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UNDERSTANDING THE PROCESS OF AGRICULTURAL ADAPTATION TO CLIMATE CHANGE: ANALYSIS OF CLIMATE-INDUCED INNOVATION IN RICE BASED CROPPING SYSTEM OF NEPAL

A Thesis in

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ABSTRACT

The development of technological solutions to minimize risks of current climate can lead to two possible outcomes: increase in agricultural productivity and insights about adaptation to future climate change. Drawing upon the hypothesis of induced innovation this research investigates whether spatial variations in climatic resource prompted the development of location-specific technologies that led to an increase rice productivity in Nepal. Using the country's district level time-series data (1991/92 and 2002/03), I examine whether districts with comparatively lower initial rice productivity levels have increased their rates of production relatively faster than those with higher initial productivity. Complementing this analysis with relevant case studies, I also investigate the extent to which Nepal's research establishments have provided farmers with technological options to alleviate climatic constraints in rice cultivation across the country's climatically diverse terrain.

I find that rice productivity has increased steadily across the districts of Nepal during the 12 year period and is not just skewed towards climatically favorable regions but is also observed in areas that are relatively marginal for rice production. While the emerging patterns of productivity growth may have been the autonomous response to the increasing demand, it may also have been facilitated by conscious decisions to develop technologies that are location-specific. I find that the research establishments in Nepal have developed technological innovations as a buffer against the deleterious effect of climatic risks. The findings from both empirical and qualitative assessments indicate that Nepal's research establishment is engaged in and

committed to the development of location-specific technologies that address the constraints of climate. The outcome of such commitment has been a series of technological innovations such as development of drought resistant varieties, improved irrigation management and agronomic practices, and change in research and development policies. Together, this may have been responsible for higher yields among districts with marginal climate, which have subsequently led to convergence of the rice productivity growth rate in the country. If the current trend in limiting the deleterious effects of climate in agriculture through appropriate technological as well as institutional changes continues then the prospect of adapting to future climate is more plausible in Nepal.

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CHAPTER ONE

INTRODUCTION

Introduction

One of the challenges in estimating the potential consequences of climate change on agricultural production anywhere in the world is understanding how farmers and their supporting institutions adapt. Using Nepal's district level time-series data for the period between 1991/92 and 2002/03, I examine the extent to which technological innovations have provided farmers with options to substitute for climate in order to enhance rice (*Oryza sativa* L) productivity in climatically diverse regions of the country. Drawing upon the hypothesis of induced innovation, which states that the direction of technological innovation in agriculture is induced by differences in relative resource endowments, my goal in this research is to investigate whether spatial variations in climatic resources prompted the development of location-specific technologies that substituted for climatic limitations in the rice-based cropping system of Nepal.

The justification for this research is built on the premise that in order to know how well farmers and their supporting institutions might be prepared to cope with the change in climate (the characteristic of which remains relatively unknown), it is important to understand how well society has adapted to variability in climate in the past, and consequently to minimize the risks associated with it. Exploring the ways in which technological innovations have provided farmers with the means to respond to climatic limits can offer insights about the adaptation of agricultural systems to future climate change (Easterling, 1996). With this notion, I argue that continued growth in productivity, defined as growth in crop yield net of inputs, over time is a function of a dynamic process of adjustment to existing spatial differences in climatic resources. This can have important implications for the analysis of adaptation of agriculture to future climate change.

The remainder of this chapter will review salient research that supports the central argument of this study. I will briefly discuss the concerns surrounding climate change and its impact on the food security of developing countries. Then the rationale of this study will be discussed. In this chapter I will also introduce the induced innovation hypothesis as a basis for the theoretical argument of climate-induced innovation in agriculture.

Background

The vulnerability of the agricultural sector to climate change is well established in recent literature (Reilly et al., 1996; Gitay et al., 2001; Parry et al., 2004). The consensus among climate scientists is that global warming from increased radiative forcing will alter climatic conditions (e.g., soil moisture regime, humidity, solar radiation) thereby affecting plant growth and development, and subsequently agricultural productivity. While scientific consensus predicts that global food production will remain robust in the foreseeable future, at the regional level the impacts may vary widely, with some regions benefiting from altered climate and others being adversely affected (Gitay et al., 2001).

Generally, researchers engaged in climate change impact studies conclude that food production would likely decline in the developing countries, whereas the more developed countries may actually benefit from global warming, at least in the early stages (Darwin et al 1995; Antle, 1995; Downing et al., 1996; Parry, 1999; Reilly, 1999; Winters et al. 1999). Two reasons underlie the differential impact that climate change is expected to have in agricultural productivity between the developed and developing countries. The first is the *physical* factor. In developed countries, most of which are located within the higher latitudes (temperate zone), agriculture would benefit from the longer growing season that would accompany a warmer climate. However, in developing countries situated in the lower latitudes (tropics), most crops have already attained their climatic threshold and therefore crop yields would likely be adversely affected even with a small change in climate.

The second reason is the *socioeconomic* factor. Compared with the developed countries, developing countries have lesser economic resources to help farmers adjust to climate change. The technical capabilities and institutional structures in developing nations needed to cushion the adverse effects of climate change are comparatively less developed or may even be non-existent. These comparative disadvantages, whether physical or socioeconomic, underscore the greater vulnerability of developing countries to climate change, and subsequently its effect on food security.

However, despite such a gloomy prognosis, for developing countries there are scholars who present a more optimistic perspective. They argue that farmers and their supporting institutions will respond to climate change through innovation of technologies to minimize yield loss from deleterious climate changes or maximize yield gain from beneficial climate changes (Parry, 1990; CAST, 1992; Ausubel, 1995; Easterling, 1996), in both developed and developing counttries. Historical analogues of the adaptability of agriculture to climate change include experience with climate fluctuations, deliberate translocation of crops across different agro-climatic zones, substitutions of new crops for old ones, and substitutions of technology induced by scarcity of resources (Easterling, 1996). Examples of crop translocation include thermal expansion of hard-red winter wheat in the Great Plains region of the United States and Canadian Prairie (Rosenberg 1982), and the expansion of the northern boundary of winter wheat in China, aided by the introduction of freeze-resistant varieties from Russia and Canada (Lin 1997, Chen and Libai, 1997). Adaptation of canola in Canadian agriculture in the 1950s and 60s shows how rapidly farmers are able to modify their production systems to accommodate new crops (NRC, 1991). These examples provide evidence of adaptive research specifically targeted to address location-specific climatic needs. Similarly, the example of dry land agriculture substituting for irrigated systems in the Great Plains region of the United States in response to increasing scarcity of water resources provides additional evidence of technological substitution to scarce resources (Glantz and Ausubel, 1988).

