurnool	Andhra Pradesh	281	15.5	78.04
Leh	(N/A)	Jammu & Kashmir	3514	34.09	77.34
Lucknow	Lucknow	Uttar Pradesh	111	26.52	80.56
Ludhiana	Ludhiana	Punjab	247	30.56	75.52
Lumding	(N/A)	Assam	149	25.45	93.11
Machilipatam	Krishna	Andhra Pradesh	3	16.12	81.09
Madras (Minambakkam)	Chengalpattu	Tamil Nadu	16	13	80.11
Madurai	Madurai	Tamil Nadu	133	9.55	78.07
Mahabaleshwar	Satara	Maharashtra	1382	17.56	73.4
Mainpuri	Mainpuri	Uttar Pradesh	157	27.14	79.03
Malda	Maldah	West Bengal	31	25.02	88.08
Malegaon	Nashik	Maharashtra	437	20.33	74.32
Mangalore	Dakshin Kannad	Karnataka	22	12.52	74.51
Marmugao	North Goa	Goa	62	15.25	73.47
Mercara	Kodagu	Karnataka	1152	12.25	75.44
Midnapore	Medinipur	West Bengal	45	22.25	87.19
Minicoy	(N/A)	(Island)	2	8.18	73
Miraj (Sangli)	Sangli	Maharashtra	554	16.49	74.41
Motihari	Champaran	Bihar	66	26.4	84.55
Mount Abu	Sirohi	Rajasthan	1195	24.36	72.43
Mowgong	Hamirpur	Uttar Pradesh	229	25.04	79.27
Mukteswar (Kumaon)	Almora	Uttar Pradesh	2311	29.28	79.39
Mussoorie	Tehri Garwahal	Uttar Pradesh	2042	30.27	78.05
Mysore	Mandya	Karnataka	767	12.18	76.42
Nagappattinam	Thanjavur	Tamil Nadu	9	10.46	79.51
Nellore	Nellore	Andhra Pradesh	20	14.27	79.59
New Delhi-Safdarjang	(N/A)	New Delhi	216	28.35	77.12
Nimach	Mandsaur	Madhya Pradesh	496	24.28	74.54
Nizamabad	Nizamabad	Andhra Pradesh	381	18.4	78.06
Pachmarhi	Hoshangabad	Madhya Pradesh	1075	22.28	78.26
Pamban	(N/A)	(Island)	11	9.16	79.18

Table 4D.1: List of weather stations (cont.)

Station	District	State / Union Territory	Altitude (m)	Latitude (°,/)	Longitude (°,/)
Patna	Patna	Bihar	53	25.37	85.1
Pendra	Bilaspur	Madhya Pradesh	625	22.46	81.54
Phalodi	Jodhpur	Rajasthan	234	27.08	72.22
Poona	Pune	Maharashtra	559	18.32	73.51
Puri	Puri	Orissa	6	19.48	85.49
Purnea	Bhagalpur	Bihar	38	25.16	87.28
Raichor	Raichor	Karnataka	400	16.12	77.21
Raipur	Raipur	Madhya Pradesh	298	21.14	81.39
Rajkot	Rajkot	Gujarat	138	22.18	70.47
Ranchi	Ranchi	Bihar	655	23.26	85.24
Rentachintala	Guntur	Andhra Pradesh	106	16.33	79.33
Roorkee	Saharanpur	Uttar Pradesh	274	29.51	77.53
Sabaur	Bhagalpur	Bihar	37	25.14	87.04
Sagar	Sagar	Madhya Pradesh	551	23.51	78.45
Sagar Island	(N/A)	(Island)	3	21.39	88.03
Salem	Salem	Tamil Nadu	278	11.39	78.1
Sambalpur	Sambalpur	Orissa	148	21.28	83.58
Satna	Satna	Madhya Pradesh	317	24.34	80.5
Seoni	Seoni	Madhya Pradesh	619	22.05	79.33
Shillong	(N/A)	Meghalaya	1598	25.34	91.53
Sholapur	Solapur	Maharashtra	479	17.4	75.54
Sibsagar	(N/A)	Assam	97	26.59	94.38
Silchar	(N/A)	Assam	29	24.49	92.48
Simla	(N/A)	Himachal Pradesh	2202	31.06	77.1
Srinagar	(N/A)	Jammu & Kashmir	1586	34.05	74.5
Surat	Surat	Gujarat	12	21.12	72.5
Tezpur	(N/A)	Assam	79	26.37	92.47
Tiruchchirapalli	Tiruchchirappalli	Tamil Nadu	88	10.46	78.43
Trivandrum	Thiruvanenthapuram	Kerela	64	8.29	76.57
Umaria	Shahdol	Madhya Pradesh	459	23.32	80.53
Varanasi (Babatpur)	Varanasi	Uttar Pradesh	85	25.27	82.52
Vellore	North Arcot Ambedkar	Tamil Nadu	214	12.55	79.09
Veraval	Junagarh	Gujarat	8	20.54	70.22
Vishakhapatnam	Visakhapatnam	Andhra Pradesh	3	17.43	83.14

As with the districts, the distance to sea of these weather stations was calculated by using Geographical Information Systems Software (MAPINFO) for India.

For the purposes of this study, normal temperatures (°C) and precipitation (mm) for the months of January, April, July, and October were used to predict district-level climates. The climate variables are 30 year norms (1931-1960).

APPENDIX E: EDAPHIC VARIABLES

Two types of sources[16] were used to collect edaphic data: tables and figures. The figures display, by color and pattern, the value of some variable for areas which may be smaller than districts, and which often span district boundaries. Most of the time, districts contain areas of more than one value, such as more than one soil type within the district, or regions of different slope within the district, or areas with different Ph within the district, etc. This was handled in the data set in two distinct ways.

1. In constructing the variables for soil type, the proportion of each district's area under each soil type was estimated. The current data set contains nineteen soil type dummy variables, one for each type. The value of a soil type dummy variable is 1 for a district if that type is one of the two predominant soil types in the district [that is, if that type's proportion is one of the two highest proportions in the district]. This implies, obviously, that a district will have two soil type dummies with the value of 1 (except for the few districts all of whose soil is of one type), and thus that one cannot interpret the dummies' coefficients in the customary way.
2. In constructing all of the other variables derived from "color and pattern" maps [namely, Ph, the depth of aquifers, topsoil depth, and slope] the dominant value (which covered more of the district's area than did any other value) was selected. This approach does not distinguish between districts which are entirely covered by one value [say, a Ph of 7; or a moderately steep slope], on the one hand, as against districts with several values, one of which covers slightly more area than do any others [say, 19% of the soil has a Ph of 5,19% has a Ph of 6, 24% has a Ph of 7, 19% with Ph of 8, and 19% with Ph of 9; or 20% of the district's area is flat, 41% is moderately steep, and 39% is very steep], on the other hand. A possible avenue for further research is to enrich the data set in this way.

SOIL TYPE

1. variable names of the form DMSnn: a) for example, DMS02, DMS03, DMS04, ..., DMS19, DMS20; b) DM denotes a dummy variable; c) S denotes soil type d. nn ranges from 02 to 20, for "traditional" soil types
2. source: visual inspection of soil maps for each State: a) S. P. Raychaudhuri et al, *Soils of India* (New Delhi: Indian Council of Agricultural Research, 1963); b) soil maps
3. types

a. 01	not used
b. 02	Laterite
c. 03	Red and Yellow
d. 04	Shallow Black
e. 05	Medium Black
f. 06	Deep Black

[16] This appendix was compiled by James McKinsey, Stonehill College. We acknowledge his efforts in gathering the soil data as described in this appendix.

g. 07	Mixed Red and Black
h. 08	Coastal Alluvial
i. 09	Deltaic Alluvium
j. 10	Calcerous
k. 11	Gray Brown
l. 12	Desert
m. 13	Tarai
n. 14	Black (Karail)
o. 15	Saline and Alkaline
p. 16	Alluvial River
q. 17	Skeletal
r. 18	Saline and Deltaic
s. 19	Red
t. 20	Red and Gravely

STORIE INDEX

1. variable names and components
   a. STRA
      - measuring the character of the soil profile
      - values range from 0.65 to 1.00, where a higher value represents a more favorable or more productive rating.

   b. STRB
      - measuring topography, texture and structure
      - values range from 0.65 to 1.00, where a higher value represents a more favorable or more productive rating.

   c. STRC
      - measuring the degree of climatic suitability, salinity, stoniness and the tendency to erode
      - values range from 0.65 to 1.00, where a higher value represents a more favorable or more productive rating.

   d. STORIE
      - product of STRA, STRB and STRC
      - thus the values of STORIE could range from as low as 0.274625 to 1.00. 1) 0.274625 = 0.653, and thus is the theoretical minimum 2) the actual minimum value in any district is 0.
      - the combined Storie index is designed as an overall measure of soil productivity

2. source
   a. K. B. Shome and S. P. Raychaudhuri, Rating of Soils of India Proceedings,
   b. National Institute of Sciences of India, vol. 26, Part A, 1960
   c. method adapted from R. E. Storie, Transactions, Fourth International
   d. Conference of Soil Science, 1950

Soil Fertility Status

1. variable names and components
   a. N
      i. nitrogen fertility level
      ii. values include 1 for low, 2 for medium and 3 for high
   b. P
      i. phosphorous fertility level
      ii. values include 1 for low, 2 for medium and 3 for high
   c. K
      i. potassium fertility level
      ii. values include 1 for low, 2 for medium and 3 for high

   d. twelve fertility class groups

      i. dummy variables
      ii. each involves a combination of fertility level of N, P and K
      iii. the groups, and the levels of N, P and K, are listed in the following table:

Variable	N Level	P Level	K Level
DMF01	Low	Low	Low
DMF02	Low	Low	High
DMF03	Low	Low	Medium
DMF04	Low	Medium	Low
DMF05	Low	Medium	High
DMF06	Low	Medium	Medium
DMF07	Medium	Low	Low
DMF08	Medium	Low	Medium
DMF09	Medium	Low	High
DMF10	Medium	Medium	Low
DMF11	Medium	Medium	Medium
DMF12	Medium	Medium	High

2. Source
   a. originally compiled by A. B. Ghosh and Rehanul Hasan, Indian Agricultural Research Institute, New Delhi, based on the results of soil tests carried out, and data provided by, state and regional soil testing laboratories
   b. data presented by M. Velayuthan and A. B. Ghosh, *Proceedings,* Fertilizer Association of India National Seminar on Strategies for Achieving Fertilizer Consumption Targets and Improving Fertilizer Use Efficiency, 1981
   c. published in various annual editions of *Fertilizer Statistics of India,* published by the Fertilizer Association of India.

Soil Ph

1. source: National Atlas of India, vol. 1, plate 59
2. Variables:
   a. a series of dummy variables

DMPH5:	strongly alkali	4.5<pH<5.5
DMPH6:	slightly alkali	5.5<pH<6.5
DMPH7:	neutral	6.5<pH<7.5
DMPH8:	slightly acid	7.5<pH<8.5
DMPH9:	strongly acid	8.5<pH<9.5

   b. single variable PH# whose value is PH reading from 5 to 9

Aquifers

1. source: National Atlas of India, vol. 1, several plates
   a. plate 87: All-India
   b. plate 88: Northern India
   c. plate 89: Western India
   d. plate 90: Central India
   e. plate 91: Eastern India
   f. plate 92: Southern India

2. Variables:

DMAQ1:	dummy variable = 1 if aquifer is <100 meters thick
DMAQ2:	dummy variable = 1 if aquifer is 100 - 150 meters thick
DMAQ3:	dummy variable = 1 if aquifer is > 150 meters thick

3. [obviously this is not exhaustive, in the sense that major areas of the nation are above no aquifers at all, so for many districts none of these dummy variables has the value of one.]

Topsoil Depth

1. Source: National Atlas of India, vol. 1, Plate 50: "Depth of Soil, All-India"
2. Variables:

   a. DMTS1: dummy variable = 1 if topsoil is 0 - 25 cm. thick
   b. DMTS2: dummy variable = 1 if topsoil is 25-50 cm. thick
   c. DMTS3: dummy variable = 1 if topsoil is 50 - 100 cm. thick
   d. DMTS4: dummy variable = 1 if topsoil is 100 - 300cm. thick
   e. DMTS5: dummy variable = 1 if topsoil is > 300 cm. thick

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5 CLIMATE CHANGE IMPACTS ON INDIAN AGRICULTURE: THE RICARDIAN APPROACH

K.S.Kavi Kumar and Jyoti Parikh

INTRODUCTION

The present debate on global climate change problem is centered around the costs of initiating policy actions to control greenhouse gas (GHG) emissions, and the associated benefits of such actions in terms of reduced impacts. Though there has been a lot of research carried out on the costs side of the above debate, the benefits side received relatively less attention, mainly due to the complexity and the uncertainty associated. The knowledge about impacts of climate change becomes very crucial to formulate appropriate abatement policies at international and national levels. Research carried out at global level in this area has revealed that the climate change impacts may not be uniform across countries and there could be some losers and some gainers. According to these studies the countries in the higher latitudes (mostly developed countries) would have relatively less severe impacts due to climate change, than the countries in the lower latitudes (mostly developing countries) (Rosenzweig and Parry, 1994; Reilly, 1994). Such disparity assumes greater significance if one views at the responsibilities of various countries for the climate change problem in the first place. The Northern countries with per capita GHG emissions far above those of the Southern countries, have contributed more towards perpetuating the climate change problem so far, and are likely to get benefited also due to climate change.

With such background, it becomes very crucial to understand exactly how the developing countries are going to get affected due to climate change. Research in this area, so far has concentrated mainly on developed countries and the need of the hour is to get reliable estimates for developing countries. With its huge population and relatively high dependence on climate sensitive sector like, agriculture, India provides an ideal case study. The present study focuses on climate change impacts on Indian agriculture, recognizing the significance of the same in India's economy, and its vulnerability to potential changes in climate. In the coming decades, Indian agriculture is bound to face a number of challenges which include the pressure from increasing population, changing scenario of world trade in agriculture, and also the potential changes in the global climate.

Some of the characteristics of Indian agriculture are:

- this climate sensitive sector still accounts for more than 30% of India's GDP
- more than 60% of population, directly or indirectly, depend on agriculture
- despite significant progresses made in food grain production, the per capita net availability of food grains still fluctuates between 400 to 500 gms/day, which is way below to the international standards
- with a weight of 57% in the consumer price index, the food prices have close link with the inflation and any adverse shock on agriculture could have cumulative effects on the economy.

Before outlining the objectives of this study, the methodological background of estimating climate change impacts on agriculture is discussed.

CLIMATE CHANGE IMPACTS ON AGRICULTURE - METHODOLOGICAL BACKGROUND

Two broad methodologies have evolved so far in the literature for assessing the climate change impacts on agriculture: (a) production function approach, and (b) ricardian approach. The production function approach estimates the changes in yield directly from crop-response models. This approach provides a detailed understanding of the physical, biological and economic responses and adjustments. However, given the site specific nature of the approach, one has to draw broad inferences while aggregating from a relatively few sites and crops to large areas and diverse production systems. Also, using this approach it would become rather difficult to model farm level adaptations, because in theory innumerable number of such adaptation possibilities are available for the farmer to respond to changes in the climate. On the positive side, the production function approach is the only approach which can estimate in a satisfactory manner the potential beneficial effects due to increase in CO_2 concentration levels in the atmosphere. There is scientific evidence that CO_2 increases plant growth and yields, even at farm level conditions (Senft, 1995). Studies by Kimball (1983), Cure and Acock (1986), Kimball (1985) and Woodward (1993) have indicated that the potential increase in yields of C3 crops (most of cereal crops, excluding Sorghum and Corn) could be 30% following doubling of atmospheric CO_2 concentration. A number of national and global level studies have followed the production function approach to estimate the impacts due to climate change. These include, Adams et.al. (1988, 1990), Kane et.al. (1991), Rielly et.al. (1994), Rosenzweig and Iglesias (1994) and Rosenzweig and Parry (1994). For India, Rao and Sinha (1994) have used this approach to assess climate change impacts on wheat yield. More recently, Kumar and Parikh (1996) have estimated the climate change impacts on Rice and Wheat crops and assessed the associated economic and welfare implications using an applied general equilibrium framework.

Ricardian approach, developed by Mendelsohn and others (1994), uses the cross-section evidence on current production in various regions, and attempts to draw implications with regard to how the cooler regions could adapt the practices of warm regions if climate becomes warmer. The Ricardian approach, in its original form as developed by Mendelsohn and others (1994), relates cross-sectional climate differences to differences in agricultural land values. However, as used in this study, other variations of this original approach are possible.

Ricardian approach provides direct evidence on how profit-maximizing farmers have responded to various climatic conditions. On the positive side, this approach takes the farm-level adaptations into consideration while assessing impacts. However, a major limitation of the approach is that it assumes the prices to be in equilibrium, and in case of large climate change the crop prices could change for prolonged periods. Under such circumstances, the Ricardian estimates would be either over or under estimating the climate change impacts, depending on how the prices change. Also, this approach can not include in its estimates the possible positive impacts due to CO_2 fertilization.

There have been a few other studies estimating the climate change impacts on agriculture, which can not be strictly classified under either of these two broad methodologies. These include studies by Leemans and Solomon (1993) and Kaiser et.al. (1993).

OBJECTIVES

The general objective of this study is to asses the climate change impact on Indian agriculture.

The specific objectives of the study are:

- to apply the Ricardian approach with appropriate modifications, to account for specific characteristics of Indian agriculture, to assess functional relation between farm level net-revenue and climate using the cross-sectional observations;
- to assess the regional and seasonal distribution of impacts due to plausible climate change scenarios;
- to assess the influence of yearly weather on the functional relation estimated between farm level net-revenue and long term climate.

The structure of this report is as follows. In the next section, the methodology and main findings of production function approach followed by Kumar and Parikh (1996) are described. The net-revenue methodology, and its link with the traditional Ricardian methodology are discussed in the following section. This is followed by discussion on the data and the model specifications. The next section discusses the estimation of the functional relation between farm level net-revenue and long term climate, estimated using net-revenue methodology. This section also discusses the seasonal and regional distribution of impacts due to changes in climate. This is followed in the next two sections by discussion on implications of the results for global climate change, and the influence of yearly weather on functional relation between net-revenue and climate. The final section provides the conclusions and policy guidelines.

THE PRODUCTION FUNCTION APPROACH

In this section, we briefly discuss the methodological aspects related to production function approach for assessing climate change impacts on agriculture. Since production function approach serves as an alternative way of assessing the climate change impacts on agriculture, the discussion in this section would provide a back-drop for the approach followed in the present study, namely Ricardian approach.

Specifically, this section would describe the approach followed in Kumar and Parikh (1996), and the major findings obtained therein. There are two broad stages in the study, namely the physical impacts assessment and the economic implications of such physical impacts.

The future climate change scenarios have been developed using results from the equilibrium experiments of general circulation models (GCMs), along with the observed climate. For assessing the physical impacts of climate change on agriculture, the study has followed crop simulation modeling approach. Crop simulation models are among the most powerful tools for analysing the interactions of the crop-management-climate-soil system. Generally carefully calibrated models can be used to assess the situations that do not exist at present. Impact analyses of future climate change are of this type. The crop model should be sensitive to major weather variables (namely, precipitation, temperature, solar radiation and sunshine) and to the CO_2 concentration in the climate. Erosion, Productivity and Impact Calculator (EPIC) (Jones et.al., 1991), one of the widely used crop model, has been used in the study for assessing physical impacts of climate change.

After calibrating the crop model at a specific site, the site specific base yield of a particular crop is assessed. The climate change scenarios are then applied to modify the climate parameters, and the simulations are carried out to estimate the future yield of the crop. Since the crop models do not accurately reproduce the observed crop yields due to a variety of limitations in the input data and crop model formulation, the percentage deviations of future yield, with respect to base yield are used for further analysis.

To translate the physical impacts - which can be viewed as gradually occurring supply shocks to the production sectors - into economic terms, one has to consider the consequences of such shocks on both producer and consumer surpluses. Such an approach would allow estimation of the true social welfare loss/gain of the impacts of climate change on agricultural output. Also, it is important to consider the consequences on different sections of the economy in the present as well as the future time periods. A natural framework satisfying these concerns is a dynamic applied general equilibrium model. The Agriculture, Growth and Redistribution of Income Model (AGRIM), developed by Narayana, Parikh and Srinivasan (Narayana et.al., 1991) is used for assessing the socio-economic implications of climate change. In the economic modeling framework, the imposed yield changes would trigger changes in production levels, and also prices. The price changes would result in a host of other changes, such as movement of labor and capital between various sectors. The yield changes imposed on the system are assumed to occur gradually, i.e., though the climate change induced yield changes start occurring in the year1990, they reach their full impact in the year 2060. This allows the economic agents to adjust their behaviour over this time period. Thus, even though specific farm level adaptations have not been taken into consideration, possible adaptations by the economic agents have been modeled. The final objective of the economic modeling exercise is to assess the welfare implications, in terms of equivalent incomes and population proportions in various expenditure classes of the economy.

The major findings of the study are that wheat crop, grown generally in the winter season of the year, is likely to be affected more than rice crop following climate change; CO_2 fertilization effects seem to dramatically reduce the negative impacts due to climate change. From the welfare angle, the study showed that substantial number of people move from higher income classes to lower income classes as a result of climate change induced shocks, and the social welfare is adversely affected.

As wheat crop is expected to get affected more adversely than rice, one possible inference could be that the wheat growing regions, such as Haryana, Punjab, and Uttar Pradesh, may experience more severe negative impacts, than predominantly rice growing states such as West Bengal and Orissa.

THE NET-REVENUE APPROACH

Absence of well-functioning land markets in the Indian context makes it rather difficult to apply the Ricardian approach in strict sense. However, as shown below, and argued by Sanghi et.al. (1998), one can develop an alternative, namely, 'Net-Revenue' approach.

Consider profit maximizing farmers producing outputs Y, using variable inputs X, and quasi-fixed factors (such as, land, irrigation facilities etc.) F. Let these farmers be facing climate factors C, soil characteristics S, technologies T, and infrastructure I. For a given output (P_y) and input (P_x) prices, the short-run (maximized) profits can be expressed as, $\Pi^* = \Pi(P_y, P_x, F, I, T, C, S)$

Using Hotelling's lemma we can obtain the output supply and factor demand equations:

$Y^* = \partial\Pi^*/\partial P_y$; $X^* = \partial\Pi^*/\partial P_x$

and using these the variable profit function can be written as,

$\Pi_v = P_y Y^* - P_x X^* = \Pi(P_y, P_x, F, I, T, C, S)$

In the above equation, the farmers have completely adapted to the climate variables C, by adjusting their short and long-term inputs such as, F, I, and T, that they are facing and have arrived at profit maximizing mix of outputs and inputs.

In equilibrium, short-term profits, Π_v can be measured and expressed as net revenues per unit of land, (Π_v / L). The net revenues can then be considered to incorporate the optimizing choices of outputs and inputs by farmers. This implies that, the climate impacts ($= (\partial\Pi_v/L)/\partial C$) calculated from the above equation represents the responses of farmers to climate, soil and other factors.

Following Mendelsohn et.al., (1994), one can argue that the prices P_y and P_x are 'equilibrium' prices and in a cross-section differ only by transport costs (which would continue to exist in future). Similarly, arguments can be made for the elimination of technology and infrastructure variables. Refer Sanghi et.al. (1996) for more details.

As mentioned in the beginning of this section, lack of land prices does not allow one to estimate Ricardian estimates in strict sense. However, land prices are presumably based on expected future net revenue. And, in the present study, the current net revenues are considered as a proxy for expected future net revenues. To the extent that this is true, the estimates provided in this study are similar to those of Ricardian approach.

Also, to account for the specific characteristics of Indian agriculture, certain modifications have been introduced in the 'traditional' Ricardian methodology. The key characteristics of Indian (and also other developing countries) agriculture are:

a) government administered prices for crucial agricultural inputs such as tractors and bullocks;

b) introduction of high yielding variety (HYV) seeds in phased manner across the nation, which has led to differences between regional observations;

c) participation of household labor in agricultural activities, leading to underestimation of input costs.

To address these issues, appropriate proxies have been included in the list of independent variables while estimating the model.

DATA AND MODEL SPECIFICATIONS

To test the above net-revenue model, district level cross-sectional data of India has been considered in this study. The districts are considered as units of analysis because most of the data, with the exception of climate (see below for more details about this), is available at district level, and substantial variations in climatic, edaphic and economic factors exist among districts. Most of the agricultural data used in the study was obtained from a data set compiled from various publications by James McKinsey and Robert Evenson at Yale University, USA. This data set includes time-series data on various agricultural variables for 271 districts covering 13 major states of India, from 1957 to 1987. Though the data set as such includes many variables, this study has used for each district the crop-wise production, area, price; area under High Yielding Varieties (HYV); fertilizer input and its price; agricultural labor and their wage rate; fraction of cultivators in the total number of people engaged in agricultural activities; quantities and prices of bullocks and tractors; and dummies representing various soil characteristics.

A number of corrections have been made in the original data set after cross checking the same with the available records. The corrections have been made mainly on area, production and prices of various crops. Additional data on various census variables, such as, population density and literacy proportion, has been added to the above data set. Similarly, data on districts altitude, estimated using figures and data on various meteorological stations across India, has also been added to the original data set. For predicting the district level climate, this altitude data has been used. It has also been used to proxy solar energy in the main net-revenue regressions.

In the following sections, we discuss in detail about the use of edaphic and other control variables in the study; and the estimation of net-revenue and district level climate variables.

NET-REVENUE

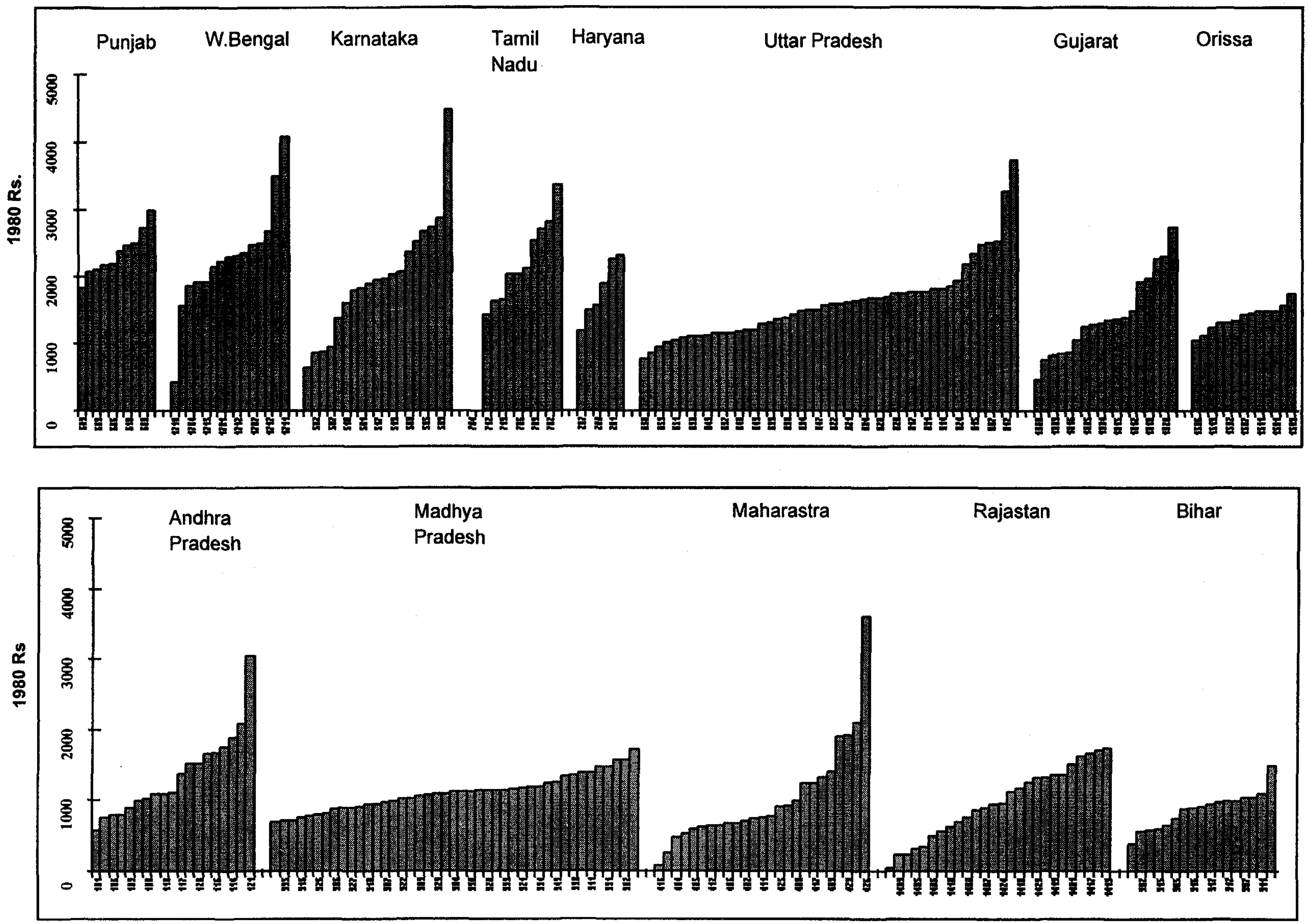
District level net-revenue per hectare, which has been used as the dependent variable in the main regressions, is defined as,

Net Revenue per hectare =

[(Value of production of crops) - (Expenditure on fertilizer and hired labor)] / (Total area under crops)

The study has considered 20 crops while estimating the net-revenue. These 20 crops consist five major crops, namely, Bajra, Jowar, Maize, Rice and Wheat; and 15 minor crops, including Barley, Cotton, Groundnut, Gram, Soybean, and Sugarcane. While assessing the value of production of crops, the farm harvest prices have been used. These prices have been considered appropriate for the analysis in this study, because based on these prices only farmers form their expectations and behave. As Ricardian approach, and the net-revenue approach used here, assume that 'equilibrium' prices exist, it is important to estimate the net revenues at local prices; and the study has used district level prices only in this study. In the net revenue calculations the expenditure on family labor has not been included, because appropriate wage rate for the same is difficult to obtain. Using the wage rate of agricultural labor would overestimate the expenditure on family labor, as the agricultural labor are typically hired during peak demand periods and thus the wages tend to be high. However, in the main regressions an independent variable has been included to this extent, namely, fraction of cultivators in the total number of people engaged in the agricultural activities. Similarly, In the case of bullocks and tractors, due to government's policies the official prices do not vary much across districts in India, and hence using these prices for calculating the rental costs of these inputs may not be appropriate. However, the quantities of these crucial inputs vary across districts and to capture their influence the study has used the district level per hectare quantities of bullocks and tractors as independent variables in the net-revenue regressions. While calculating the revenue and costs, all prices and wages have been deflated using the agricultural GDP deflator, and are expressed in 1980 rupee terms. Figure 5.1 provides the regional distribution of net-revenue per hectare, averaged over 20 year time period.

Figure 5.1: District level net-revenues per hectare (1980 Rs.)



Note: Values on horizontal axis are districts' codes.

EDAPHIC VARIABLES

In the original data set, no quantitative data on edaphic variables has been recorded, because no such data at district level exists in India. However, inclusion of edaphic variables is very crucial to the analysis, as districts differ substantially in the soil characteristics they possess and thus have differences among the crops that could be grown. Though various other soil characteristics have been considered in the initial runs, in the final model specification, two sets of soil dummies, one representing the soil types and another the top soil depth classes, have been used.

In the data set, there are 19 soil types and five top soil depth classes. However, these have been 'clubbed' in the main regressions, for ease of handling. For clubbing these dummies, the criteria followed is that the dummies with similar influence on the net-revenue can be combined. Thus, first regressions with all the dummies included was run and then using the magnitude and signs of their coefficients as guiding elements appropriate dummies have been clubbed. The idea behind including these dummies has been only to control for edaphic variation across districts in the main regressions, and hence direct interpretation of the soil dummy coefficients is not appropriate in the analyses. Also, the soil variables that could have climate information in-built in them have not been included in the model.

OTHER CONTROL VARIABLES

Other than fraction of cultivators, per hectare bullocks and tractors, as defined above, few other variables have been used as independent variables to control for the cross-sectional variations that could result in variations in the dependent variable. These variables including, population density and literacy proportion, are expected to proxy urban development. The spread of 'green-revolution' across different districts is captured by the control variable, fraction of area under high yielding varieties (HYV). Altitude has also been included as an independent variable to act as a proxy for solar energy.

CLIMATE VARIABLES

The appropriate climate variables that are suitable for the present study are the 'normal' climate variables. The normal climate is defined in climatology as 30 year average climate. As against the yearly weather, the normal climate is considered appropriate for the Ricardian approach because it is against these climate variables that farmers have made adaptations. However, the present study using net-revenue approach, does depend on yearly weather along with the normal climate. Keeping this in view, and also the data available, the following two analyses have been carried out:

a) Analysis I : Estimating functional relation between net-revenues and the normal climate, where normal climate is the average temperature and precipitation observed over the period 1960-'80;

b) Analysis II: Estimating functional relation between net-revenues and the normal climate, in the presence of yearly weather deviations from this normal climate. Here, the normal climate corresponds to the period 1960-1980, and the yearly weather data is for the same period. The focus here is to see whether inclusion of yearly weather influences in the estimation procedure brings down the fluctuations in the results.

The data for Analysis I and II is based on a new data set provided by Indian Meteorological Department (IMD), Pune. This data set corresponds to 120 meteorological stations across India. Each year's daily average temperature and monthly total rainfall (for all 12 months) for the period 1960 to 1980 are available. For Analysis I mentioned above, simply the average temperature and precipitation over the 20 year period has been used and considered as 'normal' climate. Note that this is not exactly 'normal' climate in Climatologist's sense, because it is the average of 20 years data only.

For Analysis II, the normal climate of the period 1960-1980, along with the deviation of each year's weather from this climate has been used.

There is one old data set available from Food and Agriculture Organization (FAO) for climate data. This data set covers the time period 1930-1960; and has climate data for about 160 meteorological stations across India. This data set has been used in a parallel study by Sanghi et.al (1997). There are a number differences between the IMD and FAO data sets:

- they correspond to different time periods
- the geographical coverage of stations under the two data sets is different
- the same station under two data sets has different climate. Figure 5.1 provides a comparison between the two data sets; and Appendix A gives the coverage under IMD data set and its correspondence with the FAO data.

ESTIMATING DISTRICT LEVEL CLIMATE AND WEATHER

As mentioned above the climate (and weather) data is available at meteorological station level, whereas the rest of the data is available at district level. To bring the climate (and weather) data from station level to district level, a spatial statistical analysis is carried out, which examines the determinants of the climate of each district. For doing this, it is assumed that all the meteorological stations within 600 miles radius from the geographic center of the district provide some useful information about that district's climate. The choice of 600 mile radius is arbitrary; and the intention was to draw as many stations as possible into the circle, so that the estimates do not depend too heavily on any one station. A climate surface in the vicinity of the district is then estimated by running a weighted regression across all meteorological stations within 600 miles. The stations which are nearer to the district center presumably contain more information, than the stations that are far away. Hence the inverse of the square root of a station's distance[1] from the districts center is used as the weight. Separate regressions have been run for each district, as each district's set of meteorological stations and the corresponding distances would be different.

[1] The distance between any two points on the Earth's surface with known latitude and longitude, can be calculated using the formula:

$$\cos D = \sin \alpha \sin \beta + \cos \alpha \cos \beta \cos L$$

where, D = angle subtended at the Earth's center by the arc distance between points A and B
α, β = latitudes of points A and B respectively
L = difference in longitude of points A and B.

Using the Earth's radius and D, the distance between A and B can be estimated.

The dependent variables are monthly temperatures and precipitations, and the independent variables include latitude, longitude, altitude and shoreline distance. Based on the evidence from US and Brazil studies (Mendelsohn et.al., 1994; Sanghi et.al., 1996), a second order polynomial had been fitted over these four basic variables, including interactive terms. Thus the climate regressions included 14 variables and a constant term. Under analysis I, a total of 6504 (= 12x2x271) regressions were run, to assess district-level normal temperature and precipitation using the normal climate available at meteorological stations. Where as for analysis II, a total of 71544 (=11x12x2x271) regressions were carried out to assess district level yearly weather for the period 1970 to 1980 (i.e., for 11 years), using the yearly weather data available at meteorological stations. A sample regression is shown in Table 5.1. Though in the final analysis the temperature and precipitation corresponding to only four months was used, estimations were carried for all the twelve months for each district. This is expected to be useful for any future analyses.

Using the regression coefficients, the predicted value of climatic variables for the geographic center of the district is estimated. These predicted climate (and weather) variables are used as independent variables in the main net-revenue regression. This complicated procedure for assessing district level climate (and weather) has been adapted to obtain accurate estimates.

Figures 5.2 and 5.3 show the district level seasonal distribution of temperature and rainfall. For comparison, the district level seasonal distribution of temperature as estimated using FAO data has been shown in Figure 5.4. Because of the inherent differences between the two data sets, the district level climate estimations are also different.

MODEL SPECIFICATIONS

The following are the common specifications for models used under Analysis I and II:

- net-revenue per hectare has been used as the dependent variable
- normal temperature and precipitation of months January, April, July and October - representing the four seasons - have been considered to represent climate
- linear and quadratic the above climate terms have been used as independent variables, as the inherent functional relation is expected to be non-linear
- climate interaction terms have also been used as independent variables
- all the climate terms have been 'demeaned'
- all the observations have been weighted by the total area under the crops considered in the study[2]
- control variables included are soil dummies, fraction of cultivators, bullocks, tractors, fraction of HYV, population density, literacy proportion, and altitude

For Analysis II, along with the above specifications, eight more independent variables are included to account for the deviation of each year's weather from the normal climate.

2 As the data is at the district level and not at the farm level, the extent of measurement error in each district's observation is not known. Assuming that larger districts contain more number of farms and hence would have less measurement error, higher weights are provided to larger districts by using acreage as weight. However, such specification has inherent bias associated with it. A particular district could be large in size, but may not have many farms due to climatic conditions prevailing; and hence acreage weight would be misleading.

Econometric Procedures

For Analysis I, three econometric procedures have been applied for checking the robustness of the estimates. These are:

- Pooled Procedure: Observations corresponding to the study period, 1966 to 1986, have been pooled and yearly dummies have been added to control for year-to-year variation in weather, prices etc. for running a single regression.
- Averaged Procedure: Averaged values of dependent and independent variables over the period 1966 to 1986 have been used for running a single regression.
- Repeated Cross-sectional Procedure: For each year a separate regression is run.

Since the overall objective is to assess the long-run impact of climate on net-revenue, the first two procedures are assumed to provide appropriate estimates; on the other hand, as the dependent variable in the present study, namely, net-revenue, is more an yearly phenomena, the third procedure is expected to capture the yearly fluctuations in the estimates.

For Analysis II, the period of analysis has been restricted to 1970 to 1980. In this analysis, the objective was to assess the influence of yearly weather on the climate coefficients. Towards meeting this objective, two procedures have been applied:

- Pooled Procedure: For the period 1970 to 1980, all the observations have been pooled, once without weather terms and once with weather terms, to run a single regression. Each time, yearly dummies have been included to capture the year-to-year variations. Without weather terms included, the year dummies would account for the year-to-year influences of weather, prices and other variables affecting agriculture. With weather terms included in the model, the year dummies would account for the year-to-year influences due to prices and other variables affecting agriculture.
- Repeated Cross-sectional Procedure: For each year a separate regression is run.

From the pooled estimates, one would know to what extent the inclusion of weather terms has influenced the estimation of climate coefficients. Whereas from the repeated cross-sectional procedure, it is possible to see whether the inclusion of weather terms has been useful in explaining the year-to-year fluctuations of climate coefficient estimations. If weather were to be the cause behind year-to-year fluctuations, one would expect that climate coefficients would get stabilized with the inclusion of weather terms in the regression.

Figure 5.2: State level seasonal temperatures as per IMD data

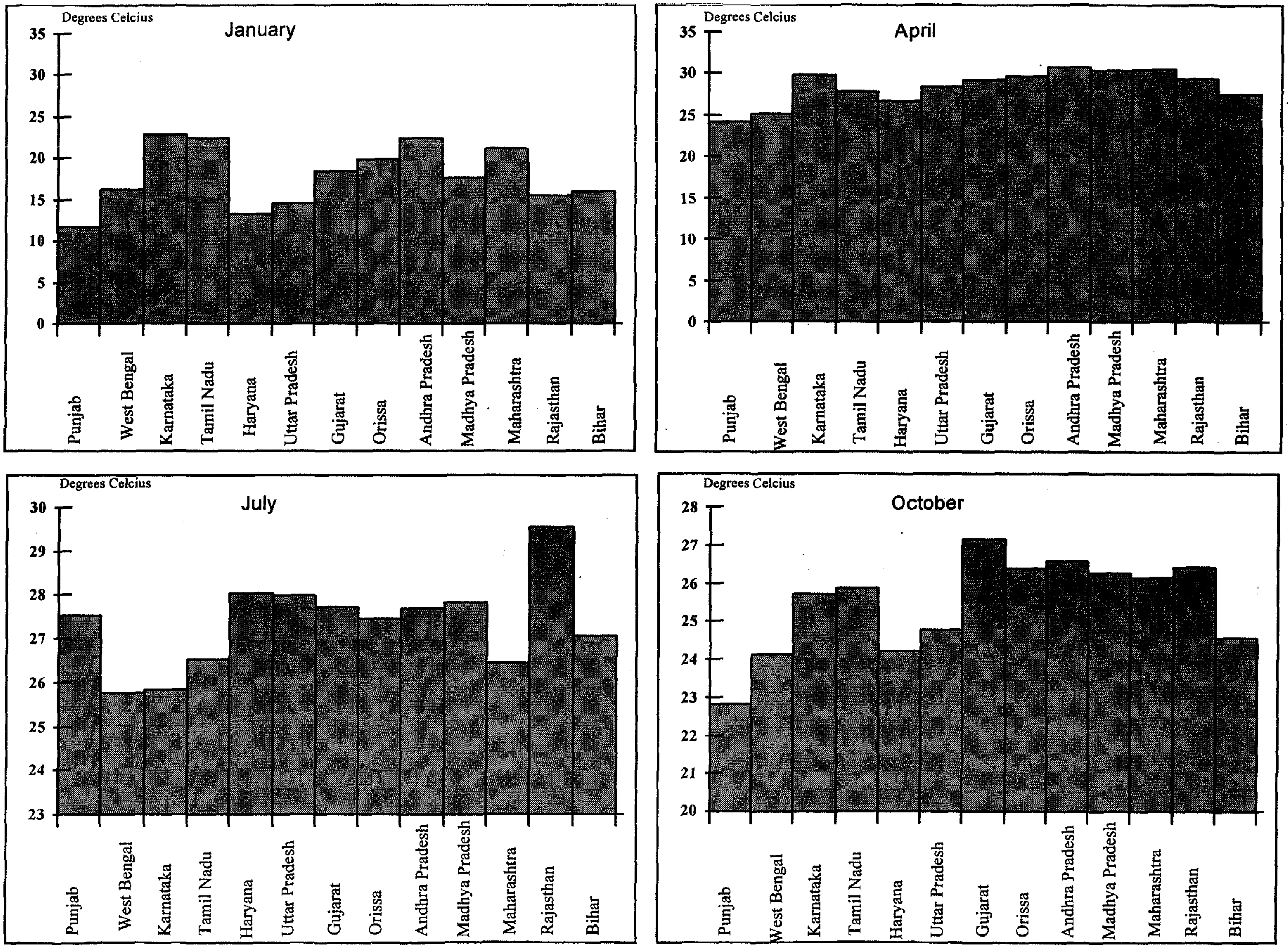


Figure 5.3: State level seasonal rainfall as per IMD data

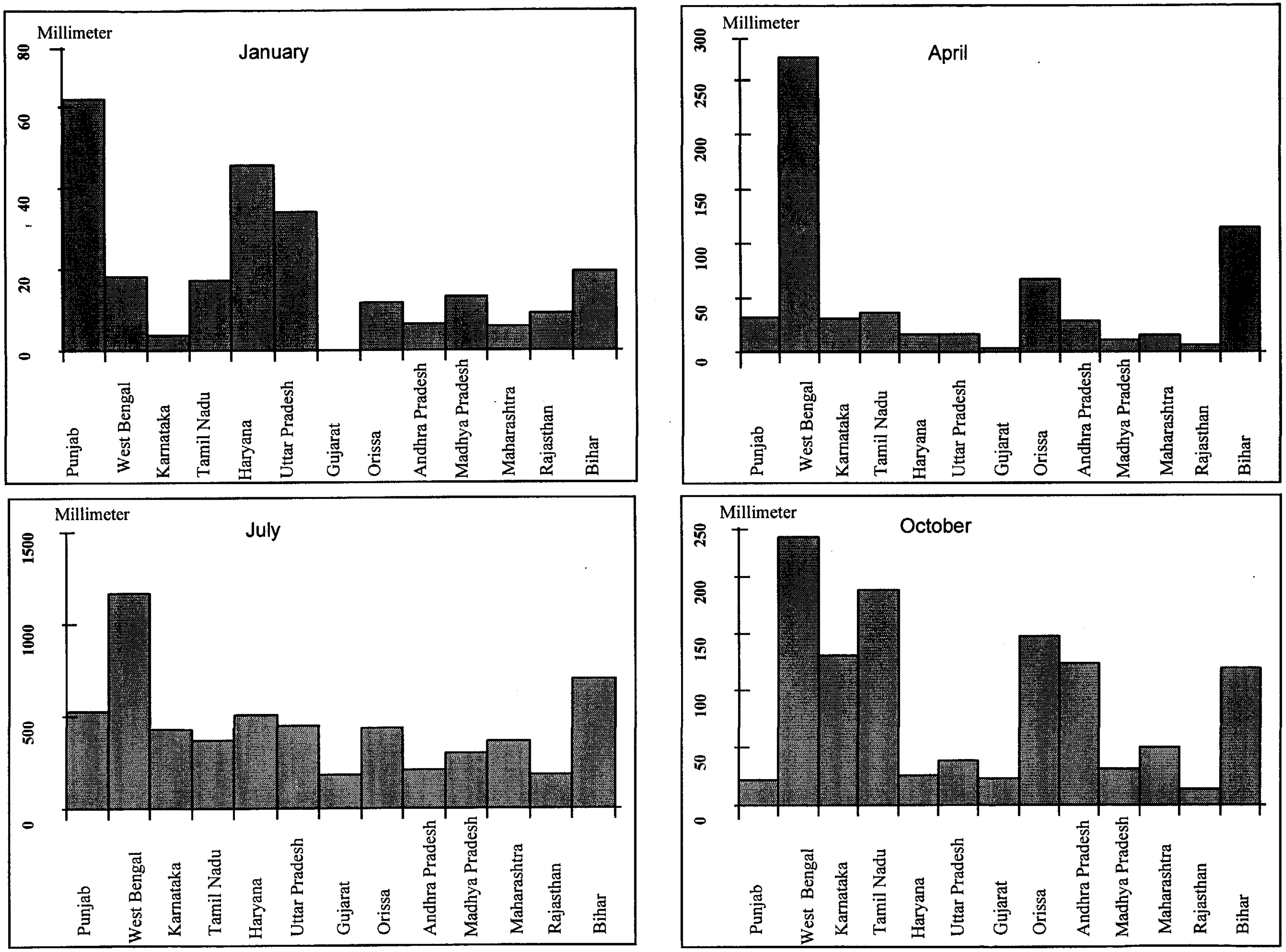
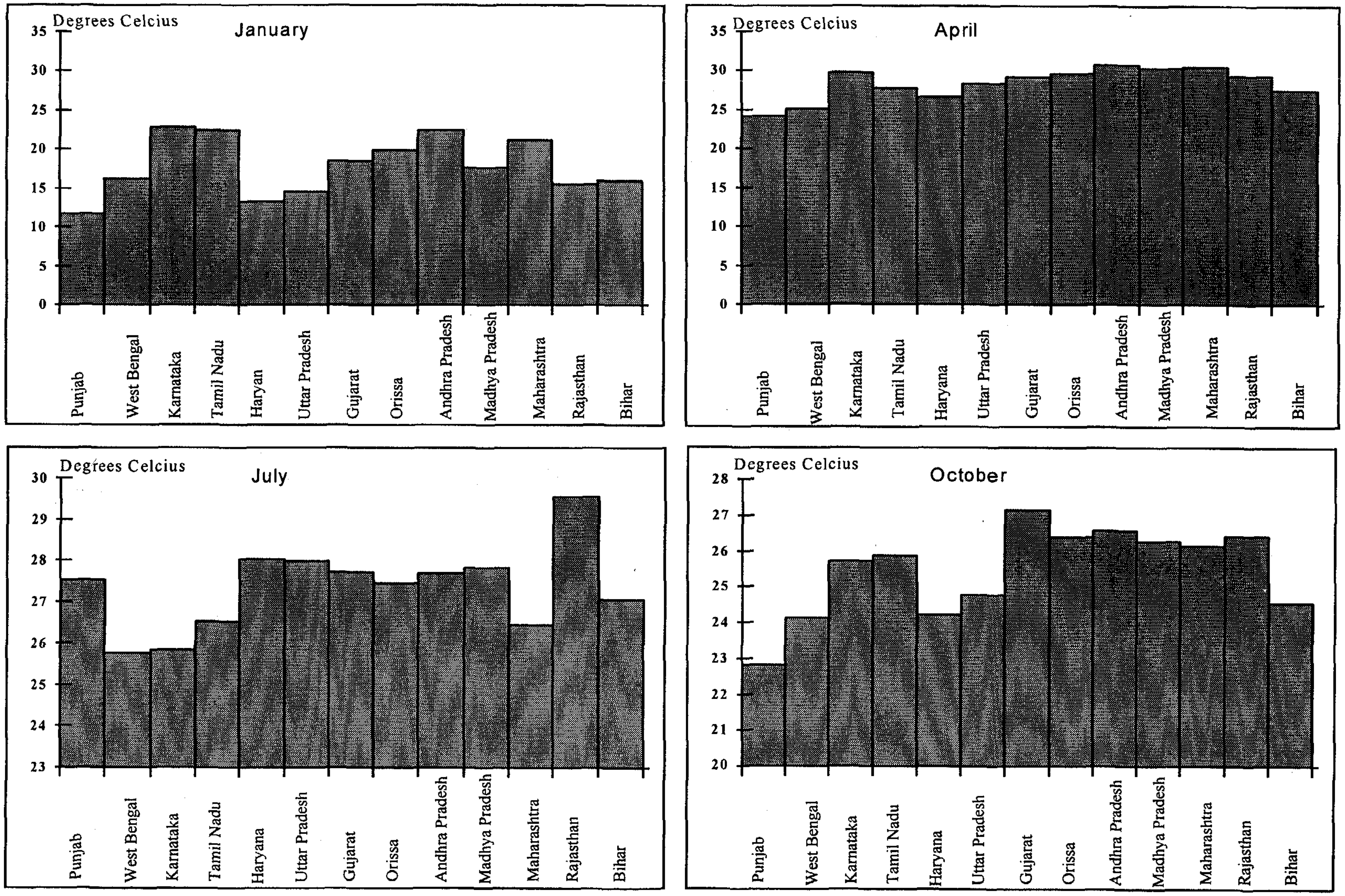


Figure 5.4: State level seasonal temperatures as per FAO data



EMPIRICAL ESTIMATION OF CLIMATE RESPONSE FUNCTION

In this section, the results of the analysis I are presented and the characteristics of climate response function estimated are discussed. Table 5.2 gives the coefficients estimated using pooled and averaged procedures; while Table 5.3 provides the coefficients estimated using repeated cross-sectional procedure. Note that, though the repeated cross-sectional procedure has been carried-out for all the years from 1966 to 1986, only the results corresponding to years from 1970 to 1980 have been presented in Table 5.3.

As could be seen from Table 5.2, the two estimation procedures, namely pooled and averaged, provided remarkably close estimates. The estimates from repeated cross-sectional procedure have also retained to a large extent the significance levels and signs of the coefficients. For the rest of the discussion here, the estimates from the pooled procedure are considered.

CONTROL VARIABLES

As the net-revenues for the year 1979 were lowest among all the years, the dummy for this year has been omitted. Accordingly, the dummy coefficients for all the years are significantly positive. Fraction of cultivators has positive effect on net-revenue, implying that more of household labor is beneficial. As expected other control variables, population density, literacy proportion, bullocks and tractors have positive influence on the dependent variable.

IMPACT ESTIMATIONS

Using the above coefficients estimated under pooled procedure, the possible impacts on district level net-revenue per hectare are calculated. The climate coefficients indicate that there are significant influences on net-revenue, and that they are highly non-linear. As direct interpretation of climate coefficients is not easy because of the inclusion of climate interaction terms, the changes in the dependent variable are assessed under a scenario with 2.0°C temperature rise and 7% increase in precipitation.

For each district, to get a measure of possible change in net-revenue per hectare, the dependent variable is estimated once with base climate and once with the modified climate. To get a measure of national level change in net-revenue, the district level estimates are summed up. While calculating the seasonal effects, the changes in climate are applied to the appropriate month; and similarly while estimating the partial effects due to temperature alone and precipitation alone, the changes are applied to the appropriate climate variable keeping the other climate variable at its base value. Thus while estimating the partial effect due to temperature alone, the precipitation variable is kept at its base value.

The national level estimates indicate that:

- January, April and July seasons have negative influence on net-revenue; whereas October effects are positive
- Negative temperature effects have major share in the overall effects, which are negative. Though precipitation contributed positively, it gets nullified by the large negative effect due to temperature rise

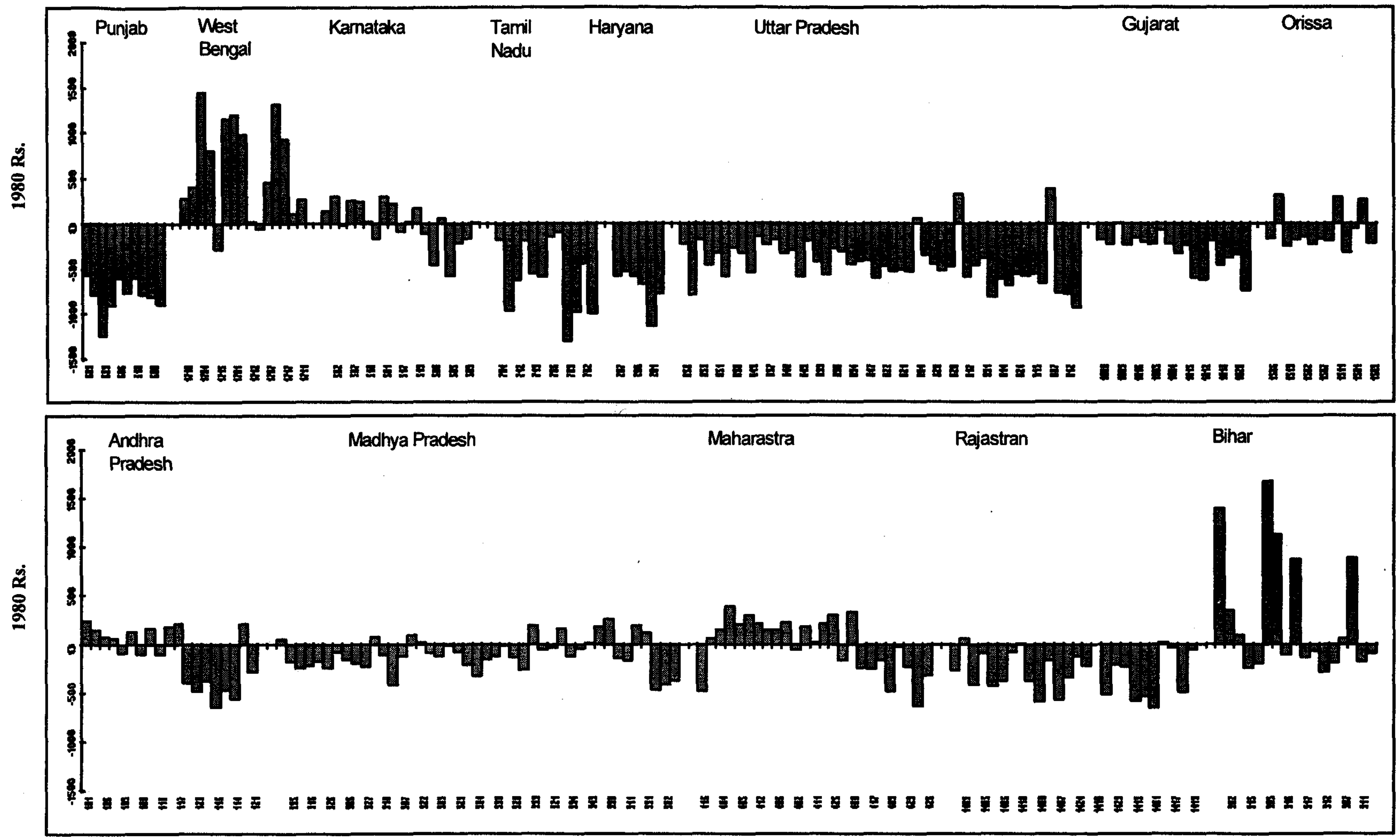
The general trend of these results is in tune with those obtained by Sanghi et.al. (1997) using the FAO climate data set. The regional distribution of partial effects due to temperature and precipitation are shown in Figure 5.5a and 5.5b respectively; while Figure 5.6 shows the regional distribution of overall effects. As it is clear from these Figures, the trend of effects observed under partial temperature change is same as that observed under overall change in climate. The regional distribution of overall effects shows that the sub-tropical regions, namely, the states of Haryana, Punjab, and Western Uttar Pradesh get adversely affected along with few western coastal regions and few in the south India. In comparison, the eastern states, West Bengal, Orissa and to some extent Bihar enjoy beneficial effects due to changes in climate.

YEARLY FLUCTUATIONS IN THE IMPACTS

As discussed earlier, the net-revenue is more of a yearly phenomena and accordingly the estimates from repeated cross-sectional procedure are expected to provide an idea of how the climate coefficient estimates vary from year to year. Figure 5.8 gives the estimates from year-wise regression analysis. Here, the impacts due to four scenarios are shown, of which scenario II corresponds to the 2.0°C temperature rise and 7% precipitation increase. Discussion on other scenarios is made in the next section.

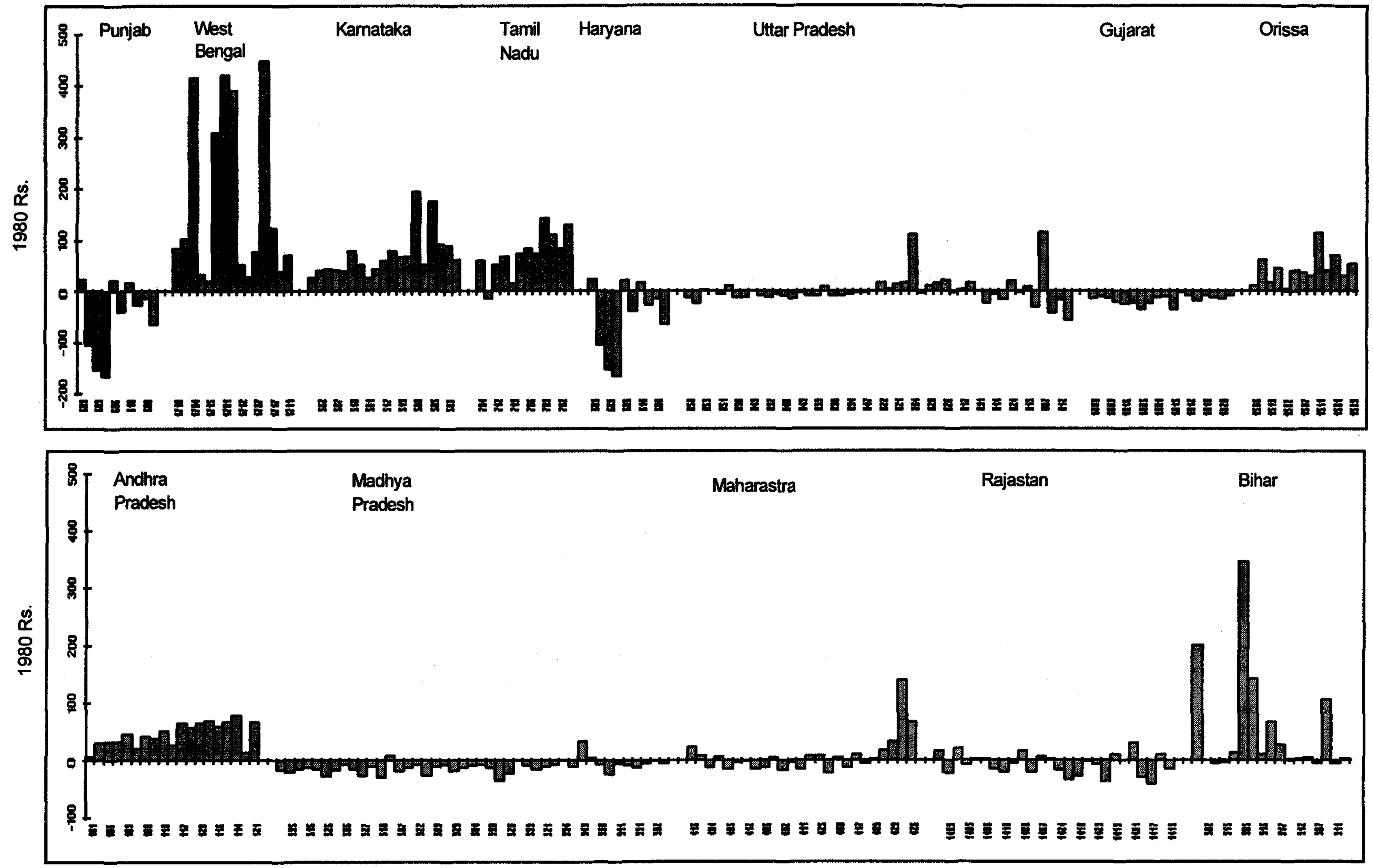
As could be seen from the figure, the estimates vary substantially from year to year. There could be a number of reasons for these fluctuations in the impacts, including weather, prices and other variables influencing agriculture. In order to see to what extent year-to-year variation in weather causes these fluctuations in impacts, in the later section includes the weather variables in the regression and estimates the climate coefficients.

Figure 5.5a: Impacts on district level net-revenues per hectare due to +2.0°C temperature rise



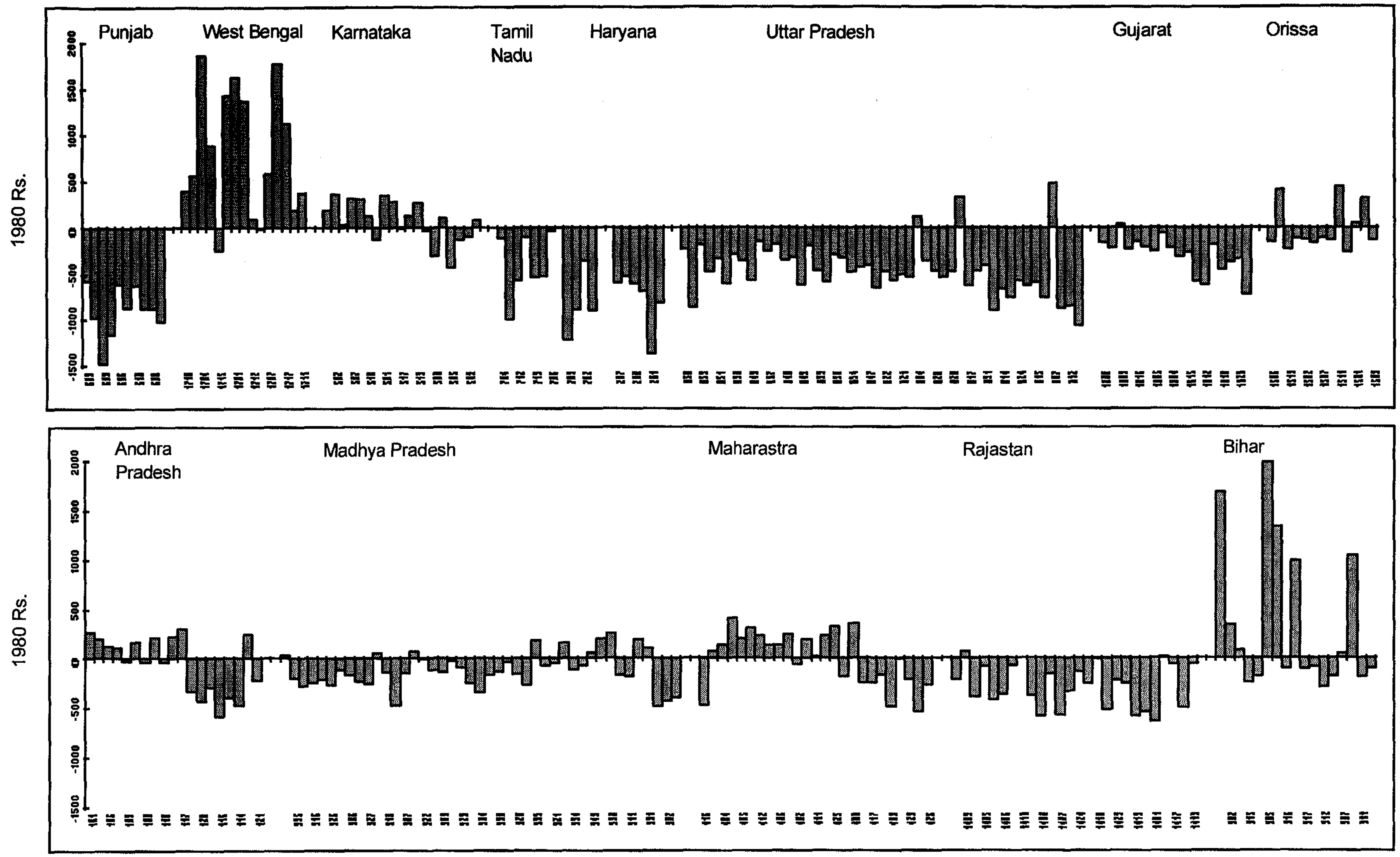
Note: Values on horizontal axis are districts' codes.

Figure 5.5b: Impacts on district level net-revenues per hectare due to +7.0% increase in rainfall



Note: Values on horizontal axis are districts' codes.

Figure 5.6: Impacts on district level net-revenues per hectare due to +2.0oC and +7% rainfall scenario



Note: Values on horizontal axis are districts' codes.

IMPLICATIONS FOR GLOBAL CLIMATE CHANGE

Earlier IPCC estimates have put the possible changes in the global mean temperature to lie between 1.5 to 4.5°C, following a doubling of atmospheric concentration of CO_2 equivalent (IPCC, 1990). The best guess estimate of the above range was placed at 2.5°C. The latest estimates (IPCC, 1996), however indicate a lower temperature change following CO_2 doubling. The differences are due to the differences in the structure of underlying models, and the latest estimates are based on more advanced coupled ocean general circulation models (GCMs) and are expected to be more reliable. As GCM scenarios at the district level details are not easy to estimate, the present study has considered the following four scenarios for assessing the possible impacts due to climate change at state and national levels:

a) Scenario I : +1.0°C temperature change and 0% increase in precipitation
b) Scenario II : +2.0°C temperature change and 7% increase in precipitation.
c) Scenario III : +2.5°C temperature change and 15% increase in precipitation.
d) Scenario IV : +3.5°C temperature change and 15% increase in precipitation.

For calculating the overall impacts due to a particular climate change scenario, the district level per hectare estimates are first converted to district level total estimates by multiplying the per hectare estimates by the total cropped area of the district. The district level total effects are then aggregated to state and national level.

Tables 5.4 and 5.5 present the results of above scenarios for Analysis I. The break-up of results for all the seasons and for temperature and precipitation are given in Table 5.4. From the results one can observe that the temperature response function is of inverted 'U' shape. That is, with higher climate change, more losses would occur. However, the response function of precipitation appear to be of 'U' shape. The overall response function is of inverted 'U' shape.

The overall impacts estimated using IMD data set appear to be lower than those estimated using FAO data set. One possible explanation for this is that, the response function obtained using IMD data is more nearer to peak of the inverted 'U' curve, than the one estimated using FAO data. However, results from both the data sets concur that the overall response function would be of inverted 'U' shape.

Figures 5.9 and 5.10 provide the regional distribution of impacts due to the above climate change scenarios, for results from using IMD data set and FAO data set respectively. The general pattern followed in both the graphs is similar, except for a few differences, notable among them being the case of sub-tropical belt, i.e., Haryana, Punjab and UP. These three states are in sub-tropical climates and winter crop, wheat is the main crop grown there. With results from many studies, including those by Rao and Sinha (1994) and Kumar and Parikh (1996), showing that climate change would have relatively higher negative impacts on wheat crop production, the regional distribution of impacts as obtained under Figure 5.9 appears to be more in tune with the conventional wisdom.

CLIMATE RESPONSE FUNCTION WITH YEARLY WEATHER INFLUENCE

As discussed above, one of the possible reasons for the yearly fluctuations in impacts observed in Figure 5.4 could be due to the fluctuations in the yearly weather. In this section the results from Analysis II are presented, where along with the independent variables included in Analysis I, the yearly weather deviation terms are added to the list of independent variables. The time period has been restricted to 11 years, from 1970 to 1980. First to assess to what extent the coefficients of climate terms would get disturbed due to the presence of weather terms, pooled analysis has been conducted, once without weather terms and once with weather terms. The results are presented in Table 5.6.

From Table 5.6 it is evident that though the weather variables are significant, they do not drastically change the climate coefficients. The weather variables themselves are also significant, indicating that they do have some influence. All the control variables retain their signs and significance.

To assess to what extent the variability of climate coefficients has reduced with the inclusion of weather terms in the model, repeated cross-sectional analysis has been carried out for the period 1970 to 1980. The results from this are presented in Table 5.7, and the results are compared with those obtained under Analysis I in Figure 5.11 for the impacts under scenario II - i.e., 2.0°C temperature rise and 7% increase in precipitation. The hypotheses was that, if the weather were the cause behind the yearly fluctuations in impacts, then inclusion of yearly weather deviation would bring down the fluctuations. From Figure 5.11 it appears that the above hypotheses may not be holding. Though the variation in impacts has come down under Analysis II, compared to that under Analysis I, the fluctuations are still significant.

This indicates that there are influences other than weather, that dictate the movement of net-revenue from year to year. One possible explanation is that the relative prices between crops is not constant as assumed under Ricardian approach. Another explanation could be fluctuations in the government policies.

CONCLUSIONS AND POLICY GUIDELINES

This study estimated the relationship between farm level net-revenue and climate variables using the cross-sectional evidence in India. The district level data has been used for the analysis. Using the observed reactions of the farmers, the study tried to understand how they have adapted to different climatic conditions across India. Using data from 1966 to 1986, in Analysis I, the cross-sectional evidence between net-revenue and long-term normal climate variables has been explored, while controlling for a host of other variables which could have influence on net-revenue. The climate data used for this analysis has been obtained from Indian Meteorological Department, and the results are compared with those arrived at using an older climate data set available from FAO.

The underlying relation between net-revenue and climate variables appear to be non-linear. The seasonal variation in impacts shows that but for October, all other seasons would have negative influence on net-revenue. The positive influence of October is not sufficient to counter the negative influence of all other seasons, and hence the overall impact is negative. The impacts due to temperature change are negative and are much more than the positive impacts due to precipitation change. The results show that an inverted 'U' shape relation exists between temperature and net-revenue; and that a 'U' shape relation exists between net-revenue and rainfall. The coefficients are remarkably stable across three different econometric procedures, namely, pooled, averaged and repeated cross-sectional procedures.

The impacts due to a set of climate change scenarios have been estimated using the functional forms obtained from the above analyses. The results from this study show that the losses expected from the climate change on Indian agriculture would be more than similar estimates made in USA and Brazil. The regional distribution of impacts seem to concur with the conventional wisdom.

In an attempt to explain the yearly fluctuations in the climate coefficients, in Analysis II, the study has included the weather deviation terms in the cross-sectional regression. The hypotheses being, if weather were to explain the yearly fluctuations in the climate coefficients, inclusion of weather deviation terms would make the climate coefficients stable over years. However, the study showed that inclusion of yearly weather deviations terms has not brought down the fluctuations in the estimates in substantial manner. This indicates that there could be influences other than weather, such as prices and government policies. The climate variables retained their significance even in the presence of yearly weather terms, thus proving the robustness of the estimates.

The estimates provided in this study could be considered as only a beginning of an attempt to quantify some of the impacts and the costs, despite adaptation, that Indian agriculture is likely to face in the event of climate change. One need to be careful to use them for policy purposes. They should be used in a very conservative manner. They are in no way accurate enough to judge courses of action for more than a billion people for years to come. Evidence from the literature on risk avoidance should be taken into consideration to understand how many billions of dollars are spent to avoid possible risk in, say nuclear power plants. Such knowledge would give a criteria to compare with for understanding how much the food security is of worth for billions of people including those outside India.

Table 5.1: District climate interpolation - Guntur, Andhra Pradesh

Independent Variable	Temperature		Rainfall	
	January	October	January	October
Intercept	61.731	47.357	3470.9*	-4043.1
Altitude	-2.05E-03	1.35E-04	-0.15406	0.32095
Latitude	-3.1441*	2.2618*	55.342*	-126.22*
Longitude	6.88E-04	-1.0203	-101.64*	126.01
Distance to sea	8.56E-02*	2.36E-02	-0.40994	3.1553
Latitude x longitude	5.16E-02*	-2.49E-02*	-0.82535*	1.4656*
Latitude x altitude	2.36E-04*	-2.66E-05	-3.72E-04	7.08E-03
Altitude x longitude	-1.04E-04	-6.59E-05	1.99E-03	-5.75E-03
Alitude squared	4.40E-07	-4.91E-07*	1.48E-05*	3.57E-05*
Latitude squared	-4.23E-02*	-1.26E-02*	9.58E-02	0.11844
Longitude squared	-6.66E-03	9.55E-03	0.75089*	-0.89006
Distance to sea squared	-1.79E-05	-1.81E-05*	-2.73E-04	1.88E-03*
Distance x altitude	-4.06E-07	5.71E-08	1.44E-06	6.79E-06
Distance x latitude	-1.00E-04	1.88E-05	2.69E-02*	-1.28E-02
Distance x longitude	-9.29E-04*	-1.83E-04	1.08E-03	-5.04E-02*
Adjusted R^2	0.9952	0.997	0.7509	0.8891
Number of observations	79	79	79	79

* Statistically significant at the 5% significance level

Table 5.2: Net revenue regression for the period 1966-1986, pooled and averaged procedure - analysis I

Variable Name (Abbreviation)	Pooled Procedure		Averaged Procedure	
	Coefficient	T-ratio	Coefficient	T-ratio
January Temperature (JanT)	-94.872	-6.808	-99.544	-2.054
April Temperature (AprT)	-174.035	-11.961	-137.744	-2.623
July Temperature (JulT)	-140.771	-5.203	-149.422	-1.598
October Temperature (OctT)	457.583	13.055	468.182	3.880
January Temperature Square ($JanT^2$)	-7.645	-3.386	-7.824	-1.010
April Temperature Square ($AprT^2$)	32.481	8.362	31.977	2.343
July Temperature Square ($JulT^2$)	-20.587	-2.581	-23.309	-0.833
October Temperature Square ($OctT^2$)	-56.070	-12.113	-56.433	-3.545
January Rain (JanR)	7.454	4.391	7.476	1.281
April Rain (AprR)	-4.502	-8.908	-4.335	-2.503
July Rain (JulR)	-0.446	-3.861	-0.321	-0.801
October Rain (OctR)	6.370	10.782	6.771	3.334
January Rain Square ($JanR^2$)	-0.656	-12.354	-0.604	-3.310
April Rain Square ($AprR^2$)	0.041	9.394	0.040	2.649
July Rain Square ($JulR^2$)	0.001	3.094	0.001	1.176
October Rain Square ($OctR^2$)	0.004	0.928	0.003	0.183
Jan. Temperature X January Rain (JanInt)	-7.687	-11.871	-7.045	-3.153
April Temperature X April Rain (AprInt)	3.608	17.857	3.541	5.031
July Temperature X July Rain (JulInt)	-0.325	-4.294	-0.249	-0.944
Oct. Temperature X October Rain (OctInt)	-0.535	-2.084	-0.689	-0.785
Soil Type Dummy (Soil1)	104.833	5.698	80.121	1.268
Soil Type Dummy (Soil2)	315.436	13.074	314.670	3.821
Soil Type Dummy (Soil3)	-243.170	-7.694	-208.299	-1.901
Soil Type Dummy (Soil4)	73.963	2.818	62.200	0.693
Top Soil Depth Dummy (Soil5)	-40.264	-0.850	-56.176	-0.342
Top Soil Depth Dummy (Soil6)	111.073	2.140	97.401	0.543

Table 5.2: Net revenue regression for the period 1966-1986 : pooled and averaged procedure - analysis I (cont.)

Variable Name (Abbreviation)	Pooled Procedure		Averaged Procedure	
	Coefficient	T-ratio	Coefficient	T-ratio
Cultivators per Ha. (Cultiv)	76.030	2.288	230.736	1.632
No. of Bullocks per Hectare (Bullock)	23.127	0.552	-99.847	-0.627
No. of Tractors per Hectare (Tractor)	24449.370	7.583	60717.790	3.396
Population Density (Popden)	33.866	4.834	44.290	1.752
Literacy Proportion (Litprop)	720.208	6.958	582.393	1.559
Fraction of HYV (Hyvfr)	-172.055	-2.762	-254.218	-0.839
Altitude (Alt)	-0.299	-5.070	-0.243	-1.205
Year Dummy (dy66)	226.647	4.711		
Year Dummy (dy67)	398.713	8.485		
Year Dummy (dy68)	172.021	3.650		
Year Dummy (dy69)	174.145	3.757		
Year Dummy (dy70)	303.212	6.651		
Year Dummy (dy71)	259.206	5.710		
Year Dummy (dy72)	260.161	5.742		
Year Dummy (dy73)	528.277	11.930		
Year Dummy (dy74)	496.972	10.962		
Year Dummy (dy75)	455.348	10.272		
Year Dummy (dy76)	321.300	7.174		
Year Dummy (dy77)	384.584	8.748		
Year Dummy (dy78)	312.276	7.150		
Year Dummy (dy80)	292.776	6.717		
Year Dummy (dy81)	179.790	4.187		
Year Dummy (dy82)	145.872	3.345		
Year Dummy (dy83)	287.872	6.733		
Year Dummy (dy84)	134.542	2.982		
Year Dummy (dy85)	85.294	1.878		
Year Dummy (dy86)	-44.700	-0.977		
Constant (Const)	630.311	7.722	858.006	3.234
Adjusted R-square	0.5331		0.6582	

Table 5.3: Net revenue regressions for the period 1970 to 1974 : repeated cross-sectional procedure - analysis I

	1970		1971		1972		1973		1974	
JanT	-149.380	-2.666	-112.240	-1.859	-221.630	-3.817	-35.902	-0.601	-132.380	-2.173
AprT	-235.590	-3.672	-139.640	-2.015	84.282	1.269	-132.040	-1.923	153.320	2.170
JulT	-146.920	-1.342	-140.430	-1.168	-231.110	-1.999	-189.620	-1.616	-160.770	-1.331
OctT	605.930	4.261	486.150	3.124	303.900	2.045	284.550	1.891	183.770	1.211
$JanT^2$	-7.681	-0.868	-5.477	-0.583	-3.075	-0.336	-17.610	-1.910	-14.199	-1.435
$AprT^2$	21.342	1.292	14.738	0.831	-3.983	-0.239	-0.036	-0.002	15.475	0.905
$JulT^2$	-16.332	-0.521	-38.276	-1.120	18.093	0.542	17.595	0.511	60.774	1.686
$OctT^2$	-73.584	-3.940	-50.412	-2.476	-35.359	-1.806	-41.022	-2.051	-23.945	-1.188
JanR	1.163	0.171	1.744	0.235	7.523	1.060	-3.734	-0.510	-9.954	-1.353
AprR	-4.559	-2.195	-5.551	-2.409	-7.486	-3.449	-3.641	-1.670	-5.248	-2.364
JulR	-0.773	-1.631	-0.557	-1.079	-0.613	-1.259	-1.017	-2.060	0.031	0.061
OctR	10.371	4.354	8.938	3.429	12.638	5.051	5.761	2.282	7.319	2.856
$JanR^2$	-0.432	-2.037	-0.449	-1.917	-0.207	-0.936	-0.541	-2.444	0.430	-1.844
$AprR^2$	0.042	2.335	0.036	1.839	0.033	1.749	0.024	1.242	0.034	1.812
$JulR^2$	0.001	1.474	0.000	0.392	0.000	0.190	0.001	1.354	0.002	1.689
$OctR^2$	-0.019	-0.982	0.000	-0.016	0.000	-0.006	0.029	1.459	0.040	1.929
JanInt	-8.182	-3.203	-7.751	-2.769	-5.150	-1.940	-10.225	-3.892	-9.458	-3.332
AprInt	3.370	3.927	2.709	2.945	1.787	2.057	2.689	3.086	3.134	3.598
JulInt	-0.164	-0.541	-0.444	-1.331	-0.358	-1.105	-0.111	-0.336	0.166	0.507
OctInt	-1.185	-1.111	-0.310	-0.263	1.259	1.132	-0.482	-0.422	0.998	0.868
Soil1	89.741	1.249	251.270	3.172	172.680	2.238	177.240	2.287	137.770	1.746
Soil2	543.290	5.644	529.830	4.945	288.060	2.765	394.000	3.740	149.260	1.414
Soil3	-162.240	-1.291	-72.056	-0.527	-213.180	-1.603	-90.009	-0.659	-243.480	-1.733
Soil4	-71.678	-0.685	76.507	0.667	50.541	0.451	79.354	0.712	96.176	0.877
Soil5	-326.110	-1.691	-83.554	-0.394	-226.580	-1.084	-72.990	-0.345	-48.897	0.213
Soil6	-243.140	-1.167	85.959	0.373	44.206	0.195	225.720	0.992	220.270	0.904
Cultiv	-37.792	-0.378	70.544	0.719	157.330	1.532	308.990	2.626	502.260	4.011
Bullock	96.199	0.608	-27.491	-0.171	2.487	0.017	96.116	0.621	-207.750	-1.341
Tractor	59764.00	1.425	65193.00	1.621	56360.00	1.640	88554.00	2.534	69863.00	2.122
Popden	72.660	2.079	69.759	1.812	41.710	1.186	123.470	3.616	80.593	2.449
Litprop	34.990	0.073	149.190	0.294	452.050	0.940	-589.610	-1.204	-80.727	-0.168
Hyvfr	-568.560	-1.041	173.410	0.334	471.630	1.081	42.034	0.106	985.170	2.757
Alt	-0.393	-1.703	-0.564	-2.213	-0.638	-2.631	-0.021	-0.083	-0.428	-1.699
Const	1473.700	4.901	920.020	2.798	1055.500	3.306	868.860	2.654	636.570	1.896
Adj.R^2	0.6152		0.5978		0.6378		0.5919		0.5933	

Table 5.3: Net revenue regressions for the period 1975 to 1980 : repeated cross-sectional procedure - analysis I (cont.)