Evidence also shows that technological innovation responds to changing socioeconomic conditions and resource endowments in ways that can be analogous to future climate change (CAST, 1992). For example, technological change, such as the replacement of traditional cultivars with modern varieties, introduction of irrigation infrastructure, and chemical fertilizers, have been very effective in stimulating growth in agricultural production (Pinstrup-Andersen, 1982). In South and Southeast Asia, the outcomes of the Green Revolution – characterized by development and diffusion of high yielding varieties (HYVs) of food crops, expansion of irrigation to assure the timely supply of water required to grow HYVs, multiple cropping made possible by the availability of irrigation water, and early maturing HYVs facilitated by wider distribution of chemical fertilizers to maintain productivity – are considered to be positive developments, despite criticisms regarding distributional inequities and environmental concerns (Evenson and Gollin, 2000).

In response to a lengthening of the frost-free growing season since the middle of 20^{th} century, farmers have changed planting dates and varietal choices of wheat across much of Australia (Howden, et al., 2003). In another example, farmers in the semiarid tropics of Kenya and Ethiopia have been able to increase water use efficiency through a combination of water harvesting techniques and drip irrigation that has enabled them to diversify cropping systems and minimize risk from increasing drought spells and erratic rainfall pattern (Ngigi et al., 2000). Research and technological innovations in agriculture have enabled farmers to cope with various climatic challenges and have been fundamental to the growth and development of agriculture around the world (Rosenberg, 1992).

Yet, notwithstanding this recognition, there is a dearth of research that unravels the role of climate as a stimulus for innovation of appropriate technologies (Ruttan, 1996; Ausbel, 1995; NRC, 1999; Smithers and Blay-Palmer, 2001). Little is known about the manner in which technology has altered the relationship between climate and crop production and the roles that climate has played in development of the new innovations. This is one of the reasons why studies conducted to understand the impact of climate change in agriculture remain inconclusive, and have limited policy implications.

This research is a response to the challenge of developing a conceptual model that can be used as a basis for understanding agricultural adaptation to future climate change. More specifically, by using the hypothesis of induced innovation, this research extends the boundaries of climate change research to take into consideration the environmental inducements of technology in developing countries. It is my contention that this relationship is an important area of investigation for at least three reasons. First, a productive and sustainable agricultural system is necessary for providing food security to an ever-growing population of developing countries. Second, traditionally agriculture occupies an important role in the local and national economies of most developing countries and is an important source of rural employment. Finally, the relation between climate change and agricultural adaptation represents a classic example of the human-environment interface, an area of long-standing interest within geography.

The main thrust of this study is to investigate if climatic limitations have been factored into the research and development of agricultural technologies, so that rice yield of climatically constrained regions could be sustained through innovations, thereby ensuring productivity convergence across Nepal. Insights from this research will provide informed choices about possible adaptation strategies that could be considered to ensure food security in the face of deleterious climate change. Easterling (1996) suggests that one way to draw insights about the adaptation of agricultural system to changing climate is the use of retrospective analysis to understand how previous technological innovations have been targeted to address climatic constraints in specific locations. Building upon this notion of retrospective analysis, I investigate the process by which Nepal's agricultural research and development systems have addressed specific climatic challenges and opportunities in the past. Logically, the research questions that follow are:

i. *Do local climatic limitations, such as patterns of rainfall and other biophysical factors, provide incentives for farmers and public institutions to invest in research and development of technologies to overcome those limitations?*
ii. *Is the degree of rice productivity differentials across climatically diverse districts of Nepal narrowing over time?*

These questions, which lie at the heart of the debate of agricultural development, are also important in understanding the impacts climate change in agriculture. In the following section I discuss the significance of these questions in light of the relationship of climate and technology with agriculture.

Climate and technology in agriculture

While the geographic distribution of agricultural production is largely dependent on the spatial range of thermal and moisture regimes, human beings have established agriculture in virtually every climatic region of the earth (Brush and Turner, 1987). The systems of food production have been transformed from simple technology, hardly distinguishable from hunting and gathering, into vastly complex and varied ones. Although climate variability is an obvious source of environmental risk in agricultural production, it has also spawned technological innovations to assist farmers from its deleterious effect (Lansigan et al., 2000). As future climatic conditions unfold, farmers and their supporting institutions could make adjustments in their cropping activities, such as change in crop varieties that better suit the new environment or investment in irrigation infrastructure should drier conditions be created due to change in rainfall patterns, to ensure crop growth and development.

Climate and its effect on agriculture have continued to stimulate technological innovations that best suit specific climatic conditions. For instance, in Zimbabwe farmers have switched to more drought-tolerant crops in areas where frequent recurrence of droughts has made agricultural production difficult using the traditional crop varieties (Matarira et al., 1996). In the semiarid tropical environment of Kenya and Nigeria, rainwater harvesting techniques and drip irrigation are promoted to deal with inadequate precipitation during the growing season (Oweis et al., 1999). The introduction of early maturing wheat varieties in the early 1970s (e.g., RR21) fueled significant increases in wheat cultivation in Nepal (Morris et al., 1994), which made it possible for double cropping of wheat and rice in areas where farmers had previously been restricted to one crop of rice per year. Technological adjustments made in response to climatic shocks and economic hardships are ancient, widely implemented, and primarily household based. They have proven to minimize the losses resulting from such conditions (Jodha, 1978; 1989; Swinton, 1988; Fafchamps et al., 1998; Kinsey et al, 1998; Jalan and Raavallion, 2001; Rockstrom et al., 2002).

Emerging scholarship from the hazard and risk management literature demonstrates that technological adjustment to climatic resources is a largely time-dependent and location-specific learning process. Among small farmers, who make up the majority of the rural population in developing countries, traditional practices, such as switching crops and conserving soil and water, have been the main technological adjustments to both short- and longer-term climate changes. In Nepal, farmers grow a wide array of crops with different environmental response characteristics to ensure at least some yield under a broad spectrum of climatic conditions. Morduch (1990) shows that small farmers in semiarid India devote a large share of their agricultural land to traditional (but safer) varieties of rice and castor than the riskier and high-return varieties. In a similar vein, Dercon (1996) finds that Tanzanian households with limited liquid assets (e.g., livestock) grow proportionately more sweet potatoes, a low-risk and low-return crop than farmers with more liquid assets. Watts (1983) reports that, among others, sale of livestock played a central role in response to drought. Using a variety of crop management strategies, farmers minimize losses during poor years and maximize profit during good years (Huda et al., 1994).