	1975		1976		1977		1978		1979		1980	
JanT	-107.250	-1.618	-28.937	-0.489	-25.840	-0.431	155.790	2.705	6.535	0.118	-49.608	-0.805
AprT	-53.765	-0.733	-238.840	-3.756	-275.100	-4.399	-418.300	-6.864	-259.230	-4.322	-159.330	-2.392
JulT	-198.320	-1.525	-97.079	-0.844	-247.210	-2.144	195.780	1.748	-118.450	-1.097	-140.610	-1.174
OctT	422.240	2.534	378.100	2.557	385.910	2.602	348.890	2.416	362.240	2.599	480.880	3.164
JanT^2	-9.878	-0.914	-13.136	-1.366	-17.060	-1.830	-6.756	-0.744	-7.867	-0.890	-6.593	-0.635
AprT^2	4.423	0.235	55.910	3.335	59.762	3.553	49.532	3.011	29.247	1.831	16.563	0.925
JulT^2	-53.517	-1.372	31.047	0.896	40.508	1.193	-71.140	-2.175	-9.499	-0.300	-70.777	-1.934
OctT^2	-51.205	-2.322	-57.033	-2.931	-66.498	-3.396	-40.212	-2.087	-48.465	-2.636	-54.614	-2.685
JanR	6.881	0.844	-0.209	-0.029	8.790	1.230	17.050	2.464	2.786	0.414	11.458	1.516
AprR	-2.176	-0.894	-7.413	-3.466	-3.726	-1.755	-5.190	-2.508	-0.594	-0.297	-5.263	-2.316
JulR	-0.977	-1.787	-0.195	-0.400	-1.249	-2.597	-0.045	-0.095	-0.416	-0.896	-0.275	-0.532
OctR	4.053	1.437	4.692	1.877	3.600	1.445	1.065	0.435	-0.483	-0.204	4.288	1.641
JanR^2	-0.935	-3.689	-0.493	-2.129	-0.625	-2.717	-0.643	-2.914	-0.663	-3.110	-0.872	-3.587
AprR^2	0.029	1.384	0.034	1.847	0.034	1.865	0.031	1.656	0.022	1.236	0.040	2.078
JulR^2	0.000	0.247	0.001	1.471	0.001	0.696	0.000	0.262	0.001	1.348	0.000	0.012
OctR^2	0.030	1.307	0.038	1.876	0.032	1.613	0.027	1.352	0.033	1.728	0.009	0.432
JanInt	-13.837	-4.443	-6.036	-2.147	-4.769	-1.747	-3.966	-1.493	-7.371	-2.886	-9.581	-3.183
AprInt	3.251	3.357	4.037	4.715	3.890	4.573	3.808	4.471	3.267	3.937	3.315	3.619
JulInt	-0.893	-2.437	0.279	0.859	0.072	0.223	-0.324	-1.026	-0.055	-0.180	-0.714	-2.112
OctInt	-0.156	-0.126	-2.375	-2.186	-1.348	-1.245	-3.754	-3.544	-1.463	-1.429	-1.157	-1.020
Soil1	-24.814	-0.285	-57.573	-0.727	-32.276	-0.411	37.744	0.489	-63.087	-0.846	-4.044	-0.049
Soil2	378.790	3.235	196.120	1.904	366.770	3.471	258.290	2.564	163.910	1.719	286.010	2.732
Soil3	-20.996	-0.140	-254.330	-1.879	-302.520	-2.186	-267.020	-1.968	-270.530	-2.071	-255.760	-1.778
Soil4	75.221	0.608	173.170	1.546	170.310	1.626	18.329	0.170	136.070	1.299	-40.725	-0.349
Soil5	176.250	0.741	-144.530	-0.677	-106.600	-0.490	-124.360	-0.589	-1.481	-0.009	-10.226	-0.056
Soil6	309.650	1.205	162.120	0.698	180.060	0.764	100.170	0.440	83.967	0.446	131.380	0.632
Cultiv	23.287	0.146	267.180	1.715	414.790	2.350	136.790	0.705	176.810	0.893	286.660	1.233
Bullock	750.800	3.975	-193.860	-1.130	2.670	0.015	37.815	0.197	-238.380	-1.240	134.290	0.594
Tractor	16778.00	0.488	53422.00	1.982	56818.00	2.271	28578.00	1.367	39062.00	2.277	77547.00	4.739
Popden	12.289	0.341	80.828	2.546	30.684	1.017	-0.097	-0.003	52.689	1.789	44.184	1.424
Litprop	1310.900	2.485	551.730	1.198	526.780	1.146	1286.600	2.905	657.650	1.591	1122.800	2.488
Hyvfr	315.320	0.823	396.050	1.213	270.410	0.943	157.300	0.558	77.071	0.287	-735.830	-2.682
Alt	-0.127	-0.443	-0.193	-0.753	-0.111	-0.432	-0.374	-1.527	-0.304	-1.287	-0.200	-0.777
Const	112.380	0.302	676.860	2.056	782.400	2.343	864.050	2.654	531.570	1.838	657.630	2.073
Adj.R^2	0.4819		0.6329		0.604		0.6437		0.5563		0.5365	

Note:Under each year, the first column provides the coefficient and the second one the corresponding t-ratio

Table 5.4: Break-up of impacts under various climate change scenarios

Climate Scenario	Impacts						
	January	April	July	October	Temperature	Rainfall	Total
I	-29.563	-18.546	-46.507	90.436	-4.182	0	-4.182
II	-38.106	-18.355	-62.439	104.018	-18.172	3.265	-14.882
III	-47.746	-14.889	-76.790	114.339	-32.414	7.264	-25.852
IV	-57.274	-10.676	-95.656	120.754	-50.190	7.264	-42.852

Table 5.5: Possible impacts due to different climate change scenarios

	Pooled Analysis				Averaged Analysis				Repeated Cross-Sectional Analysis			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
Total Impacts	-5.495	-15.031	-23.905	-43.269	-4.182	-14.880	-25.086	-42.852	-5.509	-13.999	-23.157	-39.642
As Percent of Total Revenue	-3.176	-8.685	-13.813	-24.991	-2.410	-8.574	-14.453	-24.689	-3.085	-7.821	-13.061	-22.403
As Percent of AGDP	-0.745	-2.037	-3.241	-5.865	-0.567	-2.017	-3.401	-5.809	-0.747	-1.898	-3.139	-5.352
As Percent of GDP	-0.236	-0.644	-1.026	-1.857	-0.179	-0.639	-1.077	-1.839	-0.236	-0.601	-0.994	-1.695

Note: Total impacts are in billions of rupees (1980 prices); AGDP represents agricultural GDP; both AGDP and GDP correspond to the 1990 economy.

Table 5.6: Net revenue regression for the period 1970-1980, pooled procedure with and without weather terms - analysis II

Variable Name (Abbreviation)	Without Weather Terms		With Weather Terms	
	Coefficient	T-ratio	Coefficient	T-ratio
January Temperature (JanT)	-56.245	-2.981	-51.588	-2.705
April Temperature (AprT)	-178.624	-8.735	-183.949	-8.739
July Temperature (JulT)	-127.858	-3.471	-124.959	-3.356
October Temperature (OctT)	388.030	8.181	381.156	7.970
January Temperature Square ($JanT^2$)	-9.626	-3.197	-10.017	-3.324
April Temperature Square ($AprT^2$)	23.671	4.449	25.187	4.669
July Temperature Square ($JulT^2$)	-12.874	-1.183	-12.341	-1.119
October Temperature Square ($OctT^2$)	-49.815	-7.941	-53.151	-8.142
January Rain (JanR)	5.036	2.192	5.168	2.252
April Rain (AprR)	-4.677	-6.822	-4.442	-6.406
July Rain (JulR)	-0.591	-3.789	-0.637	-4.077
October Rain (OctR)	5.286	6.592	5.266	6.570
January Rain Square ($JanR^2$)	-0.606	-8.438	-0.598	-8.337
April Rain Square ($AprR^2$)	0.033	5.587	0.034	5.674
July Rain Square ($JulR^2$)	0.001	2.050	0.001	1.983
October Rain Square ($OctR^2$)	0.020	3.167	0.020	3.157
January Temperature X January Rain (JanInt)	-8.088	-9.339	-8.019	-9.230
April Temperature X April Rain (AprInt)	3.225	11.703	3.289	11.892
July Temperature X July Rain (JulInt)	-0.293	-2.841	-0.298	-2.888
October Temperature X October Rain (OctInt)	-0.865	-2.473	-0.939	-2.645
January Rain Development (JanDevR)			-0.114	-0.218
April Rain Development (AprDevR)			0.029	0.223
July Rain Development (JulDevR)			0.134	2.265
October Rain Development (OctDevR)			-0.610	-4.022
January Temperature Development (JanDevT)			-42.951	-3.162
April Temperature Development (AprDevT)			15.626	0.987
July Temperature Development (JulDevT)			29.779	1.627
OctoberTemperature Development (OctDevT)			10.254	0.612

Table 5.6: Net revenue regression for the period 1970-1980 : pooled procedure with and without weather terms - analysis II (cont.)

Variable Name (Abbreviation)	Without Weather Terms		With Weather Terms	
	Coefficient	T-ratio	Coefficient	T-ratio
Soil Type Dummy (Soil1)	62.909	2.523	59.182	2.378
Soil Type Dummy (Soil2)	335.556	10.147	334.239	10.142
Soil Type Dummy (Soil3)	-216.848	-5.011	-218.035	-5.047
Soil Type Dummy (Soil4)	69.964	1.985	69.095	1.962
Top Soil Depth Dummy (Soil5)	-78.395	-1.202	-74.526	-1.145
Top Soil Depth Dummy (Soil6)	125.031	1.759	126.274	1.782
Fraction of Cultivators (Cultiv)	89.017	2.120	92.602	2.211
Number of Bullocks per Hectare (Bullock)	106.468	2.001	108.278	2.036
Number of Tractors per Hectare (Tractor)	39279.390	5.418	40480.100	5.579
Population Density (Popden)	54.322	5.303	53.539	5.238
Literacy Proportion (Litprop)	578.029	3.902	560.647	3.771
Fraction of HYV (Hyvfr)	60.295	0.585	61.158	0.591
Altitude (Alt)	-0.330	-4.118	-0.329	-4.112
Year Dummy (dy70)	357.037	7.641	360.141	7.190
Year Dummy (dy71)	308.242	6.668	296.661	5.443
Year Dummy (dy72)	302.992	6.632	310.717	6.265
Year Dummy (dy73)	561.541	12.682	542.441	9.682
Year Dummy (dy74)	525.985	11.683	541.288	10.427
Year Dummy (dy75)	477.014	10.878	491.465	9.098
Year Dummy (dy76)	334.455	7.581	379.796	7.738
Year Dummy (dy77)	393.051	9.089	395.817	8.318
Year Dummy (dy78)	315.564	7.367	340.790	6.816
Year Dummy (dy80)	288.656	6.752	326.925	6.914
Constant (Const)	484.052	4.478	488.322	4.439
Adjusted R-square		0.5411	0.5785	

Table 5.7: Net revenue regressions for the period 1970 to 1973: repeated cross-sectional procedure - analysis II

	1970		1971		1972		1973	
JanT	-177.000	-2.090	-32.505	-0.428	-245.780	-3.143	-72.421	-0.797
AprT	-187.450	-2.205	-30.044	-0.346	95.128	1.084	-141.810	-1.569
JulT	-253.970	-1.824	-60.618	-0.379	-339.070	-2.551	-224.980	-1.599
OctT	663.490	3.785	290.240	1.365	386.780	2.100	178.470	1.096
$JanT^2$	-19.642	-1.939	-7.086	-0.662	5.959	0.551	-13.538	-1.196
$AprT^2$	49.064	2.422	29.253	1.322	-11.061	-0.534	-25.322	-1.179
$JulT^2$	24.897	0.673	-2.494	-0.061	14.165	0.349	3.944	0.097
$OctT^2$	-6.384	-0.201	-31.325	-0.797	2.647	0.080	-6.200	-0.177
JanR	1.223	0.124	10.211	1.189	-18.095	-1.093	-1.784	-0.169
AprR	-8.650	-2.330	-4.106	-1.350	-6.196	-2.424	-0.425	-0.137
JulR	-0.960	-1.966	0.132	0.226	-0.287	-0.463	-0.329	-0.573
OctR	14.098	4.973	7.900	2.291	13.458	4.246	4.978	1.392
$JanR^2$	-0.377	-1.785	-0.375	-1.555	0.052	0.196	-0.448	-1.549
$AprR^2$	0.064	3.474	0.045	2.131	0.018	0.893	0.011	0.588
$JulR^2$	0.001	0.764	0.000	-0.038	0.001	0.952	0.002	2.317
$OctR^2$	-0.066	-3.468	0.001	0.032	-0.004	-0.196	0.025	1.198
JanInt	-5.543	-2.103	-3.869	-1.335	-2.899	-0.956	-8.636	-2.067
AprInt	3.902	4.170	2.765	2.728	1.794	1.804	1.985	2.144
JulInt	-0.047	-0.141	-0.390	-1.052	-0.196	-0.501	0.079	0.226
OctInt	0.885	0.650	1.346	0.776	-0.968	-0.717	-2.212	-1.476
JanDevR	0.540	0.099	11.272	2.759	27.321	1.415	33.411	3.321
AprDevR	-1.541	-1.350	4.669	1.231	4.393	1.532	8.528	2.725
JulDevR	0.178	0.271	-2.539	-2.865	-0.260	-0.209	-0.003	-0.003
OctDevR	-3.746	-1.688	5.639	2.220	0.622	0.344	-0.200	-0.081
JanDevT	-388.960	-2.872	-102.230	-0.525	-44.026	-0.214	133.600	0.841
AprDevT	621.050	4.425	85.917	0.723	-75.074	-0.470	85.133	0.721
JulDevT	-387.180	-2.667	-15.927	-0.093	-160.050	-0.921	245.310	1.607
OctDevT	-338.620	-1.691	451.350	2.290	386.990	2.204	-382.910	-1.510
Soil1	171.050	2.481	222.630	2.793	193.290	2.434	125.470	1.571
Soil2	516.720	5.773	417.470	3.914	199.120	1.857	310.140	2.969
Soil3	-179.060	-1.508	-114.710	-0.857	-131.640	-0.931	-168.460	-1.233
Soil4	-52.679	-0.538	58.675	0.529	13.829	0.118	108.240	0.976
Soil5	-160.820	-0.903	85.275	0.421	-197.690	-0.942	-13.938	-0.068
Soil6	-90.981	-0.473	221.450	1.010	49.230	0.217	290.900	1.307
Cultiv	43.156	0.464	67.092	0.705	199.880	1.935	352.450	2.998
Bullock	33.043	0.208	-120.570	-0.735	-51.214	-0.347	105.960	0.676
Tractor	98280.000	2.412	121640.000	2.969	64648.000	1.854	107500.0	3.092
Popden	91.977	2.746	94.650	2.473	58.785	1.558	164.900	4.751
Litprop	-632.750	-1.285	-859.850	-1.514	189.480	0.364	-1432.900	-2.551
Hyvfr	462.100	0.845	556.770	1.105	922.420	1.974	345.480	0.810
Alt	-0.307	-1.414	-0.553	-2.272	-0.719	-2.934	-0.074	-0.300
Const	1429.000	4.768	1275.000	3.528	626.480	1.367	1447.400	3.344
Adj.R^2	0.6786		0.6456		0.6486		0.6232	

Table 5.7: Net revenue regressions for the period 1974 to 1977: repeated cross-sectional procedure - analysis II (cont.)

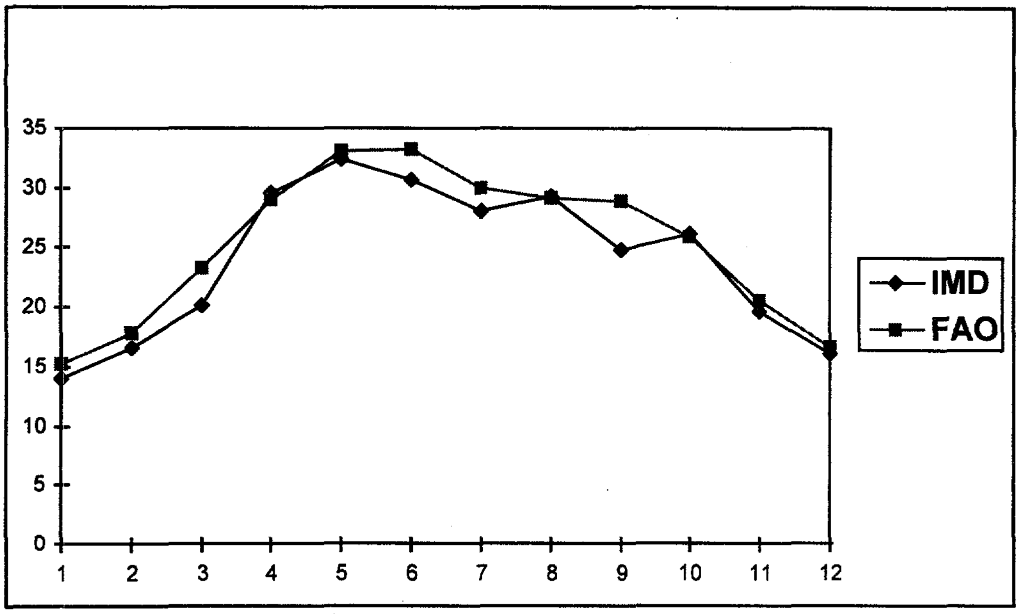
	1974		1975		1976		1977	
JanT	-132.130	-1.555	-81.938	-0.836	142.600	1.438	-74.549	-0.879
AprT	100.030	1.225	-71.433	-0.768	-238.450	-2.797	-264.22	-3.161
JulT	-169.880	-1.042	-179.450	-0.853	27.615	0.167	-245.99	-1.633
OctT	247.940	1.258	214.010	0.704	90.056	0.416	466.610	2.618
$JanT^2$	-10.383	-0.825	-17.561	-1.146	-43.845	-3.775	-54.921	-5.461
$AprT^2$	45.112	2.214	4.806	0.195	78.043	4.044	56.718	3.178
$JulT^2$	23.365	0.523	18.157	0.379	72.627	2.035	110.480	2.557
$OctT^2$	-49.558	-1.540	-26.531	-0.542	-66.340	-2.126	-80.830	-3.549
JanR	5.703	0.324	4.975	0.391	-16.025	-1.389	-7.427	-0.961
AprR	-2.726	-0.688	0.101	0.028	-7.955	-3.608	0.042	0.013
JulR	-0.599	-0.921	-0.913	-1.307	-0.957	-1.699	-1.978	-3.956
OctR	9.831	3.323	1.799	0.550	7.537	2.607	4.918	1.775
$JanR^2$	-0.181	-0.741	-0.757	-2.677	-0.553	-2.267	-0.689	-2.824
$AprR^2$	0.038	1.989	0.023	0.955	0.047	2.721	0.034	1.933
$JulR^2$	0.001	1.113	0.001	0.599	0.000	-0.011	0.001	0.609
$OctR^2$	0.017	0.818	0.025	1.007	-0.022	-1.067	-0.025	-1.258
JanInt	-2.710	-0.895	-9.014	-2.305	-10.324	-2.974	-13.284	-4.139
AprInt	4.002	4.258	2.482	2.209	3.678	4.395	2.661	3.182
JulInt	-0.227	-0.622	-0.407	-0.926	0.050	0.156	0.265	0.843
OctInt	-1.009	-0.689	1.424	0.973	-1.242	-1.016	0.045	0.029
JanDevR	-1.715	-0.089	-5.469	-0.727	-2.833	-0.222	0.437	0.263
AprDevR	5.038	1.747	2.985	1.748	0.435	0.602	2.666	1.226
JulDevR	-0.216	-0.621	0.211	0.326	-1.180	-1.716	0.590	1.028
OctDevR	-3.198	-1.988	-2.613	-1.425	6.166	4.434	-6.817	-6.399
JanDevT	-160.360	-1.008	-153.990	-0.768	-514.580	-4.023	-566.33	-3.403
AprDevT	58.679	0.450	208.820	1.704	347.550	2.939	498.030	3.671
JulDevT	341.130	3.042	-273.110	-1.281	-241.300	-1.807	-120.76	-0.896
OctDevT	213.010	1.483	-10.956	-0.061	-204.080	-1.231	-367.15	-3.218
Soil1	155.480	2.036	-20.743	-0.227	-43.679	-0.569	-89.882	-1.207
Soil2	175.280	1.728	357.180	2.957	247.950	2.639	343.410	3.485
Soil3	-149.250	-1.089	-174.310	-1.095	-195.340	-1.505	-295.31	-2.211
Soil4	144.890	1.346	101.860	0.821	247.940	2.363	140.970	1.354
Soil5	182.110	0.814	203.820	0.859	-80.242	-0.410	-41.880	-0.208
Soil6	407.610	1.729	370.380	1.447	204.690	0.967	258.620	1.189
Cultiv	528.330	4.417	91.476	0.572	246.850	1.671	531.890	3.196
Bullock	-252.670	-1.554	842.300	4.248	-267.910	-1.674	-45.716	-0.269
Tractor	81870.000	2.563	21557.000	0.628	53410.000	2.165	56223.0	2.411
Popden	88.303	2.536	39.669	1.067	155.540	4.892	59.212	2.006
Litprop	-290.860	-0.574	790.960	1.317	-258.740	-0.586	-267.71	-0.588
Hyvfr	1320.300	3.591	484.240	1.191	947.190	2.913	547.270	1.988
Alt	-0.296	-1.229	-0.095	-0.328	-0.074	-0.315	-0.081	-0.339
Const	749.710	1.440	489.970	0.976	252.380	0.719	1078.70	3.076
$Adj.R^2$	0.6377		0.4973		0.6989		0.6709	

Table 5.7: Net revenue regressions for the period 1974 to 1977: repeated cross-sectional procedure - analysis II (cont.)

	1978		1979		1980	
JanT	138.550	1.493	53.537	0.563	12.315	0.156
AprT	-536.640	-5.596	-497.200	-4.295	-373.000	-3.950
JulT	66.040	0.427	-114.260	-0.749	-126.740	-0.950
OctT	432.640	2.408	439.930	1.908	516.720	3.033
$JanT^2$	-19.464	-1.980	-10.302	-1.001	-3.768	-0.329
$AprT^2$	89.893	4.311	48.552	2.749	38.794	1.933
$JulT^2$	-44.630	-1.116	37.916	0.943	-21.708	-0.545
$OctT^2$	-48.125	-1.474	-69.976	-2.044	-124.500	-3.694
JanR	15.301	1.734	-2.230	-0.287	12.668	1.272
AprR	-3.139	-1.106	1.162	0.268	-14.690	-3.572
JulR	-0.969	-1.641	-1.145	-1.572	-0.262	-0.414
OctR	0.146	0.048	-0.079	-0.022	2.305	0.760
$JanR^2$	-0.644	-2.831	-0.549	-2.257	-0.615	-2.394
$AprR^2$	0.037	1.820	0.027	1.458	0.050	2.540
$JulR^2$	-0.001	-0.562	0.001	1.119	0.000	-0.225
$OctR^2$	0.014	0.642	0.025	1.263	0.001	0.061
JanInt	-1.375	-0.448	-5.957	-1.580	-7.753	-2.278
AprInt	4.198	4.263	3.665	4.158	4.276	4.458
JulInt	-0.459	-1.296	0.004	0.011	-0.587	-1.640
OctInt	-3.165	-2.221	-1.691	-1.277	-2.234	-1.575
JanDevR	1.736	0.278	-0.861	-0.145	-22.650	-1.674
AprDevR	-1.415	-0.725	1.607	0.285	14.030	3.266
JulDevR	0.782	0.918	0.230	0.237	-0.001	-0.002
OctDevR	-0.292	-0.113	1.138	0.450	-1.681	-1.259
JanDevT	-470.660	-2.462	-294.360	-1.607	-414.720	-2.415
AprDevT	574.340	4.349	365.520	2.154	252.650	1.501
JulDevT	51.785	0.293	177.990	1.145	335.060	1.721
OctDevT	-211.210	-1.204	-267.000	-1.381	-235.440	-1.616
Soil1	85.397	1.069	-97.013	-1.279	-28.871	-0.353
Soil2	292.770	2.899	200.980	2.053	259.060	2.472
Soil3	-291.750	-2.123	-315.130	-2.270	-286.810	-1.982
Soil4	159.230	1.401	231.820	2.144	-45.784	-0.386
Soil5	-2.490	-0.012	72.617	0.432	7.028	0.038
Soil6	150.080	0.672	138.840	0.743	151.280	0.740
Cultiv	114.290	0.574	174.460	0.861	373.100	1.603
Bullock	32.699	0.171	-351.920	-1.762	111.070	0.499
Tractor	26542.000	1.298	44400.000	2.604	80645.000	4.980
Popden	-20.605	-0.649	50.200	1.699	56.673	1.833
Litprop	1191.800	2.461	-60.833	-0.133	661.950	1.382
Hyvfr	348.830	1.205	453.760	1.617	-313.260	-1.062
Alt	-0.231	-0.948	-0.332	-1.397	-0.222	-0.879
Const	1011.000	2.787	494.130	1.420	411.460	1.015
Adj.R^2	0.6667		0.5755		0.5678	

Note: Under each year, the first column provides the coefficient and the second one the corresponding t-ratio.

Figure 5.7: Comparison of IMD and FAO normal temperature (Bareilly Station)



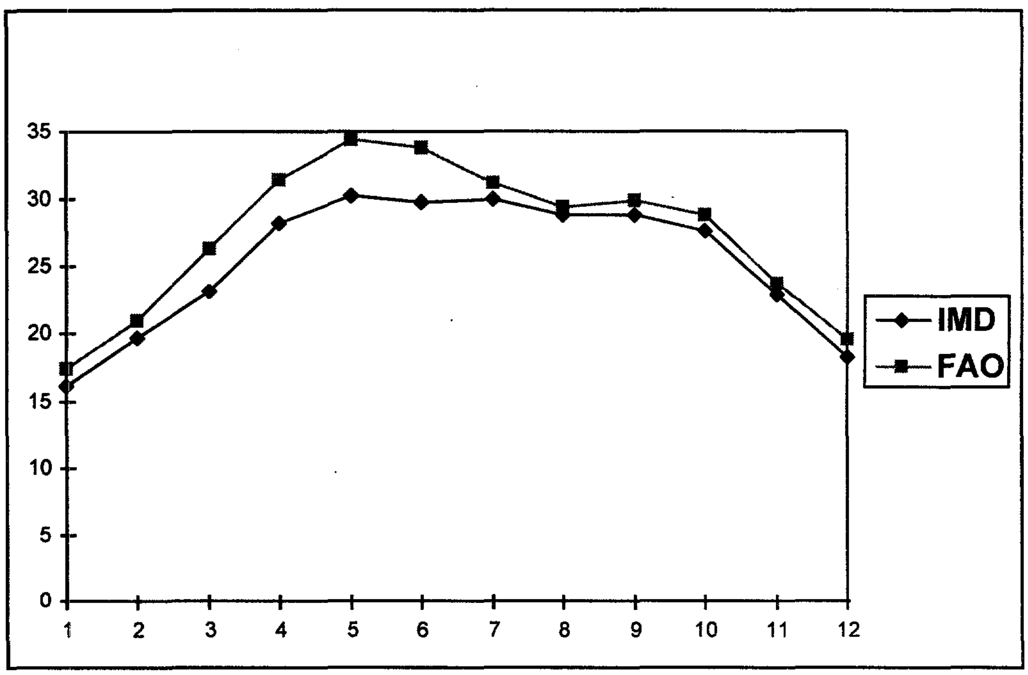


Figure 5.8: Impacts due to various climate scenarios - repeated cross-sectional procedure

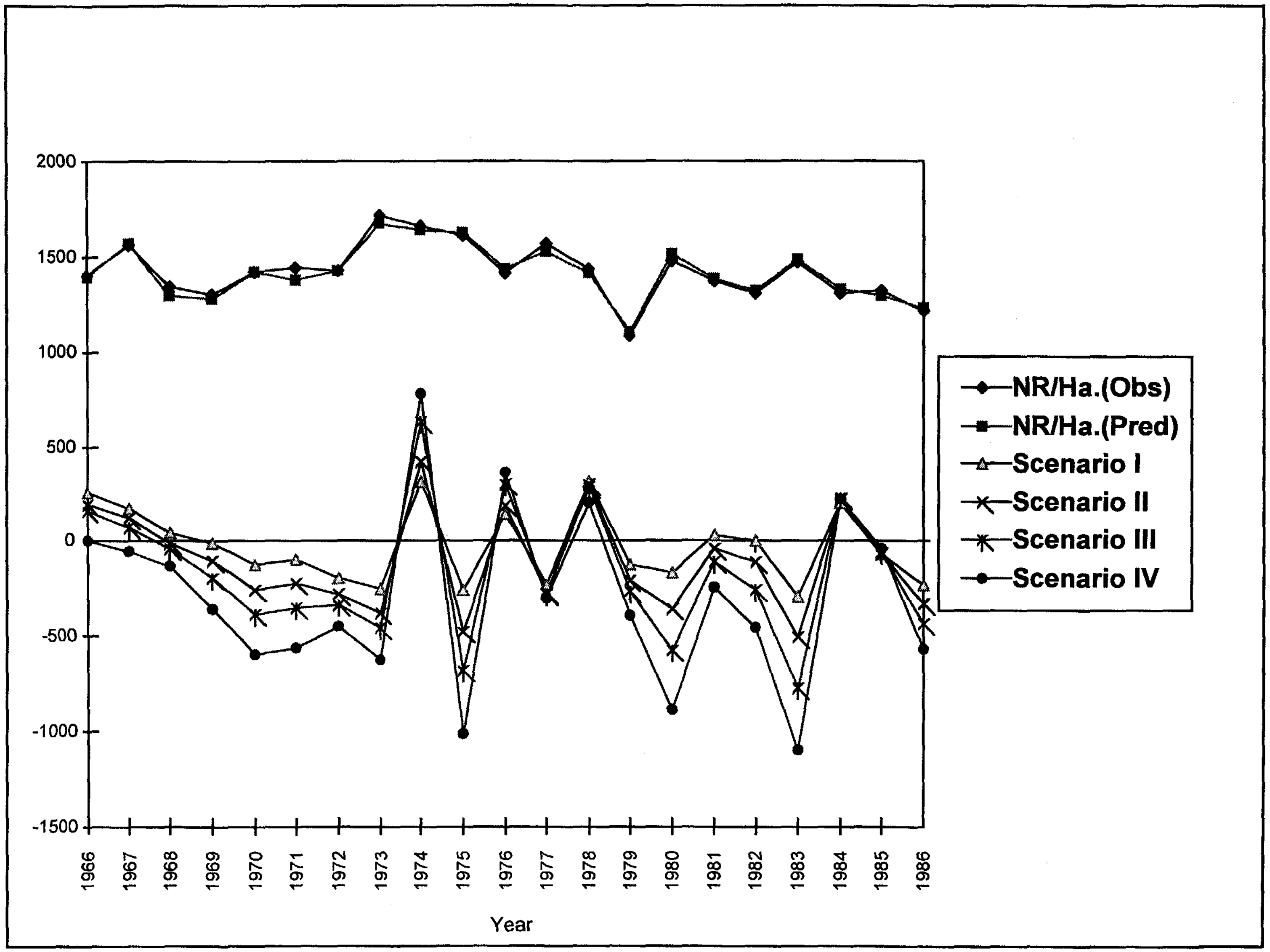


Figure 5.9: State-wise impacts due to various climate scenarios (IMD climate data)

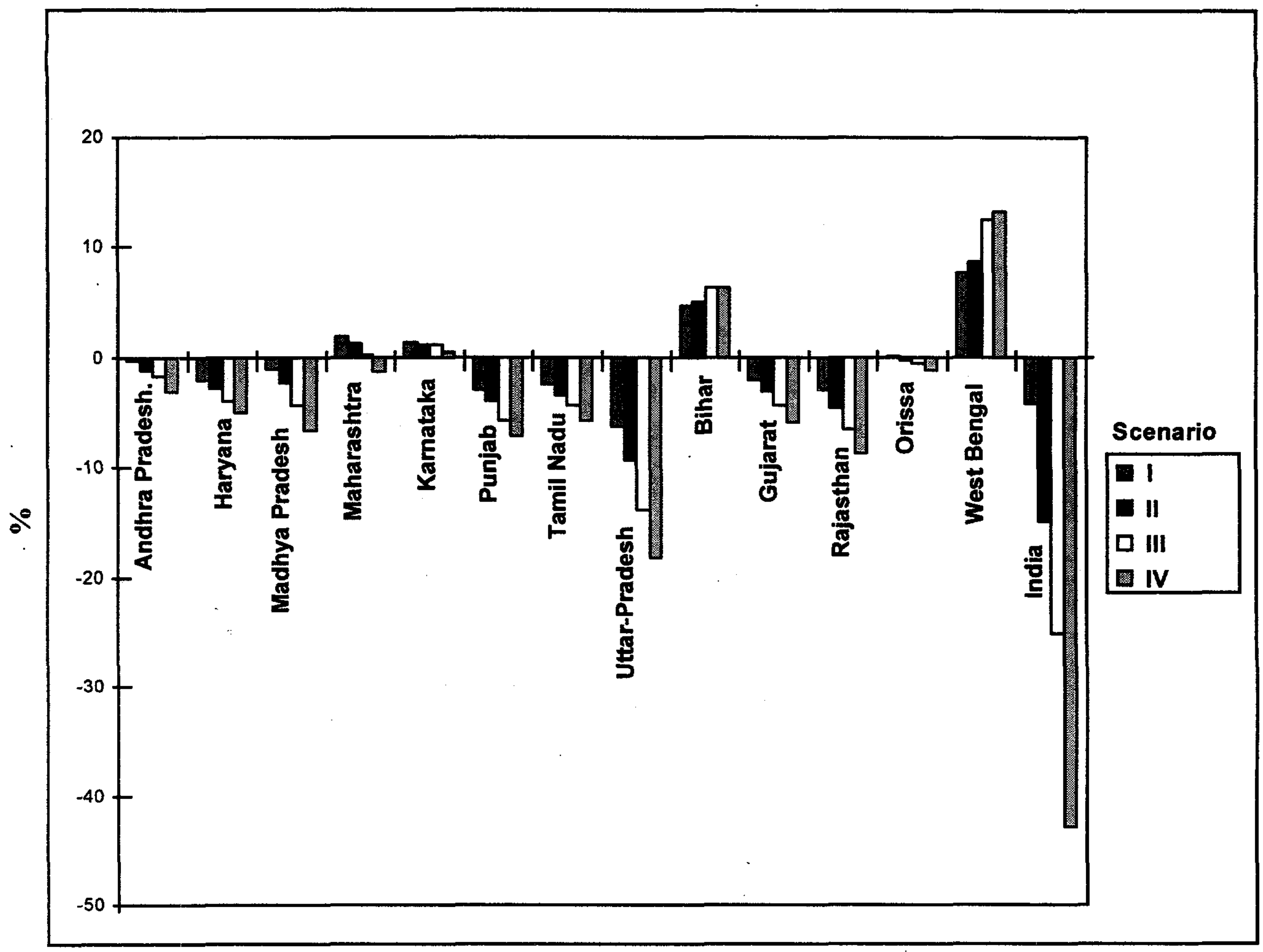


Figure 5.10: State-wise impacts due to various climate scenarios (FAO climate data)

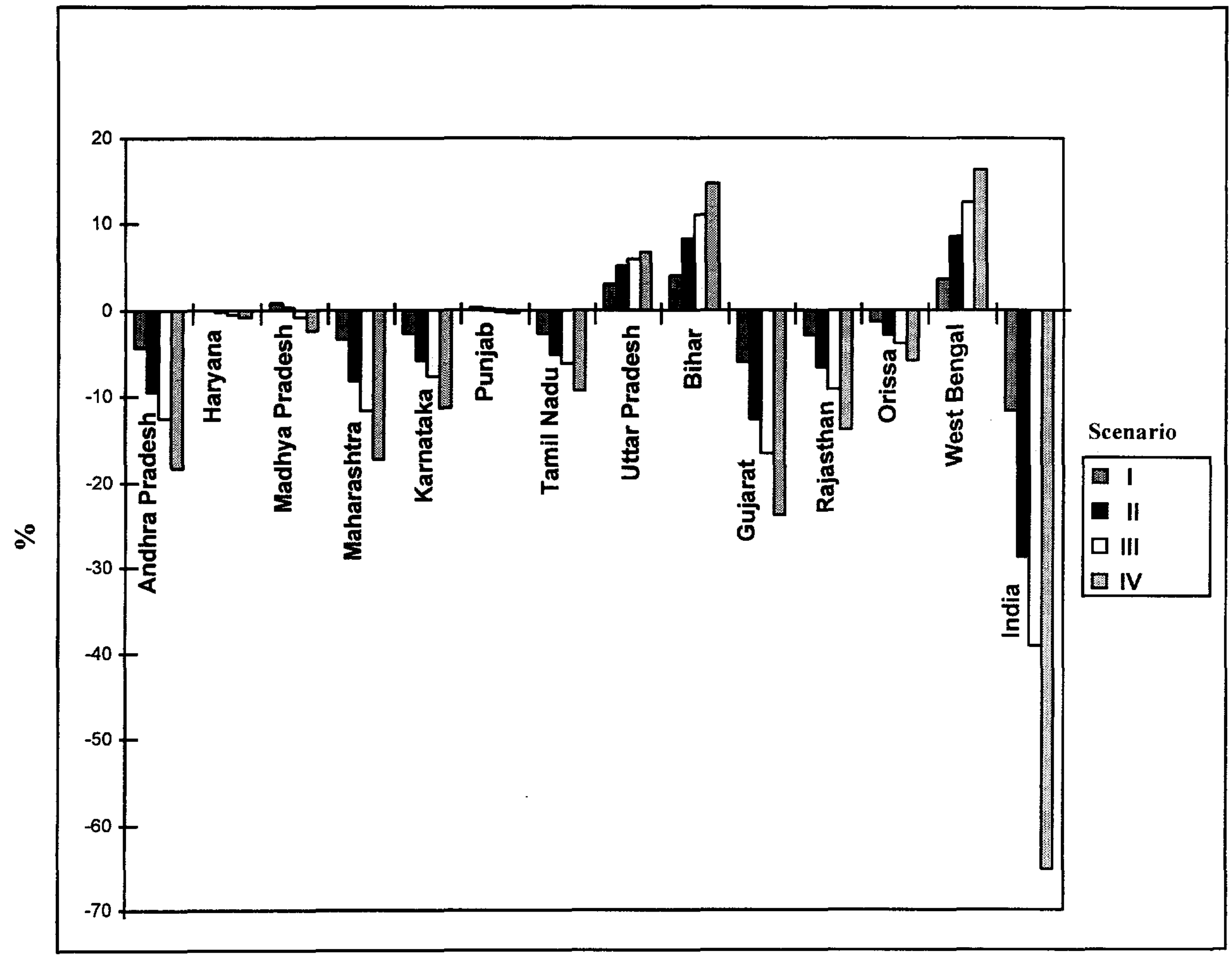
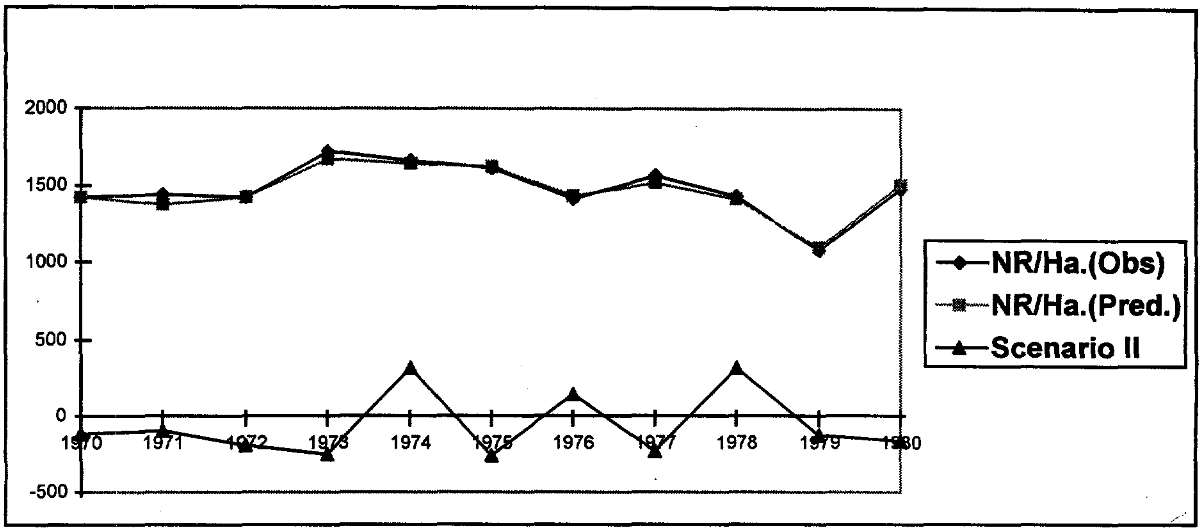
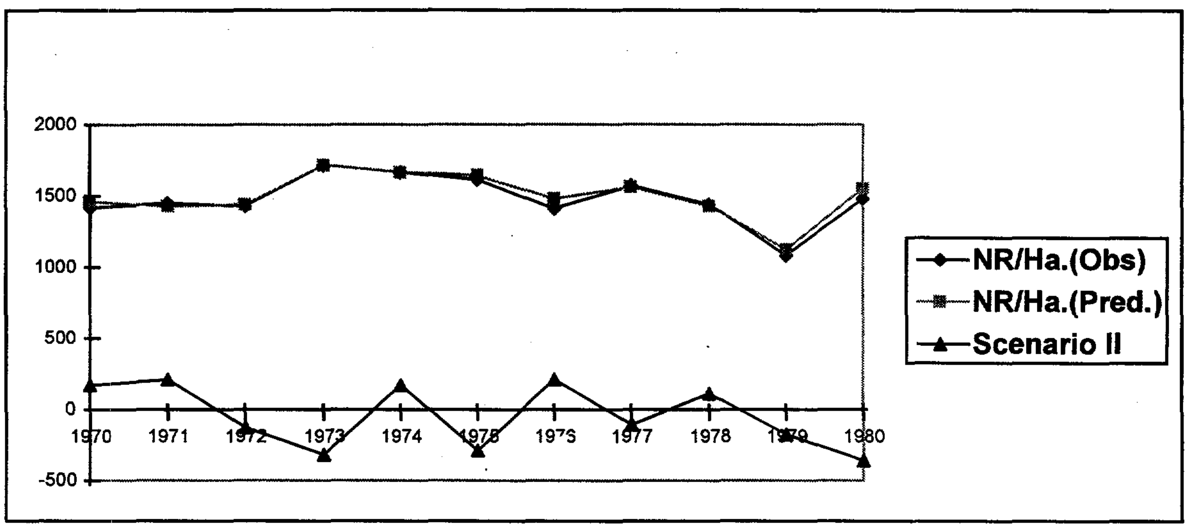


Figure 5.11: Repeated cross sectional procedure





Appendix A: Characteristics of Meteorological Stations Used in the Analyses

Table 5.A.1: Meteorological stations' data

Station Number	Station Name	Latitude (deg.min.)	Longitude (deg.min.)	Altitude (meters)	DSEA (miles)	160 Stn Set (FAO data set)
42027	Srinagar	34.05	74.50	1587.00	801.03	yes
42056	Jammu	32.40	74.50	367.00	715.20	yes
42062	Dharamashala	32.16	76.23	1211.00	710.00	no
42071	Amritsar	31.38	74.52	234.00	646.03	yes
42083	Simla	31.06	77.10	2202.00	660.06	yes
42099	Ludhiana	30.56	75.52	247.00	630.69	yes
42101	Patiala	30.20	76.28	251.00	612.48	no
42103	Ambala	30.23	76.46	272.00	607.06	yes
42111	Dehradun	30.19	78.02	682.00	636.98	yes
42123	Ganganagar	29.55	73.53	177.00	519.24	yes
42131	Hissar	29.10	75.44	221.00	533.26	yes
42147	Mukteswar	29.28	79.39	2311.00	653.56	yes
42165	Bikaner	28.00	73.18	224.00	396.29	yes
42170	Churu	28.15	74.55	291.00	420.00	no
42182	New-Delhi	28.35	77.12	216.00	508.64	yes
42189	Bareilly	28.22	79.24	173.00	680.88	yes
42260	Agra	27.10	78.02	169.00	461.64	yes
42273	Bahraich	27.34	81.36	124.00	417.30	yes
42309	North-Lakhimpu	27.14	94.07	102.00	340.00	no
42314	Dibrugarh	27.29	95.01	111.00	392.23	yes
42328	Jaisalmer	26.54	70.55	242.00	281.42	no
42339	Jodhpur	26.18	73.01	217.00	275.60	yes
42343	Ajmer	26.27	74.37	486.00	320.72	yes
42348	Jaipur	26.49	75.48	390.00	370.61	yes
42361	Gwalior	26.14	78.15	207.00	437.68	yes
42369	Lucknow	26.45	80.53	128.00	538.35	yes
42379	Gorakhpur	26.45	83.22	77.00	292.09	yes
42410	Gauhati	26.06	91.35	54.00	225.37	yes
42435	Barmer	25.45	71.23	194.00	197.29	yes
42452	Kota	25.09	75.51	274.00	275.95	yes
42463	Jhansi	25.27	78.35	251.00	421.34	yes
42475	Allahabad	25.27	81.44	98.00	433.90	yes
42483	Varanasi (Bhu)	25.18	83.01	76.00	385.30	yes
42492	Patna	25.36	85.06	60.00	163.36	yes
42515	Cherrapunji	25.15	91.44	1313.00	173.37	yes
42516	Shillong	25.34	91.53	1598.00	198.88	yes
42542	Udaipur (Dabok)	24.37	73.53	514.00	180.00	no
42559	Guna	24.39	77.19	478.00	323.52	yes
42571	Satna	24.34	80.50	317.00	453.03	yes
42577	Sidhi	24.25	81.52	272.00	390.00	no
42587	Dattonganj	24.03	84.04	221.00	246.42	no
42591	Gaya	24.45	84.57	116.00	174.38	yes
42620	Silchar	24.55	92.59	97.00	162.63	yes

Table 5.A.1: Meteorological stations' data (cont.)

Station Number	Station Name	Latitude (deg.min.)	Longtitude (deg.min.)	Altitude (meters)	DSEA (miles)	160 Stn Set (FAO data set)
42623	Imphal	24.46	93.54	781.00	200.00	no
42631	Maliya	23.15	68.51	21.00	19.88	no
42634	Bhuj	23.15	69.40	80.00	28.89	yes
42647	Ahmedabad	23.04	72.38	55.00	58.95	yes
42667	Bhopal	23.17	77.21	523.00	301.65	yes
42675	Jabalpur	23.12	79.57	393.00	463.64	yes
42701	Ranchi	23.19	85.19	652.00	171.48	yes
42704	Asansol	23.28	86.26	74.00	91.27	yes
42708	Sri Niketan	23.39	87.42	59.00	120.00	no
42724	Agartala	23.53	91.15	16.00	50.00	no
42730	Okha	22.29	69.07	7.00	5.00	no
42737	Rajkot	22.18	70.47	138.00	49.48	yes
42754	Indore	22.43	75.48	567.00	194.47	yes
42763	Hoshangabad	22.46	77.46	302.00	318.65	yes
42779	Pendra	22.46	81.54	625.00	337.28	yes
42807	Calcutta	22.39	88.27	6.00	61.18	yes
42809	Calcutta-Dumdu	22.36	88.30	5.00	61.18	no
42830	Porbandar	21.39	69.40	7.00	5.00	no
42867	Nagpur	21.06	79.03	309.00	360.00	no
42875	Raipur	21.14	81.39	298.00	248.24	yes
42886	Jharsuguda	21.55	84.05	230.00	190.00	no
42895	Balasore	21.31	86.56	20.00	10.05	yes
42909	Veraval	20.54	70.22	8.00	5.64	yes
42916	Daman	20.25	72.51	12.00	8.00	no
42920	Ozar	20.08	73.55	608.00	70.00	no
42934	Akola	20.42	77.04	309.00	278.65	yes
42971	Bhubaneshwar	20.15	85.50	46.00	30.00	no
43001	Dahanu	19.58	72.43	5.00	5.00	no
43003	Bombay-Santacr	19.07	72.51	15.00	9.00	yes
43014	Aurangabad	19.51	75.24	579.00	177.01	yes
43041	Jagdalpur	19.05	82.02	553.00	126.04	yes
43049	Gopalpur	19.16	84.53	17.00	2.55	yes
43053	Puri	19.48	85.49	6.00	4.91	yes
43057	Bombay	18.54	72.49	11.00	10.00	no
43063	Pune	18.32	73.51	559.00	70.82	yes
43081	Nizamabad	18.40	78.06	381.00	345.79	yes
43086	Ramgundam	18.46	79.26	156.00	230.00	no
43105	Kalingapatnam	18.20	84.08	6.00	1.00	yes
43110	Ratnagiri	16.59	73.20	67.00	7.00	no
43111	Mahabaleswar	17.56	73.40	1382.00	51.43	yes
43117	Sholapur	17.40	75.54	479.00	186.12	yes
43128	Hyderabad	17.27	78.28	545.00	174.41	yes
43149	Vishakhapatnam	17.43	83.14	3.00	3.59	yes
43181	Gannavaram	16.32	80.48	24.00	40.00	no

Table 5.A.1: Meteorological stations' data (cont.)

Station Number	Station Name	Latitude (deg.min.)	Longitude (deg.min.)	Altitude (meters)	DSEA (miles)	160 Stn Set (FAO data set)
43185	Musulipatnam	16.11	81.08	3.00	2.13	yes
43189	Kakinada	16.57	82.14	8.00	2.83	yes
43192	Panjim	15.29	73.49	60.00	6.00	no
43196	Mormugao	15.25	73.47	62.00	4.00	yes
43198	Belgaum	15.51	74.37	747.00	60.94	yes
43201	Gadag	15.25	75.38	650.00	116.78	yes
43213	Kurnool	15.50	78.04	281.00	128.33	yes
43220	Baptala	15.54	80.28	6.00	10.00	no
43225	Karwar	14.47	74.08	4.00	5.00	no
43226	Honavar	14.17	74.27	26.00	3.10	yes
43233	Chitradurga	14.14	76.26	733.00	124.51	yes
43237	Anantpur	14.41	77.37	350.00	170.00	no
43245	Nellore	14.27	79.59	20.00	12.13	yes
43257	Agumbe	13.30	75.06	659.00	30.00	no
43279	Madras (Meenam	13.00	80.11	16.00	3.38	yes
43284	Mangalore	12.55	74.53	102.00	1.00	yes
43295	Bangalore	12.58	77.35	921.00	171.43	yes
43311	Amini	11.07	72.44	4.00	1.00	yes
43314	Kozhikode	11.15	75.47	5.00	7.31	yes
43321	Coimbatore	11.02	77.03	400.00	74.34	yes
43329	Cuddalore	11.46	79.46	12.00	1.03	yes
43333	Port-Blair	11.40	92.43	79.00	5.00	no
43339	Kodaikanal	10.14	77.28	2343.00	84.12	yes
43344	Tiruchirapalli	10.46	78.43	88.00	179.66	yes
43346	Karaikal	10.55	79.50	7.00	4.00	no
43347	Nagapattinam	10.46	79.51	9.00	3.70	yes
43348	Adirampattinam	10.20	79.23	6.00	10.00	no
43361	Tondi	9.44	79.02	5.00	5.00	no
43363	Pamban	9.16	79.18	11.00	1.00	yes
43369	Minicoy	8.18	73.00	2.00	1.00	yes
43371	Trivandrum	8.29	76.57	64.00	6.83	yes
43377	Kanyakumari	8.05	77.30	37.00	4.00	no
43379	Tuticorin	8.48	78.09	4.00	7.00	no

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6 Technology–Climate Interactions: Was the Green Revolution in India Climate Friendly?

James W. McKinsey, Jr. and Robert E. Evenson

Introduction

Estimates of the impact of a rise in normal temperatures and of increases in rainfall levels for different regions in India are reported in this chapter. Technology–climate interactions are incorporated into the estimates, enabling an assessment of the climate "friendliness" of the Green Revolution in Indian agriculture.

The analytic model underlying our estimation specification is related to the "Ricardian" model developed by Mendelsohn, *et al.* (1994). In this chapter we report estimates of a "net revenue" specification of the model (which is related to, but not the same as, the Ricardian specification), in which we include variables characterizing technological change. The second section reviews the methodology underlying the specifications. The third section summarizes the data set. Sections 4 and 5 report estimates of the technology specification and climate effects thereon. Sections 6 and 7 report estimates of the net revenue specification and climate effects thereon. Section 8 reports estimates of technology effects, and section 9 reports computed "secondary" effects of technology on the climate effects.

Methodology

The Model

We begin with a very general characterization of agricultural production using the transformation function

(1) $G(Y, X, H, E, C, T, I, W) = 0$

where Y is a vector of outputs (with prices P_Y);
X is a vector of inputs (with prices P_X);
H is a vector of land allocations;
E is a vector of edaphic factors;
C is a vector of normal climate factors (temperature, rainfall, etc.);
T is a vector characterizing available technology;
I is a vector characterizing infrastructure and institutions; and
W is a vector of current weather (expressed as departures from normal).

The maximized variable profits function from (1) is

(2) $\Pi^* = Y^*P_Y - X^*P_X = P^*(P_Y, P_X, H, E, C, T, I, W)$

One can apply the Shephard–Hotelling lemma to (2) to obtain the output supply – factor demand system

$$\partial\Pi^*/\partial P_Y = Y = Y(P_Y, P_X, H, E, C, T, I, W)$$

(3)

$$\partial\Pi^*/\partial P_X = X = X(P_Y, P_X, H, E, C, T, I, W)$$

Our interest is in variable profit per unit of land, which can be expressed as

(4) $\Pi^*/H = \Pi^{**}(P_Y, P_X, E, C, T, I, W)$

and which we shall call "net revenue per hectare", or simply "net revenue" (NR; measured by the variable LNOFPKRE)[1].

We do not observe land values, but we do observe net revenue per hectare of land; thus we estimate a version of (4) rather than (5). As described in the following section, we extend (4) in two dimensions over previous work (e.g., Sanghi *et al.*, 1998):

i. We treat T as endogenously determined by adding three equations for T to the model:

(5) $T = T(E, C, I^*)$

ii. We estimate technology–climate interactions terms in the net revenue equation (4)[2].

MODEL STRUCTURE

Given the importance of the technology specification (6) to this paper, we want to develop this further. Over the period of this study (1970/71 through 1987/88: popularly known as the "Green Revolution" period in Indian agricultural history), Indian agriculture was realizing rapid technological gains. It was characterized by three major activities:

1) the development and diffusion of "High Yielding Varieties" of cereal grains, especially wheat and rice (which we measure as WHYV, the proportion of area under the five major food crops which are planted to high yielding varieties);

2) the expansion of multiple-cropped area, i.e., area cropped more than once during a year (which we measure as Gross Cropped Area divided by Net Cropped Area, GCANCA, in which NCA is area cropped at least once during the year, and GCA is total cropped area during the year); and

3) the expansion of area under irrigation (which we measure as net irrigated area divided by net cropped area, NIANCA).

It is clear, however, that these three activities cannot be treated as exogenous variables in equation (4). They must be modeled as endogenous variables and treated accordingly. Our basic econometric model is then a four equation model with the following structure:

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[1] The Ricardian methodology for measuring climate effects treats (4) as one of the land use revenues capitalized into land values.

[2] A bit of nomenclature: we call approaches and models which are almost identical to the Ricardian models, except that the dependent variable is net revenue per hectare instead of land price or land value, "Semi-Ricardian". Our approach goes beyond the Ricardian or Semi-Ricardian in that we explicitly model the process of technological change in agriculture; we call this approach "Supra-Ricardian".

1. Technology and related infrastructure (the first three equations)

$$\text{WHYV} = f_1\,(\text{GCANCA, NIANCA, STRES5, EXT, E, C})$$

$$\text{NIANCA} = f_2\,(\text{IRR57, WHYV, E, C})$$

$$\text{GCANCA} = f_3\,(\text{GCANCA57, WHYV, NIANCA, E, C})$$

2. Net Revenue (the fourth equation, following equation (4) above)

$$\text{LNOFPKRE} = f_4\,(\text{LNCSTCLT, LNCSTBUL, I, STRES5, EXT, WHYV, NIANCA, GCANCA, E, C, WHYVxC, NIANCAxC, GCANCAxC})$$

These four variables — WHYV, NIANCA, GCANCA and LNOFPKRE — are the endogenous variables in the model. The first three are designed to capture the main features of the green revolution, where the area planted to HYVs is determined by multiple-cropping, irrigation, public agricultural research (STRES5) and extension (EXT), and edaphic (E) and climatic (C) variables. Irrigation intensity is driven by its 1957 level (IRR57), the adoption of HYVs, and edaphic and climatic variables. Multiple-cropping is driven by its 1957 level (GCANCA57), HYV adoption, irrigation intensity, and edaphic and climatic variables.

The first three equations (the adoption of modern varieties, the index of multiple-cropping, and irrigation intensity) are estimated in a two-stage least squares framework. The predicted values of each of these three variables, based on the results of the 2SLS procedure, are then computed.

Then (the logarithm of) net revenue per cropped hectare, the fourth equation, is determined by the logarithms of the imputed value of family labor per hectare (LNCSTCLT) and bullock labor per hectare (LNCSTBUL)[3] research and extension, infrastructural variables (I), and the edaphic and climate variables. In addition, net revenue per hectare is also determined by the three endogenous technology variables and their interactions with climate variables. This equation is estimated by weighted Ordinary Least Squares.

FUNCTIONAL FORM

The models described thus far impose no restrictions on the functional form to be estimated. We use a very general form, with quadratic and interaction terms in order to capture non-linearities and moderating impacts of technology on climate effects and *vice versa*. Modern varieties, multiple-cropping and irrigation intensity are estimated in the 2SLS system with linear and quadratic terms. Unpriced and poorly-measured bullock and cultivator data appear in the right-hand-side of our net revenue regression equation; that prompts us to cast those terms, as well as the dependent variable, net revenue, in logarithmic form, as a Cobb-Douglas. The climate variables already appear in quadratic (flexible) form, so the logarithmic status is not inconsistent with them. The equation is weighted by net cropped area, to control for excessive influence on the estimates by larger districts.

[3] These variables are generally not marketed and priced in India. Thus this specification treats them in a production function framework.

ADAPTATION AND INTERACTION

Expressions such as (4) allow for farmer adaptation to climate change. This adaptation includes investments in farm level irrigation and drainage as well as changes in farm practices including cropping patterns. There is, as well, potential adaptation by the organizations producing technology and infrastructure for farmers. These organizations include private firms who conduct R&D to develop improved factors to be supplied to the agricultural sector, and the public sector agricultural research and extension organizations who also provide improved technology to agriculture. It also includes public sector units providing, and maintaining, infrastructure.

Implicitly, this suggests that there may be important climate-technology and climate-infrastructure interactions in (4). We cannot observe expected interactions, and there is a serious question whether actual interactions, estimated from (4), would be good predictors of future interactions. Some might argue that since climate has changed little over the past 25 years or so, the (public and private) inventors of technology and the investors in infrastructure have not responded to climate change. However, the underlying premise of the estimates obtained from cross-section data where climate varies over locations, is that these do measure responses to climate. If technology and infrastructure are exogenous to farmer decisions one may argue that climate-technology and climate-infrastructure interactions estimated from (4) are reasonable estimates of future effects.

We know that researchers do respond to climate conditions. Plant breeders continually seek genetic traits to change the length of growing seasons and to endow plants with host plant tolerance (HPT) to cold and warm temperatures, to drought and flood stress, and related climate effects. Their motivation for seeking to incorporate these traits in crop varieties is to allow superior genetic material (e.g., the semi-dwarf wheat and rice) to overcome climate and edaphic barriers to their "migration" to new areas. This cross-section motive is likely to be a good proxy for a time series motive, that is, to respond to a long-term rise in temperature.

Suppose, for example, that we have two regions (1 and 2) which differ in temperature (t_1, t_2) and edaphic factors (E_1, E_2). Suppose that a rise in temperature damages crops in both regions if crops do not migrate. If t_1 rises to the former level of t_2, region 1 can minimize the damage if the crops suited to region 2 migrate to region 1. This cannot happen if there are edaphic barriers to such migration. Plant breeders can mitigate these edaphic barrier effects through HPT breeding. They can also mitigate the non-migration effects through HPT breeding for high temperature tolerance.

These interactions enable us to estimate two dimensions of the technology–climate relationship. In system (5) we estimate the effects of climate on the production and diffusion of technology. (That is, we can capture dT/dC.) From these estimates we can ask: Will an increase in normal temperatures and rainfall be "friendly" to the development and diffusion of agricultural technology?

From the estimation of (4) with interaction terms we can ask the following question: What is the impact of an increase in rainfall and temperature on net revenue (including the effects operating through technology)?

$$(7) \qquad dNR/dC = \partial NR/\partial C + \partial NR/\partial T \cdot \partial T/\partial C$$

We can also capture the secondary impacts of technology on the climate effects:

(8) d(dNR/dC)/dT

which enables us to ask whether climate effects on net revenue per hectare were altered by changes in these variables during the period of the Green Revolution. This will tell us whether this technology was "friendly" to projected temperature and rainfall effects or "unfriendly" to them.

DATA

VARIABLES

The dependent variable in a Semi-Ricardian or Supra-Ricardian study is "out-of-pocket" net revenue per hectare (hereafter simply "net revenue"). To compute net revenue first sum the products of all crop outputs multiplied by their farm harvest prices, then subtract the cost of purchased inputs (which are fertilizer, tractors, and hired agricultural labor), then divide the entire quantity by net cropped area.

In this study we go one step further, and take the natural logarithm of the just-computed net revenue per hectare, as described above, yielding the variable LNOFPKRE.

Two important inputs are excluded from this computation: bullocks and family labor. Bullocks are primarily used by their owners (with little renting in or out), as obviously is true for family labor; these inputs are treated as quasi-fixed factors, and the logarithms of the imputed values of these inputs, per hectare, are included as independent variables.

All variables are described in detail in Appendix A[4] The variables are measured at the district level, covering nearly all (271) of the districts in the 13 major crop-producing states of India. Table 6.1 displays the variable names, descriptions and summary statistics of the major variables used.

[4] Appendix A contains definitions, sources, discussions of transformations, and other information about the inputs, crop outputs, technology and infrastructure, prices, edaphic and climatic variables.

Table 6.1: Variables in the Supra-Ricardian framework

Variable Name	Description	Mean	Standard Deviation
A. Endogenous Variables			
LNOFPKRE	Log of Out-of-Pocket Net Revenue	6.95	.80
WHYV	Modern (High-Yielding) Variety Use	.28	.25
GCANCA	Multiple-Cropping Index	1.24	.20
NIANCA	Index of Irrigation Intensity	.29	.24
B. Exogenous Variables			
Edaphic Variables (E)			
DMSnn	Soil Type Dummy Variables; nn: 03 to 21	--	--
DMpHn	Soil pH Dummy Variables; n: 5, 6, 8 and 9	--	--
DMTSn	Topsoil Depth; n: 1, 2 and 3	--	--
Geographic Variables			
DMSLPn	Slope Dummy Variables; n: 1 to 4	--	--
DMSEA	Dummy: 1 if District is on the seacoast	--	--
DMSEANEI	Dummy: 1 if District abuts one on seacoast	--	--
ALT	Altitude of District's weather station, meters	296.89	316.36
(Normal) Climate Variables (C)			
JANMDT	January Normal Temperature Midpoint	18.55	3.69
JANMDTSQ	January Normal Temp. Midpoint Squared	357.86	138.29
JANRN	January Normal Rainfall	12.38	13.14
JANRNSQ	January Normal Rainfall Squared	325.75	725.31
APRMDT	April Normal Temperature Midpoint	29.59	2.35
APRMDTSQ	April Normal Temp. Midpoint Squared	881.23	125.86
APRRN	April Normal Rainfall	16.19	22.65
APRRNSQ	April Normal Rainfall Squared	775.13	2355.60
JULMDT	July Normal Temperature Midpoint	28.34	2.55
JULMDTSQ	July Normal Temp. Midpoint Squared	809.90	134.44
JULRN	July Normal Rainfall	245.77	234.42
JULRNSQ	July Normal Rainfall Squared	115342.86	430432.59
OCTMDT	October Normal Temperature Midpoint	26.05	1.88
OCTMDTSQ	October Normal Temp. Midpoint Squared	682.01	90.17
OCTRN	October Normal Rainfall	66.64	66.03
OCTRNSQ	October Normal Rainfall Squared	8800.36	15815.10
JURNCV	Coef. of Variation, June Rain, 1957 - 1987	.61	.21
JARNCV	Coef. of Var., July/Aug Rain, 1957 - 1987	.35	.21

Table 6.1: Variables in the Supra-Ricardian framework (cont.)

Variable Name	Description	Mean	Standard Deviation
(Current) Weather Variables (W)			
JUNERAIN	Actual Rainfall in June	131.46	121.98
JUAURAIN	Actual Rainfall in July and August	561.55	364.05
YEARRAIN	Actual Annual Rainfall	1088.33	602.14
Technology and Infrastructural Variables (T, I)			
WHYVNEW	Proportion of Area under HYVs	.29	.25
GCANCA	Multiple-Cropping Index	1.24	.21
NIANCA	Irrigation Intensity	.29	.24
STRES5	Cumulated Stock of Agricultural Research	36.30	43.15
EXT	Index of Extension Activity	7.39	5.65
LITERACY	Literacy Rate, Adult Rural Males	.37	.11
RELWAGE	Ratio of Rural Factory Wage to Farm Wage	1.20	.60
Interaction Terms			
JANMDTRN	January Temperature times Rainfall	213.90	231.26
APRMDTRN	April Temperature times Rainfall	464.13	597.08
JULMDTRN	July Temperature times Rainfall	6711.02	5267.12
OCTMDTRN	October Temperature times Rainfall	1741.94	1754.22
Other			
DMYRnn	Year Dummies; nn: 71 to 87	--	--
IRR57	Value of NIANCA in 1957	.18	.18
GCANCA57	Value of GCANCA in 1957	1.15	.15

This study applies to the years 1970/71 through 1987/88. By 1970 the use of modern high-yielding varieties of several crops had become established in nearly every district, and partly in concert with the expansion of HYV there was substantial new investment in irrigation, fertilizer distribution, research and extension activities, and so forth. The 1970s and 1980s also were the years during which the interaction of technology and infrastructure with climate was more marked and more important.

The data set includes a number of interactions between climate variables, on the one hand, and some of the technological variables, on the other hand: those interactions, and the moderating influence of the technology and infrastructure investments on climatic effects which the interactions embody, are in fact among the primary foci of this study.

Econometric Issues

Obvious econometric issues in this study involve, first, the existence of heteroscedasticity; second, the high degree of multicollinearity which necessarily inheres in data of the sort used in this study; and third, specification issues of variable inclusion or exclusion.

Heteroscedasticity is prevalent in this study. But even in its presence, least squares estimators of coefficients are consistent; thus the sample sizes in the thousands are sufficient to justify use of OLS. However, the standard errors of the coefficients estimated by OLS are not consistent, so the reported t-statistics would be somewhat deficient. The standard errors are estimated by White's consistent estimator[5] of the least squares covariance matrix, and the resultant estimated t-ratios are consistent.

The problems of multicollinearity are likely to be severe[6], especially given the inclusion of so many climate terms, and their squares. Future work will include the computation of condition indices to determine just how severe the multicollinearity is. The inclusion of the climate terms is crucial and the squared terms are necessary to allow for nonlinearities in climate effects.

Because of the likely rampant multicollinearity, one should use caution in interpreting, and in using, any individual coefficient estimate: its true value may substantially differ from its estimated value, and the variable may be a valid, important regressor even if the estimated t-ratio is below the customary critical value. But of crucial importance to later Sections, the computations of estimated effects of climate change, using all the estimated coefficients (whether significant or not), are likely to be valid, for any mis-estimation of the value of one coefficient is likely to be compensated for in the estimation of the values of the coefficients of the other collinear variables; thus the joint impact of all the variables together is probably much more accurate.

Finally is the issue of variable inclusion or exclusion. In the 1994 Ricardian estimates of Mendelsohn *et al.*, (1994) a cross-section of land values was regressed on climate (C), edaphic (E) and infrastructure (I) variables. Prices and technology variables were excluded on the grounds that prices did not vary in cross-section for specific commodities[7] and that technology was "equally" accessible to all farmers in the United States[8]. The price question is less important in the Ricardian model because future expected prices are relevant. In a semi-Ricardian (net revenue) specification, prices must enter because in any given year the price of a particular commodity may be unusually high or low.

Technology is more difficult. A large number of agricultural productivity studies have measured significant differences in cross-section productivity levels which are at least partly due to edaphic and climate differences. More importantly, the studies have also measured time series differences in rate of change of partial or total factor productivity change for different regions (Evenson & Huffman (U.S.), Avila & Evenson (Brazil), McKinsey & Evenson (India)). These differences have persisted over long periods of time and have been related to cross-section (and time-series) differences in investments in regionally oriented agricultural research programs.

One might argue (as Mendelsohn *et al.*, (1994) do) that regional differences in the productivity growth are likely to "converge" over time as technology from the leading regions is diffused to the laggard regions. If so, the regional productivity differences would not be capitalized into land values. Yet this is quite unlikely, given the nature of agricultural technology which is highly location-specific: studies of agricultural research indicate that regions with little

[5] See, for example, Kathleen Segerson and Bruce L. Dixon (June 1996).
[6] See again Dixon and Segerson, op. cit.
[7] Or that transport-related differentials would continue in the future.
[8] Obviously, this precluded climate-technology interaction estimates.

or no research effort targeted to their particular climate and edaphic conditions remain laggard regions. And even if productivity were to converge over time, such that current productivity differences would not be capitalized into differences in land values, current net revenues would still reflect existing productivity differences.

In a similar way, variables measuring current weather are important in net revenue specifications, but not in land value specifications where current weather gets averaged into climate. It is extremely difficult to construct meaningful weather indices. Rainfall affects production in a non-linear way and its effect is sensitive to the timing of planting, flowering, etc.

ESTIMATES: TECHNOLOGY AND RELATED INFRASTRUCTURE

In the Supra-Ricardian framework we treat the three technology variables as endogenous variables, whose predicted values then contribute to the determination of net revenue per hectare.

In this Section we report estimates of the determinants of these variables, in a two-stage least squares framework. Then in Section five we report computed climate effects on technology and related infrastructure.

HYV – MULTIPLE CROPPING – IRRIGATION SYSTEM

The proportion of area sown to modern varieties (WHYV), a measure of multiple-cropping (GCANCA), and irrigation intensity (NIANCA) were estimated by two-stage least squares. Appendix Table 6B.1 displays the variables used as instruments in the 2SLS system; an asterisk following a variable name denotes that that variable also appears in one or more second-stage regression equations, and/or the net revenue equation. These instruments include fundamental climatic and edaphic variables, as well as two technology variables and a number of price ratios proxying institutional factors.

Appendix Tables 6B.2 through 6B.4 then display the regression results from the second stage; WHYV in Table 6B.2, GCANCA in Table 6B.3, and NIANCA in Table 6B.4. A number of striking results emerge.

First is the degree to which this system captures the modeled behavior. Grossly, all three second-stage regressions have highly significant F-statistics, and adjusted R^2s. For each of the three regressions, we tested the null hypotheses that the rainfall variables taken as a group did not significantly influence the technology variables, that the temperature variables taken as a group did not significantly influence the technology variables, and that the climate variables (that is, the temperature and rainfall variables combined) taken as a group did not significantly influence the technology variables. The results of the F-tests of sets of excluded variables are reported in Appendix Table 6B.5. All three of the null hypotheses were rejected in all three of these regressions: as groups, the climate variables do significantly influence the adoption of modern varieties, irrigation intensity, and the extent of multiple-cropping.

But even more important than the general goodness-of-fit of these regression equations, and the significance of groups of variables, are the patterns revealed within each equation.

Slope significantly influences both multiple-cropping and, to a lesser extent, irrigation intensity[9] And irrigation intensity tends to be higher in districts above aquifers which are geologically thickest[10].

The second-stage variables exercise an important influence on each other: the coefficients of both GCANCA and NIANCA on WHYV are significantly positive, as are the coefficients of both WHYV and NIANCA on GCANCA and the coefficient of WHYV on NIANCA. That is to say, the adoption of modern high-yielding varieties, multiple-cropping and irrigation are mutually-reinforcing.

The adoption of modern varieties also responds favorably to greater extension activity; perhaps surprisingly, though, additional state-level agricultural research does not significantly increase the adoption of modern varieties. There is considerable inertia in this behavior: both the extent of multiple-cropping and irrigation intensity are highest in those districts in which such activity was largest in 1957[11].

CLIMATE CHANGE EFFECTS ON TECHNOLOGY AND INFRASTRUCTURE

Based on the regression results reported in the previous Section, and the actual district-level values of the climate and technology variables, one can compute the predicted effects on high-yielding variety use, multiple cropping, and irrigation intensity of changes in normal temperature and rainfall. The motivation for these computations is the by-now familiar predictions of global warming; we make no effort to validate or calibrate the predicted changes, but merely use the familiar predictions to drive a simulation.

A number of possible values for temperature and rainfall change have been proposed; no scenario has received unanimous agreement. We predict the effects of a one degree Celsius temperature increase, and a three percent rainfall increase, values which some models predict could be achieved from a generation to a century from now. The impacts of different changes could easily be scaled[12]. These predicted effects are presented in Table 6.2, in which appear first the temperature effects on the adoption of modern varieties, the extent of multiple-cropping, and irrigation intensity. Next appear the rainfall effects on WHYV, GCANCA and NIANCA.

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[9] This may reflect the importance of drainage to avoid waterlogging or soil salinity; it may reflect the geological requirements for proper functioning of a canal system.

[10] This does not measure the annual water depth within the aquifer, but rather a long term geological potential. Farmers may respond to this in their cropping choices; farmers and probably governments also respond in their irrigation investments.

[11] There is no related variable for the use of modern varieties, because no such modern variety existed before the onset of the Green Revolution in the middle 1960s.

[12] Most global climate change scenarios also posit an increase in atmospheric (and thus soil-based) carbon - usually, in fact, the climate change is initiated by an increase in atmospheric CO_2. Nearly every experimental crop model predicts higher crop yields associated with increases in available carbon. This study deals with changes in temperature and rainfall,, but not with changes in carbon; thus the actual effects on crop output (and thus on net revenue) of climate change, taking into account carbon changes as well as temperature, rainfall and okta changes, would almost certainly be more beneficial than the results of this study predict.

Predicted impacts are computed for each district; they are presented in Table 6.2 as state-wide and national averages[13].

We first consider the impact of a one degree Celsius rise on the technology variables. The national average temperature impact on HYV adoptions is negative but relatively small. It is most negative in Gujarat and is actually positive in a belt of states stretching from Karnataka on the southwest coast, through Andhra Pradesh, Orissa, and West Bengal moving up the east coast.

The temperature impact on multiple-cropping is positive on average, although some regions (notably Karnataka, and to a lesser extent the entire nation from the Deccan plateau south: Madhya Pradesh, Maharashtra, Orissa, Andhra Pradesh and Tamil Nadu) suffer a negative impact. The temperature impacts on irrigation are uniformly negative.

The effects of an increase in rainfall on HYV adoption and irrigation intensity are negative but small throughout India except in the Punjab. Similarly, increased rainfall has negative and relatively small effects on multiple-cropping in every state.

Thus, these estimates generally show an increase in temperature is "unfriendly" to HYV adoption and to irrigation. A temperature increase is on balance friendly to multiple-cropping. Increased rainfall is unfriendly to all three technology variables. The regional impact estimates show that these potential temperature and rainfall effects are least unfriendly in the states where the early Green Revolution gains in wheat were made.

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[13] And see Appendix C, in which are displayed the temperature, rainfall and cloud cover effects by season, revealing interesting alternating patterns.

Table 6.2: Climate effects on technology and related infrastructure
(Supra-Ricardian Model, 1970/71 through 1987/88)

	Temperature			Rainfall		
	HYV	GCA	NIA	HYV	GCA	NIA
India	-.0075	. 0035	-.0358	-.0093	-.0100	-.0054
1:Andhra Pradesh	.0051	-.0024	-.0298	-.0157	-.0121	-.0099
2:Haryana	-.0108	. 0287	-.0462	-.0019	-.0083	-.0003
3:Madhya Pradesh	-.0134	-.0056	-.0432	-.0077	-.0092	-.0046
4:Madhya Pradesh	-.0072	-.0063	-.0341	-.0129	-.0107	-.0082
5:Karyana	.0018	-.0193	-.0076	-.0176	-.0128	-.0114
6:Punjab	-.0123	. 0339	-.0428	. 0004	-.0079	.0011
7:Tamil Nadu	-.0155	-.0008	-.0331	-.0118	-.0150	-.0068
8:Uttar Pradesh	-.0077	.0123	-.0412	-.0051	-.0086	-.0024
9:Bihar	-.0047	.0055	-.0036	-.0069	-.0098	-.0036
10:Gujarat	-.0223	.0075	-.0544	-.0104	-.0093	-.0062
14:Rajasthan	-.0133	.0160	-.0456	-.0072	-.0081	-.0039
15:Orissa	.0114	-.0045	-.0158	-.0125	-.0116	-.0075
17:West Bengal	.0016	. 0017	-.0146	-.0126	-.0121	-.0070

Note: Temperature Effect: Percentage change due to a 1° Celsius temperature increase.
Rainfall Effect: Percentage change due to a 3% rainfall increase.

ESTIMATES: NET REVENUE

Appendix Table 6B.6 displays the results of the regression of net revenue on edaphic, climatic, and geographic variables, the predicted values of the technology and infrastructure variables from the two-stage system described above, interactions between climate and technology or between climate and infrastructure, and dummy variables for time[14].

This equation also fits the data very well: the adjusted R^2 is nearly 0.6, and the F-statistic is highly significant. Appendix Table 6B.7 presents results of F-tests of the null hypotheses that the set of edaphic variables, the set of temperature variables, the set of rainfall variables, the set of all climate variables, the set of technology and related infrastructure variables, the set of technology interactions, and the set of year dummies do not influence net revenue. All of these null hypotheses were rejected: each set of variables does significantly influence net revenue; most of the variables in fact by themselves significantly influence net revenue.

In addition to their role in the second-stage equations reported in the previous section, the edaphic variables are important determinants of net revenue: fourteen of the nineteen soil type

[14] The climate-technology interactions involve temperature squared and rainfall squared, rather than simple temperature or rainfall, in order to capture nonlinearities in the interactions.

dummies have significant coefficients, and soil of neutral pH[15] contributes more to net revenue than either acidic or base soil.

The coefficient on the predicted value of modern varieties (WHYVPRDK) is positive and significant while the coefficient on the predicted value of multiple-cropping (GCNCPRDK) is positive and not significant. The coefficient on the predicted value of irrigation intensity (NINCPRDK) is negative and significant. All those variables are interacted with climate terms, as discussed below, and half of the interactions' coefficients are significant. Research and extension contribute to net revenue (the coefficient of extension on net revenue, although negative, is quite small and insignificant, but extension significantly increased the adoption of modern varieties; the coefficient of research on WHYV is significantly positive in both the WHYV and the net revenue regressions).

Higher bullock costs reduce net revenue, as does an increase in the ratio of off-farm wages relative to agricultural wages, which probably denotes a decline in the quality of available farm workers as off-farm opportunities attract more and more of the best and most-highly-skilled laborers. Sixteen of the seventeen year dummies are positive and significant; the dummy for 1970, the first year in the sample, is omitted, so these dummies are picking up omitted time trends and price index effects.

Current weather, and its timing, also obviously influences current net revenue: given a normal seasonal rainfall, higher rainfall in July and August (the variable JUAURAIN) will increase net revenue[16].

The climate variables represent long-term averages or norms, to which farmers respond in their decisions about cropping patterns, input use, investment in technology and infrastructure, and so forth. This model displays quite rich (normal) temperature and rainfall effects on net revenue. The squared and "raw" terms are usually of the opposite sign. The impacts of temperature and rainfall differ by month. Interestingly a higher coefficient of variation of rainfall contributes to net revenue[17].

A key focus of this study is the interaction of climate with technology, infrastructure, and geographic variables, beyond the so-called "purely climate" variables. six such interactions each month are included.

The interactions of temperature squared and rainfall squared with the predicted values of modern varieties, multiple-cropping and irrigation intensity are complex, yielding significant coefficients in some months.

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[15] In terms of the data, of pH 7, whose variable (DMPH7) is the omitted dummy.

[16] Probably occurring during crucial maturation phases of many important crops in most states; actual June rain (holding constant the level of normal seasonal rainfall) had a negative but insignificant coefficient, perhaps reflecting the difficulty in planting when the ground is too wet.

[17] This may reflect monsoon timing: a higher coefficient of variation may indicate that the rains were spread more evenly across the two months.

CLIMATE CHANGE EFFECTS ON NET REVENUE

Based on the regression results reported in the previous section, the actual district-level values of the climate and technology variables, and the computed climate change effects on the technology variables, one can similarly compute the predicted effects on net revenue of changes in normal temperature and normal rainfall. Those effects (and their sum) are presented in Table 6.3.

Temperature and rainfall affect net revenue via three avenues. The first could be called direct, operating via the temperature and rainfall terms, their squares, and the temperature-rainfall interaction term in the net revenue equation. The second avenue could be called local, beginning with the temperature and rainfall effects on WHYV, GCANCA and NIANCA and operating through their terms in the net revenue equation. The third avenue, meandering, operates through the terms in the net revenue equation which capture the interactions between climate and the predicted values of WHYV, GCANCA and NIANCA. Thus one cannot simply glance at the direct climate terms in the net revenue equation to perceive the temperature and rainfall effects; one must compute carefully the effects through all three avenues, and use in the appropriate places in the computations the values of the climate terms and the technology variables.