Adjustment strategies that are applied by the farmers show sources of resilience in the systems and offer insights as to how adjustments can be made in the face of climate change. However, many of these techniques may prove inadequate in adaptation to climate change. For example, in the case of severe environmental stress, such as consecutive droughts of West Africa in the 1980s, most of the techniques applied by the farmers were found to be generally less effective in preventing overall loss (Eriksen and Olmos, 2001). Researchers caution that in the developing world vulnerability from climate-induced risks is increasing because successful traditional methods applied by the farmers to cope during the period of climatic stresses are disappearing with no concurrent development of alternate public support systems to cushion them from these losses (Kates, 2000).

In addition, the traditional options for handling climatic risks in agriculture are fairly static and do not include new technological options based on scientific advancement in agriculture. At best, traditional technologies ensure the balancing of losses, but do not offer enough scope for generating a surplus to ensure internal cushions to effectively sustain the effects of severe climatic threat due to prolonged drought (Jodha and Mascarenhas, 1985). Small farmers who apply a conservative strategy in adaptation to climatic risks incur substantial opportunity costs by forfeiting the potential profit that could be generated through the application of modern technologies (Sadras et al., 2003). According to the Third Assessment Report of the Working Group II of the Intergovernmental Panel on Climate Change (IPCC) (Gitay et al., 2001), successful adaptation not only depends on advances made in technological innovation but also on the appropriate use of technologies recommended for different climatic conditions. Therefore, the ability of the farmers in developing countries to make smooth and cost-effective adjustments to climate extremes caused by global warming is by no means assured.

Food security in developing countries: with and without climate change

It is argued that over the last 50 years the world has performed well in terms of increasing food security. Summary statistics show that in the period between 1960-1990 global cereal production doubled, per capita food availability increased by 37 percent, and per capita calories available per day increased from 2,420 kcal per day in 1958 to 2,808 kcal in 1999 (McCalla, et al., 1999: 97). Food production outpaced population growth as a result of crop improvement, alteration of agricultural practices, use of inorganic fertilizers and pesticides, and development of infrastructures (Pinstrup-Anderson and Pandey-Lorch, 1998; Gilland, 2002). New technologies continue to demonstrate that growth in yield is not being limited by general climatic constraints in crop productivity (Hafner, 2003). Major global studies conducted by the International Food Policy Research Institute (IFPRI) (Mitchell and Ingco, 1993), the Food and Agriculture Organization (FAO) (Alexandratos, 1995), and the World Bank (Agcaoili and Rosengrant; 1995) anticipate aggregate grain yield to increase by 1.5-1.7 percent per year for the foreseeable future and the real prices of grain to remain constant or even decline.

Though evidence continues to support the fact that global agricultural production could be maintained relative to the demand, significant regional departures from that trend are expected. For example, studies from Sub-Saharan Africa and South Asia, where agriculture is a key economic sector and accounts for high portion of the national Gross Domestic Product (GDP), show a less sanguine picture of food security in the future. McCalla, et al. (1999) reports declining trends of per capita food availability in Sub-Saharan Africa due to the combined effects of increasing population and slow or sometimes negative, growth in agricultural production. The same trend has been reflected in South Asia where malnourishment has increased significantly among the population in recent decades. Clearly, policymakers of these countries are pressed to make continued investment in agricultural technologies and infrastructures in order to meet growing food demand. This has been compounded by growing concern regarding the ability of farmers and institutions in these countries to cope with and respond to the threats and opportunities of changing climate.

Over the last decade or so, climate change (in terms of long-term changes in mean temperature or precipitation, as well as increased frequency of extreme climate events) has been recognized (Hulme, 1999; Reilly, 1999) as an additional factor that will have significant impact on agricultural productivity. Sensitivity studies of world agriculture to potential climate change have indicated that global warming may have only a small overall impact on world food security as the reduced production in some areas are offset by increases in others (Reilly et al., 1996; Reilly and Fugile, 1998; Parry, 1999). There is, however, a general agreement that climate change will lead to a significant reduction in agricultural food productivity in developing countries (Rosenweiz and Parry, 1994; Reilly et al., 1996; Parry et al., 1999; Gitay et al., 2001). By most measures, many of the countries in Sub-Saharan Africa and South Asia appear to be the most vulnerable to climate change (Reilly et al., 1996; Rosenweiz and Hillel, 1998; Gitay et al., 2001).

The concern with future climate change is heightened given the possibility that adverse impacts of climate change in agriculture could exacerbate rural poverty in developing countries. In Africa and South Asia, estimates indicate that nearly 60-70 percent of population is dependent on the agricultural sector for employment, and that it contributes over 30 percent of the GDP. With lower technological and capital stocks, the agricultural sector in these countries is unlikely to withstand the additional pressures imposed by climate change without a concerted response strategy (Crosson, 1997).

Climate change can affect crop yield via change in temperature, precipitation, soil moisture and soil fertility, change in length of growing season, and an increased probability of extreme climatic conditions (Parry, 1990). The number of studies that model the impact of climate change on agriculture across the different parts of the world has continued to increase since the early 1990s. A major study by Matthews et al. (1995) on climate change and rice has estimated the potential impacts of equilibrium doubled CO_2 climate change scenarios in many countries of Asia. This study finds that rice production in the Asian region is estimated to decline by 3.8 percent in the next century with substantial variations across the region. Decline in yield has been predicted for Thailand, Bangladesh, southern China, and western India, while an increase is predicted for Indonesia, Malaysia, Taiwan and parts of India and China. This prospect is reinforced by global climate models that are disaggregated to examine the effects of global warming in smaller regions (e.g., Lal et al., 1995, 1997; Pradhan, 1999; Saseendran et al., 2000; Aggarwal, 2002). Impacts of climate change on crop yields depend on both technological considerations and farmers' response to changing environmental conditions. Historically modest investments in agricultural research have enabled societies characterized by different native resources to achieve relatively rapid growth in agricultural production (Ruttan, 1991:27).

It is apparent that the issues of technological innovation have increasingly permeated discussions about the impact of climate change on agriculture (Rosenberg, 1992; Ausubel, 1995; Ruttan, 1996; Reilley and Fuglie, 1998). However, despite the importance accorded to technologies in agriculture, few researchers have investigated how differences in climatic resources induce technological changes (Smithers and Smit, 1997; Gitay, 2001). Furthermore, much of the attention on the effects of climate change on agriculture in developing countries has focused on its impact on crop yield and provides little agreement on the current and future adaptability of agriculture to a variable and changing climate. However, the effect of climate variability on innovation of technologies is a crucial factor in the calculus of impact on crop yield. In the following section, the theoretical foundation of the induced innovation hypothesis will be discussed in the context of climate change and agriculture.