The predicted temperature and rainfall effects on net revenue are high compared to estimates for U.S. and Brazilian agriculture: on average over all the districts in this study, a one degree increase in normal temperature would reduce net revenue by three and one-third percent[18]. The differences in estimated effects might be due to the fact that these estimates are based on a net revenue framework, while other estimates are based on reasonably well-defined land prices; other differences include the time period involved, the use of a panel of cross-sections here, and the inclusion of endogenous technology variables. Appendix C reports estimates based on seasonal climate variables that are closer to estimates for the United States and Brazil.

The States whose net revenue is most adversely affected by an increase in temperature are Maharashtra, Haryana and Tamil Nadu, while the States least adversely affected are Karnataka, West Bengal, Orissa and Gujarat (where in fact higher temperatures would increase net revenue).

The predicted rainfall effects on net revenue are negative in all states, are on average nearly twice as large as the temperature effects, and are especially large and negative in Tamil Nadu[19], Andhra Pradesh, Orissa and Karnataka. In all States except Gujarat and Karnataka higher temperature and rainfall together are predicted to decrease net revenue: in four of the thirteen States the combined temperature and rainfall effects would in fact decrease net revenue by nearly one-fifth or more, and on average in the nation as a whole the combined climate effects would decrease net revenue by nearly one-tenth.

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[18] Recall that net revenue is crop revenue minus purchased inputs. Nationwide, net revenue averages far less than twenty percent of crop revenue: thus a 3% temperature impact on net revenue amounts to less than 1% impact on crop revenue. Impacts on net revenue are appropriate to maintain approximate comparability with impacts on land value in Ricardian systems, but considering impacts on crop revenue as well offers important perspective.

[19] Tamil Nadu poses difficulties in estimation and calculation of effects based on rainfall and irrigation; those difficulties likely arise from its position on the Eastern edge of the tip of the Indian sub-continent, the influence of its ghats, and -- linked to those two -- the dramatic variation and amounts of rainfall the state receives from both monsoon systems. The extremely large predicted climate effects in Tamil Nadu are unlikely to be accurate.

Table 6.3: Climate effects on net revenue
(Supra-Ricardian Model, 1970/71 through 1987/88)

	Temperature	Rainfall	Sum of Temperature and Rainfall
INDIA	-.0330	-.0624	-0.0954
1:Andhra Pradesh	-.0425	-.1665	-0.2090
2:Haryana	-.1681	-.0243	-0.1924
3:Madhya Pradesh	-.0695	-.0185	-0.0880
4:Maharashtra	-.1883	-.0773	-0.2656
5:Karnataka	.1715	-.1403	0.0312
6:Punjab	-.0835	-.0108	-0.0943
7:Tamil Nadu	-.1340	-.2348	-0.3688
8:Uttar Pradesh	-.0453	-.0181	-0.0634
9:Bihar	-.0145	-.0340	-0.0485
10:Gujarat	.0328	-.0023	0.0305
14:Rajasthan	-.0124	-.0037	-0.0161
15:Orissa	.0478	-.1536	-0.1058
17:West Bengal	.0734	-.0999	-0.0265

Note: Temperature Effect: Percentage change due to a 1° Celsius temperature increase.
Rainfall Effect: Percentage change due to a 3% rainfall increase.

TECHNOLOGY AND INFRASTRUCTURE EFFECTS

As discussed above, our specification in equation (4) includes important technology and related infrastructure variables which are central to India's Green Revolution experience. Section four presented two stage least squares estimates of NIANCA, GCANCA and WHYV, in which each of the three variables was determined *inter alia* by one or both of the other two. And Section five presented estimates of Net Revenue, in which all three of the technology and related infrastructure variables, as well as their interactions with climate variables, appeared on the right-hand side.

Table 6.4 presents the computed effects of an increase in any of the three technology and related infrastructure variables on the other two and on Net Revenue. The computations reveal the total effects, involving direct terms, indirect effects through a third variable, and (for effects on Net Revenue) interaction terms[20]. The broad message of Table 6.4 is that each of the

[20] For example, the direct effect of WHYV on Net Revenue derives from the predicted WHYV term (which is named WHYVPRDX) in the net revenue equation. The indirect effects - in calculus, requiring the use of the chain rule - arise from the impact of WHYV on predicted GCANCA and on predicted NIANCA, and subsequently the effects of predicted GCANCA and predicted NIANCA on Net Revenue. And the interaction effects arise from the terms in which predicted WHYV is multiplied by various climate variables - in calculus, requiring the use of the product rule.

technology and related infrastructure variables encourages and reinforces the others, and contributes to Net Revenue.

The HYV effects are consistently positive. A one percent increase in the proportion of crops planted to modern varieties would induce an increase in multiple-cropping of about one-ninth of one percent nationwide, nearly one-quarter of one percent in Haryana, two-firths of one percent in the Punjab. The effects of increased modern variety adoption are considerably larger on Net Revenue, especially in the States along the northeastern rim of the country (the Punjab, Haryana and Western Uttar Pradesh, which were the early beneficiaries of the Green Revolution in wheat, as well as Eastern Uttar Pradesh, Bihar and West Bengal, and in Rajasthan and Gujarat), and smaller but still consistently positive on irrigation intensity. The effects on irrigation are not difficult to understand, given the responsiveness of nearly all modern varieties to an assured[21] supply of water: as farmers use more and more modern varieties, the payoff to irrigation increases, inducing more investment (privately and by both state and Central governments) in irrigation capacity and facilities. And the HYV effects on Net Revenue are also easy to understand: to have been selected and released, the modern varieties will already have been shown to offer yield increases in excess of their additional input requirements.

The multiple-cropping effects on modern varieties, irrigation intensity and net revenue are positive and rather small: on average for the entire nation, a one percent increase in multiple-cropping would induce an increase in the use of modern varieties by nearly one-fifth of one percent, an increase in irrigation intensity of only four hundredths of one percent, and an increase in Net Revenue of about three-fifths of one percent. Surprisingly, an increase in multiple-cropping would reduce net revenue in Haryana, the Punjab, and to a lesser extent in Tamil Nadu and West Bengal.

An increase in irrigation intensity would increase the adoption of modern varieties, for essentially the reason discussed above: with more assured water availability, the payoff to the adoption of HYVs is much higher. The effect of an increase in NIANCA on multiple-cropping and on Net Revenue is larger, with an increase in irrigation intensity of one percent increasing net revenue on average nearly one percent.

Effects in Table 6.4 are expressed in quasi-elasticity form. For example, the upper-left entry indicates that, on average for the nation as a whole, a one percent increase in the proportion of crops sown to modern high-yielding varieties would tend to increase multiple cropping by 0.1141 percent, which is about one-ninth as much.

[21] Assured not only in quantity, but at least as importantly in timing.

Table 6.4: Technology and infrastructure effects
(Supra-Ricardian Model, 1970/71 through 1987/88)

Effect of:	HYV	GCA			NIA				
on:	**GCA**	**NIA**	**NR**	**HYV**	**NIA**	**NR**	**HYV**	**GCA**	**NR**
India	.1141	.0601	1.0960	.1824	.0416	0.6023	.1127	.1546	0.9604
1:Andhra Pradesh	.0978	.0566	0.8690	.1564	.0364	0.9017	.0986	.1455	1.2538
2:Haryana	.2353	.1123	1.5720	.3761	.0956	-1.4792	.2589	.2889	1.7052
3:Madhya Pradesh	.0527	.0222	0.9188	.0843	.0085	0.8103	.0230	.0571	0.9457
4:Maharashtra	.0749	.0168	0.8714	.1197	.0080	0.7361	.0217	.0433	1.1006
5:Karnataka	.0595	.0309	0.8543	.0951	.0130	1.5471	.0353	.0795	0.7578
6:Punjab	.4190	.1903	1.6187	.6698	.2364	-1.8535	.6403	.4894	1.4382
7:Tamil Nadu	.1415	.0768	09138	.2262	.0707	-0.5613	.1915	.1976	1.1642
8:Uttar Pradesh	.1659	.1083	1.2247	.2651	.0735	-0.0759	.1992	.2786	1.0710
9:Bihar	.1571	.0644	1.0576	.2512	.0497	0.6254	.1346	.1656	0.6704
10:Gujarat	.0592	.0308	1.2041	.0946	.0126	2.5879	.0342	.0793	0.1552
14:Rajasthan	.0535	.0400	1.4951	.0855	.0129	0.6171	.0349	.1030	1.1016
15:Orissa	.0756	.0541	0.6954	.1208	.0161	0.8548	.0435	.1392	0.5494
17:West Bengal	.1347	.0591	1.2435	.2153	.0389	1.3450	.1054	.1520	0.8345

SECONDARY IMPACTS ON CLIMATE AND TECHNOLOGY EFFECTS

We have seen from Table 6.2 and the associated discussion, and from Table 6.3 and its associated discussion, the predicted effects of changes in climate variables on the three technology and related infrastructure variables, and on Net Revenue. One of the strengths of our approach, integrating climate and edaphic variables with technological and infrastructural variables, is that we can also compute the predicted impact of changes in technology and related infrastructural variables on the already-reported climate or other effects. In simple terms, these secondary impacts on, say, the temperature effects simply measure the extent to which changes in technology and infrastructure — over which policy-makers exercise some influence — might modify or ameliorate the effect of temperature changes on Indian agriculture.

Table 6.5 presents the impacts of increases in the technology and related infrastructure variables on the effect of higher temperature on Net Revenue; Table 6.6 presents the impacts of increases in the technology and related infrastructure variables on the effect of higher rainfall on Net Revenue.

Table 6.5: Secondary impacts on the temperature effects on net revenue
(Supra-Ricardian Model, 1970/71 through 1987/88)

	Research	Extension	WHYV	GCANCA	NIANCA
India	.00000419	.0004	.0308	-.0182	.1756
1: Andhra Pradesh	.00000490	.0004	.0360	.0018	.2084
2: Haryana	.00000603	.0005	.0443	-.0897	.1932
3: Madhya Pradesh	.00000295	.0002	.0217	-.0249	.1766
4: Maharashtra	.00000331	.0003	.0243	.0139	.1813
5: Karnataka	.00000344	.0003	.0253	.0374	.1706
6: Punjab	.00000652	.0006	.0479	-.0932	.1826
7: Tamil Nadu	.00000723	.0006	.0532	-.0034	.2163
8: Uttar Pradesh	.00000426	.0004	.0313	-.0503	.1727
9: Bihar	.00000387	.0003	.0284	-.0218	.1645
10: Gujarat	.00000419	.0004	.0308	.0283	.1494
14: Rajasthan	.00000460	.0004	.0338	-.0405	.1649
15: Orissa	.00000368	.0003	.0271	.0083	.1755
17: West Bengal	.00000390	.0003	.0287	-.0012	.1523

Table 6.6: Secondary impacts on the rainfall effects on net revenue
(Supra-Ricardian Model, 1970/71 through 1987/88)

	Research	Extension	WHYV	GCANCA	NIANCA
India	-.00000127	-.000010	-.0093	-.0257	-.0091
1: Andhra Pradesh	-.00000054	-.000046	-.0040	-.0136	-.0011
2: Haryana	-.00000269	-.000200	-.0198	-.0488	-.0244
3: Madhya Pradesh	-.00000140	-.000100	-.0103	-.0269	-.0120
4: Maharashtra	-.00000066	-.000056	-.0048	-.0158	-.0035
5: Karnataka	-.00000012	-.000010	-.0008	-.0095	.0056
6: Punjab	-.00000321	-.000300	-.0236	-.0580	-.0292
7: Tamil Nadu	-.00000331	-.000300	-.0243	-.0663	-.0220
8: Uttar Pradesh	-.00000179	-.000200	-.0132	-.0333	-.0158
9: Bihar	-.00000186	-.000200	-.0137	-.0363	-.0147
10: Gujarat	-.00000018	-.000015	-.0013	-.0048	-.0008
14: Rajasthan	-.00000058	-.000049	-.0043	-.0112	-.0050
15: Orissa	-.00000133	-.000100	-.0098	-.0289	-.0079
17: West Bengal	-.00000065	-.000055	-.0048	-.0191	.0010

In broad strokes, an increase in the technology and related infrastructure variables tends to worsen the (already negative) rainfall effects on net revenue somewhat, and except for multiple-cropping tends to improve the (negative) temperature effects on net revenue. In both cases, the research and extension impacts are smaller than the modern variety, multiple-cropping and irrigation impacts. The largest impact is that of an increase in irrigation on the temperature effect, 0.1756: this may represent the possibility of shifting the growing season to less-hot months with assured water from irrigation infrastructure.

CONCLUSIONS

We have constructed a four-equation model of the Indian agricultural sector which is rich and powerful. We begin by modeling the processes of technological and infrastructural change which have characterized India's Green Revolution: the adoption of modern high-yielding varieties; the expansion of multiple-cropping; and the expansion of irrigation. These are estimated in a 2SLS system in which the independent variables include one or both of the other technology variables, climatic and edaphic variables, and in some of the equations base-year values of the dependent variables or public investment in agricultural technology. Instruments in the 2SLS system include private investment in agricultural technology, measures of infrastructure (including price ratios), many climatic and edaphic and geographic variables, and regional and time dummies.

Many others have studied the Green Revolution, and the accompanying changes in productivity, in India and elsewhere. But never before has it been studied in a framework in which the three primary technological variables which characterize the processes of change (namely, WHYV, GCANCA and NIANCA) are directly modeled, in a system which includes detailed edaphic and climatic variables as well as the more familiar public and private investment variables, prices, etc.

The system is well-specified. Tests reveal that each group of variables, as well as most individual variables, significantly affect the three variables whose expansion characterizes India's Green Revolution experience, in ways which are consistent with prior studies.

We then estimate our fourth equation, the logarithm of net revenue per hectare, modeled as dependent upon climate, edaphic and geographic variables, the predicted values of WHYV, GCANCA and NIANCA obtained from the 2SLS system, interactions between these variables and climate variables, and additional public investment and infrastructure variables. As before, this fourth equation is also quite well-specified: tests reveal that each group of variables, as well as most individual variables, significantly affect the net revenue.

We then computed effects of climate change, and of continued increases in technology and related infrastructure, on the process of technological change and on net revenue per hectare. Our broad findings are summarized below:

Climate affects technology development and diffusion; conversely, technology development and diffusion affects the impacts of climate on productivity in India. Technology development and diffusion, as well as climate, also affect net revenue in agriculture in India.

First consider the effects of climate on the development and diffusion of technology. Estimates indicate small but negative effects of a rise in rainfall on all three indices of technology (modern varieties, irrigation intensity and multiple-cropping). The effects of an increase in temperature are mixed: a small negative effect on the adoption of modern varieties, a somewhat larger negative effect on irrigation intensity, and a small positive effect on multiple-cropping. Thus potential climate change is not substantially adverse to the development and diffusion of technology of the type realized in India since 1965.

Next, consider the estimates of the secondary impacts of technology on the climate effects on net revenue. These show that all indices of technology worsen (that is, make more negative) the estimated negative impacts of an increase in rainfall on farm production. They also show that all but one of the indices of technology improve (that is, make less negative) the effects of an increase in temperature. Thus technology is temperature friendly and rainfall unfriendly.

Finally, the net revenue estimates show that the technology variables significantly affect crop production and that many technology – climate interactions are statistically significant. The exclusion of technology variables probably leads to some bias in predictions of climate impacts on crop production.

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APPENDIX A:
VARIABLES IN THE COMBINED INDIA AGRICULTURAL DATA SET

INTRODUCTION

This Appendix describes the variables which are used in this study: their definitions, units, sources, any transformations which they underwent, and any special treatment which they required.

These variables come from two distinct data sets: one, which is sometimes called the "original" data set, which was created between 1980 and 1990, and has been used in numerous studies of production and productivity in Indian agriculture; the other, created in 1996, which added edaphic and climatic variables. Not every variable from either of the sets is used in this study; this Appendix covers only those which are used.

COVERAGE

The data set covers nearly all the districts (for a total of 271 districts) within thirteen of the States of India:

Andhra Pradesh	Madhya Pradesh	Rajasthan
Bihar	Maharashtra	Tamil Nadu
Gujarat	Orissa	Uttar Pradesh
Haryana	Punjab	West Bengal
Karnataka		

These thirteen States constitute the three primary Northern Wheat and Northern Rice producing states (viz., Haryana, Punjab and Uttar Pradesh), two Northwestern Bajra-producing states (Gujarat and Rajasthan), three Eastern states (Bihar, Orissa and West Bengal), as well as all of the Semi-Arid Tropics States as specified by ICRISAT. The major agricultural states which are absent from the data set are Kerala, at the southern tip of the subcontinent and the Eastern state of Assam; also absent, but less important agriculturally, are the minor states and Union Territories in the Northeastern part of India, as well as the far-northern states of Himachal Pradesh, Jammu and Kashmir.

During the period covered by the data set, there have been numerous adjustments in the boundaries (and even existence!) of some of the districts. These changes have occurred, for example, upon the division of the former Punjab into Punjab, Haryana and Himachal Pradesh; in the division of certain districts into two or more smaller districts in many places (especially in Bihar); or in the transfer of parts of one district to another. Insofar as possible, the data set preserves the original district boundaries: where districts have been broken up, values for the resultant districts in later years have been summed to yield values appropriate to a "shadow"consolidated district[22]. (However, the data set treats Haryana's districts as though they

[22] This obviously means that the actual number of modern-day districts covered is considerably larger than 271, because many current districts have been "consolidated" into the larger districts from which they had emerged.

always belonged to a State named Haryana even though, before 1966, they were part of the original Punjab.)

Some districts which currently exist will not appear in the data set, therefore, because they have been combined with other districts to create aggregations which approximate historical boundaries. Other current districts may not appear for other reasons, primarily because of dearth of agricultural activity (e.g., Bombay, a few Himalayan districts of northwestern Uttar Pradesh, or a few desert districts of Rajasthan) but occasionally because very little data is available for them.

Each district is assigned a unique identification code in the data set, composed of a two-digit State code (in the variable STATE) and a two-digit district code (in the variable DISTRICT). Some State and district codes contain leading zeros. The State and district codes have been combined into a three- or four-digit code named ID. In addition, the variable STNAME contains the name of each state, or its abbreviation. Part VI contains a list of districts and their identification codes.

The data set contains observations for each of the variables for the agricultural years 1957/58 through 1987/87 The agricultural year 1957/58 is denoted by 1957 in the variable YEAR in the data set; the agricultural year 1983/84 is denoted by 1983; and so forth. With the exception of three of the rainfall variables (which are clearly identified to refer only to a few specified months during the given year) and the wage variable (which refers to a daily wage), all variables are expressed as annual flows or average annual stocks or average annual levels or amounts.

OUTPUTS

The data set contains data pertaining to five "major" and thirteen "minor" crops, enumerated below:

Major Crops

BAJRA
JOWAR
MAIZE
RICE
WHEAT

Minor Crops

BAR (Barley)
COTN (Cotton)
GNUT (Groundnut)
GRAM
JUTE
OPULS ("Other" Pulses, other than Gram)
POTAT (Potato)
RMSEED (Rapeseed and Mustard)

SESA (Sesamum)
SOY (Soybeans)
SUGAR
SUNFL (Sunflower)
TOBAC (Tobacco)

For each of the so-called minor crops the data set includes:

Area Planted (1000 hectares; A followed by crop code)
Production (1000 tonnes; Q followed by crop code)
Farm Harvest Price (Rupees per quintal; P followed by crop code).

For the five major crops, the data includes the three variables listed above *plus*:

Area irrigated under the crop (1000 hectares; I followed by the crop code)
Area planted to HYV in each crop (1000 hectares; H followed by an abbreviated crop code).

The primary sources of data on Area and Production include:

Area and Production of Principal Crops in India, GOI
Crop and Season Reports of the various States
Statistical Abstracts of the various States
Agricultural Situation in India, GOI.

Beginning in 1954 and extending until the late 1960's, the Directorate of Economics and Statistics published *Area and Production* in two Parts: Part I contained All-India and Statewide data, while Part II (Detailed Tables) contained District-level data. Typically each issue of Part I would cover three years or so, while Part II would appear less frequently and cover a longer time span. But no Part II has been published for twenty years. Therefore, recently, the most convenient source for Area and Production data has been the monthly *Agricultural Situation.* This creates two small problems. The first is practical: One must cull through twelve issues each year, finding usually no more than three or four crops' data presented in any one issue.

The second, and far more significant, problem is substantive: the district-level estimates of Area and Production presented in *Agricultural Situation* are called "Final" estimates, and usually are the first estimates to be published. But so-called "Final" estimates are still subject to change, to be superseded by what are called "Revised" estimates. No such changes are reported in *Agricultural Situation* so there is no way to know whether such revisions have even been made without consulting sources other than *Agricultural Situation.* Seldom are the revisions large, however, so this data set relies heavily upon estimates from *Agricultural Situation* throughout much of the 1970's and 1980's.

Whenever it was possible to gain access to the *Statistical Abstracts* and/or *Crop and Season Reports* of any States for any of the years covered by the data, those sources were used for the estimates of Area and Production. In addition, those sources were especially valuable in providing data, for the major crops, on Area Irrigated under each crop and Area planted to HYVs in each of the crops, although *Agricultural Situation* has begun to include that data as well.

District-level Farm Harvest Prices are easily available from *Farm Harvest Prices of Principal Crops in India*, published every four years or so by the Directorate of Economics and Statistics. The prices are reported in Rupees per quintal. (Both wholesale and retail prices of all crops are also available, published regularly in *Bulletin on Food Statistics*, in *Agricultural Prices in India*, and elsewhere. Retail prices would be appropriate, for example, in a study of consumption behavior or poverty. Wholesale prices would be of interest, for example, in studying government grain procurement policies or interstate food movements. The obvious prices of most interest to this study are Farm Harvest Prices, because it is on the basis of those prices, or farmers' expectations of their future values, that farmers determine their behavior. But the data set also includes the wholesale prices of most crops, as well as a computed weighted and aggregated average Relative Price variable, RELPRICE, whose weights are the share of the crop in total area in the district, computed as the Farm Harvest Prices divided by the Wholesale Prices. Relative Price is one of the institutional variables which help to determine the levels of investment in infrastructure and public goods.)

VARIABLE INPUTS

The data set includes three categories of variable inputs: labor, fertilizer, and power.

The variables relating to labor include:

Rural Population:	(the total population of the district, male and female, residing in areas classified as rural: RURPOP)
Agricultural Labor:	(the number of rural males whose primary job classification is agricultural labor: AGLABOR)
Cultivators:	(the number of rural males whose primary job classification is Cultivators: CULTIVAT)
Total Farm Labor:	(a weighted sum of Agricultural Labor and Cultivators: QLABOR)
Wages:	(weighted annual labor cost: WAGE)
Factory Earnings:	(weighted annual earnings in a rural factory: FACTEARN)

The first three variables are obtained from the decennial population census, which reports the job classifications of all persons enumerated as well as many population totals. The population census has been conducted in India for more than a century and is widely deemed to be highly accurate. Census results are published in an extensive series of volumes for each state; the district-level values of the rural population and job classifications are reported in the *Primary Census Abstract*, and are reprinted frequently in *Statistical Abstracts* as well as many other sources. The data set is based on the reported values for the census years 1951, 1961, 1971 and 1981; the values of RURPOP, AGLABOR and CULTIVAT for the other years in the data set are linear interpolations (for 1956 through 1960, 1962 through 1970, and 1972 through 1980) and linear extrapolations (1982 through 1987) of the reported data. Interpolating population values is probably benign: such variables change in relatively regular and consistent ways. The numbers of agricultural laborers and cultivators often change substantially within a decade, so linear interpolations between census years may mask more volatile behavior. Unfortunately, however, the values of the population variables are not measured during any inter-censal years, so no better data could exist.

The Rural Population values appear in the data set exactly as they had been recorded. The Cultivator and Agricultural Labor values, however, measure a stock: the number of people who claim those activities as their primary job. The economically appropriate variable is a flow: the amount of labor performed during the year by such workers. The number of Agricultural Laborers and Cultivators are added, and their sum is multiplied by the average number of days worked in the State by farm workers (as obtained from various Farm Management Surveys; see the table on the subsequent page) in order to compute the appropriate flow of labor services variable: QLABOR.

State	# of days worked by farm workers
Andhra Pradesh	230
Bihar	
Gujarat	215
Haryana	244
Karnataka	217
Madhya Pradesh	239
Maharashtra	240
Orissa	
Punjab	244
Rajasthan	215
Tamil Nadu	293
Uttar Pradesh	210
West Bengal	

Agricultural Wages are obtained from *Agricultural Wages in India*, published by the Directorate of Economics and Statistics every two or three years, reporting daily wages and normal daily working hours for each of the twelve months from reporting centers in most districts for different farming activities. Wages are reported separately for men, women and children for some activities. Whenever possible, the wages of a male ploughman were recorded; if a district did not record such a wage, the wages of a male field laborer or male "Other Agricultural Labour" were selected instead. An average annual wage was constructed from the monthly wages, weighting June and August more heavily than other months because of the intensity in those months of field work in most cropping patterns and most states.

Factory Earnings measure the average annual earnings of an unskilled laborer working in a rural "factory" (which could include establishments employing as few as two persons). This variable not only measures the opportunity cost of working on one's own farm, but captures to an extent some of the supply conditions of the local rural labor market. We compute a Relative Wage (simply by dividing annual farm earnings by average annual factory earnings), which is one of the institutional variables which help to determine the levels of investment in infrastructure and public goods.

The variables relating to fertilizer include the quantities of nitrogen, phosphorous and potassium fertilizers (in tonnes: denoted NITRO_TQ, P2O5_TQ and K2O_TQ) and the prices of the three fertilizers (in Rupees per tonne of nutrient: NITRO_TP, P2O5_TP, K2O_TP). The fertilizer data source is *Fertilizer Statistics*, published annually by The Fertilizer Association of India. Quantity data is given by district, by nutrient, and often by season; only yearly data is included in the set. Prices of fertilizers are strictly controlled by the Central Government, so the only cross-section price variation arises from the cost of transportation from the railhead to the field; the prices of the nutrients in the data set, therefore, exhibit no cross-section variation, but are based on reported maximum sale prices of common fertilizer compounds adjusted for the proportion of the nutrient present in each compound. Prices are not reported for all nutrients for all years; prices for intervening years are estimated based on movements of the fertilizer wholesale price index during those years.

Farm (draft) power is obtained from two primary sources: bullocks and tractors. The quantities of both are enumerated in the quinquennial Livestock Census. The results of each Livestock Census are published in two Parts: Part I contains All-India and statewide data, while Part II contains district-level data. Part II has been published for the Censuses of 1956, 1961, 1966, 1972 (the census which had been scheduled to occur in 1971, according to the former sequence, had to be postponed to 1972) and 1977, but district-level data is not yet available for the census of 1982. (The publication backlog seems to be increasing, and since the 1977 district-level data were not released until December, 1987, it is unlikely that 1982 district-level data will be available within in the next four or five years.)

Bullocks (QBULLOCK), as recorded for the data set, refer to castrated (male) cattle, over the age of 3 years, which are used in rural areas for work only. Tractors (QTRACTOR) are four-wheel (not tracked, nor walk-behind two-wheeled) machines.

The numbers of bullocks and tractors in the inter-censal years (1957-1960, 1962-1965, 1967-1971, and 1973-1976) are estimated by linear interpolation. For years after 1977, for which no district-level data have yet been published, the data set contains estimates computed by extrapolating the 1982 observations at a rate equal to the percentage change in the state values from 1977 to 1982.

Tractor prices do not vary across India: a single tractor price therefore appears for all districts in any given year. The tractor price is constructed as follows: The price index for Agricultural Machinery and Transport Equipment from 1954 through 1985 was compared to observed prices for Eicher 24-horsepower tractors during selected months from 1978 to 1987. (The Eicher prices were collected by P. C. Bansil of the Techno-Economic Research Centre, New Delhi). Movements in the price index mirrored movements in the Eicher tractor prices almost perfectly. So the Eicher price series was extended back to 1956, on the basis of proportional changes in the Agricultural Machinery and Transport Equipment price index. Eicher commands more than 50% of the market of tractors in the 1 to 25 horsepower range, which is the largest segment of the tractor market in India, but larger tractors command a higher price, so the Eicher 24-horsepower tractor's share in the total value of tractors is smaller than its share in the number of tractors. So the average price of a tractor would be larger than the price of an Eicher 24-horsepower (an "average"?) tractor. To adjust for that, the estimated Eicher price series was multiplied by 1.66 (based on data showing the difference in prices for Escort tractors of various horsepower ratings in the early 1970's), producing a tractor price series which is consistent with both the movements of the price index and independent data on the prices of actual tractors. The resulting tractor price series was finally multiplied by one-fourth to derive an annual tractor cost variable (PTRACTOR). The value of one-fourth, or 25%, represents both the depreciation and debt service on the investment, as well as the rate of return which is required for tractors to be bought in the first place. Thus the annual tractor cost variable represents a sort of shadow rental cost of a tractor, in the appropriate flow form.

The data set contains three bullock prices, reflecting the physical differences in bullocks in different parts of India. Each price series is based on retail price indices reported in various issues of *Agricultural Prices in India*, published by the Directorate of Economics and Statistics, in which bullocks are identified by state (e.g., Bihar, Gujarat, Haryana, and Uttar Pradesh). The so-called Haryana price was applied to bullocks in Haryana and Punjab; the Gujarat price was applied to bullocks in Gujarat, and the more prevalent Uttar Pradesh price was applied to bullocks in all other states. Rental fees for bullocks are very difficult to obtain. The annual bullock cost variable (PBULLOCK) was obtained by multiplying each bullock price by 0.50, representing both the substantial annual flow of expenses entailed in breeding, raising and feeding bullocks, as well as the necessary rate of return on their ownership.

In closing the discussion of the variable inputs, it is interesting to note that the values of these prices and quantities are "realistic" in the sense that they imply input cost shares which are consistent with the range of cost shares obtained in earlier research.

OTHER INPUTS

The data set contains additional "inputs" which cannot be considered to be subject to the control of farmers in the short run. Some of this class of inputs, such as rainfall, are for all practical purposes beyond the influence of any human agency. And some, such as certain forms of irrigation, and perhaps literacy, can be influenced by farmers' decisions and behavior only over a substantially long period of time. Others, such as research and extension, are in part the result of governmental decisions, possibly in response to a diffuse and highly-lagged "demand" from farmers which is as much political as economic. Although not variable in the traditional sense, these "other" inputs do significantly influence agricultural output and productivity.

These "other" inputs can be classified as members of three subgroups: Agro-climatic, Public, and Socioeconomic.

AGRO-CLIMATIC INPUTS

The inputs which are classified as agro-climatic pertain to the most basic agricultural inputs: soil and water. Two of them measure the use of land: Gross Cropped Area (GCA) and Net Cropped Area (NCA). Net Cropped Area is the total geographic area on which a crop has been planted at least once during the year. Gross Cropped Area is the total area planted to crops during all the growing seasons of the year; if any land has been doublecropped it will appear only once in Net Cropped Area, but twice in Gross Cropped Area. Both GCA and NCA are measured in units of 1000 hectares[23]. From these two variables is computed a third, GCANCA, the ratio of total acreage during all seasons of the year to land planted only once; a measure of multiple-cropping. (See Section VI below for a discussion of more detailed edaphic variables from the second data set).

Water is supplied in two ways: naturally, as Rainfall, and artificially, as irrigation. Data relating to irrigation are reported in several forms: area irrigated by source (e.g., by canal or tank or tubewell), area irrigated under certain crops, or total areas irrigated.

The data set includes two variables of this last form: Net Irrigated Area (NIA) measures the total geographic area which has received irrigation (from any source) during the year, and Gross Irrigated Area (GIA) measures the total area under crops which has received irrigation during all the growing seasons of the year. As was true for NCA and GCA, if any irrigated land has been double-cropped it will appear only once in Net Irrigated Area, but twice in Gross Irrigated Area; again, the variables are measured in units of 1000 hectares[24]. (From NIA and NCA we compute the variable named NIANCA, the ratio of net irrigated area to net cropped area, which measures irrigation intensity.)

Estimates of Gross and Net Cropped Area and of Gross and Net Irrigated Area are available from the annual *Indian Agricultural Statistics* which are published in two volumes: Volume I presents All-India and Statewide data, while Volume II contains District-wide data. This data is also available in most states' *Crop and Season Reports* and *Statistical Abstracts*, and has been published in the *Agricultural Situation in India* since the early 1980's. Crop-specific irrigated area is also reported in *Fertilizer Statistics*.

Rainfall is measured daily in most districts in India at so-called "meteorological observatories" established by the India Meteorological Department. The district data are aggregated into approximately three dozen so-called "sub-divisions", which range from parts of a State (such as Coastal Karnataka, North Interior Karnataka and South Interior Karnataka) to an entire State (such as Orissa or Punjab). The monthly sub-divisional data are then published in a number of sources, including *Agricultural Situation in India*. Annual sub-divisional data are reprinted in many sources, most conveniently in *Fertilizer Statistics*. District-level (that is, non-aggregated) data are also published in some states' *Crop and Season Reports*, *Statistical Abstracts*, and in some specialized meteorological publications such as the occasional *Climatological Tables of Observatories in India*; a number of states augment the India Meteorological Department's data collection (and publication) with data collected by their own means.

The data set contains five rainfall variables, four of which measure actual precipitation during parts or all of the agricultural year. The first, YEARRAIN, is the total rainfall in the given year: it is the sum of the rainfall in each of the twelve months. The other two rainfall variables measure rainfall in only one or a few months, at periods crucial to crop production: rainfall in June, at the beginning of the monsoon in most states (JUNERAIN), and in July and August,

[23] We also compute a variable which measures the *intensity* of double-cropping: GCANCA, which is GCA divided by NCA. It obviously ranges from a value of one, at which no double-cropping occurs, upwards.

[24] And, as before, we compute a variable which measures the *intensity* of irrigation: NIANCA, which is NIA divided by NIA. It ranges from a value of zero, at which no irrigation occurs, upwards.

during the remainder of the monsoon in most parts of India (JUAURAIN). The fourth rainfall variable is a dummy variable (DROUGHT) which takes the value of one for those districts which are designated as "drought-prone" by the ICAR; it has no time-series variation, and does not measure whether a drought, by whatever definition, had occurred in any given year, but instead simply denotes those districts which historically have had low levels and high variability of rainfall. (See Section VI below for a discussion of more detailed normal rainfall variables from the second data set.)

PUBLIC SECTOR INPUTS

The public sector provides physical infrastructure which facilitates agricultural production. One of the most important inputs into agriculture provided by the public sector is research results, in the form of new seeds, or improved implement design, or improved management practices, or any number of other forms. Research activities are undertaken by all of the states as well as by numerous Central schemes and projects, focussing on practically every crop grown in India as well as many inputs and all of the basic agricultural sciences. The specification of a valid and appropriate research variable is difficult, for a number of familiar reasons. Budget data are seldom available in a form which allows the separation of the accounts of research units from their parent organizations; even the unsatisfactory budget data that exists is flawed in that it is seldom obvious how to separate the current from the capital, and the researchers from the other staff. Even if one could confidently measure staff and expenditures, it is difficult to measure research output, especially if one recognizes the problems posed by quality differences, the almost-stochastic nature of most research efforts, and well-known vintage issues.

In constructing the research variables for this data set, therefore, special efforts have been made to address those problems as fully as possible. The research variables are based on three sets of data. First is the indigenous State agricultural research expenditures series, covering the years 1953 through 1971, which was reported in R. Mohan, D. Jha and R. Evenson, "The Indian Agricultural Research System" *Economic and Political Weekly* (vol VIII, # 13, 31 March 1973). Second is a data set which contains the number of articles reporting research results which were abstracted in *Indian Science Abstracts* from 1950 through 1979. This data set provides crop-specific (for the crops wheat, rice, maize, jowar, bajra, cotton, sugar, for "other" crops, and for "general" agricultural research) and State-specific (including Delhi) data measuring the output of the research activity; the editorial authority exercised by the abstractors in imposing and enforcing quality thresholds for inclusion in the *Indian Science Abstracts* makes this set particularly useful. Third is recent state budget information regarding research spending, especially at the State Agricultural Universities during the late 1970's and the 1980's. These three were combined to create commodity-specific expenditures data series for each of the states from 1950 through 1983, multiplying each year's research expenditures by the ratio of the number of publications abstracted for that commodity in that state to the total number of commodity-level (that is, not "general") publications in the state. In addition, for each state a "general" expenditures data series was created by multiplying the year's research expenditures by the ratio of "general" abstracts to the total publications. (This procedure obviously uses the proportion of abstracted publications in each crop to allocate the total research effort, as measured by expenditures, among the various commodities.)

For each state and each commodity a research "stock" variable was then defined by cumulating past research activity utilizing several patterns of time-shape "inverted V" weights as first used in Evenson (1968). The inverted V has three regions. The first, sloping upward, refers to the number of years between the first appearance of the research result and its full effect, during which the research outcome has successively-greater impact. In this region more-recent results are multiplied by smaller fractions, while moderately-distant results are multiplied by larger fractions, until at the top of the upward-sloping region the weights become one. The second region, a horizontal plateau, refers to the number of years during which the research output can continue to contribute at "full strength", during which time the weights remain equal to one. The third region, sloping downward, represents a sort of "decay" in the research contribution, due perhaps to biological changes or merely being supplanted by later, superior discoveries. In this region earlier (that is, more distant in the past) research contributions are multiplied by successively-smaller weights.

The data set contains six measures of public research, which differ in the time pattern of the three sets of weights. The table below lists the six statewide crop research variables, followed by the number of years specified in their upward-sloping, horizontal and downward-sloping regions, respectively:

STRES1:	333	STRES4:	666
STRES2:	336	STRES5:	999
STRES3:	366	STRES6:	699

(In order not to lose early observations because of the lengthy lag structure, research activity in years prior to 1950 was set equal to one half of the activity in 1950.)

Finally, each of the STRES variables was weighted by the share of the crop in the total value of output, summed across districts, and by the Gross Cropped Area planted to that crop in the state.

The data set also includes a variable measuring private research activity (PRIVRES), which has increased in importance markedly during the past two decades. This variable is based on data collected by Prof. Carl Pray, measuring research spending by private firms in the seed, fertilizer and machinery industries. From this expenditure data three research stock variables were constructed using a linear five-year lag structure with no decay: the stock was defined as one-fifth of the previous year's spending plus two-fifths of the spending two years ago plus three-fifths of the spending three years ago plus four-fifths of the spending four years ago plus the sum of all spending five years ago and earlier. The lag structure obviously reflects the time required for are search program to produce economically meaningful results: from inception of spending to invention to innovation to manufacture to marketing to full diffusion.

From the three input-specific private research stocks was then created the variable PRIVRES, measuring the <u>local contribution</u> (or potential) of this private research knowledge within each district, by adding the year's stock of seed research multiplied by the district's input share of land, plus the year's stock of fertilizer research multiplied by the district's input share of fertilizer, plus the year's stock of machinery research multiplied by the district's input share of bullocks and tractors.

The extension variable (EXT) is based on three sets of information. The first is data measuring the size of the extension service staff in 1975, 1980, 1983 and 1986 in each state, based on surveys by the World Bank. The second is the number of villages in each state. And the third is data published in various years' annual *Reports* of the Department of Community Development of the Ministry of Agriculture (during some years the Ministry of Food, Agriculture, Community Development and Cooperation), covering the years 1955 through 1972,. which report the number of Community Development Blocks in each state which were classified as Stage I, Stage II or Stage III. A Stage III block (strictly speaking, the blocks were called "post-Stage II") is the most advanced, not only denoting more contemporary extension activity but also resulting from the success of past and current extension activity. The expectation was that a block would remain in Stage I for about five years, and in Stage II for another five years, so to some extent the variability in Stages reflects the staggered onset of extension activity in the various blocks. (By the middle 1970's practically 100% of all blocks had progressed beyond Stage II).

The staffing data were interpolated to obtain estimates for the years 1976 through 1979, 1981 and 1982. Then the staffing data were divided by the number of villages (in units of hundreds) to obtain a measure of the number of extension workers per hundred villages, interpreted as an indicator of extension presence. This variable was then extended backward, from 1975 to 1956, as follows: First, the Stage data were combined into a single weighted variable by multiplying the number of Stage I blocks by two-fifths, adding the number of Stage II blocks multiplied by four-fifths, adding the number of Stage III blocks, and dividing the final sum by the total number of blocks. (The coefficients 0.4 and 0.8 are admittedly a bit arbitrary; they were chosen to reflect the lower intensity of extension activity in the earlier Stages.) The resulting quotient is necessarily a positive fraction, which can be interpreted as the degree to which the extension effort has reached the norm.

Under the assumption that the extension effort had reached the norm by 1975, the weighted Stage variable would equal one for 1975 (because all blocks are assumed to have reached Stage III, the numerator contains only one term, the number of Stage III blocks, and the denominator equals the numerator, since all the blocks are in Stage III) and the 1975 staffing level can be taken to represent the "normal" staffing. Thus for years before 1975 the estimated extension variable is computed as the product of the 1975 staffing levels times the weighted Stage coefficient, interpreted as the level of staffing which would prevail at the particular "sub-norm" level of extension activity which the pattern of Stages discloses.

SOCIOECONOMIC INPUTS

The variable LITERACY, obtained from the decennial population census, measures the proportion of rural males who are classified as literate, which is defined as "the ability to read and write in any language". Census enumerators, beginning with the 1971 Census, were required to observe each individual's ability to read and write before classifying him or her to be literate. As is true for all census variables, values for the inter-censal years were obtained by linear interpolation. Literacy rates change so slowly and so regularly that this procedure seems amply justified.