Theoretical Framework

As stated earlier, this research will utilize the theoretical framework of the induced innovation hypothesis to examine the interaction between climate and technology as a foundation for understanding potential future agricultural adaptation to climate change and variability in Nepal. Induced innovation refers to the process by which societies develop technologies that facilitate the substitution of relatively abundant (hence, cheap) factors of production for relatively scarce (hence, expensive) factors in the economy. Although the hypothesis of induced innovation was originally based on the experience of agricultural development the United States and Japan (Hayami and Ruttan, 1985), lately it has been used to explain the complex process of technological and institutional change, which represents a major perspective on international agricultural development (Koppel, 1995). The most fundamental insight of this hypothesis is that *investment in innovation of new technology is the function of change (or difference) in resource endowment and the price of the resources that enters into the agricultural production function*. This has spawned a conceptual infrastructure that addresses the broader issues of how farmers and their supporting institutions determine priorities for agricultural production.

Technological innovation in agriculture does not evolve with respect to climatic condition alone; non-climatic forces such as economic and political environment clearly have significant implications for innovation and adaptation of new technologies (Bryant et al., 2000). However, in this research I argue that, along with other non-climatic factors, technological innovations in the rice-based farming system in Nepal are made routinely in response to the variable climatic conditions of the country.

Climate is one of the important resources for crop growth and development. While specific climatic requirements for agricultural production vary among geographic regions, the most important ones are soil moisture, heat, and sunlight. As shown in Figure 1.1, climate change may alter these climatic resources by changing growing season length and soil moisture regimes, and by adding heat stress to the plant. Such changes, following the hypothesis of induced innovation, will provide appropriate signals to farmers and public institutions to induce technologies suitable for the new environment. Translating this argument, as presented in the conceptual model, the induced innovation hypothesis suggests an important pathway for the interaction of climate and technology and for the study of the agricultural adaptation to climate change.

The strength of this simple framework lies in its ability to highlight the central role of climate as a motivator of technological innovation and ultimately as a source of adaptation. Within this conceptual framework, I will examine the role of spatial variability in climate as an incentive to the innovation of technologies in the Nepalese agricultural system. My argument will detail expected technological responses of Nepalese agriculture to future climate change.

One of the assumptions made by the induced innovation hypothesis is that when agents of production (e.g., farmers, public institutions) experience problems with change in resource endowments such as that, perhaps, brought about by climate change, they are likely to seek new knowledge that will help overcome these constraints. The change in resource endowment (see Figure 1.1), therefore, may solicit an adaptive response whereby farmers and their supportive institutions may adjust management techniques and the allocation of resources to offset the effect of climate change. More specifically, in a society (e.g., Nepal) where land is already a scarce resource due to the combined effect of population growth and unfavorable climate for crop growth and development, as the pressure to grow food on climatically less favored areas continues, the marginal cost of production increases relative to the marginal cost of production via the application of technologies. Eventually societies will reach a stage where land augmentation will become an appropriate means of increasing agricultural output. This will ultimately lead to the development of technologies based on climatic resources of an area. This may be through the adoption of location-specific crop varieties combined with other management strategies, such as efficient irrigation or application of chemical fertilizers.

Hypothesis of the study

Based on the analytical framework discussed in the previous section, I form a null hypothesis that *climatic limitations cannot be shown to provide incentives for farmers to urge their supporting institutions to invest in research and development of location-specific rice production technologies that substitute for climatic scarcity*. How far the historical evidence of technological substitutions made in response to climatic limits are relevant to future climate remains an open question, but it is reasonable to expect continuity in the response strategies by farmers and their supporting institutions to a new crop growing environment in the same manner that they are responding to climatic limits in the past and at present. It is within these premises that the hypothesis of induced innovation has been used as a framework to study the extent to which technological innovation has provided farmers with options for adaptation to mitigate potential climatic risks in the rice-based cropping system in Nepal.

This leads to two working hypotheses for this study. The first hypothesis is that *the farmers and the research establishment in Nepal have devised location-specific cropping technologies to reduce the climatic risks in rice production leading to the convergence of rice productivity across climatically diverse districts of Nepal*. The location-specific[1] technological innovations that are devised by the agricultural research establishment of Nepal not only have been an increasingly important source for reducing climatic risks in rice production, but also they are an important factor of growth in rice productivity. I believe, in the future, Nepal's agricultural research establishment will remain sensitive and active in devising technological innovations to ameliorate the negative effects of climate change.

The second hypothesis is that *the technological innovations appropriate for different climatic regions of Nepal are the result of conscious policy choices to allocate necessary resources for research.* In Nepal, I argue that technological innovations in agriculture are made routinely in response to the climatic conditions of a region in question. Over time, the subsistence agricultural system of the country has been gradually transformed into a more modern one through the introduction of new agricultural techniques and irrigation infrastructure; a deliberate policy strategy to

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[1] Rice production technologies that are appropriate for one part of the country are not, in most cases, transferable to other parts with different climatic conditions. It is therefore important to devise location-specific technologies to be able to adapt to the resource endowments of a geographic region.

increase food productivity. For example, traditional rice and fallow rotation has been replaced by a more intensive production system in which rice and wheat are double cropped within the same year (Moris et al., 1994). This became possible only after the introduction of early maturing varieties of rice and wheat. Similarly, in areas with adequate irrigation, farmers began replacing traditional varieties of rice with the improved ones (Brown and Shrestha, 2000). This is largely in response to the growth in demand created for rice. The rice-based cropping system of Nepal has experienced adaptation of improved technologies such as high yielding varieties (HYVs) of rice, increased use of chemical fertilizers, and pesticides, as well as has benefited from the expansion of infrastructure such as irrigation (Thapa et al., 1994) – all pivotal in achieving greater food security.