CLIMATIC AND EDAPHIC VARIABLES

These additional variables extend the original data set in two dimensions. First are included climatic variables which were not available in the original data set (which contained only the three actual rainfall variables, measuring current weather). This data set adds monthly normal minimum and maximum temperatures (from which can be computed the monthly normal temperature range or the monthly normal temperature midpoint) for all twelve months; normal monthly rainfall (again for all twelve months) and the coefficient of variation of actual rainfall; and for some of the districts still other monthly climate variables. These climatic variables are described below.

The second dimension includes edaphic variables which were not included in the original data set (which contains only the area under particular crops). This additional data set includes soil type, soil pH, the depth of aquifers, and topsoil depth; in addition, this data set includes geographic variables measuring latitude, longitude, altitude, slope, and proximity to the ocean. These additional land variables are described below.

Some of the climatic and edaphic variables are multiplied by each other, and/or by other variables, capturing the interactions of the phenomena which those variables represent. Notable among those interactions are the maximum temperature squared, rainfall times maximum temperature, rainfall squared, and both rainfall and maximum temperature times the the predicted values of modern varieties, multiple-cropping and irrigation intensity.

When each variable is described in the subsequent sections, its source is identified. In general, there were two types of sources used: tables and maps. Data from tables offers no problems. A few preliminary words about obtaining numeric data from maps, however, are in order.

First, two general kinds of maps were used. Some (e.g., the maximum temperature map mentioned below in b)i)) are small, all-India maps which exhibit isotherms (or other isobars) weaving across the nation, usually at intervals of 2.5° C. To determine the air temperature for a district for which a direct temperature observation is not reported in any tables, we superimposed copies of these maps, made on transparencies, over maps showing district boundaries, and interpolated temperatures at one-half degree intervals between the isotherms. If an isotherm split a district substantially down the middle, that temperature was assigned as a "reference value" to that district. Otherwise, we assigned to the district the value of the half-degree interpolated isotherm which most nearly approached the middle of the district. We then used these "reference value" temperatures to determine which neighboring district, for which we did have complete temperature data from tables, was climatologically most like the district without temperature data, and thus whose temperature data we would assign to the district in question.

The other kind of map displays, by color and pattern, the value of some variable for areas which may be smaller than districts, and which often span district boundaries. Most of the time, districts contain areas of more than one value, such as more than one soil type within the district, or regions of different slope within the district, or areas with different pH within the district, etc. This was handled in the data set in two distinct ways.

1. In constructing the variables for soil type (using the maps cited below), we estimated the proportion of each district's area under each soil type. The current data set contains

nineteen soil type dummy variables, one for each type. The value of a soil type dummy variable is one for a district if that type is one of the two predominant soil types in the district (that is, if that type's proportion is one of the two highest proportions in the district). This implies, obviously, that a district will have two soil type dummies with the value of one (except for the few districts all of whose soil is of one type), and thus that one cannot interpret the dummies' coefficients in the customary way.

2. In constructing all of the other variables derived from "color and pattern" maps (namely, pH, the depth of aquifers, topsoil depth, and slope) we simply selected the value which seemed predominant, which covered more of the district's area than did any other value. This approach does not distinguish between districts which are entirely covered by one value (say, a pH of 7; or a moderately steep slope), on the one hand, as against districts with several values, one of which covers slightly more area than do any others (say, 19% of the soil has a pH of 5, 19% has a pH of 6, 24% has a pH of 7, 19% with pH of 8, and 19% with pH of 9; or 20% of the district's area is flat, 41% is moderately steep, and 39% is very steep), on the other hand. A possible avenue for further research is to enrich the data set in this way.

CLIMATIC VARIABLES

1. Air Temperature

a. Monthly Normal Maximum
  - i. variable names of the form _ _ _ x t
    - 1) for example, janxt, febxt, marxt, ..., decxt
    - 2) _ _ _ is a three-character abbreviation of the month: jan, feb, etc.
    - 3) x refers to maximum and t of course refers to temperature
  - ii. sources
    - 1) *Climatological Tables of Meteorological Observatories in India*
      - a) 235 observatories' observations are reported
        - i) 35 observatories are in states (or even countries: Pakistan, for example) not included in our data set
        - ii) this leaves 200 observatories in relevant districts
      - b) 32 of these remaining observatories are duplicates
        - i) in a district which had two or more observatories
          - (1) we chose the observatory which was located in the district headquarters, if present
          - (2) otherwise closest to the geographic center
        - ii) so the *Climatological Tables...* provided 168 distinct districts' observations
          - (1) 130 of them, identified by the value of 1 for the dummy variable DMPEN, are full 30-year norms based on data from 1931 through 1960
          - (2) thus the other 38 of them, identified by the value of 1 for the dummy variable DMCLMTAB, are norms based on less than 30 years of observations, from

observatories which began recording temperature data after 1931.

2) temperature maps
   a) for remaining 102 districts (for which we had no temperature data from the *Climatological Tables...*), we assigned temperature data identical to a "neighboring" district (for which we did have temperature data from the *Climatological Tables...*)
   b) We determined which adjacent district to use by visual inspection of a temperature map, pairing districts with same normal mean daily maximum temperature
      i) maps from *Agroclimatic Atlas of India*, India Meteorological Department, Pune, P.DGM.118(N) / 1000-1987 (DSKII)
         (1) first published in 1978
         (2) subsequently reprinted many times
      ii) Plate 21: July mean daily maximum temperature

b. Monthly Normal Minimum
   i. variable names of the form _ _ _ n t
      1) where the n refers to minimum
      2) for example: jannt, febnt, marnt, ..., decnt
   ii. same sources and procedures as for maximum temperature, above

c. Monthly Normal Temperature Range
   i. variable name of form _ _ _ t r g
      1) where the t r g refers to temperature range
      2) for example: jantrg, febtrg, martrg, ..., dectrg
   ii. computed, for each month, as (_ _ _ x t − _ _ _ n t)

d. Monthly Normal Temperature Midpoint
   i. variable name of form _ _ _ m d t
      1) where the m d t refers to midpoint
      2) for example: janmdt, febmdt, marmdt, ..., decmdt
   ii. computed, for each month, as (_ _ _ x t + _ _ _ n t) / 2

2. Rainfall

a. Normal Monthly Rainfall
   i. variable names of the form _ _ _ r n
      1) for example: janrn, febrn, marrn, ..., decrn
      2) again, _ _ _ is a three-character abbreviation of the month
      3) r n denotes "rainfall norm"
   ii. sources
      1) *Climatological Tables...*
         a) normal rainfall data is available for the same districts for which we obtained normal temperature data
         b) similar pattern of 30-year and shorter norms

2) *Monthly & Annual Rainfall & Number of Rainy Days, 1901 - 1950*
   a) Indian Meteorological Department, in several volumes
   b) some 3000 rainguage stations across the subcontinent
      i) obviously then most districts have more than one rainguage station
      ii) as before, we used the rainguage station in the district headquarters, if it existed
   c) We computed 30-year normals (1921 – 1950) for districts for which no data was available in the *Climatological Tables...*
   d) thus, obviously, we did not have to resort to **neighboring** districts to obtain normal rainfall data for all districts

b. Variability of actual rainfall
   i. coefficients of variation computed from the actual rainfall data
   ii. JURNCV: coefficient of variation of June rainfall, 1957 through 1987
   iii. JARNCV: coefficient of variation of July & August rain, 1957 – 1987

3. Oktas of cloud cover

a. variables of the form _ _ _ ok
   i. as always, _ _ _ is the three-character month abbreviation
   ii. for example, janok, febok, marok, ..., decok
b. measures the extent to which clouds obscure the sun
c. values range from to
d. source: *Climatological Tables....*

EDAPHIC VARIABLES

1. Soil Type

a. variable names of the form DMSnn
   i. for example, DMS02, DMS03, DMS04, ..., DMS19, DMS20
   ii. DM denotes a dummy variable
   iii. S denotes soil type
   iv. nn ranges from 02 to 20, for "traditional" soil types

b2.source: visual inspection of soil maps for each State
   i. S. P. Raychaudhuri et alia, *Soils of India* (New Delhi: Indian Council of Agricultural Research, 1963)
   ii. recall the discussion, in the Introductory section of this Appendix, of the methodology by which these variables were created

c. types
   01 not used
   02 Laterite
   03 Red and Yellow
   04 Shallow Black

05 Medium Black
06 Deep Black
07 Mixed Red and Black
08 Coastal Alluvial
09 Deltaic Alluvium
10 Calcereous
11 Gray Brown
12 Desert
13 Tarai
14 Black (Karail)
15 Saline and Alkaline
16 Alluvial River
17 Skeletal
18 Saline and Deltaic
19 Red
20 Red and Gravelly
21

2. Soil pH

   a. source: National Atlas of India, vol 1, plate 59

   b. variables:
      i. a series of dummy variables
         1) DMPH5: strongly alkali: $4.5 < pH < 5.5$
         2) DMPH6: slightly alkali: $5.5 < pH < 6.5$
         3) DMPH7: neutral $6.5 < pH < 7.5$
         4) DMPH8: slightly acid $7.5 < pH < 8.5$
         5) DMPH9: strongly acid $8.5 < pH < 9.5$

      ii. single variable PH# whose value is pH reading from 5 to 9

3. Aquifers

   a. source: National Atlas of India, vol 1, several plates
      i. plate 87: All-India
      ii. plate 88: Northern India
      iii. plate 89: Western India
      iv. plate 90: Central India
      v. plate 91: Eastern India
      vi. plate 92: Southern India

   b. variables:
      i. DMAQ1: dummy variable, = 1 if aquifer is < 100 meters thick
      ii. DMAQ2: dummy variable, = 1 if aquifer is 100 - 150 meters thick

iii. DMAQ3: dummy variable, = 1 if aquifer is > 150 meters thick

c. (obviously this is not exhaustive, in the sense that major areas of the nation are above no aquifers at all, so for many districts none of these dummy variables has the value of one.)

4. Topsoil depth

a. source: National Atlas of India, vol. 1, Plate 50: "Depth of Soil, All-India"

b. variables:
i: DMTS1: dummy variable, = 1 if topsoil is 0 – 25 cm. thick
ii. DMTS2: dummy variable, = 1 if topsoil is 25 – 50 cm. thick
iii. DMTS3: dummy variable, = 1 if topsoil is 50 – 100 cm. thick
iv. DMTS4: dummy variable, = 1 if topsoil is 100 – 300 cm. thick
v. DMTS5: dummy variable, = 1 if topsoil is > 300 cm. thick

5. Geography

a. variable names
i. Latitude
1) LATDEG the degree portion of the latitude (North)
2) LATMIN the minutes portion of the latitude
ii. Longitude
1) LONGDEG the degree portion of the longitude (east of Greenwich)
2) LONGMIN the minutes portion of the longitude
iii. Altitude
1) ALTITUDE
2) the altitude of the meteorological observatory, in meters, above mean sea level

b. sources
i. *Climatological Tables...*
ii. for districts which have no observatories within their boundaries
1) we assigned Latitude and Longitude by visual inspection of detailed state-level maps
2) we estimated the latitude and longitude of the district headquarters
iii. those districts, though, lack Altitude data

6. Slope

a. source: National Atlas of India, vol. 1, several plates
i. plate 44: All-India
ii. plate 45: Northern India

iii. plate 46: Western India
iv. plate 47: Central India
v. plate 48: Eastern India
vi. plate 49: Southern India

b. variables:
   i. a series of dummy variables included in the data set
      1) DMSL1: flat: less than 10 meters / km.
      2) DMSL2: flat: 10 to 20 meters / km.
      3) DMSL3: gentle slope: 20 to 80 meters / km.
      4) DMSL4: moderately steep slope: 80 to 150 meters / km.
      5) DMSL5: steep slope: > 150 meters / km.

   ii. the maps had more gradations, which exist in the data set but from which the preceding variables were constructed:

      DMSL1a: flat (<10), < 100 meters above mean sea level
      DMSL1b: flat (<10), 100 to 500 meters above mean sea level
      DMSL1c: flat (<10), > 500 meters above mean sea level

      DMSL2a: flat (10–20), < 100 meters above mean sea level
      DMSL2b: flat (10–20), 100 to 500 meters above mean sea level
      DMSL2c: flat (10–20), > 500 meters above mean sea level

      DMSL3a: gentle (20–80), < 100 meters above mean sea level
      DMSL3b: gentle (20–80), 100 to 500 meters above mean sea level
      DMSL3c: gentle (20–80), > 500 meters above mean sea level

      DMSL5 originally was: steep slope: 150 to 300 meters / km.
      DMSL6: steep slope: 300 to 600 meters / km.
      DMSL7: very steep slope: > 600 meters / km.

   iii. No districts in the data set were steeper than 300 meters / km., so levels 6 and 7 were superfluous.

7. Proximity to the ocean

   a. variables
      i. DMSEA: value is one if the district is on the seacoast
      ii. DMSEANEI: value is one if the district is not itself on the seacoast, but borders another district which is on the seacoast; that is, if the district is in the "second tier" inland

   b. source: easily constructed by visually inspecting a district-boundary map

APPENDIX B: REGRESSION RESULTS

Table 6B.1: List of Instruments for WHYV, GCANCA and NIANCA
(Supra-Ricardian model, 1970/71 through 1987/88)

Variable Name	Description	Mean	Standard Deviation
Edaphic Variables			
* DMSnn	Soil Type Dummies	--	--
DMTSn	Topsoil Depth Dummies	--	--
Geographic Variables			
* AGROBn	Agroeconomic Region Dummies	--	--
DMAQn	Aquifer Depth Dummies	--	--
Institutional Variables			
PRWTWG	Price Ratio: Wheat to Wage	28.52	14.41
PRRCWG	Price Ratio: Rice to Wage	28.60	17.76
PRMZWG	Price Ratio: Maize to Wage	20.86	9.77
PRJWWG	Price Ratio: Jowar to Wage	19.63	13.19
PRBJWG	Price Ratio: Bajra to Wage	19.09	12.34
PRFRWG	Price Ratio: Fertilizer to Wage	683.69	301.06
PRTRWG	Price Ratio: Tractor to Wage	2309.40	811.41
POPDEN1	Population Density:	3948.41	2717.01
Technology Variables			
EXT	Extension		
PRIVRES	Private Research	247.94	187.08
LITERACY	Male Rural Literacy rate	.37	.11
Climate Variables	(as defined in Appendix A and in Table 6.3)		
* JANMDT, * JANMDTSQ, * JANRN, * JANRNSQ, * JANMDTRN			
* APRMDT, * APRMDTSQ, * APRRN, * APRRNSQ, * APRMDTRN			
* JULMDT, * JULMDTSQ, * JULRN, * JULRNSQ, * JULMDTRN			
* OCTMDT, * OCTMDTSQ, * OCTRN, * OCTRNSQ, * OCTMDTRN			

Table 6B.2: Second stage regression of modern varieties (WHYV)
(Supra-Ricardian Model, 1970/71 through 1987/88)

Multiple R	.83346
R Square	.69465
Adjusted R Square	.69173
Standard Error	.13390

Analysis of Variance:

	DF	Sum of Squares	Mean Square
Regression	43	183.22723	4.2610984
Residuals	4492	80.54089	.0179299

F = 237.65387 Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
GCANCA	.357154	.075073	.292757	4.757	.0000
NIANCA	.738063	.062316	.709577	11.844	.0000
STRES5	.000136	.000177	.021037	.772	.4404
EXT	.011476	.000776	.260476	14.790	.0000
DMS03	.002540	.013125	.001881	.194	.8466
DMS04	-.007558	.011651	-.005889	-.649	.5166
DMS05	.042430	.008296	.057862	5.114	.0000
DMS06	.016136	.008695	.019592	1.856	.0636
DMS07	-.001629	.009299	-.001757	-.175	.8610
DMS08	.040662	.017034	.042854	2.387	.0170
DMS09	.036131	.018201	.021988	1.985	.0472
DMS10	.033140	.025236	.016534	1.313	.1892
DMS11	.048609	.020029	.029581	2.427	.0153
DMS12	.055735	.018096	.041287	3.080	.0021
DMS13	-.290194	.022068	-.190360	-13.150	.0000
DMS14	-.055462	.014052	-.041084	-3.947	.0001
DMS15	-.075280	.012060	-.084823	-6.242	.0000
DMS16	.052262	.007149	.103660	7.310	.0000
DMS17	.024859	.019893	.010762	1.250	.2115
DMS18	-.261465	.029374	-.092609	-8.901	.0000
DMS19	-.071279	.008601	-.119033	-8.287	.0000
DMS20	.118241	.018723	.058990	6.315	.0000
DMS21	.267520	.022617	.175487	11.828	.0000
JANMDT	.093802	.015983	1.386612	5.869	.0000
JANMDTSQ	-.002110	.000402	-1.168254	-5.250	.0000
JANRN	-.000751	.001318	-.039501	-.570	.5688
JANRNSQ	9.89963339E-05	1.2586E-05	.287959	7.866	.0000
JANMDTRN	-.000218	6.2448E-05	-.201555	-3.491	.0005
APRMDT	-.181868	.033151	-1.722097	-5.486	.0000
APRMDTSQ	.003237	.000567	1.638528	5.713	.0000
APRRN	.007816	.002042	.709219	3.827	.0001
APRRNSQ	-1.50380489E-05	4.6485E-06	-.142133	-3.235	.0012

Table 6B.2: Second stage regression of modern varieties(WHYV) (cont.)

Variable	B	SE B	Beta	T	Sig T
APRMDTRN	-.000158	5.9340E-05	-.377586	-2.664	.0077
JULMDT	.200461	.045647	2.041751	4.392	.0000
JULMDTSQ	-.003297	.000813	-1.766686	-4.055	.0001
JULRN	.000565	.000164	.530478	3.446	.0006
JULRNSQ	-5.88238133E-08	2.2397E-08	-.101628	-2.626	.0087
JULMDTRN	-1.43573001E-05	5.7564E-06	-.302688	-2.494	.0127
OCTMDT	-.087417	.050046	-.653945	-1.747	.0808
OCTMDTSQ	.000831	.000935	.296904	.888	.3745
OCTRN	-.006904	.001134	-1.823514	-6.086	.0000
OCTRNSQ	-2.96119591E-06	7.4229E-07	-.187707	-3.989	.0001
OCTMDTRN	.000277	4.3940E-05	1.939733	6.295	.0000
(Constant)	-.282918	.395738		-.715	.4747

Table 6B.3: Second stage regression of multiple–cropping (GCANCA (Supra-Ricardian Model, 1970/71 through 1987/88)

Multiple R	.75632
R Square	.57202
Adjusted R Square	.56763
Standard Error	.13308

Analysis of Variance:

	DF	Sum of Squares	Mean Square
Regression	46	106.25928	2.3099844
Residuals	4489	79.50351	.0177107

F = 130.42845 Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
GCANCA57	.377395	.072195	.273130	5.227	.0000
WHYVNEW	.233151	.037748	.284436	6.177	.0000
NIANCA	.186687	.085350	.218962	2.187	.0288
DMSLP1	-.222332	.079963	-.537994	-2.780	.0055
DMSLP2	-.263840	.077798	-.547231	-3.391	.0007
DMSLP3	-.309631	.096053	-.502036	-3.224	.0013
DMSLP4	.003765	.102212	.003904	.037	.9706
DMS03	-.065678	.031961	-.059353	-2.055	.0399
DMS04	-.018027	.018577	-.017137	-.970	.3319
DMS05	.008785	.009415	.014616	.933	.3508
DMS06	.047887	.010892	.070935	4.397	.0000
DMS07	-.003753	.011360	-.004940	-.330	.7411
DMS08	-.106929	.020690	-.137485	-5.168	.0000

Table 6B.3: Second stage regression of multiple–cropping (GCANCA) (cont.)

Variable	B	SE B	Beta	T	Sig T
DMS10	.031258	.028509	.019025	1.096	.2730
DMS11	-.132306	.022050	-.098226	-6.000	.0000
DMS12	.052284	.019974	.047249	2.618	.0089
DMS13	.005629	.032748	.004505	.172	.8635
DMS14	.015973	.016649	.014435	.959	.3374
DMS15	-.017206	.014650	-.023651	-1.174	.2403
DMS16	.001827	.009475	.004421	.193	.8471
DMS17	.069544	.027366	.036730	2.541	.0111
DMS18	.270371	.028586	.116828	9.458	.0000
DMS19	.028059	.008770	.057166	3.199	.0014
DMS20	-.008698	.026683	-.005294	-.326	.7445
DMS21	-.044489	.031543	-.035603	-1.410	.1585
JANMDT	.070836	.019834	1.277451	3.572	.0004
JANMDTSQ	-.002380	.000533	-1.607883	-4.462	.0000
JANRN	.001382	.001533	.088625	.901	.3676
JANRNSQ	6.27504887E-05	1.8917E-05	.222677	3.317	.0009
JANMDTRN	-.000316	7.5886E-05	-.356233	-4.162	.0000
APRMDT	-.023535	.037061	-.271876	-.635	.5254
APRMDTSQ	-5.23051397E-05	.000630	-.032299	-.083	.9339
APRRN	-.000348	.002880	-.038496	-.121	.9039
APRRNSQ	-3.44414657E-06	6.1910E-06	-.039713	-.556	.5780
APRMDTRN	6.22573446E-05	8.2954E-05	.181406	.751	.4530
JULMDT	.170149	.056273	2.114218	3.024	.0025
JULMDTSQ	-.003390	.000989	-2.216250	-3.427	.0006
JULRN	-.000296	.000236	-.339023	-1.254	.2097
JULRNSQ	1.11617210E-07	3.7958E-08	.235256	2.941	.0033
JULMDTRN	6.12137530E-06	7.5253E-06	.157442	.813	.4160
OCTMDT	-.070827	.053375	-.646389	-1.327	.1846
OCTMDTSQ	.001586	.000996	.691561	1.593	.1113
OCTRN	-.007233	.001545	-2.330586	-4.682	.0000
OCTRNSQ	-3.83635353E-06	1.0744E-06	-.296675	-3.571	.0004
OCTMDTRN	.000309	6.3457E-05	2.639487	4.862	.0000
(Constant)	-.117862	.503849		-.234	.8151

Table 6B.4: Second Stage Regression of Irrigation Intensity (NIANCA)
(Supra-Ricardian Model, 1970/71 through 1987/88)

Multiple R	.91081
R Square	.82957
Adjusted R Square	.82774
Standard Error	.09001

Analysis of Variance:

	DF	Sum of Squares	Mean Square
Regression	48	176.93205	3.6860843
Residuals	4487	36.35033	.0081013

F = 455.00160 Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
IRR57	.607678	.039646	.455961	15.328	.0000
WHYVNEW	.324140	.013507	.337153	23.998	.0000
DMSLP1	.000940	.056591	.001940	.017	.9867
DMSLP2	-.121120	.060933	-.214187	-1.988	.0469
DMSLP3	-.133937	.064869	-.185156	-2.065	.0390
DMSLP4	.092177	.093152	.081502	.990	.3225
DMAQ1	.011689	.007550	.014998	1.548	.1216
DMAQ2	-.016622	.009135	-.031045	-1.820	.0689
DMAQ3	.031595	.008186	.036257	3.860	.0001
DMS03	-.090025	.030794	-.069365	-2.923	.0035
DMS04	-.054744	.016915	-.044371	-3.236	.0012
DMS05	-.004834	.006798	-.006856	-.711	.4771
DMS06	.016641	.007905	.021017	2.105	.0353
DMS07	-.027274	.009410	-.030609	-2.898	.0038
DMS08	-.043401	.014476	-.047578	-2.998	.0027
DMS09	-.046483	.011528	-.029423	-4.032	.0001
DMS10	-.042864	.021094	-.022243	-2.032	.0422
DMS11	-.022515	.017738	-.014252	-1.269	.2044
DMS12	-.131475	.014065	-.101301	-9.348	.0000
DMS13	.193763	.016890	.132206	11.472	.0000
DMS14	.056663	.011440	.043659	4.953	.0000
DMS15	.041244	.007509	.048337	5.492	.0000
DMS16	-.018724	.007442	-.038629	-2.516	.0119
DMS17	.058669	.022247	.026419	2.637	.0084
DMS18	.069127	.020466	.025467	3.378	.0007
DMS19	.005167	.007203	.008975	.717	.4732
DMS20	.022416	.023211	.011632	.966	.3342
DMS21	-.047832	.023625	-.032636	-2.025	.0430
JANMDT	-.075087	.014990	-1.154514	-5.009	.0000
JANMDTSQ	.001802	.000428	1.037849	4.205	.0000
JANRN	.002441	.000963	.133489	2.535	.0113

Table 6B.4: Second stage regression of irrigation intensity (NIANCA) (cont.)

Variable	B	SE B	Beta	T	Sig T
JANRNSQ	-4.40948615E-05	1.6107E-05	-.133411	-2.738	.0062
JANMDTRN	-2.34731078E-05	5.1270E-05	-.022571	-.458	.6471
APRMDT	.203175	.026003	2.001085	7.814	.0000
APRMDTSQ	-.003398	.000446	-1.789259	-7.628	.0000
APRRN	.001231	.002390	.116163	.515	.6066
APRRNSQ	-1.62990113E-05	5.4190E-06	-.160236	-3.008	.0026
APRMDTRN	-4.44743028E-05	6.5099E-05	-.110488	-.683	.4945
JULMDT	-.295957	.039746	-3.135410	-7.446	.0000
JULMDTSQ	.005195	.000707	2.896080	7.352	.0000
JULRN	-.001103	.000162	-1.077133	-6.798	.0000
JULRNSQ	1.38994064E-07	2.8499E-08	.249777	4.877	.0000
JULMDTRN	3.17318491E-05	5.0643E-06	.695845	6.266	.0000
OCTMDT	.082512	.040323	.642036	2.046	.0408
OCTMDTSQ	-.001284	.000766	-.477208	-1.677	.0937
OCTRN	.003635	.001313	.998629	2.769	.0056
OCTRNSQ	-8.48787353E-07	8.8791E-07	-.055964	-.956	.3392
OCTMDTRN	-.000134	5.4693E-05	-.979306	-2.455	.0141
(Constant)	.824730	.370357		2.227	.0260

Table 6B.5: F-Tests of exclusion of groups of variables

Excluded Variables	WHYV Regression	GCANCA Regression	NIANCA Regression
Temperature (M = 12)	F = 7.64521	F = 26.55391	F = 141.65357
Rainfall (M = 12)	F = 48.33569	F = 870.91645	F = 482.25801
Temperature & Rain (M = 20)	F = 18.59580	F = 16.58001	F = 130.18181

Note: Entries in Table 6B.5 are the F-statistics on the null hypotheses that the excluded variables specified in the left column do not influence the given technology/infrastructure variable. Depending upon the number of variables excluded in each group (given as M = i in the left column), the degrees of freedom of these F-tests range from 12 to 20 for the numerator and more than 4000 for the denominator; thus the 5% critical value of the F statistic is about 1.83; the 1% critical value is about 2.32.

Table 6B.6: Regression of the logarithm of net revenue (LNOFPKRE)
(Supra-Ricardian Model, 1970/71 through 1987/88)

Multiple R	.78082	R Square	.60968
Adjusted R Square	.59977	Standard Error	11.27194

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	100	781161.51146	7811.61511
Residual	3936	500094.70342	127.05658

F = 61.48139 Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
DMS03	.056995	.053022	.015449	1.075	.2825
DMS04	-.022639	.051602	-.005374	-.439	.6609
DMS05	-.136949	.039221	-.069474	-3.492	.0005
DMS06	-.137941	.040012	-.059337	-3.448	.0006
DMS07	-.002828	.040420	-9.040E-04	-.070	.9442
DMS08	.215560	.082023	.064469	2.628	.0086
DMS09	-.229059	.070459	-.052726	-3.251	.0012
DMS10	-.721042	.116297	-.110921	-6.200	.0000
DMS11	-.266854	.085911	-.052064	-3.106	.0019
DMS12	-.408711	.074279	-.128383	-5.502	.0000
DMS13	.726649	.114239	.110821	6.361	.0000
DMS14	-.306930	.072960	-.067544	-4.207	.0000
DMS15	.090879	.057281	.027618	1.587	.1127
DMS16	-.072123	.035097	-.043765	-2.055	.0399
DMS17	-.378172	.075430	-.058659	-5.014	.0000
DMS18	.181294	.132379	.022327	1.370	.1709
DMS19	-.127367	.037370	-.064565	-3.408	.0007
DMS20	-.230053	.080763	-.034807	-2.848	.0044
DMS21	-.415604	.104479	-.081832	-3.978	.0001
DMPH5	-.087309	.044646	-.042833	-1.956	.0506
DMPH6	-.082979	.039210	-.041612	-2.116	.0344
DMPH8	-.189117	.038805	-.110127	-4.873	.0000
DMPH9	-.351368	.044711	-.162234	-7.859	.0000
JANMDT	.127274	.084063	.569203	1.514	.1301
JANMDTSQ	-.003552	.002651	-.605100	-1.340	.1805
JANRN	.059188	.010767	.879678	5.497	.0000
JANRNSQ	.001392	2.4704E-04	1.002708	5.634	.0000
JANMDTRN	-.004232	5.2131E-04	-1.208540	-8.119	.0000
APRMDT	-.165682	.153778	-.407409	-1.077	.2814
APRMDTSQ	.001998	.003222	.277708	.620	.5352
APRRN	.033379	.012428	.810168	2.686	.0073
APRRNSQ	-2.42956E-04	8.4262E-05	-.513442	-2.883	.0040
APRMDTRN	-4.16256E-04	3.6987E-04	-.287228	-1.125	.2605
JULMDT	.393804	.204485	1.173100	1.926	.0542
JULMDTSQ	.007152	.003604	1.157598	1.985	.0473
JULRN	.005808	.001133	1.637535	5.125	.0000

Table 6B.6: Regression of the logarithm of net revenue (LNOFPKRE) (cont.)

Variable	B	SE B	Beta	T	Sig
TJULRNSQ	3.02613E-06	1.3168E-06	1.768303	2.298	.0216
JULMDTRN	-2.18016E-04	3.8814E-05	-1.330956	-5.617	.0000
OCTMDT	.830156	.225847	1.572793	3.676	.0002
OCTMDTSQ	-.030153	.005132	-2.846942	-5.875	.0000
OCTRN	-.029832	.006642	-2.353529	-4.491	.0000
OCTRNSQ	3.71860E-05	1.0508E-05	.690590	3.539	.0004
OCTMDTRN	.001230	2.5186E-04	2.617094	4.885	.0000
JURNCV	.307770	.084846	.081715	3.627	.0003
JARNCV	.550359	.081982	.122917	6.713	.0000
JUNERAIN	2.30215E-05	1.2469E-04	.003477	.185	.8535
JUAURAIN	2.34096E-04	7.7756E-05	.085834	3.011	.0026
YEARRAIN	3.95782E-05	5.6573E-05	.023636	.700	.4842
DMSEA	.044959	.060905	.018225	.738	.4605
DMSEANEI	.131669	.039196	.058391	3.359	.0008
LNCSTCLT	.088365	.025583	.098499	3.454	.0006
LNCSTBUL	-.045104	.020480	-.051291	-2.202	.0277
RELWAGEK	-.105498	.026671	-.076487	-3.955	.0001
GCNCPRDX	2.320813	1.513060	.508790	1.534	.1251
EXT	-.001490	.004236	-.010294	-.352	.7250
WHYVPRDX	1.737278	1.022308	.493028	1.699	.0893
STRES5	.002314	2.8632E-04	.118217	8.080	.0000
NINCPRDX	-3.796297	1.417844	-1.032130	-2.678	.0074
JAMDSQHX	6.47420E-04	.001463	.065089	.443	.6581
JAMDSQGX	-.001685	.001714	-.313307	-.983	.3256
JAMDSQNX	.005567	.001817	.534606	3.064	.0022
APMDSQHX	-.004586	.001154	-1.092933	-3.973	.0001
APMDSQGX	2.34319E-04	.002139	.049470	.110	.9128
APMDSQNX	.005238	.001680	1.187119	3.118	.0018
JUMDSQHX	.004363	.001201	1.155292	3.634	.0003
JUMDSQGX	-.015282	.001791	-4.702900	-8.532	.0000
JUMDSQNX	.012216	.001644	3.144438	7.430	.0000
OCMDSQHX	-5.29263E-04	.002051	-.103950	-.258	.7964
OCMDSQGX	.016836	.003339	3.135448	5.043	.0000
OCMDSQNX	-.019089	.002955	-3.576864	-6.459	.0000
JARNSQHX	-1.11001E-04	1.5172E-04	-.049372	-.732	.4644
JARNSQGX	-8.28585E-04	2.4846E-04	-.772173	-3.335	.0009
JARNSQNX	-6.41624E-05	1.7826E-04	-.026867	-.360	.7189
APRNSQHX	5.71100E-06	7.5223E-05	.003227	.076	.9395
APRNSQGX	7.29124E-05	6.0648E-05	.200157	1.202	.2293
APRNSQNX	1.01295E-04	8.6140E-05	.052133	1.176	.2397
JURNSQHX	4.64521E-07	2.7251E-07	.053208	1.705	.0883
JURNSQGX	-3.32555E-06	1.2816E-06	-2.173201	-2.595	.0095
JURNSQNX	1.54934E-06	1.2672E-06	.134677	1.223	.2215
OCRNSQHX	-5.61231E-06	7.0628E-06	-.047969	-.795	.4269
OCRNSQGX	-3.74039E-05	9.4436E-06	-.904898	-3.961	.0001
OCRNSQNX	6.04045E-06	1.1142E-05	.056100	.542	.5878
ALT	1.81160E-04	1.3479E-04	.057730	1.344	.1790
DMYR71	.002039	.047913	5.828E-04	.043	.9661

Table 6B.6: Regression of the logarithm of net revenue (LNOFPKRE) (cont.)

Variable	B	SE B	Beta	T	Sig T
DMYR72	.120618	.049685	.034072	2.428	.0152
DMYR73	.577850	.049345	.166707	11.711	.0000
DMYR74	.620182	.050498	.175841	12.281	.0000
DMYR75	.488680	.049782	.140511	9.816	.0000
DMYR76	.339487	.051720	.096642	6.564	.0000
DMYR77	.504268	.052922	.145091	9.528	.0000
DMYR78	.397011	.053030	.114114	7.487	.0000
DMYR79	.199352	.055501	.056621	3.592	.0003
DMYR80	.576301	.057131	.164354	10.087	.0000
DMYR81	.555922	.061011	.159137	9.112	.0000
DMYR82	.585726	.065561	.167167	8.934	.0000
DMYR83	.783142	.069882	.227598	11.207	.0000
DMYR84	.682641	.072775	.191490	9.380	.0000
DMYR85	.648057	.074738	.180197	8.671	.0000
DMYR86	.574351	.077147	.158605	7.445	.0000
DMYR87	.700880	.079386	.186410	8.829	.0000
(Constant)	-12.005503	3.161783		-3.797	.0001

Table 6B.7: F-Tests of exclusion of groups of variables - LNOFPKRE regression

Excluded Variables	F-Statistic
Edaphic (M = 23)	F = 20.17573
Temperature (M = 12)	F = 20.89333
Temperature and Interactions (M = 24)	F = 16.13143
Rainfall (M = 12)	F = 23.12331
Rainfall and Interactions (M = 24)	F = 14.71552
Temperature & Rain (M = 20)	F = 21.46841
Temperature, Rain and Interactions (M = 44)	F = 15.71037
Technology and Related Infrastructure (M = 30)	F = 24.89907
Technology – Climate Interactions (M = 24)	F = 12.51359
Year Dummies (M = 17)	F = 26.34394

Note: Entries in Table 6B.7 are the F-statistics on the null hypotheses that the excluded variables specified in the left column do not influence Net Revenue. Depending upon the number of variables excluded in each group (given as M = i in the left column), the degrees of freedom of these F-tests are anywhere from 12 to 44 for the numerator and more than 4000 for the denominator; thus the 5% critical value of the F statistic would range from about 1.5 to about 2.1; correspondingly, the 1% critical value of the F statistic would range from about 1.8 to about 2.8.

Appendix C: Alternate Estimates of Climate Effects Utilitizing Seasonal Climate Variables

Introduction

An earlier stage of work on this project led to the development of alternative specifications of the normal climate variables. This specification differed in two dimensions from that reported in the body of this paper (which was designed to conform to the simple "Ricardian" estimates of Sanghi *et al.*, 1997). The first was to include maximum temperatures and the maximum - minimum temperature range. The second was to utilize cropping season weights to define "seasonal" normal temperature and climate variables.

The seasonal weights are open to the criticism that they may be "endogenous"; i.e., that they reflect farmers' behavioral responses to climate. In the simple Ricardian estimates of Sanghi *et al.* where technology is ignored the strategy of using four arbitrary months to characterize climate worked reasonably well. When the model is expanded to incorporate technology the four-month specification appears to be less stable than the seasonal specification. Hence we report results here for comparative purposes.

The advantage of the seasonal weights is that we do not expect all months to have equal effects. For example, many parts of India ahve single cropping seasons - wet versus dry or warm versus cool, etc. A single linear and quadratic term (i.e., with only two coefficients) may not capture the differences between cropping seasons which vary by region. The question of the endogeneity of these weights is really a question of profit-maximizing behavior of farmers. If cropping seasons are optimizing responses to prices, technology and normal climate they can be regarded to be functions of exogenous variables.

(Normal) Temperature Range Variables

Most studies of the climate impact on agriculture use only one temperature variable, measured over several months. Though often not specified precisely, it is usually (and incorrectly) termed an "average" temperature: incorrectly, because it is almost always constructed as the average of (thus the midpoint between) the monthly normal minimum temperature and the monthly normal maximum temperature, rather than a true average of all the normal temperatures experienced at all hours through the month. But even if the average were constructed properly, this practice of collapsing all temperature data into a single variable discards very useful information, and will almost certainly render simulations of responses to long-term climate change inferred from cross-sectional differences in so-called average temperatures biased and unstable.

In the study reported in this Appendix we use two normal temperature variables instead of only one: the normal maximum temperature and normal temperature range, which is defined as the difference between the normal maximum and minimum temperatures. Agronomically, if a change in temperature is going to harm Indian (crop) agriculture, the maximum temperature will be the culprit, and distinctly not the temperature midpoint. And the difference between maximum temperature and the so-called average temperature can be so large and so variable in parts of India that only small differences in so-called average temperature might appear, masking substantial differences in the maximum temperature. So it is important that maximum temperature be included in the regression equations.

To put the point a different way: the temperature midpoint, or the so-called average temperature, varies from 12.8344 (in the maturation season, in Rajasthan) to 31.7237 (in the sowing season, in Orissa). The correlation between state-wise maximum temperature and temperature midpoint is 0.96, which might seem to indicate that either variable can interchangeably be used. But there is a wide distribution of normal maximum temperatures corresponding to the districts and seasons (or months) whose temperature range falls in any interval. Those ranges of normal maximum temperatures overlap substantially: Given that, in the current cross-section, District B's temperature midpoint is one degree higher than District A's temperature midpoint, the maximum temperature in District B could be several degrees higher or even lower than the maximum temperature in District A, and simply knowing the difference in their temperature midpoints tells us nothing about any differences in their normal maximum temperatures. In fact, many districts with higher temperature midpoints than others have a lower maximum temperature, and thus are under less current temperature stress.

We want to simulate (the effects of, and farmers' responses to) an increase in temperature over time by looking at current cross-section differences in temperature. As explained above, the appropriate temperature variable is maximum temperature, but we cannot infer much of anything about cross-sectional (let alone future!) differences in maximum temperature from cross-sectional differences in temperature midpoint. Thus using cross-section differences in temperature midpoints to infer differences in (either current or future) maximum temperatures is biased and imprecise, at best: the maximum temperature itself must be included in the regression equation and in all the resulting effects computations, so that current cross-section differences in maximum temperatures (as well as farmers' current responses to those cross-sectional differences) can be used, directly and validly, to simulate long-term changes in maximum temperature (and farmers' responses over time to any such long-term climate changes).

For our second temperature variable we choose to use temperature range, rather than minimum temperature (which would convey the same information), because the former is a more appropriate framework within which to consider the effects of temperature changes.

Few if any global climate change scenarios explicitly treat the issue of what would happen to minimum temperatures; in the absence of any compelling reason to believe otherwise, it is reasonable to assume that global climate change would cause both the minimum and the maximum temperatures to increase by the same amount[25]. This implies that the temperature range would not change. Now in computing the impact of a temperature change, it makes no sense to have two terms each season -- both the minimum and the maximum temperatures -- changing in response to the single phenomenon that temperatures are rising. By casting the model in terms of the maximum temperature and the temperature range, we capture the increase in temperature, while we also maintain the richness of the data with two variables.

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[25] Or possibly by the same proportion, but the difference between saying that they both increase by one degree Celsius vs. that they both increase by, say, three percent is quite small.

SEASONAL CLIMATE VARIABLES

One important transformation in the data is the creation of seasonal climate variables. Most Ricardian studies, including all those in this volume and the Supra-Ricardian study reported in the body of this paper, choose four evenly spaced months for climate variables: often, January, April, July and October[26]. The stated intent is to capture seasonal climatic effects throughout the year, although in some cases those may be the only four months available[27].

Data for the important climate variables in India -- maximum temperature, temperature range, rainfall, and cloud cover -- are available for each of the twelve months. The values of these variables within any given month differ widely across India, as do the cropping patterns and cropping seasons. That is to say, the planting season for a given crop in one state may differ by four or five months from the planting season for the same crop in another state; further, the sowing (or harvesting) season for one crop in one state may differ by many months from the sowing (or harvesting) season of another crop in that state[28]. Rather than arbitrarily choose four months from the twelve available, and rather than lose the important information which cropping calendars provide, this study is based on seasonal climate variables rather than on monthly climate variables.