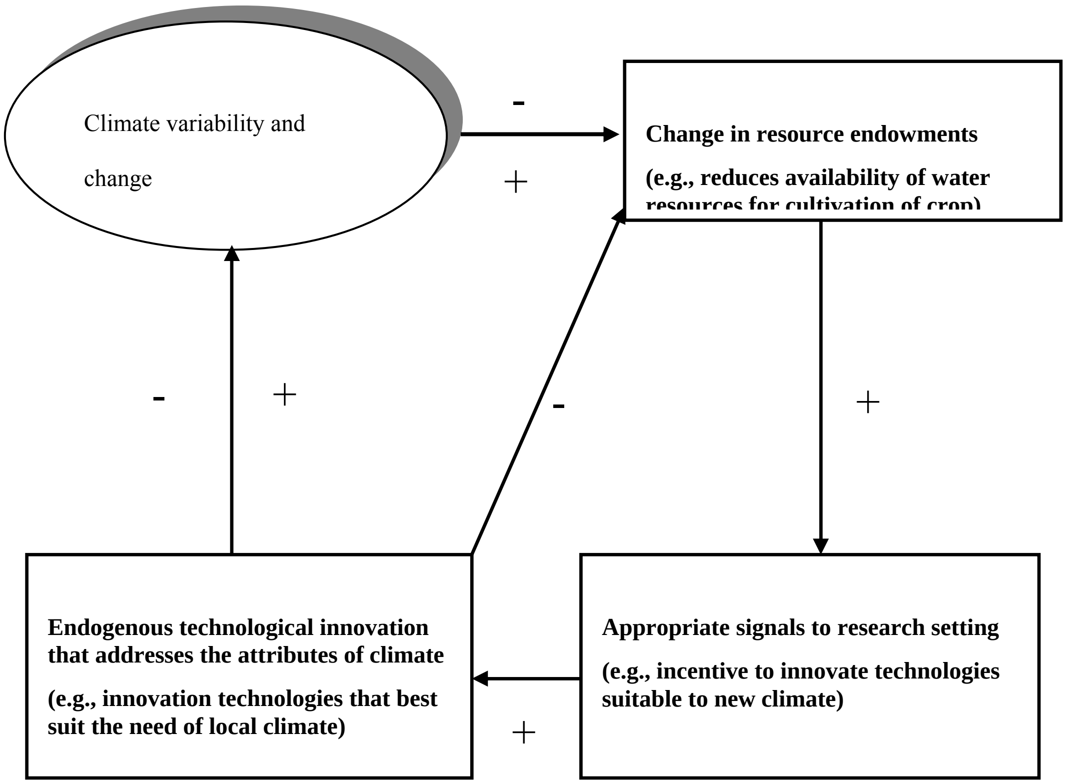
Focus of the Research

Climate is the natural endowment of a geographic region that greatly influences the many decisions about agricultural production (Lovell and Smith, 1985). For example, a typical rice farmer in Nepal may consider plentiful monsoon rainfall as a favorable climate and hence highly desirable for rice production. In contrast, regions with less than adequate monsoon rainfall can be considered as inferior for rice production. However, I argue that technological advances made in response to scarcity of climatic resources such as rainfall will alleviate these constraints by compensating for climate. Theoretically, this process may enhance productivity of rice, leading to convergence of yield across geographic regions over time even when climatic conditions are very different. By treating climate as a factor of production in the process of technological development in the rice-based cropping system of Nepal, this dissertation extends the conventional boundaries of the hypothesis of induced innovation.

As mentioned earlier, this research will use time-series data on rice productivity across the 73 districts of Nepal to test whether technological innovation made in response to climatic limitations provided opportunities for less productive districts to *catch-up* with the more productive ones over time. With this notion, I argue that continued growth in rice productivity over time is a function of a dynamic process of adjustment to existing spatial differences in climatic resources. This can have important implications for the analysis of adaptation of agriculture to future climate change. It is expected that the districts with less favorable climate will show greater rice productivity growth rates compared to districts with more favorable climate. Through the analysis of rice productivity convergence, I examine whether spatial variations in climatic resources condition the regional patterns of investment in rice technologies, and conversely if the process that constituted the adaptation to existing climate might ameliorate the negative effects of future climate change.

Preview

The reminder of this dissertation will consider the following topics. Chapter Two will provide an overview of agricultural setting of Nepal. This chapter will also discuss Nepal's agricultural research and development setting in its historical context. This is important because public research institutions are largely responsible for development and dissemination of improved technologies in agricultural development. In chapter Three, I will provide review of literature with focus on impact assessment and adaptation to climate change. I will elaborate on the significance of the theory of induced innovation, already introduced in this chapter, to provide the basis for the climate-induced innovation, highlighting the significance of this perspective in adaptation to future climate change. Chapter Four will detail the methodological approach of this dissertation, highlighting the importance of climate-induced innovation in Nepalese agriculture. The data and their sources will also be described in this chapter. Chapter Five will present the results and discuss the findings of this dissertation. The final and sixth chapter will summarize the findings and draw conclusions.



+ = positive change, - = negative change

Figure 1.1: Conceptual framework: climate-technological interaction

CHAPTER TWO

AGRICULTURE IN NEPAL: BIOPHYSICAL AND TECHNOLOGICAL CONSIDERATIONS

Understanding the potential impact of climate change on agriculture in Nepal is critical for two reasons. First, the existing system of food production in the country is highly climate sensitive because of its low level of capital and technology. Second, agriculture is the main source of livelihood for the majority of the population in Nepal. Over 88 percent of Nepal's population lives in rural area, and 80 percent of this population over 15 years of age is engaged in agriculture (HMG/ADB, 1995). Nearly two-thirds of the rural household income is derived from agricultural activities, and 8 out of 10 people working in the agriculture sector are self employed farmers. Agriculture is the only activity in which 90 percent of the poor and very poor can earn some cash (IBRD, 1998). The consequences of an adverse climate change could therefore significantly affect food security of the country and the well-being of the Nepalese people, in which the average per capita calorie intake is already among the lowest in the world.

Given the importance of the effects of climate change on agriculture, the paucity of research related to the relationship between climate and agricultural productivity is cause for concern. As discussed in the previous chapter, understanding technological innovations made in response to environmental considerations in the past can be a guide for policy aimed at increasing the efficiency of adaptation to future climate change. Thus, knowing how Nepal has addressed climatic constraints in the past can offer insights about the process by which the country may respond to climate change in the future.

This chapter begins with a discussion of Nepal's biophysical characteristics, climate, and agricultural system, all of which provide the context for this research. This is followed by a brief history of the country's agricultural research and technological development, chronicling innovations made to address the agro-climatic variations within the country.

Biophysical characteristics

Nepal's oblong 147,181 square kilometers of land mass is located between 26° 22' to 30° 27' north latitude and 80° 14' to 88° 12' east longitude, between India and China. It extends 885 kilometers in the east-west direction and has a non-uniform mean width of 193 kilometers from the north to south. It is a landlocked country, bounded on the east, south, and west by India and on the north by the Tibetan autonomous region of the People's Republic of China (Figure 2.1). For administrative purposes, the country is divided into five development regions: eastern, central, western, mid-western, and far-western, which are further divided into 14 zones and 75 districts. The districts are the smallest administrative entity in the country and have been used as units of observation for this research. Kathmandu is the capital city.