Three climatic seasons are defined: sowing, maturation, and harvesting. The sowing and harvesting seasons for a district are a weighted average of the sowing and harvesting seasons for the five major food crops: rice, wheat, maize, jowar and bajra. For example, to construct the sowing season maximum temperature variable for a district, we first computed the average normal maximum temperature, in that district, during the months of the rice sowing season in that district's state. We did the same for the wheat sowing season, for the maize sowing season, and for jowar and bajra. Then we constructed a weighted average of the five crop-based sowing season maximum temperatures, using the share of area under each crop as weights. The procedure for the harvest season maximum temperature variable was the same, using of course each state's harvest months instead. And the procedures for temperature range, rainfall and oktas were similar as well. The maturation season is defined as the middle third of the interval from the beginning of the sowing season to the end of the harvesting season.

Appendix D contains comparisons of regressions using the seasonal climate variables here defined, *vs.* regressions equivalent except for the use of four monthly climate variables. The comparisons are semi-Ricardian: no technology or infrastructural variables appear. The seasonal specifications are superior not only because of the theoretical reasons discussed above (namely, that the seasonal climate variables capture crop calendar information, and that the seasonal specification includes months appropriate for each given district rather than four arbitrarily chosen months imposed uniformly across the nation) but also as seen in Appendix D the seasonal

[26] For which it could be argued, for example in North America, that in April the planting might begin, that in July nearly every summer crop is growing, that by October the harvesting should be well underway, and that December represents either the maturation experience of winter crops or the effects of frost on weed and insect control or of snow on next season's soil moisture content.

[27] Even if they are the only months available, the use for the entire area of the study of only four months, spaced over the year, may serve the purpose well if the entire area of the study is sufficiently homogeneous in terms of cropping seasons.

[28] See Appendix D for a table displaying the cropping seasons of the major crops in each State.

specification is superior in terms of the consistency of the computed climate effects (especially the temperature effects) across states.

There is still considerable cross-sectional variation in the seasonal climate variables, especially rainfall; the state-wise means of the six major seasonal climate variables are displayed below in Table 6C.1a (normal maximum temperature and normal rainfall) and in Table 6C.1b (normal temperature range and normal oktas of cloud cover).

Table 6C.1a: Means of seasonal climate variables: maximum temperature and rainfall

	Seasonal Maximum Temperature			Seasonal Rainfall		
	SOWXT1	MATXT1	HARXT1	SOWRN1	MATRN1	HARRN1
India	31.9168	25.9508	28.1703	125.4206	130.0125	67.7689
Andhra Pradesh	34.8194	33.3519	32.8285	79.4097	94.0577	138.0382
Haryana	32.9257	18.5846	25.0597	70.2200	46.8836	16.2340
Madhya Pradesh	30.9787	27.7285	30.0951	139.0140	113.4026	39.0939
Maharastra	27.8751	23.2293	26.3539	282.7803	128.2241	16.7087
Karnataka	28.4505	24.5282	26.4117	213.9141	183.5560	71.9228
Punjab	31.5863	26.2758	34.7293	49.0225	69.2831	20.7722
Tamil Nadu	32.1970	27.9427	26.5515	102.0830	126.6152	100.6109
Uttar Pradesh	31.7724	27.7984	30.6421	64.0392	103.1376	42.5272
Bihar	31.8867	28.7979	32.7372	142.0795	235.3772	184.8334
Gujarat	31.9103	19.5360	21.2827	138.8117	60.6682	6.5967
Rajasthan	34.3675	15.7135	17.8448	68.2971	30.5153	6.7726
Orissa	36.9648	30.4839	31.0263	127.9972	328.0940	177.0605
West Bengal	33.5293	31.3290	30.4340	120.3099	285.3750	198.5125

Estimates: Technology and Related Infrastructure

Recall that in the Supra-Ricardian framework we treat the three technology variables (the use of modern varieties, irrigation intensity and multiple-cropping) as endogenous variables, whose predicted values then contribute to the determination of net revenue per hectare.

In this Section we report estimates of the determinants of these variables, in a two-stage least squares framework. Then in the next Section we report computed climate effects on technology and related infrastructure.

Table 6C.1b: Means of seasonal climate variables: temperature range and Oktas

	Seasonal Temperature Range			Seasonal Cloud Cover (Oktas)		
	SOWTR 1	MATTR 1	HARTR 1	SOWOK1	MATOK 1	HAROK 1
India	10.2370	8.5968	10.9071	4.3093	4.1253	2.9320
Andhra Pradesh	10.0475	9.7746	8.3156	4.6233	5.0553	6.0997
Haryana	12.9440	8.9384	10.4906	2.5807	2.0279	1.1753
Madhya Pradesh	10.3878	11.1489	14.4372	4.7274	3.9616	2.5719
Maharashtra	7.4549	7.5450	12.2927	6.0890	4.1782	2.0043
Karnataka	7.9985	6.7725	9.1874	6.2053	5.8455	4.2788
Punjab	14.7541	12.5580	15.8348	1.9663	2.8732	1.6549
Tamil Nadu	8.3840	7.2662	7.4497	5.7079	5.0726	4.2446
Uttar Pradesh	11.8617	10.6232	13.0831	2.5260	3.4288	1.8594
Bihar	9.5451	7.4634	8.8069	4.1308	5.3137	4.8124
Gujarat	8.0186	6.3123	10.2572	4.8153	2.6433	1.0618
Rajasthan	11.2709	5.7583	8.1286	3.8902	1.9670	1.1171
Orissa	10.4822	5.7740	7.4696	5.2171	6.9747	5.4721
West Bengal	11.1471	7.0478	7.9376	3.7219	5.9979	4.7859

HYV – MULTIPLE CROPPING – IRRIGATION SYSTEM

The proportion of area sown to modern varieties (WHYV), a measure of multiple-cropping (GCANCA), and irrigation intensity (NIANCA) were estimated by two-stage least squares. Table 6C.2 displays the variables used as instruments in the 2SLS system; an asterisk following a variable name denotes that that variable also appears in one or more second-stage regression equations, and/or the net revenue equation. These instruments include fundamental climatic and edaphic variables, as well as two technology variables and a number of price ratios proxying institutional factors.

Tables 6C.3 through 6C.5 then display the regression results from the second stage; WHYV in Table 6C.3, GCANCA in Table 6C.4, and NIANCA in Table 6C.5. A number of striking results emerge.

First is the degree to which this system captures the modeled behavior. Grossly, all three second-stage regressions have highly significant F-statistics, and adjusted R^2s which range from 0.59 to 0.85. For each of the three regressions, we tested the null hypotheses that the rainfall variables taken as a group did not significantly influence the technology variables, that the temperature variables taken as a group did not significantly influence the technology variables, and that the climate variables (that is, the temperature and rainfall variables combined) taken as a group did not significantly influence the technology variables. The results of the F-tests of sets of excluded variables are reported in Table 6C.6. All three of the null hypotheses were rejected in all three of these regressions: as groups, the climate variables do significantly influence the adoption of modern varieties, the extent of multiple-cropping, and irrigation intensity.

But even more important than the general goodness-of-fit of these regression equations, and the significance of groups of variables, are the patterns revealed within each equation.

The coefficients on six or seven of the seven agroeconomic region dummies, and on either twelve or fifteen of the nineteen soil type dummies, are significant[29]. Slope significantly influences irrigation intensity[30] but not multiple-cropping. And irrigation intensity tends to be higher in districts above aquifers which are geologically thickest[31].

The second-stage variables exercise an important influence on each other: the coefficients of both GCANCA and NIANCA on WHYV are significantly positive; as are the coefficients of both WHYV and NIANCA on GCANCA and the coefficient of WHYV on NIANCA. That is to say, the adoption of modern high-yielding varieties, multiple-cropping and irrigation are mutually-reinforcing.

The adoption of modern varieties also responds favorably to greater extension activity; perhaps surprisingly, though, additional state-level agricultural research does not significantly increase the adoption of modern varieties. There is considerable inertia in this behavior: both the extent of multiple-cropping and irrigation intensity are highest in those districts in which such activity was largest in 1957[32].

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[29] In neither the WHYV nor the NIANCA equation is the coefficient on AGROB6 significantly different from zero; once the coefficient has a negative sign, once positive.

[30] This may reflect the importance of drainage to avoid waterlogging or soil salinity; it may reflect the geological requirements for proper functioning of a canal system.

[31] This does not measure the annual water depth within the aquifer, but rather a long term geological potential. Farmers may respond to this in their cropping choices; farmers and probably governments also respond in their irrigation investments.

[32] There is no related variable for the use of modern varieties, because no such modern variety existed before the onset of the Green Revolution in the middle 1960s.

Table 6C.2: List of instruments for WHYV, GCANCA and NIANCA
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

	Variable Name	Description	Mean	Standard Deviation
Edaphic Variables				
*	DMSnn	Soil Type Dummies	--	--
	DMTSn	Topsoil Depth Dummies		
	STRA	Storie A: character of the soil profile	82.48	4.36
	STRB	Storie B: topography, texture, structure	88.39	7.23
	STRC	Storie C: salinity, climatic suitability, erodability	82.48	6.49
Geographic Variables				
*	AGROBn	Agroeconomic Region Dummies	--	--
	DMAQn	Aquifer Depth Dummies	--	--
Institutional Variables				
	PRWTWG	Price Ratio: Wheat to Wage	28.52	14.41
	PRRCWG	Price Ratio: Rice to Wage	28.60	17.76
	PRMZWG	Price Ratio: Maize to Wage	20.86	9.77
	PRJWWG	Price Ratio: Jowar to Wage	19.63	13.19
	PRBJWG	Price Ratio: Bajra to Wage	19.09	12.34
	PRFRWG	Price Ratio: Fertilizer to Wage	683.69	301.06
	PRTRWG	Price Ratio: Tractor to Wage	2309.40	811.41
	POPDEN1	Population Density:	3948.41	2717.01
Technology Variables				
	PRIVRES	Private Research	247.94	187.08
	LITERACY	Male Rural Literacy rate	.37	.11
Climate Variables		(as defined in Appendix B and in Table 6B.1)		
*	SOWXT1			
*	SOWXT1SQ			
*	SOWRN1			
*	SOWRN1SQ			
*	SOWXT1RN			
*	MATXT1			
*	MATXT1SQ			
*	MATRN1			
*	MATRN1SQ			
*	MATXT1RN			
*	HARXT1			
*	HARXT1SQ			
*	HARRN1			
*	HARRN1SQ			
*	HARXT1RN			

Table 6C.3: Second stage regression of modern varieties (WHYV)
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

Multiple R	.84331
R Square	.71118
Adjusted R Square	.70838
Standard Error	.12904

Analysis of Variance:

	DF	Sum of Squares	Mean Square
Regression	45	190.60630	4.2356956
Residuals	4649	77.40926	.0166507

F = 254.38492 Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
GCANCA	.307627	.043664	.253495	7.045	.0000
NIANCA	.680667	.032664	.659120	20.838	.0000
STRES5	.000139	.000152	.024447	.912	.3617
EXT	.011441	.000677	.260217	16.903	.0000
AGROB1	.033334	.014025	.030187	2.377	.0175
AGROB2	-.125362	.030126	-.100506	-4.161	.0000
AGROB3	-.058120	.013451	-.071144	-4.321	.0000
AGROB4	-.057650	.011483	-.115212	-5.021	.0000
AGROB5	.062355	.018212	.060123	3.424	.0006
AGROB6	-.012877	.013247	-.019376	-.972	.3311
AGROB7	-.071478	.021040	-.057726	-3.397	.0007
DMS03	.034400	.013131	.026541	2.620	.0088
DMS04	-.010029	.011680	-.007738	-.859	.3906
DMS05	.076805	.007870	.105194	9.759	.0000
DMS06	.031945	.008021	.039103	3.983	.0001
DMS07	.020784	.009085	.022222	2.288	.0222
DMS08	-.026146	.012428	-.027304	-2.104	.0354
DMS09	-.006688	.014582	-.004029	-.459	.6465
DMS10	-.002967	.023812	-.001465	-.125	.9008
DMS11	.082018	.021682	.049407	3.783	.0002
DMS12	-.020910	.013926	-.016764	-1.501	.1333
DMS13	-.132632	.015649	-.086129	-8.475	.0000
DMS14	-.083213	.013004	-.061030	-6.399	.0000
DMS15	-.058156	.010260	-.064943	-5.668	.0000
DMS16	.069466	.007234	.138456	9.603	.0000
DMS17	.015308	.020943	.006559	.731	.4649
DMS18	-.213001	.025426	-.074659	-8.377	.0000
DMS19	-.042767	.008908	-.072323	-4.801	.0000
DMS20	.119588	.017363	.059050	6.888	.0000
DMS21	.247663	.020872	.160828	11.866	.0000

Table 6C.3: Second stage regression of modern varieties (WHYV) (cont.)
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

Variable	B	SE B	Beta	T	Sig T
SOWXT1	-.047284	.009889	-.571475	-4.781	.0000
SOWXT1SQ	.000729	.000153	.548439	4.778	.0000
SOWRN1	-.000342	.000301	-.210549	-1.138	.2552
SOWRN1SQ	-1.66367627E-07	6.9280E-08	-.122731	-2.401	.0164
SOWXT1RN	2.98864445E-05	8.4443E-06	.484225	3.539	.0004
MATXT1	.031145	.005044	.877787	6.174	.0000
MATXT1SQ	-.000489	8.1288E-05	-.597553	-6.011	.0000
MATRN1	-.000267	.000285	-.142633	-.938	.3481
MATRN1SQ	1.38146584E-07	9.2523E-08	.046088	1.493	.1355
MATXT1RN	1.53320826E-06	9.2947E-06	.024058	.165	.8690
HARXT1	-.050837	.005432	-1.399910	-9.359	.0000
HARXT1SQ	.000937	8.4973E-05	1.124229	11.024	.0000
HARRN1	.000602	.000372	.210397	1.619	.1056
HARRN1SQ	-1.12173086E-07	2.4333E-07	-.014344	-.461	.6448
HARXT1RN	-1.95967163E-05	1.0734E-05	-.207222	-1.826	.0680
(Constant)	.522724	.166049		3.148	.0017

Table 6C.4: Second stage regression of multiple cropping (GCANCA)
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

Multiple R	.77336
R Square	.59809
Adjusted R Square	.59394
Standard Error	.12441

Analysis of Variance:

	DF	Sum of Squares	Mean Square
Regression	48	107.01720	2.2295251
Residuals	4646	71.91493	.0154789

F = 144.03649 Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
GCANCA57	.381691	.036234	.277712	10.534	.0000
WHYVNEW	.275614	.025884	.334468	10.648	.0000
NIANCA	.098844	.040834	.116154	2.421	.0155
DMSLP1	.071175	.078187	.172870	.910	.3627

Table 6C.4: Second stage regression of multiple cropping (GCANCA) (cont.)

Variable	B	SE B	Beta	T	Sig T
DMSLP2	.020761	.076208	.043331	.272	.7853
DMSLP3	.033498	.078041	.055677	.429	.6678
DMSLP4	.170439	.109421	.180864	1.558	.1194
DMS03	-.015676	.015219	-.014677	-1.030	.3031
DMS04	.036112	.015209	.033812	2.374	.0176
DMS05	-.021918	.010062	-.036430	-2.178	.0294
DMS06	.001582	.009056	.002350	.175	.8613
DMS07	-.029221	.009996	-.037913	-2.923	.0035
DMS08	-.058410	.015207	-.074020	-3.841	.0001
DMS09	-.050500	.014687	-.036917	-3.439	.0006
DMS10	.095620	.023465	.057297	4.075	.0000
DMS11	.048599	.027299	.035527	1.780	.0751
DMS12	-.002948	.015659	-.002868	-.188	.8507
DMS13	.091849	.016475	.072381	5.575	.0000
DMS14	.032304	.013171	.028751	2.453	.0142
DMS15	-.025041	.010672	-.033934	-2.346	.0190
DMS16	-.001320	.008165	-.003192	-.162	.8716
DMS17	-.021727	.022379	-.011297	-.971	.3316
DMS18	.213185	.025692	.090680	8.298	.0000
DMS19	.054043	.008284	.110909	6.524	.0000
DMS20	-.016090	.020713	-.009641	-.777	.4373
DMS21	-.041430	.021991	-.032649	-1.884	.0596
AGROB1	-.054427	.014016	-.059815	-3.883	.0001
AGROB2	-.151715	.030114	-.147608	-5.038	.0000
AGROB3	-.040815	.013362	-.060629	-3.055	.0023
AGROB4	-.072686	.011229	-.176281	-6.473	.0000
AGROB5	-.214874	.014623	-.251425	-14.695	.0000
AGROB6	-.112961	.013604	-.206276	-8.303	.0000
AGROB7	-.108151	.024184	-.105994	-4.472	.0000
SOWXT1	.043482	.013748	.637744	3.163	.0016
SOWXT1SQ	-.000699	.000223	-.637951	-3.129	.0018
SOWRN1	-.000788	.000543	-.587800	-1.451	.1468
SOWRN1SQ	2.34341245E-07	1.2344E-07	.209791	1.898	.0577
SOWXT1RN	1.37449868E-05	1.5139E-05	.270253	.908	.3640
MATXT1	.000923	.005955	.031561	.155	.8769
MATXT1SQ	9.23301170E-06	.000101	.013703	.092	.9269
MATRN1	.001206	.000415	.781618	2.903	.0037
MATRN1SQ	-1.38682103E-07	8.8016E-08	-.056146	-1.576	.1152
MATXT1RN	-2.64236313E-05	1.3191E-05	-.503164	-2.003	.0452
HARXT1	-.010345	.006535	-.345695	-1.583	.1135
HARXT1SQ	.000200	.000108	.291898	1.854	.0638
HARRN1	-.000294	.000558	-.124585	-.527	.5984
HARRN1SQ	5.81148921E-07	2.5216E-07	.090181	2.305	.0212
HARXT1RN	-7.11900123E-06	1.7506E-05	-.091354	-.407	.6843
(Constant)	.145277	.176192		.825	.4097

Table 6C.5: Second stage regression of irrigation intensity
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

Multiple R	.92280
R Square	.85156
Adjusted R Square	.84996
Standard Error	.08526

Analysis of Variance:

	DF	Sum of Squares	Mean Square
Regression	50	193.66011	3.8732022
Residuals	4644	33.75719	.0072690

F = 532.83907 Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
IRR57	.745007	.024082	.555960	30.937	.0000
WHYVNEW	.320394	.012394	.330868	25.851	.0000
DMSLP1	-.150492	.056412	-.311043	-2.668	.0077
DMSLP2	-.235273	.055060	-.417866	-4.273	.0000
DMSLP3	-.243622	.053418	-.344580	-4.561	.0000
DMSLP4	-.201977	.080731	-.182390	-2.502	.0124
DMAQ1	.010877	.006393	.014141	1.701	.0889
DMAQ2	.014509	.005800	.026799	2.501	.0124
DMAQ3	.036886	.007265	.042537	5.077	.0000
DMS03	-.019474	.011098	-.015516	-1.755	.0794
DMS04	-.029165	.010978	-.023238	-2.657	.0079
DMS05	-.029956	.007280	-.042370	-4.115	.0000
DMS06	.016773	.006453	.021202	2.599	.0094
DMS07	-.007098	.006890	-.007837	-1.030	.3030
DMS08	-.051066	.011035	-.055070	-4.628	.0000
DMS09	-.047315	.010345	-.029434	-4.573	.0000
DMS10	-.052963	.015832	-.027007	-3.345	.0008
DMS11	-.125462	.019036	-.078048	-6.591	.0000
DMS12	-.067498	.010703	-.055884	-6.306	.0000
DMS13	.083194	.010846	.055790	7.670	.0000
DMS14	.064895	.008689	.049152	7.468	.0000
DMS15	.043998	.007045	.050738	6.245	.0000
DMS16	-.020143	.005578	-.041460	-3.611	.0003
DMS17	.010536	.015530	.004662	.678	.4976
DMS18	.056925	.018037	.020605	3.156	.0016
DMS19	-.005673	.005783	-.009906	-.981	.3267
DMS20	-.016687	.014836	-.008509	-1.125	.2607

Table 6C.5: Second stage regression of irrigation intensity (cont.)

Variable	B	SE B	Beta	T	Sig T
DMS21	.020128	.015612	.013498	1.289	.1974
AGROB1	-.025563	.009554	-.023907	-2.676	.0075
AGROB2	.088847	.020363	.073560	4.363	.0000
AGROB3	.040550	.009240	.051260	4.389	.0000
AGROB4	.021023	.007540	.043387	2.788	.0053
AGROB5	-.036529	.010704	-.036373	-3.413	.0006
AGROB6	.007476	.009072	.011617	.824	.4100
AGROB7	.047768	.016626	.039839	2.873	.0041
SOWXT1	.036231	.009450	.452201	3.834	.0001
SOWXT1SQ	-.000604	.000152	-.469461	-3.967	.0001
SOWRN1	-.002409	.000352	-1.529429	-6.847	.0000
SOWRN1SQ	6.03110265E-07	7.8799E-08	.459464	7.654	.0000
SOWXT1RN	6.19190596E-05	9.9217E-06	1.036017	6.241	.0000
MATXT1	-.039183	.003710	-1.140457	-10.562	.0000
MATXT1SQ	.000594	6.3898E-05	.750042	9.294	.0000
MATRN1	.001392	.000269	.767824	5.184	.0000
MATRN1SQ	1.17076740E-07	6.0084E-08	.040336	1.949	.0514
MATXT1RN	-5.09914616E-05	8.5788E-06	-.826286	-5.944	.0000
HARXT1	.047641	.004131	1.354770	11.533	.0000
HARXT1SQ	-.000778	6.9216E-05	-.964553	-11.243	.0000
HARRN1	-.001426	.000378	-.514398	-3.776	.0002
HARRN1SQ	1.09153369E-07	1.7617E-07	.014414	.620	.5356
HARXT1RN	4.38773168E-05	1.1826E-05	.479140	3.710	.0002
(Constant)	-.344438	.120651		-2.855	.0043

Table 6C.6: F-Tests of exclusion of groups of variables
(Seasonal climate terms)

Excluded Variables	WHYV Regression	GCANCA Regression	NIANCA Regression
Temperature (M = 9)	F = 41.12268	F = 34.37395	F = 42.05588
Rainfall (M = 9)	F = 4.38067	F = 13.99238	F = 53.77791
Temperature and Rain (M = 15)	F = 28.24379	F = 31.86579	F = 42.88782

Note: Entries in Table 6C.6 are the F-statistics on the null hypotheses that the excluded variables specified in the left column do not influence the given technology/infrastructure variable. Depending upon the number of variables excluded in each group (given as M = i in the left column), the degrees of freedom of these F-tests range from 9 to 15 for the numerator and more than 4000 for the deno-minator; thus the 5% critical value of the F statistic is about 1.83; the 1% critical value is about 2.32.

The role of the climate variables in determining these three is especially interesting. Fifteen climate variables appear in each of these three equations, five for each of the three seasons: normal maximum temperature, normal maximum temperature squared, normal rainfall, normal rainfall squared, and the interaction of maximum normal temperature and normal rainfall. Of the fifteen, the coefficients of nine are significantly different from zero in the WHYV equation; the coefficients of seven are significantly different from zero in the GCANCA equation, and the coefficients of fourteen in the NIANCA equation. In both the WHYV and the NIANCA equations, which exhibit a better fit with the climate variables, one can see three important alternating patterns in the temperature variables: first, the sign on maximum maturation season temperature is the opposite of the sign on both maximum sowing season and maximum harvesting season temperature; further, the sign on each temperature squared term is the opposite of the sign on the same season's temperature term, denoting diminishing returns to the temperature effects; and third, the signs on the temperature terms in the WHYV equation are the opposite of the signs on the corresponding temperature terms in the NIANCA equation. (The computed net effect of temperature and rainfall on the adoption of modern varieties, multiple-cropping and irrigation are reported subsequently.)

CLIMATE CHANGE EFFECTS ON TECHNOLOGY AND INFRASTRUCTURE

Based on the regression results reported in the previous section, and the actual district-level values of the climate and technology variables, one can compute the predicted effects on high-yielding variety use, multiple cropping, and irrigation intensity of changes in normal temperature and rainfall. The motivation for these computations is the by-now familiar predictions of global warming; we make no effort to validate or calibrate the predicted changes, but merely use the familiar predictions to drive a simulation.

A number of possible values for temperature and rainfall change have been proposed; no scenario has received unanimous agreement. We predict the effects of a one degree Celsius temperature increase, and a three percent rainfall increase, values which some models predict could be achieved from a generation to a century from now. The impacts of different changes could easily be scaled. These predicted effects are presented in Table 6C.7 in which appear first the temperature effects on the adoption of modern varieties, the extent of multiple-cropping, and irrigation intensity. Next appear the rainfall effects on WHYV, GCANCA and NIANCA. Predicted impacts are computed for each district; they are presented in Table 6C.7 as state-wide and national averages[33].

[33] And see Appendix C, in which are displayed the temperature, rainfall and cloud cover effects by season, revealing interesting alternating patterns.

Table 6C.7: Climate effects on technology and related infrastructure
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

	Temperature			Rainfall		
	HYV	**GCA**	**NIA**	**HYV**	**GCA**	**NIA**
India	.0108	.0006	.0005	.0012	.0057	.0001
1:Andhra Pradesh	.0140	.0008	.0018	−.0005	−.0023	−.0006
2:Haryana	.0064	−.0009	−.0073	.0011	.0007	.0002
3:Madhya Pradesh	.0150	.0053	.0027	.0013	.0039	.0000
4:Maharashtra	.0281	.0108	.0187	.0061	.0459	.0017
5:Karnataka	.0154	.0059	.0104	.0025	.0159	.0004
6:Punjab	.0135	.0055	−.0116	.0003	.0003	−.0001
7:Tamil Nadu	.0063	−.0004	.0040	−.0000	−.0007	−.0006
8:Uttar Pradesh	.0079	.0009	−.0053	.0001	.0003	−.0004
9:Bihar	.0130	−.0019	−.0018	.0006	−.0010	−.0000
10:Gujarat	.0079	−.0014	.0036	.0024	.0031	.0005
14:Rajasthan	−.0014	−.0072	−.0034	.0010	.0006	.0001
15:Orissa	.0042	−.0128	−.0117	.0015	.0004	.0004
17:West Bengal	.0045	−.0064	−.0029	−.0005	−.0001	−.0005

Note: Temperature Effect: Percentage change due to a 1° Celsius temperature increase.
Rainfall Effect: Percentage change due to a 3% rainfall increase.

Looking only at the national averages, the temperature effects on multiple-cropping and irrigation, and the rainfall effects on all three are quite small: only one-half of a percent change in multiple-cropping in response to a 1% change in rainfall, one-tenth of a percent change in modern varieties in response to a 1% change in rainfall, and less than a tenth of a percent change in the others. But these averages hide considerable local variation, with a few states experiencing negative effects and a few experiencing effects as large as 4%. There is some consistency in the patterns of the effects across states: Maharashtra always exhibits the largest (positive) impact of rainfall on WHYV, GCANCA and NIANCA; Karnataka, Gujarat, Madhya Pradesh and Orissa nearly always also enjoy relatively large positive rainfall impacts. These states form a triangle across the Deccan in the middle of the country, wider at the West and tapering towards Orissa on the East. Andhra Pradesh, Tamil Nadu, and to some extent Bihar and West Bengal exhibit the largest negative impact of a change in rainfall; these states, along with Orissa, make up the Eastern edge of the country, with Andhra and Tamil at the southern end of that ribbon.

The pattern of positive temperature impacts on multiple-cropping and on irrigation intensity is roughly similar, with Maharashtra and Karnataka exhibiting the largest positive effects, but with no similarities in the statewide patterns of negative temperature effects.

The temperature effect on the adoption of modern varieties is somewhat stronger than the others. On average across the nation, a one percent increase in temperature would increase the adoption of modern varieties by slightly more than one percent, for an elasticity of approximately one. This result is more consistent than the others: only one state, Rajasthan, exhibits a negative effect (one-seventh of one percent) while the other states' effects range from 0.42% to 2.81% (again in Maharashtra).

From these results it is clear that climate change does not inhibit the process of technological change and infrastructural investment upon which India's Green Revolution has been built.

ESTIMATES: NET REVENUE

Table 6C.8 displays the results of the regression of net revenue on edaphic, climatic, and geographic variables, the predicted values of the technology and infrastructure variables from the two-stage system described above, interactions between climate and technology or between climate and infrastructure, and dummy variables for time and agroclimatic regions.

This equation also fits the data very well: the adjusted R^2 is nearly two-thirds, and the F-statistic is highly significant at 63.0875. Table 6C.9 presents results of F-tests of the null hypotheses that the set of edaphic variables, the set of temperature variables, the set of rainfall variables, the set of cloud cover variables, the set of all climate variables, the set of temperature range variables, the set of technology and related infrastructure variables, the set of technology interactions, and the set of year dummies do not influence net revenue. All of these null hypotheses are rejected: each set of variables does significantly influence net revenue; most of the variables in fact by themselves significantly influence net revenue.

In addition to their role in the second-stage equations reported in a previous section, the edaphic variables are important determinants of net revenue: twelve of the nineteen soil type dummies have significant coefficients, and soil of neutral pH[34] contributes more to net revenue than either acidic or base soil.

The geographic variables are also important, with again six of seven agroeconomic region dummies significant. Districts on the seacoast, and especially their neighbors, or "second-tier" districts, have significantly higher net revenue than inland districts[35], and districts lying at higher altitudes[36] have lower net revenue. Each of the seasonal temperatures is interacted with latitude (a measure, among other things, of day length and of the angular incidence of solar radiation), but none of the three coefficients is significantly different from zero.

[34] In terms of the data, of pH 7, whose variable (DMPH7) is the omitted dummy.

[35] Due perhaps to a moderating influence of the ocean on annual weather, and perhaps to some degree on the fertility of delta regions which the soil type dummies do not pick up.

[36] With concomitant changes in cropping patterns, *inter alia*.

Table 6C.8: Regression of the logarithm of net revenue (LNOFPKRE)
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

Multiple R	.81205
R Square	.65942
Adjusted R Square	.64897
Standard Error	10.97377

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	125	949652.91536	7597.22332
Residual	4073	490485.28979	120.42359

F = 63.08750 Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
DMS03	.054552	.072459	.014624	.753	.4516
DMS04	.228057	.060825	.051111	3.749	.0002
DMS05	-.071670	.044797	-.035014	-1.600	.1097
DMS06	-.011457	.040655	-.004780	-.282	.7781
DMS07	-.007442	.046600	-.002248	-.160	.8731
DMS08	.088634	.078633	.025045	1.127	.2597
DMS09	-.128747	.069981	-.027979	-1.840	.0659
DMS10	-.807814	.119605	-.117262	-6.754	.0000
DMS11	.249808	.088832	.046002	2.812	.0049
DMS12	-.373038	.074994	-.126955	-4.974	.0000
DMS13	.112156	.108050	.016140	1.038	.2993
DMS14	.234469	.081655	.048710	2.871	.0041
DMS15	.211475	.055585	.060724	3.805	.0001
DMS16	-.242892	.039046	-.141758	-6.221	.0000
DMS17	-.264839	.083592	-.038763	-3.168	.0015
DMS18	.052901	.145101	.006147	.365	.7154
DMS19	-.090477	.051810	-.044261	-1.746	.0808
DMS20	-.202641	.086673	-.028930	-2.338	.0194
DMS21	-.488113	.121020	-.090713	-4.033	.0001
STORIE	-.173900	.127633	-.019854	-1.362	.1731
DMPH5	-.096539	.046371	-.046213	-2.082	.0374
DMPH6	-.064780	.040572	-.031286	-1.597	.1104
DMPH8	-.238242	.038463	-.134278	-6.194	.0000
DMPH9	-.226464	.045791	-.101747	-4.946	.0000
SOWXT1	.205087	.121377	.669816	1.690	.0912
SOWXT1SQ	-.001860	.001116	-.393458	-1.666	.0957
SOWTR1	-.757177	.142564	-2.034670	-5.311	.0000
SOWXT1LT	-9.54530E-04	7.2639E-04	-.204919	-1.314	.1889
SOWRN1	.001485	.003372	.260431	.440	.6598
SOWRN1SQ	-7.21408E-07	4.6254E-07	-.169252	-1.560	.1189

Table 6C.8: Regression of the logarithm of net revenue (LNOFPKRE) (cont.)
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

Variable	B	SE B	Beta	T	Sig T
SOWXT1RN	-1.11040E-04	5.9287E-05	-.494205	-1.873	.0612
MATXT1	-.222658	.076107	-2.218927	-2.926	.0035
MATXT1SQ	-5.58911E-04	8.1490E-04	-.226554	-.686	.4928
MATTR1	-.122923	.165009	-.456976	-.745	.4563
MATXT1LT	7.42638E-05	.002245	.019218	.033	.9736
MATRN1	-.005293	.003738	-.799679	-1.416	.1568
MATRN1SQ	3.65133E-06	9.2339E-07	.337507	3.954	.0001
MATXT1RN	3.95982E-04	6.0763E-05	1.800304	6.517	.0000
HARXT1	.101693	.066253	.996446	1.535	.1249
HARXT1SQ	-5.70657E-04	7.5346E-04	-.226169	-.757	.4489
HARTR1	.378414	.122537	1.764279	3.088	.0020
HARXT1LT	6.17475E-04	.002213	.175804	.279	.7802
HARRN1	-.002058	.005507	-.206151	-.374	.7086
HARRN1SQ	-5.35116E-06	2.7653E-06	-.182831	-1.935	.0530
HARXT1RN	-1.23765E-04	1.0975E-04	-.385230	-1.128	.2595
SOWOK1	-.191758	.166651	-.343683	-1.151	.2499
MATOK1	-.402711	.180774	-.867486	-2.228	.0260
HAROK1	.950843	.217260	2.006206	4.377	.0000
SOWXT1OK	.004516	.004792	.263935	.942	.3460
MATXT1OK	.010274	.005728	.764239	1.794	.0729
HARXT1OK	-.022267	.006642	-1.544941	-3.352	.0008
SOWRN1DR	.001415	4.0515E-04	.214677	3.493	.0005
MATRN1DR	-.001314	5.7537E-04	-.142207	-2.284	.0224
HARRN1DR	7.64760E-04	7.3235E-04	.043570	1.044	.2964
JURNCV	-.216387	.095226	-.060302	-2.272	.0231
JARNCV	.403147	.082513	.091799	4.886	.0000
JUNERAIN	-8.36467E-05	1.2053E-04	-.012126	-.694	.4877
JUAURAIN	1.44034E-04	7.4578E-05	.050938	1.931	.0535
YEARRAIN	2.70187E-05	5.4392E-05	.015666	.497	.6194
DMSEA	.138790	.066972	.053254	2.072	.0383
DMSEANEI	.202542	.041775	.087420	4.848	.0000
AGROB1	-.215229	.084060	-.055054	-2.560	.0105
AGROB2	-.274846	.143101	-.084329	-1.921	.0548
AGROB3	-.053689	.091621	-.018752	-.586	.5579
AGROB4	-.221600	.078835	-.131924	-2.811	.0050
AGROB5	-.521666	.121442	-.148867	-4.296	.0000
AGROB6	-.650403	.092375	-.304840	-7.041	.0000
AGROB7	-.596806	.114039	-.112721	-5.233	.0000
LNCSTCLT	.005070	.025429	.005481	.199	.8420
LNCSTBUL	-.118732	.019439	-.150294	-6.108	.0000
RELWAGEK	-.088414	.027528	-.061431	-3.212	.0013
GCNCPRDK	-1.829905	2.051189	-.355564	-.892	.3724
EXT	.001536	.004681	.010220	.328	.7428

Table 6C.8: Regression of the logarithm of net revenue (LNOFPKRE) (cont.)
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

Variable	B	SE B	Beta	T	Sig T
WHYVPRDK	2.529281	1.830873	.664703	1.381	.1672
STRES5	.001459	2.6241E-04	.076885	5.558	.0000
NINCPRDK	-2.929354	2.288324	-.793983	-1.280	.2006
SOWXTHYK	-.058570	.064543	-.505594	-.907	.3642
SOWXTNIK	.249874	.079263	2.223949	3.152	.0016
MATXTHYK	.106064	.052784	.812056	2.009	.0446
MATXTNIK	-.067679	.055675	-.524482	-1.216	.2242
HARXTHYK	-.123782	.046304	-1.079055	-2.673	.0075
HARXTNIK	-.144289	.054606	-1.283127	-2.642	.0083
SOWRNHYK	4.48243E-04	.001021	.020325	.439	.6607
SOWRNNIK	.002693	.002153	.088081	1.251	.2111
MATRNHYK	.003306	.001898	.171094	1.742	.0816
MATRNNIK	5.99302E-04	.002697	.031402	.222	.8241
HARRNHYK	-.001082	.002229	-.044604	-.485	.6274
HARRNNIK	.004914	.002701	.227481	1.819	.0690
SOWXTGCK	-.198333	.075241	-1.467736	-2.636	.0084
SOWRNGCK	.001556	.002039	.308685	.763	.4453
MATXTGCK	.161058	.045832	2.191050	3.514	.0004
MATRNGCK	-.007328	.003061	-1.421274	-2.394	.0167
HARRNGCK	.004602	.004017	.616189	1.146	.2520
SOWTRHYK	.103307	.095853	.346481	1.078	.2812
SOWTRGCK	.780809	.131154	3.618342	5.953	.0000
SOWTRNIK	-.430069	.115872	-1.536378	-3.712	.0002
MATTRHYK	-.103027	.114465	-.290828	-.900	.3681
MATTRGCK	.021311	.148659	.107180	.143	.8860
MATTRNIK	.168471	.119246	.500618	1.413	.1578
HARTRHYK	.069185	.063511	.238009	1.089	.2761
HARTRGCK	-.352068	.116554	-2.195637	-3.021	.0025
HARTRNIK	.300911	.080020	1.073437	3.760	.0002
GCANCA57	-.403485	.157103	-.068925	-2.568	.0103
IRR57	-.115579	.219248	-.024608	-.527	.5981
ALT	-3.39930E-04	1.0025E-04	-.104415	-3.391	.0007
SOWXT1DR	-.006635	.003318	-.131493	-2.000	.0456
MATXT1DR	.013793	.011305	.206662	1.220	.2225
HARXT1DR	-.009143	.011551	-.137737	-.792	.4287
DMYR71	-.024890	.045575	-.006876	-.546	.5850
DMYR72	.098980	.047431	.027051	2.087	.0370
DMYR73	.612971	.047082	.171189	13.019	.0000
DMYR74	.632374	.048542	.173171	13.027	.0000
DMYR75	.547989	.048000	.152391	11.417	.0000
DMYR76	.408188	.050087	.112479	8.150	.0000

Table 6C.8: Regression of the logarithm of net revenue (LNOFPKRE) (cont.)
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

Variable	B	SE B	Beta	T	Sig T
DMYR77	.579901	.051624	.161470	11.233	.0000
DMYR78	.453281	.052042	.126118	8.710	.0000
DMYR79	.239891	.054975	.065854	4.364	.0000
DMYR80	.642767	.056769	.177554	11.323	.0000
DMYR81	.636479	.061539	.176443	10.343	.0000
DMYR82	.645755	.066709	.178519	9.680	.0000
DMYR83	.846677	.071939	.238286	11.769	.0000
DMYR84	.777526	.075392	.211324	10.313	.0000
DMYR85	.738356	.077672	.199203	9.506	.0000
DMYR86	.693740	.080356	.186054	8.633	.0000
DMYR87	.754168	.082400	.194070	9.152	.0000
(Constant)	12.650747	2.843905		4.448	.0000

Table 6C.9: F-Tests of exclusion of groups of variables

Excluded Variables	Net Revenue Regression
Edaphic (M = 24)	F = 13.66114
Temperature (M = 38)	F = 17.16124
Rainfall (M = 26)	F = 7.83944
Oktas (Cloud Cover) (M = 6)	F = 8.42512
Temperature Rain and Oktas (M = 70)	F = 15.18449
Temperature Range (M = 12)	F = 12.98978
Technology and Related Infrastructure(M = 33)	F = 17.95629
Technology - Climate Interactions (M = 26)	F = 8.40978
Year Dummies (M = 17)	F = 31.10041

Note: Entries in Table 6C.9 are the F-statistics on the null hypotheses that the excluded variables specified in the left column do not influence Net Revenue. Depending upon the number of variables excluded in each group (given as M = i in the left column), the degrees of freedom of these F-tests are anywhere from 6 to 70 for the numerator and more than 4000 for the denominator; thus the 5% critical value of the F statistic would range from about 1.5 to about 2.1; correspondingly, the 1% critical value of the F statistic would range from about 1.8 to about 2.8.

The coefficients on the predicted values of modern varieties (WHYVPRDK), multiple-cropping (GCNCPRDK) and irrigation intensity (NINCPRDK) are not significantly different from zero; but those variables are interacted with climate terms, as discussed below, and nearly half of the interactions' coefficients are significant. Research and extension contribute to net revenue (the coefficient of extension on net revenue is not significant, though positive, but it significantly increased the adoption of modern varieties; the coefficient of research on WHYV was insignificant, but it appears significantly positive in the net revenue regression).

Higher bullock costs reduce net revenue, as does an increase in off-farm wages relative to agricultural wages, which probably denotes a decline in the quality of available farm workers as off-farm opportunities attract more and more of the best and most-highly-skilled laborers. Sixteen of the seventeen year dummies are positive and significant; the dummy for 1970, the first year in the sample, is omitted, so these dummies are picking up omitted time trends and price index effects.