Nepal's diverse terrain is comprised of five distinct physiographic regions including the flat plains, or the Terai, in the southern part of the country, rising to the middle hills or the Siwaliks, and to even higher elevations categorized sequentially as Middle Mountains, High Mountains, and High Himal, the latter forming the highest mountain ranges in the world (see Figure 2.2). Each of these regions represents a well defined geographic area with distinct geomorphology, climate, and hydrological characteristics that significantly different from each other. However, for the purpose of planning agricultural development, the country has traditionally been categorized into three ecological regions: the Terai (flat plains and southern portions of the Siwaliks), Hills (northern portions of the Siwaliks and middle mountains), and Mountains (high mountains and high Himal). For my research, I use the three ecological zones as proxy to the biophysical characteristics of the country. In the following sections, I describe each ecological zone separately.

The Terai is a 26 to 32 km wide band of alluvial and fertile plain rimmed by the foothills of the Siwalik range in the north and interspersed with fertile valleys, which extends east to west along Nepal's southern border with India. The Terai consists of 20 districts covering approximately 23 percent of the total land area and is home to over 45 percent of the total population (IBRD, 1998). The region is also known as the granary of Nepal and accounts for over 55 percent of the cropped area. The Siwalik range is an intricate geomorphological terrain and encompasses a smaller range of hedge-shaped hills called the Chure that rise abruptly from the plains and run east-west across the country, as well as a number of low-lying flat valleys called "Duns." The Duns, also called Inner

Terai, resemble the Terai in relief and climate. Such a complex system of biophysical characteristics naturally gives rise to a wide variation in climate, as well as agricultural practices (Chalise, 1994).

The climate is subtropical with hot, humid summers and mild winters. Average summer temperatures range from a maximum of more than 40^0C in the western Terai to about 30^0C in the valleys. In winter, average temperatures range from a maximum of about 23^0C in the western Terai to a minimum of 12^0C in the valleys (Shrestha et al., 1999). Likewise there is a significant spatial variation in the average annual rainfall ranging from as low as 250mm on the leeward side of the Mountains to as high as 4,000mm on the windward side. In general, eastern Nepal is the wettest receiving approximately 2,500 millimeters of rain annually, the central region receives about 1,420mm, and western Nepal about 1,000mm, demonstrating a clear east to west gradient of rainfall pattern. A detailed discussion of rainfall will be provided in Chapter Four.

In the Terai, rice is the main crop and accounts for over 70 percent of the production. In areas with assured irrigation, two crops of rice – early and summer – are grown annually. Early rice is planted in February/March and harvested in May/June and the summer rice is planted during June/July and harvested in October/November, followed by wheat in the winter (Ghimire, 2004). In areas with no assured irrigation, two crops, either summer rice followed by winter wheat or relay cropping of pulses with rice, are grown annually. In dryland areas, where rice cultivation is not possible due to inadequate water supply, maize is planted in early summer followed by mustard (a cash crop) in early fall.

The Hills is a wide belt of land aligned east to west in the middle part of Nepal, bordered by the Mahabharat range in the south and the High Mountains in the north. The Mahabharat, which runs north of and parallel to the Chure range, separates the Terai from the Hill region. The altitudes of the Mahabharat range from 1,525 to 4,877m, its structure is synclinal, and its topography steep and jagged (Chalise, 1994). There are 39 districts in this region and it accounts for 42 percent of the total landmass. This belt covers approximately 38 percent of the cropped area, offers a great variety of micro-climates ranging from sub-tropical humid valleys to temperate hill slopes, and has many different land-use patterns. Forests are usually found on the higher elevations, whereas the lower and gentler slopes are intensively terraced for agricultural purposes. The fertile valleys formed by major river systems, including the Katmandu Valley, are the main settlement and cultivation areas in the Hills.

Agricultural production in the Hills is determined by various factors including altitude, rainfall, slope, and aspect. The agricultural land in the Hills comprises two broad land types, *Khet* and *Bari* land. The term *Khet* land refers to a type of land where water is held for considerable period of time by earth bonds to create favorable conditions for rice cultivation. In the hills, this is created through the construction of bunds around the edge of leveled terrace (see Figure 2.3) so that uniform depth of water is maintained throughout the field. The *Khet* lands have high potential for crop production and are found in river terraces, alluvial valleys, and south-facing hill slopes. In the *Khet* land, rice and wheat based cropping prevails, whereas in the drier *Bari* land, maize and millet-based cropping patterns prevail.

The Mountain region, adjoining the Tibetan plateau in the north, has an insignificant percentage of land suitable for agriculture. There are 16 districts in this region, which accounts for 35 percent of the total land area and represents approximately 7 percent of the cropped area (Chalise, 1994). Much of the mountain region above 5,000 meters lies under the realm of snow and ice, although the permanent snow line may vary according to aspect and gradient. Snowfall in the winter occurs at an elevation of 2,000 meters and is much heavier in the western part. Winter is long and harsh, and the short summer is the only crop-growing season for mountain farmers. Though cultivation is practiced up to 4,500 meters of elevation, due to moisture and temperature limitations, farmers only grow one crop of buckwheat, barley, or potato per year or once every two years, accounting for about less than 5 percent of crop production. Rice and wheat are grown in the fertile river valleys. Livestock, such as sheep, goats, and yaks, are commonly reared on pastureland that is not suitable for cultivation.

Climate of Nepal

Nepal lies in the subtropical climate belt. Within the country, however, the climate ranges from humid subtropical in the southern Terai to alpine climate in the Mountains. This is largely due to tremendous variation in topography and altitude (60 to 8,848 meters above sea level), as described in the preceding paragraphs. The snowline is found at elevations of around 2,000 meters in winter and 4,500 meters in summer. The mean annual rainfall is estimated at 1,600 mm, but there is a considerable spatial variation (Chalise, 1994).

The most outstanding feature of Nepal's climate is the monsoon precipitation, which is characterized by two distinct phases: the "wet" and the "dry." The wet phase (June-September) refers to the summer season, when warm and moist winds enter the country from the southeast. Over 75 percent of the annual precipitation occurs during this phase (Webster, 1987; Shrestha et al., 2000). The monsoon, which is highly variable across space and time, is first experienced in the northeastern parts of the country and gradually moves westward with diminishing intensity. The variation in the pattern of rainfall from east to west is substantial and is further accentuated by the diverse terrain within each physiographic belt (Land and Barros, 2002; Kansakar et al., 2004), creating many micro-regions with differing agricultural conditions. The amount of summer monsoon rainfall decreases substantially as it moves to the northwestern part of the country (Land and Barros, 2002). Not only the amount of summer monsoon becomes less the number of days with rainfall decreases as the monsoon circulation progresses toward the western part of the country, creating variable climatic regimes for rice cultivation (Kansakar et al., 2004). The dry phase (December-January) is the period when the direction of the winds reverse to bring cool and dry air from the northwestern part of the country (Webster, 1987). While precipitation is comparatively weaker during this time, winter rain tends to be more concentrated in the western part of the country than in the east.

The annual cycle of the monsoon determines the practice of agriculture in Nepal, especially rice cultivation. Due to the disproportionate amount of the monsoon rains, variability in the monsoon is a significant factor in governing rice-cropping practices and variability in yields. Interannual variability is also a most distinguishing feature of the monsoon circulation (Shrestha, 2000). The date of its commencement at a given location is highly variable. Several recent observational studies have established that there is a strong association between El Nino/Southern Oscillation (ENSO) and monsoon rainfall in the Indian subcontinent (Sukla and Mooley, 1987; Webster and Yang, 1992; Parthasarathy et al., 1994; Lau and Yang, 1996; Soman and Salingo, 1997; Kripalani and Ashwini, 1997; Webster et al., 1998). In essence, drought year(s) in the Indian subcontinent are often, but not exclusively, related to warm sea surface temperatures (SST) in the equatorial central and east Pacific (El Nino), and wet year(s) are related to abnormally low SST (La Nina). However, there are notable exceptions. For example, in 1994, the Southern Oscillation Index (SOI) was negative and warm SST prevailed in the central and east Pacific. Based on the El Nino conditions, a slightly dry monsoon was predicted for the Indian subcontinent. In fact, the monsoon proved to be one of the strongest on record with seasonal rainfall that was over 10 percent higher than normal (Soman and Salingo, 1997).

Recent work on the impact of El Nino/La Nina on the Indian monsoon by Kripalani and Ashwini (1997) suggests that during the ENSO warm (cold) extremes the majority of episodes in the Indian monsoon include below (above) normal rainfall. However, they conclude that the epochal behavior of the Indian monsoon is not just forced by El Nino/La Nina condition events. Consistent with the findings of Kripalani and Ashwini, Webster et al. (1998) found a high correlation between the drought years in the Indian subcontinent and El Nino year in the Pacific Ocean. However, not all drought years were El Nino years. Similarly a large numbers of wet years were not associated with La Nina years. Even if the monsoon rainfall in the Indian subcontinent and ENSO relationship is far from perfect, there is a consensus that they are related in some fundamental manner and contribute to the interannual variability.

Abnormally wet or dry monsoons have also been directly responsible for frequent famines in certain parts of the country. Generally lower than normal or spatially variable monsoon rains are considered to be a cause of concern. Using the database developed by the Indian Institute of Tropical Meteorology for the years 1871–1997, Parthasarathy et al. (1994) report 21 major drought and 19 flood years when precipitation was at least ±10 percent below or above normal in India. Though neighboring Nepal lacks such a database, by virtue of lying in the same monsoon path, such findings hold true. Thus the effect of these extreme climatic events on agriculture should not be underestimated. Impending climate change may increase the intensities of these extreme events (Kripalani and Ashwini, 1997).

Climate change: observed trends and future projection

Analysis by Shrestha et al. (1999) shows a general warming trend in Nepal. The temperature differences are most pronounced during the dry winter season, and least when the monsoon peaks. The study also finds significant warming in the higher elevations of the Hills and Mountains in the western half of the country compared to the lower elevations in the south. The eastern part of the country shows no significant trends of warming.   Similar findings have also been observed by Liu and Chen (2000) on the leeward side of the Himalayas, on the Tibetan Plateau.

Unlike temperature, there is no evidence of change in aggregate precipitation (Shrestha et al., 2000). However, studies conducted to examine stream flow show an increase in number of flood days in certain rivers (Shakya, 2003). Significant glacial retreat, as well as aerial expansion of glacial lakes in the high mountain region, has also been documented in recent decades (Country Study Team, 1997), and there is a higher likelihood that such change is related to rising temperature (Agrawala, et al., 2003). Glacial retreat not only contributes to the variability in river and stream flows, but also can be an additional source of risk to agricultural activities in the valleys.

If the observed trends of temperature change, as reported by Shrestha et al. (1999), are overlain on the prevailing patterns of rainfall of the country, they reveal a negative association between the amount of rainfall and general trends of warming (see Figure 2.4). For example, the Hills and Mountain regions of the western part of the country, which receive lower average rainfall, exhibit a higher degree of warming compared to the central and eastern Hills and Mountain, which are comparatively wetter. Theoretically, if this trend continues in the foreseeable future, the drier regions of the country will become even more so due to the projected increase in temperature. For farmers, such a prognosis imposes further challenges in their effort to ensure better food security.

The Organization for Economic Co-operation and Development (OECD) recently assessed the change in average temperature and precipitation in Nepal using over a dozen general circulation models (GCMs) (Agrawala, et al., 2003). There is a significant and consistent increase in temperatures projected for Nepal for 2030, 2050, and 2100 (see Table 2.1). Consistent with observational studies, the OECD studies reveal that the absolute increase in temperature is somewhat larger during the winter months than the summer months. While the study also projects an overall increase in precipitation, mostly during the monsoon season, it is not clear whether the existing rainfall patterns will remain the same or not. It is also not apparent how these changes will affect the timing and period of monsoon rainfall. The potential increase in monsoon precipitation in an area that has already experienced heavy rainfall may lead to more flooding. Conversely, areas with low monsoon rainfall may be subject to dryer conditions in the future. In short, it is difficult to make predictions with any degree of certainty.

Nepalese agriculture

The agricultural sector forms the *sine qua non* for overall development of the country (HMGN/ADB, 1995). Although agriculture's contribution to Nepal's Gross Domestic Product (GDP) is declining over time, dropping from 62 percent in the second half of the 1970s to 40 percent at the end of the 20th century (Thapa, 1994; Sungsup, 2001), it is still the largest sector of the economy, followed by the tourism and industrial sectors (ADB, 2003).

Table 2.2 displays the performance of agricultural GDP over the 10-year period from 1990/91 to 1999/00. During this period, the overall GDP grew at about 4.72 percent, but agricultural GDP increased only 2.70 percent – the lowest among all the major sectors. A more detailed analysis of the agricultural growth shows that the average agricultural growth was only 1.75 percent (less than population growth) during the first half of the decade, but increased to 2.94 percent during the second half, in line with the goal (3 percent) set in the Government of Nepal's policy document, the Agricultural Perspective Plan (APP) (HMGN/ADB, 1995).