Current weather, and its timing, also obviously influences current net revenue: given a normal seasonal rainfall, higher rainfall in July and August (the variable JUAURAIN) will increase net revenue.

The climate variables represent long-term averages or norms, to which farmers respond in their decisions about cropping patterns, input use, investment in technology and infrastructure, and so forth. This model displays quite rich (normal) temperature and rainfall effects on net revenue. Looking first at the twentyfour purely climate terms, we find that the coefficients of thirteen are significantly different from zero. The squared and "raw" terms are usually of the opposite sign. The impact of maximum temperature, temperature range, and rainfall differ by season: four of the eight categories differ in sign between the sowing and the maturation seasons; four of eight differ in sign between the sowing and harvesting seasons; and six of the eight differ between the maturation and the harvesting seasons.

In particular, higher maximum temperature in the sowing season increases net revenue at a decreasing rate: perhaps seed germination and night-time temperatures are important here. Given the value of maximum sowing season temperature, a larger temperature range (which is to say, a lower minimum temperature) decreases net revenue. This surely also partakes of issues of germination and fragility of young plants. The coefficient of the interaction of sowing season maximum temperature and rainfall is significantly negative.

In the maturation season, higher maximum temperature would decrease net revenue, likely reflecting temperature stress. The coefficient of rainfall during this season is not significant (though negative), but the coefficient on rainfall squared is positive and significant, and rainfall during this season ameliorates the temperature damage, as evidenced by a positive and significant coefficient on the interaction between maximum temperature and rainfall (in the variable MATXT1RN). Increased cloud cover in the maturation season (given the level of rainfall) reduces net revenue, as would be expected, depriving the growing plants of sunlight to support photosynthesis; yet it also ameliorates the temperature damage (as seen in the positive and significant coefficient on the variable MATXT1OK).

The okta pattern is reversed in the harvest season: additional cloud cover increases net revenue, but worsens the temperature impact. Higher maximum temperature (though barely below significance threshold) increases net revenue, no doubt by extending somewhat the growing season; interestingly, a greater temperature range in the harvest season also increases net revenue.

Interestingly a higher coefficient of variation of June rainfall will decrease net revenue while a higher coefficient of variation of July and August rainfall contributes to net revenue.

A key focus of this study is the interaction of climate with technology, infrastructure, and geographic variables``, beyond the so-called "purely climate" variables. Eleven such interactions each season are included.

About a third of the nation's districts have been identified as "drought-prone", indicating not only low levels of normal rainfall but also poor irrigation potential, probably high rates of evapotranspiration, and so forth. For each season, normal temperature and rainfall have been interacted with a dummy whose value is one for each such drought-prone district. As one would expect, higher normal rainfall in the sowing season will increase net revenue in the drought-prone districts, allowing a crop to become established in such adverse situations (although higher rainfall in the maturation season is harmful), while higher temperatures in the sowing season, inhibiting crop establishment, would reduce net revenue in those districts.

The interactions of maximum temperature, temperature range and rainfall with the predicted values of modern varieties, multiple-cropping and irrigation intensity are complex, yielding significant coefficients in some seasons. HYVs interact positively (and significantly) with maturation season temperature and rainfall but negatively with harvest temperature. Multiple-cropping interacts positively (and significantly) with maturation season maximum temperature and sowing season temperature range, and negatively with sowing season maximum temperature and maturation season rainfall. And irrigation interacts positively with sowing season maximum temperature and harvest season rainfall, and negatively with harvest season maximum temperature.

CLIMATE CHANGE EFFECTS ON NET REVENUE

Based on the regression results reported in the previous section, the actual district-level values of the climate and technology variables, and the computed climate change effects on the technology variables, one can similarly compute the predicted effects on net revenue of changes in normal temperature, normal rainfall and oktas of cloud cover. Those effects (and their sum) are presented in Table 6C.10.

Temperature and rainfall affect net revenue via three avenues. The first could be called direct or express, operating via the temperature and rainfall terms, their squares, and the temperature-rainfall interaction term in the net revenue equation. The second avenue could be called local, beginning with the temperature and rainfall effects on WHYV, GCANCA and NIANCA and operating through their terms in the net revenue equation. The third avenue, meandering, operates through the terms in the net revenue equation which capture the interactions between climate and the predicted values of WHYV, GCANCA and NIANCA. Thus one cannot simply glance at the direct climate terms in the net revenue equation to perceive the temperature and rainfall effects; one must compute carefully the effects through all three avenues, and use in the appropriate places in the computations the values of the climate terms and the technology variables.

The predicted temperature effects on net revenue are a bit high compared to previous estimates for U.S. and Brazilian agriculture: on average over all the districts in this study, a one degree Celsius increase in normal temperature would reduce net revenue by approximately four percent. The differences in estimated effects might be due to the fact that these estimates are based on a net revenue framework, while other estimates are based on reasonably well-defined land prices; other differences include the time period involved, the use of a panel of cross-sections here, the use of seasonal climate variables, the inclusion of additional climate terms (in particular, temperature range and oktas of cloud cover), the inclusion of technology and infrastructure variables, and of course the inherent differences between the Indian and the U.S. or Brazilian agricultural environments. There also seems to be more variation within India, as the sub-continent contains widely varying agricultural environments. There iCVII-1 displays a clear geographic pattern to the temperature impacts on net revenue: the average State-wise change in net revenue ranges from an increase of 1.43% in the Punjab to a decrease of 11.7% in Andhra Pradesh.

Table 6C.10: Climate effects on net revenue
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

	Maximum Temperature	Rainfall	Sum of Temperature and Rainfall	Oktas	Climate Sum
India	-.0397	.0666	.0269	.0283	.0552
1:Andhra Pradesh	-.1170	.0041	-.1129	.1305	.0176
2:Haryana	.0116	.0252	.0378	-.0119	.0249
3:Madhya Pradesh	-.0390	-.0203	-.0593	.0111	-.0482
4:Maharashtra	-.0366	.3664	.3298	-.0189	.3109
5:Karnataka	-.0492	.1759	.1267	.0508	.1775
6:Punjab	.0143	.0075	.0218	-.0241	-.0023
7:Tamil Nadu	-.0802	.0485	-.0317	.0894	.0577
8:Uttar Pradesh	-.0168	.0334	.0166	.0047	.0213
9:Bihar	-.0735	.0405	-.0330	.0706	.0376
10:Gujarat	-.0275	.0349	.0074	-.0282	-.0208
14:Rajasthan	-.0068	.0169	.0101	-.0077	.0024
15:Orissa	-.0327	.1000	.0673	.0946	.1619
17:West Bengal	-.0737	.1108	.0371	.0883	.1254

Note: Temperature Effect: Percentage change due to a 1° Celsius temperature increase.
Rainfall Effect: Percentage change due to a 3% rainfall increase.
Okta Effect: Percentage change due to a 3% increase in cloud cover.

The States whose net revenue is most adversely affected by an increase in temperature are, in order, Andhra Pradesh, Tamil Nadu, Bihar and West Bengal, all suffering a decline in net revenue in excess of seven percent, while the States least adversely affected are, in order, the Punjab, Haryana, Rajasthan and Uttar Pradesh, the first two benefitting and the latter two harmed by less than two percent.

The predicted rainfall effects on net revenue are moderate, slightly larger than, and of the opposite sign to, the predicted temperature effects. There is considerable variation among the States, but little clear geographic pattern-. In all States except Madhya Pradesh higher rainfall is predicted to increase net revenue. and in nine of the thirteen States the combined temperature and rainfall effects would increase net revenue.

The predicted effect on net revenue of an increase in cloud cover is, surprisingly, to increase net revenue on a National average and for eight of the States; the exceptions are five States in the north-central and western parts of the nation-. Thus the combined temperature, rainfall and okta effects yield an increase in net revenue in ten of the thirteen states.

Most global climate change scenarios refer simply to increases in normal temperature; some refer to changes in normal average temperature. As discussed earlier, this study captures a richer specification, including both normal maximum temperature and the temperature range (the normal maximum temperature minus the normal minimum temperature). The literature offers essentially no guidance on the possible change in temperature range in response to global climate change. If maximum and minimum temperatures were to change by the same amount, there would be no change in the temperature range. That may be the implicit assumption underlying nearly every global climate model's silence on this issue; it was the conscious, explicit justification for our excluding changes in the temperature range from the computations upon which Table C-VII-1 was based, and the associated discussion of climate change effects on net revenue.

An alternative possibility is that normal minimum and maximum temperatures change not by the same amount, but by the same proportion. Under that scenario, one could calculate that one degree Celsius is 3.133% of the nationwide average maximum temperature in the sowing season, 3.853% in the maturation season, and 3.55% in the harvest season. One could next calculate the corresponding proportionally-equal changes in minimum temperature (0.679° in the sowing season, 0.669° in maturation, and 0.613° in the harvest season) and then the increases in temperature range (.321°, .331° and .387°).

Of course, the Kelvin scale, which has a true ("absolute") zero, may be appropriate for this computation, in which case a one degree Celsius (or Kelvin} increase in maximum temperature is a 0.33% change, implying changes in the temperature range which are only about one tenth as large as in the previous paragraph: 0.0332° in the sowing season, 0.0284° in the maturation season, and 0.0358° in the harvest season.

Nevertheless, it is of interest to calculate temperature range effects in order to learn what would happen were the range in fact to change. Given that both the normal maximum temperature and the normal temperature range are included in the regression equation, an increase in the temperature range implies either that the minimum temperature decreases, holding constant the maximum temperature, or that the minimum temperature increases by less than does the maximum temperature. From another point of view, a larger range implies that, for a given maximum temperature, the minimum temperature is lower than it otherwise would have been.

The agronomic basis for a temperature range effect then is the impact of the minimum temperature on germination or growth of crops. A larger temperature range would be beneficial, for example, if, given hot daytime temperatures, cooler nights and mornings fostered more complete germination, or reduced the temperature stress on new seedlings or on maturing plants. Alternatively, a larger temperature range might be harmful if the cooler nights inhibited growth or the formation of grains, and so forth.

Table 6C.11 displays the effects on net revenue of a one degree Celsius increase in the temperature range -- as discussed above, actual changes in the range, if there be any, are likely to be smaller, but these computed effects can be scaled downward accordingly. Appendix D reports the temperature range effects by season.

It is apparent from Table 6C.11 that increases in the temperature range are beneficial: a one degree increase in the nationwide average temperature range would increase net revenue by more than eight percent; an increase of 0.3° (based on the "proportional Censius" discussion above) would increase net revenue by about 2.5%, while a 0.03° increase (based on the "proportional Kelvin" discussion above) would increase net revenue by about one quarter of one percent.

There is a strong geographic pattern to these effects: the largest increases in net revenue would occur (in order) in the Punjab, Haryana, Uttar Pradesh, West Bengal, Orissa and Bihar: these states are the northern-most and eastern-most in our data set.

Table 6C.11: Temperature range effects on net revenue

	Temperature Range
India	.0862
1:Andhra Pradesh	.0484
2:Haryana	.2307
3:Madhya Pradesh	.0308
4:Maharashtra	.0121
5:Karnataka	.0204
6:Punjab	.2818
7:Tamil Nadu	.0712
8:Uttar Pradesh	.1553
9:Bihar	.1195
10:Gujarat	.0167
14:Rajasthan	.0562
15:Orissa	.1335
17:West Bengal	.1537

TECHNOLOGY AND INFRASTRUCTURE EFFECTS

As discussed above, our specification in equation (7b) includes important technology and related infrastructure variables which are central to India's Green Revolution experience. Section four presented two stage least squares estimates of NIANCA, GCANCA and WHYV, in which each of the three variables was determined *inter alia* by one or both of the other two. And Section six presented estimates of Net Revenue, in which all three of the technology and related infrastructure variables, as well as their interactions with climate variables, appeared on the right-hand side.

Table 6C.12: Technology and infrastructure effects
(Supra-Ricardian Model, 1970/71 through 1987/88)

Effect of:	HYV	GCA			NIA				
on:	**GCA**	**NIA**	**NR**	**HYV**	**NIA**	**NR**	**HYV**	**GCA**	**NR**
India	.0626	.6559	.1891	3.3800	3.0955	.7798	1.0273	.0634	.0652
1:Andhra Pradesh	.0802	.4334	.1116	1.9595	.5130	.3232	1.0189	.0767	-.0919
2:Haryana	.0931	.3458	.1008	1.2416	.3794	-.1017	.7896	.0966	-.0203
3:Madhya Pradesh	.0471	.8367	.1898	3.9996	2.2394	1.0307	.5807	.0302	.1591
4:Maharashtra	.0677	1.6865	.2510	2.4852	1.9166	1.3255	.5504	.0250	.2932
5:Karnataka	.0760	.8173	.2328	2.1846	1.0870	1.2733	.6798	.0449	.0619
6:Punjab	.1207	.2826	.0956	.8122	.2122	.2653	.9114	.1454	-.1363
7:Tamil Nadu	.1013	.3199	.1674	1.0034	.9328	.7778	.8365	.1060	.0148
8:Uttar Pradesh	.0562	.1884	.1748	2.2212	.3133	.7804	1.7204	.1048	-.0209
9:Bihar	.0607	.4796	.1890	3.0893	1.0371	.7359	.8448	.0612	-.0304
10:Gujarat	.0740	.6741	.1922	2.0000	.7678	.5304	.7007	.0469	.3091
14:Rajasthan	.0394	.4901	.1957	12.2518	21.7892	-.0099	1.7183	.0468	.1408
15:Orissa	.0384	.4556	.2412	3.4718	1.0431	1.0394	1.2607	.0429	-.0157
17:West Bengal	.0499	.7508	.2393	2.0837	1.3646	1.3952	.9335	.0623	-.1046

Note: Effects expressed in elasticity form.

Table 6C.12 presents the computed effects of an increase in any of the three technology and related infrastructure variables on the other two and on Net Revenue. The computations reveal the total effects, involving direct terms, indirect effects through a third variable, and (for effects on Net Revenue) interaction terms. The broad message of Table 6C.12 is that each of the technology and related infrastructure variables encourages and reinforces the others, and contributes to Net Revenue.

The HYV effects are consistently positive, yet inelastic (except for the effect of modern varieties on irrigation intensity in Maharasthra, which is positive and elastic). A one percent increase in the proportion of crops planted to modern varieties would induce a minute increase in multiple-cropping: six one-hundredths of one percent nationwide, nearly one-tenth of one percent or more in Haryana, the Punjab and Tamil Nadu. The effects of increased modern variety adoption are somewhat larger (and considerably more consistent) on Net Revenue, and larger still on irrigation intensity. The effects on irrigation are not difficult to understand, given the responsiveness of nearly all modern varieites to an assured supply of water: as farmers use more and more modern varieties, the payoff to irrigation increases, inducing more investment (privately and by both state and Central governments) in irrigation capacity and facilities. And the HYV effects on Net Revenue, somewhat smaller, are also easier to understand: to have been selected and released, the modern varieties will already have been shown to offer yield increases in excess of their additional input requirements.

The multiple-cropping effects are substantially larger (except for two relatively small and negative effects of multiple-cropping on Net Revenue, in the two adjacent states of (surprisingly) Haryana and Rajasthan): on average for the entire nation, a one percent increase in multiple-cropping would induce an increase in the use of modern varieties and in irrigation intensity by more than three percent, and an increase in Net Revenue of more than three-quarters of one percent. The computed effects of an increase in multiple-cropping in Rajasthan are anomolous and improbable: an increase in WHYV of more than twelve percent, and an increase in irrigation intensity of more than twenty percent! And Rajasthan is one of the two states in which the predicted effect of an increase in multiple-cropping on Net Revenue is negative.

An increase in irrigation intensity would increase the adoption of modern varieties, with an elasticity slightly exceeding one, for essentially the reason discussed above: with more assured water availability, the payoff to the adoption of HYVs is much higher. The effect of an increase in NIANCA on multiple-cropping and on Net Revenue is much smaller.

SECONDARY IMPACTS ON CLIMATE AND TECHNOLOGY EFFECTS

We have seen from Table 6C.11 and the associated discussion, and from Table 6C.12 and its associated discussion, the predicted effects of changes in climate variables on the three technology and related infrastructure variables, and on Net Revenue. One of the strengths of our approach, integrating climate and edaphic variables with technological and infrastructural variables, is that we can also compute the predicted impact of changes in technology and related infrastructural variables on the already-reported climate or other effects. In simple terms, these secondary impacts on, say, the temperature effects simply measure the extent to which changes in technology and infrastructure -- over which policy-makers exercise some influence -- might modify or ameliorate the effect of temperature changes on Indian agriculture.

Table 6C.13 presents the impacts of increases in the technology and related infrastructure variables on the effect of higher temperature on Net Revenue; Table 6C.14 presents the impacts of increases in the technology and related infrastructure variables on the effect of higher rainfall on Net Revenue.

Table 6C.13: Secondary impacts on the temperature effects on net revenue
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

	Research	Extension	WHYV	GCANCA	NIANCA
India	-.0036	-.0618	-.1026	-.2963	-.1628
1: Andhra Pradesh	-.0021	-.0317	-.0841	-.1839	.0012
2: Haryana	-.0017	-.0252	-.0852	-.1282	.0232
3: Madhya Pradesh	-.0031	-.1194	-.1836	-.3427	-.9598
4: Maharashtra	-.0039	-.0465	-.1048	-.2298	-.1818
5: Karnataka	-.0029	-.0425	-.0948	-.2078	-.1104
6: Punjab	-.0009	-.0251	-.0828	-.0934	.0492
7: Tamil Nadu	-.0045	-.0374	-.0858	-.1098	.0276
8: Uttar Pradesh	-.0013	-.0461	-.0846	-.2046	.0655
9: Bihar	-.0019	-0184	-.0828	-.2783	.0346
10: Gujarat	-.0063	-.0598	-.0823	-.1887	-.0317
14: Rajasthan	-.0098	-.1526	-.0832	-.9699	.0323
15: Orissa	-.0087	-.0419	-.0855	-.3002	-.0571
17: West Bengal	-.0012	-.0108	-.0857	-.1938	-.0114

Table 6C.14: Secondary impacts on the rainfall effects on net revenue
(Seasonal Supra-Ricardian Model, 1970/71 through 1987/88)

	Research	**Extension**	**WHYV**	**GCANCA**	**NIANCA**
India	.0001	.0012	.0023	.0085	.0092
1: Andhra Pradesh	.0001	.0010	.0028	.0047	.0103
2: Haryana	.0001	.0009	.0030	.0030	.0099
3: Madhya Pradesh	.0000	–.0011	–.0005	.0098	.0023
4: Maharashtra	.0001	.0011	.0021	.0059	.0080
5: Karnataka	.0001	.0011	.0024	.0052	.0088
6: Punjab	.0000	.0010	.0035	.0023	.0104
7: Tamil Nadu	.0002	.0013	.0030	.0024	.0101
8: Uttar Pradesh	.0000	.0016	.0030	.0056	.0124
9: Bihar	.0001	.0005	.0029	.0780	.0101
10: Gujarat	.0002	.0020	.0028	.0046	.0093
14: Rajasthan	.0003	.0054	.0027	.0320	.0122
15: Orissa	.0002	.0012	.0027	.0085	.0105
17: West Bengal	.0000	.0003	.0028	.0049	.0100

In broad strokes, an increase in the technology and related infrastructure variables tends to worsen the (already negative) temperature effects on net revenue somewhat, and tends to improve the (already positive) rainfall effects on net revenue ever so slightly. In both cases, the research and extension impacts are smaller than the modern variety, multiple-cropping and irrigation impacts.

APPENDIX D: SEASONAL CLIMATE SPECIFICATION

SOWING AND HARVESTING SEASONS OF PRINCIPAL CROPS

The creation of seasonal climate variables, based on monthly values of the normal climate variables and on the sowing and harvesting seasons of principal crops, was described in Section III.B. of the text. This Appendix presents the cropping seasons for the five major food crops in India.

Table 6D.1 displays the sowing seasons of the five crops; Table 6D.2 displays the harvesting seasons.

Table 6D.1: Sowing Seasons of Principal Crops

	Rice (Autumn)	Jowar (Kharif)	Bajra	Maize	Wheat
1: Andhra Pradesh	March-May	June-Oct	June-Aug	June-Aug	---
2: Haryana	May-Aug	June-July	June-Aug	June-July	Oct-Dec
3: Madhya Pradesh	10Jun-15Aug	10Jun-7Aug	15Jun-8Aug	June-July	Oct-Nov
4: Maharashtra	June-July	June-July	June-July	June-July	Oct-Nov
5: Karnataka	May-Aug	May-July	June-Aug	April-July	Sept-Nov
6: Punjab	May-Aug	June-July	June-Aug	June-July	Oct-Dec
7: Tamil Nadu	May-Nov	June-Oct	May-Dec	---	---
8: Uttar Pradesh	May-July	June-July	June-Aug	June-July	Oct-Dec
9: Bihar	May-July	April-Aug	April-Aug	June-July	Oct-Dec
10: Gujarat	June-Aug	June-July	June-July	June-July	Oct-Nov
14: Rajasthan	July-Aug	June-Aug	June-July	June-July	Oct-Dec
15: Orissa	May-June	June-July	---	June-July	Oct-Nov
17: West Bengal	March-June	---	---	April-June	Oct-Dec

-- No appreciable amount of that crop is grown in the given State.

Table 6D.2: Harvesting Seasons of Principal Crops

	Rice (Autumn)	Jowar (Kharif)	Bajra	Maize	Wheat
1: Andhra Pradesh	June-Sept	Jan-April	Sept-Dec	Sept-Oct	---
2: Haryana	Sept-Nov	Sept-Nov	Sept-Nov	Sept-Nov	April-May
3: Madhya Pradesh	15Sept-15Dec	Nov-15Jan	10Oct-Dec	15Aug-Sept	15Feb-April
4: Maharashtra	Oct-Dec	Nov-Jan	Oct-Nov	Aug-Nov	Feb-March
5: Karnataka	Sept-Dec	Oct-Dec	Sept-Jan	July-Nov	Jan-March
6: Punjab	Sept-Nov	Sept-Nov	Sept-Nov	Sept-Nov	April-May
7: Tamil Nadu	Sept-Feb	Sept-Jan	Sept-March	---	---
8: Uttar Pradesh	Sept-Nov	Oct-Dec	Sept-Nov	Aug-Oct	March-May
9: Bihar	Sept-Oct	Sept-Dec	Sept-Dec	Sept-Oct	Feb-May
10: Gujarat	Oct-Dec	Nov-Dec	Sept-Nov	Sept-Nov	Feb-March
14: Rajasthan	Oct-Dec	Oct-Dec	Sept-Nov	Sept-Nov	March-May
15: Orissa	Sept-Oct	Sept-Oct	---	Sept-Oct	March-April
17: West Bengal	July-Nov	---	---	July-Aug	March-April

-- No appreciable amount of that crop is grown in the given state.

Note: Cropping calendars, from which these Tables are constructed, are available in many places. One convenient source is a set of tables printed in most of the recent issues of *Area and Production of Principal Crops in India*, published by the Directorate of Economics and Statistics, Department of Agriculture and Co-operation, Ministry of Agriculture of the Government of India.

COMPARISON OF SEASONAL *VS.* MONTHLY CLIMATE SPECIFICATIONS

As discussed in the text, we argue that the seasonal specification is preferable to a monthly specification on theoretical grounds:

- the choice of any four months is arbitrary to begin with;
- given the wide differences across India in sowing and harvesting seasons, no single choice of four months would adequately capture the important farming activities and biological processes occurring over the year in all states or districts; and
- the monthly specification simply fails to exploit the important information which is contained in cropping calendars.

We believe that these arguments are compelling on their own. Yet the case for a seasonal specification can be bolstered by its comparison with the three possible specifications which involve four equally-spaced months. This section presents a comparison of seasonal *vs.* four-monthly semi-Ricardian specifications (that is, models which contain climatic, edaphic, and geographic variables). The comparisons are based on the estimated regressions from each specification, and the climate effects computed from those regression results.

COMPARISON OF SEASONAL *VS.* MONTHLY SEMI-RICARDIAN MODELS

Table 6D.3 presents results of the four semi-Ricardian regressions on the logarithm of net revenue per hectare: using seasonal variables (the first two columns of Table 6D.3), using the months of January, April, July and October (using the third and fourth columns of Table 6D.3), using the months of February, May, August and November (using the fifth and sixth columns of Table 6D.3); and using the months of March, June, September and December (using the seventh and eighth columns of Table 6D.3). Finally, Table 6D.4 displays the estimated temperature and rainfall effects on net revenue computed from each of the four specifications.

The major conclusions to be drawn from Table 6D.4 are, first, that the temperature and rainfall effects in the semi-Ricardian formulation are worse (that is, are more damaging to net revenue) than the temperature and rainfall effects presented in the text for the supra-Ricardian specification: on average across the country, the semi-Ricardian temperature effect is to reduce net revenue by nearly 14%, rather than reduce it by less than 4%; the rainfall effect is to reduce net revenue by almost 2% rather than increase it. This underscores the potential for bias in computed climate effects if technology and related infrastructure are excluded from the model for India in the post–Green Revolution period.

Table 6D.3: Semi-ricardian regressions of net revenue
(comparison of seasonal *vs.* monthly climate variables)

Seasonal		JanAprJulOct		FebMayAugNov		MarJunSepDec	
DMS03	0.047391	DMS03	-0.064591	DMS03	0.138235	DMS03	-0.095791
DMS04	**0.156287**	DMS04	**0.194134**	DMS04	**0.428703**	DMS04	**0.332627**
DMS05	-0.057968	DMS05	-0.029151	DMS05	-0.051054	DMS05	-0.062284
DMS06	0.028143	DMS06	-0.094722	DMS06	**0.122821**	DMS06	0.05262
DMS07	0.006123	DMS07	-0.057414	DMS07	0.054629	DMS07	**0.226469**
DMS08	**0.305105**	DMS08	**0.266848**	DMS08	0.001536	DMS08	**0.536485**
DMS09	**-0.125437**	DMS09	**0.279877**	DMS09	0.101456	DMS09	**0.516419**
DMS10	**-0.687224**	DMS10	**-0.726315**	DMS10	**-0.544645**	DMS10	**-0.636275**
DMS11	**0.418193**	DMS11	0.136947	DMS11	**0.449822**	DMS11	-0.143429
DMS12	**-0.541489**	DMS12	**0.253248**	DMS12	0.116274	DMS12	**0.206286**
DMS13	**0.195525**	DMS13	**-0.67164**	DMS13	-0.02402	DMS13	**-0.302366**
DMS14	**0.165627**	DMS14	2.07E-04	DMS14	-0.051572	DMS14	**0.300579**
DMS15	**0.225131**	DMS15	**0.303233**	DMS15	**0.390857**	DMS15	**0.546584**
DMS16	-0.029486	DMS16	0.061276	DMS16	**0.125834**	DMS16	**0.108507**
DMS17	**-0.343428**	DMS17	**-0.25561**	DMS17	-0.017997	DMS17	**-0.169563**
DMS18	**0.361077**	DMS18	**0.38236**	DMS18	**0.413322**	DMS18	**0.602686**
DMS19	0.062551	DMS19	-0.02162	DMS19	-0.034553	DMS19	0.048573
DMS20	**-0.143958**	DMS20	**-0.422014**	DMS20	-0.08253	DMS20	0.110646
DMS21	0.022633	DMS21	**0.199175**	DMS21	0.010773	DMS21	0.018309
STORIE	-0.030066	STORIE	**-0.261257**	STORIE	-0.10075	STORIE	-0.055537
DMPH5	**-0.119451**	DMPH5	0.06547	DMPH5	**-0.123651**	DMPH5	**-0.154866**
DMPH6	**-0.12982**	DMPH6	-0.058365	DMPH6	**-0.161722**	DMPH6	**-0.199935**
DMPH8	**-0.300347**	DMPH8	**-0.245566**	DMPH8	**-0.315937**	DMPH8	**-0.255513**
DMPH9	**-0.20063**	DMPH9	**-0.356711**	DMPH9	-0.350658	DMPH9	**-0.333695**
SOWXT1	**-0.216174**	JANXT	**0.994395**	FEBXT	0.432457	MARXT	**0.515218**
SOWXT1SQ	0.001405	JANXTSQ	**-0.011564**	FEBXTSQ	-0.004406	MARXTSQ	-0.004235
SOWXT1LT	-7.84E-04	JANXTLT	**-0.01723**	FEBXTLT	**-0.016651**	MARXTLT	**-0.010791**
SOWRN1	-5.11E-04	JANRN	**0.08124**	FEBRN	-0.036341	MARRN	-0.038739
SOWRN1SQ	-3.47E-08	JANRNSQ	-1.98E-05	FEBRNSQ	**-3.39E-04**	MARRNSQ	-2.58E-05
SOWXT1RN	-7.62E-06	JANXTRN	**-0.004164**	FEBXTRN	**0.001541**	MARXTRN	**0.001645**
MATXT1	0.079894	APRXT	-0.049427	MAYXT	0.095467	JUNXT	0.086496
MATXT1SQ	-6.76E-04	APRXTSQ	**-0.006813**	MAYXTSQ	-0.002573	JUNXTSQ	**-0.002972**
MATXT1LT	**-0.003441**	APRXTLT	**0.018733**	MAYXTLT	0.002695	JUNXTLT	-0.001062
MATRN1	-0.00271	APRRN	**0.174133**	MAYRN	0.002219	JUNRN	**0.010013**
MATRN1SQ	**-1.30E-06**	APRRNSQ	**-2.45E-04**	MAYRNSQ	**-8.64E-06**	JUNRNSQ	**2.10E-06**
MATXT1RN	**1.46E-04**	APRXTRN	**-0.003951**	MAYXTRN	4.05E-05	JUNXTRN	**-4.05E-04**
HARXT1	0.041876	JULXT	-0.055961	AUGXT	**-0.654834**	SEPXT	**0.68286**
HARXT1SQ	**-0.001382**	JULXTSQ	6.43E-04	AUGXTSQ	1.26E-04	SEPXTSQ	**-0.013985**
HARXT1LT	0.002816	JULXTLT	**-0.009168**	AUGXTLT	**0.009234**	SEPXTLT	0.006774
HARRN1	-0.004965	JULRN	-0.001634	AUGRN	**-0.008168**	SEPRN	**-0.006182**
HARRN1SQ	2.88E-06	JULRNSQ	1.08E-07	AUGRNSQ	**1.40E-06**	SEPRNSQ	-2.43E-08
HARXT1RN	9.18E-05	JULXTRN	5.47E-05	AUGXTRN	**2.47E-04**	SEPXTRN	**2.39E-04**

Table 6D.3: Semi-ricardian regressions of net revenue (cont.)
(comparison of seasonal *vs.* monthly climate variables)

Seasonal		JanAprJulOct		FebMayAugNov		MarJunSepDec	
		OCTXT	0.245338	NOVXT	**-0.866645**	DECXT	**-0.818222**
		OCTXTSQ	-0.001604	NOVXTSQ	**0.017906**	DECXTSQ	**0.013041**
				NOVXTLT	0.003153	DECXTLT	0.005284
		OCTRN	**-0.059728**	NOVRN	0.008971	DECRN	0.032982
		OCTRNSQ	6.42E-06	NOVRNSQ	**4.65E-06**	DECRNSQ	**4.26E-05**
		OCTXTRN	**0.001801**	NOVXTRN	-2.91E-04	DECXTRN	**-0.001635**
SOWOK1	0.063237	JANOK	**1.568514**	FEBOK	**0.645663**	MAROK	0.650107
MATOK1	**-0.613005**	APROK	**-1.604114**	MAYOK	-0.393134	JUNOK	**-1.0706**
HAROK1	**0.849798**	JULOK	-0.457994	AUGOK	**-1.281817**	SEPOK	-0.059318
		OCTOK	-0.214595	NOVOK	-0.735821	DECOK	-0.105595
SOWXT1OK	-0.002229	JANXTOK	**-0.050723**	FEBXTOK	-0.019029	MARXTOK	-0.024373
MATXT1OK	**0.016289**	APRXTOK	**0.043819**	MAYXTOK	**0.01277**	JUNXTOK	**0.032293**
HARXT1OK	**-0.02389**	JULXTOK	0.009781	AUGXTOK	**0.035992**	SEPXTOK	-0.006199
		OCTXTOK	0.006886	NOVXTOK	0.022761	DECXTOK	0.013919
SOWRN1DR	**0.001216**	JANRNDR	**-0.012945**	FEBRNDR	**0.013665**	MARRNDR	**0.031834**
MATRN1DR	**-0.001416**	APRRNDR	**-0.012208**	MAYRNDR	**-0.008901**	JUNRNDR	**0.001414**
HARRN1DR	**0.002668**	JULRNDR	**9.72E-04**	AUGRNDR	**0.001317**	SEPRNDR	**-0.001291**
		OCTRNDR	0.0019	NOVRNDR	**-0.005993**	DECRNDR	**-0.006612**
JURNCV	**-0.302145**	JURNCV	0.09904	JURNCV	**0.464227**	JURNCV	0.176198
JARNCV	**0.372398**	JARNCV	**0.513689**	JARNCV	0.128412	JARNCV	**0.511188**
JUNERAIN	-1.28E-05	JUNERAIN	-4.47E-05	JUNERAIN	8.09E-05	JUNERAIN	6.28E-05
JUAURAIN	**2.18E-04**	JUAURAIN	**2.18E-04**	JUAURAIN	**3.39E-04**	JUAURAIN	**3.00E-04**
YEARRAIN	1.39E-06	YEARRAIN	5.10E-05	YEARRAIN	1.25E-05	YEARRAIN	-4.57E-06
DMSEA	**0.121358**	DMSEA	**-0.158873**	DMSEA	0.01148	DMSEA	**-0.363871**
DMSEANEI	**0.27414**	DMSEANEI	**0.129393**	DMSEANEI	**0.258619**	DMSEANEI	0.05273
AGROB1	**-0.237214**	AGROB1	**-0.806599**	AGROB1	**-0.626631**	AGROB1	**-0.456057**
AGROB2	**-0.259659**	AGROB2	**-0.811866**	AGROB2	**-0.829606**	AGROB2	**-0.905527**
AGROB3	-0.016507	AGROB3	**0.240472**	AGROB3	**0.417542**	AGROB3	0.12071
AGROB4	**-0.222141**	AGROB4	**-0.173391**	AGROB4	-0.127879	AGROB4	**-0.336791**
AGROB5	**-0.585149**	AGROB5	**-0.234677**	AGROB5	0.16182	AGROB5	**-0.849395**
AGROB6	**-0.618018**	AGROB6	**-0.617847**	AGROB6	**-0.500026**	AGROB6	**-1.015301**
AGROB7	**-0.480066**	AGROB7	**-0.837377**	AGROB7	**-1.323785**	AGROB7	**-1.216763**
LNCSTCLT	**0.082129**	LNCSTCLT	0.05652	LNCSTCLT	**0.055137**	LNCSTCLT	0.04223
LNCSTBUL	**-0.116711**	LNCSTBUL	0.010581	LNCSTBUL	**0.096032**	LNCSTBUL	**0.043916**
RELWAGEK	**-0.065124**	RELWAGEK	**-0.251109**	RELWAGEK	**-0.250618**	RELWAGEK	**-0.244593**
SOWXT1DR	-0.001309	JANXTDR	**0.063108**	FEBXTDR	**0.158244**	MARXTDR	**-0.046007**
MATXT1DR	**0.016493**	APRXTDR	0.025242	MAYXTDR	**-0.101918**	JUNXTDR	**0.16101**
HARXT1DR	**-0.023725**	JULXTDR	**0.134036**	AUGXTDR	**0.153761**	SEPXTDR	**-0.21705**
		OCTXTDR	**-0.219077**	NOVXTDR	**-0.189673**	DECXTDR	**0.078489**

Table 6D.3 Semi-Ricardian Regressions of Net Revenue (cont.)
(comparison of seasonal *vs.* monthly climate variables)

Seasonal		JanAprJulOct		FebMayAugNov		MarJunSepDec	
ALT	**-6.00E-04**	ALT	**-3.74E-04**	ALT	**-3.52E-04**	ALT	**-2.80E-04**
DMYR71	-0.024095	DMYR71	0.026187	DMYR71	0.026542	DMYR71	0.026913
DMYR72	**0.113087**	DMYR72	**0.11735**	DMYR72	**0.114339**	DMYR72	**0.112715**
DMYR73	**0.620249**	DMYR73	**0.620794**	DMYR73	**0.576533**	DMYR73	**0.614414**
DMYR74	**0.639548**	DMYR74	**0.700235**	DMYR74	**0.643728**	DMYR74	**0.687008**
DMYR75	**0.544241**	DMYR75	**0.618913**	DMYR75	**0.55726**	DMYR75	**0.60862**
DMYR76	**0.440597**	DMYR76	**0.427818**	DMYR76	**0.343059**	DMYR76	**0.408834**
DMYR77	**0.636301**	DMYR77	**0.587674**	DMYR77	**0.489512**	DMYR77	**0.568517**
DMYR78	**0.542495**	DMYR78	**0.534823**	DMYR78	**0.450097**	DMYR78	**0.517973**
DMYR79	**0.360747**	DMYR79	**0.34254**	DMYR79	**0.27588**	DMYR79	**0.335741**
DMYR80	**0.756199**	DMYR80	**0.726411**	DMYR80	**0.641845**	DMYR80	**0.70927**
DMYR81	**0.781418**	DMYR81	**0.707195**	DMYR81	**0.609599**	DMYR81	**0.691418**
DMYR82	**0.81268**	DMYR82	**0.752096**	DMYR82	**0.662783**	DMYR82	**0.740612**
DMYR83	**1.042098**	DMYR83	**1.017263**	DMYR83	**0.929758**	DMYR83	**1.007165**
DMYR84	**1.018682**	DMYR84	**0.986503**	DMYR84	**0.884251**	DMYR84	**0.966064**
DMYR85	**0.990557**	DMYR85	**0.949377**	DMYR85	**0.838518**	DMYR85	**0.929903**
DMYR86	**0.947856**	DMYR86	**0.90282**	DMYR86	**0.795348**	DMYR86	**0.88126**
DMYR87	**1.007276**	DMYR87	**1.084669**	DMYR87	**0.99966**	DMYR87	**1.085213**
SOWTR1	**0.147266**	JANTR	**0.037028**	FEBTR	**0.200087**	MARTR	**0.132593**
MATTR1	**-0.115227**	APRTR	**0.048441**	MAYTR	**-0.054387**	JUNTR	**-0.131788**
HARTR1	**0.027549**	JULTR	**-0.048389**	AUGTR	**0.139375**	SEPTR	**0.141348**
		OCTTR	**-0.092935**	NOVTR	**-0.211682**	DECTR	**-0.176978**
adj Rsq	0.60104	adj Rsq	0.62789	adj Rsq	0.62124	adj Rsq	0.62452
F	69.74246	F	53.83778	F	51.57613	F	52.57683

Note: Coefficients which appear in bold style are statistically-significant.

The second major conclusion is that, especially with respect to the temperature effects, the seasonal specification is far more stable: the standard deviation of all districts' computed temperature effect is 0.363, which is anywhere from one half to only one fourth as large as the standard deviation of the temperature effects in the monthly specifications.

Table 6D.4a: Comparison of temperature effects, semi-ricardian model

	Seasonal	JaApJulOc	FeMayAuNo	MarJunSeDe
India	–.1397	-.0742	–.0720	–.1269
1:Andhra Pradesh	–.2065	.0598	–.0592	–.0710
2:Haryana	–.1346	-.2009	–.1686	–.3384
3:Madhya Pradesh	–.1510	-.1247	–.0688	–.0616
4:Maharashtra	–.1186	-.0372	–.0096	–.0259
5:Karnataka	–.1317	.0924	–.0146	.0121
6:Punjab	–.1662	-.2139	–.2212	–.3667
7:Tamil Nadu	–.1398	-.0950	–.0699	–.1813
8:Uttar Pradesh	–.1410	-.1488	–.1381	–.2265
9:Bihar	–.1558	-.1269	–.1032	–.1867
10:Gujarat	–.1099	-.1650	.0181	–.0713
14:Rajasthan	–.1107	-.1313	–.1399	–.2597
15:Orissa	–.1134	.0379	–.0137	–.058
17:West Bengal	–.1284	-.0762	–.0558	–.1147
St.Dev.	.0361	.1504	.0876	.1360

Table 6D.4b: Comparison of rainfall effects, semi-ricardian model

	Seasonal	JaApJulOc	FeMayAuNo	MarJunSeDe
India	–.0011	-.0066	.0172	.0102
1:Andhra Pradesh	.0007	.0057	.028	.0107
2:Haryana	–.0022	-.0005	.0047	.0134
3:Madhya Pradesh	–.0009	-.0137	.0191	.0049
4:Maharashtra	–.0015	-.0032	.0278	.0089
5:Karnataka	–.0005	-.0129	.0243	.0202
6:Punjab	–.0015	.0070	.0030	.0000
7:Tamil Nadu	–.0002	-.0053	.0146	.0228
8:Uttar Pradesh	–.0012	.0002	.0079	.0076
9:Bihar	.0001	-.0084	.0113	.0093
10:Gujarat	–.0019	.0091	.0275	.0160
14:Rajasthan	–.0032	.0002	.0190	.0124
15:Orissa	–.0010	-.0101	.0138	.0014
17:West Bengal	–.0002	-.0055	.0092	.0068
St. Dev.	.0017	.0220	.0122	.0131

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