The APP is a strategic document for agriculture development in Nepal developed in 1995 that aims to reduce the constraints imposed by climatic resources by developing irrigation infrastructure and promoting drought-resistant crop varieties in the country (HMGN/ADB, 1995). It also aims to increase the availability of agricultural inputs, such as fertilizers and pesticides. While other sectors, such as manufacturing and transport, remained the dynamic sectors of Nepal's economy during the 1990s with growth rates of 8.0 and 7.8 percent, respectively, agriculture was the only sector where growth increased during the later half of the decade. Although not robust, the encouraging growth of the agricultural sector is attributed to the increased supply of modern technology and improved seed varieties introduced by the government and private sector (HMGN/MOAC, 2000; Goletti, 2001; ADB, 2003).

Rice in Nepalese agriculture: In Nepal, like in most Asian countries, rice is an important staple crop followed by maize, millet, wheat, and barley. A rice-based cropping system dominates the agriculture sector of Nepal (NARC, 2000) and accounts for about 50 percent of total agricultural area and production in the country (Pokhrel, 1997). Rice supplies 38.5 percent of the dietary energy, 29.4 percent of dietary protein per capita, and 7.2 percent of dietary fat in Nepal (FAOSTAT, 2001). According to recent estimates, rice is grown on about 1.55 million hectares of land producing 4.45 million tons of paddy with the productivity of 2.85 tons per hectare (HMGN/MOAC, 2004). The crop is grown under a wide range of biophysical and climatic conditions.

Geographically, rice is grown in all agro-ecological zones ranging from the flat Terai (60-300 meters above sea level), the valleys and foot hills (300-1000 meters above sea level), to the high altitudes of the Hills and the Mountain (1500-3050 meters above sea level). Of the total rice cultivated area, 87 percent is in the subtropical climatic region of the Terai and valleys, about 10 percent is grown in the warmer regions of the Hills at altitudes ranging from 1000 to 1400 meters, and about three percent is cultivated in the higher altitudes above 1500 and 3050 meters – the highest elevations in the world known where rice can be grown (Adhikari, 2004). Although rice is grown under a wide range of climatic conditions, the growth in rice production is low (2.07 percent per annum) compared to the rate of population growth (2.2 per annum) (HMGN/MOAC, 2004).

The two major rice cultivation practices found in Nepal are irrigated and rainfed wetland (lowland). Both of these practices are common in all three ecological regions. In irrigated areas, water may be added to the rice field during the rice growing season as a supplement to rainfall. However, due to lack of irrigation infrastructure, rainfed wetland cultivation is the dominant practice for about 66 percent of the rice area (Pokhrel, 1997). Dependability of water supply, either through irrigation or from natural monsoon rainfall, and soil fertility are the major determinants of rice production. Traditionally, rice is sown in seedbeds in early or mid spring. Once the rice seedlings complete 3-6 weeks, depending on the availability of water, they are transplanted to the main field. Edges of the terraces are raised with earth bund to retain rain water, and those with access to irrigation are flooded through gravity fed channels.

Rice, maize, and wheat are grown on 1.55 million ha, 820 thousand ha, and 660 thousand ha, respectively (HMGN/MOAC, 2004). In the 1990s, the yield of rice in Nepal grew at an average rate of 1.33 percent compared to 0.74 percent in maize, -0.61 percent in millet, 3.23 percent in wheat, and 1.72 percent in barley (HMGN/MOAC, 2000). Although the rice yield in Nepal is low by regional standards, its production has improved over time (Goletti, 2001). As mentioned earlier, the growth in productivity is attributed partly to the shift in the use of HYVs. The adoption of HYVs has induced farmers to use other technological packages, such as the use of inorganic fertilizers and pesticides, a practice not followed when local varieties of rice are grown.

Agricultural research and development in Nepal

Table 2.3 presents the various structural changes that occurred in the agricultural research and development in Nepal between 1924 and 1997. Although the beginning of agricultural research activities in Nepal can be traced back to the establishment of the Department of Agriculture (DOA) in 1924, concerted effort in research and technology development in the country began after the overthrow of the century old Rana oligarchy in 1951. From the 1960s, agricultural research stations and farms were established in different parts of the country to test and modify technologies that were borrowed from other countries (Yadav, 1987; Pokhrel, 1997).

From the mid seventies the agriculture sector has consistently been accorded higher priority in the Five-Year Plans[2] (Thapa, 1994). For example, this sector's share of development expenditure increased to 25.6 percent with the fifth Five-Year Plan (1975/76-1979/80), during which agriculture was declared as the most important sector of the economy. The agriculture sector received the highest priority in terms of budget allocation during the sixth Five-Year Plan (1980/81-1984/85), when its total development budget increased to an all time high of 28.4 percent. The more recent Five-Year Plans, while still according importance to agriculture, place it behind the social service sectors such as education and health, in terms of national priority.

A new perspective of integrated research and outreach program began to emerge in the early 1970s, leading to the development of commodity-specific research programs in major cereal crops. In the mid 1970s, with the financial support of multilateral organizations such as the United Nations and the World Bank, the country formalized its first Ten-Year (1975-85) Agricultural Development Plan (HMG/NPC, 1970: 328). This document recognized the importance of location specificity in the performance and adaptation of new technologies and, hence, regional food security. For the first time in the history of agricultural research and development, policy makers of Nepal began to incorporate agro-climatic analysis as a strategy for research and development. To give

[2] A planning approach to development in Nepal began in 1956 with the formulation of First Five-Year Plan (1956-1961). The tenth plan (2002-2007) is presently underway.

the plan an initial boost, the Nepalese government observed the Fiscal Year of 1974/75 as the Year of Agriculture (Yadav, 1987). In the history of Nepal's agricultural development, the period after the early 1980s was marked as a period of the introduction and extension of HYVs that were responsive to chemical fertilizer and irrigation.

Consequently, this period led to the development of specific agricultural strategies for different ecological zones. For example, higher cropping intensity was emphasized in the warmer Terai, integrated crop and horticultural production in the more temperate Hills, and livestock production in the cooler Mountains. Once the Ten-Year Agricultural Plan was underway, the importance of site-specific research to evaluate new technologies in multiple environments became evident. This led to the development of a cropping/farming systems research approach in the early 1980s with the broader objective of integrated research on crop and livestock production system. Consequently, the research units of the DOA were amalgamated to form the National Agricultural Research and Service Centre in 1987. The latter became the present Nepal Agricultural Research Council (NARC). Although located within the MOAC, NARC is an independent research body mandated to conduct agricultural research and development (R&D) activities in the country (Gauchan et al., 2003), and is expected to devise appropriate technology for the diverse climatic and biophysical conditions of the country.

As NARC's institutional framework covers the periods of this research, it is described in greater detail below. NARC has been responsible for developing technologies that are sensitive to the need of Nepalese farmers. To date, there are 18 Regional Agricultural Research Stations (RARS) located in the various agro-climatic regions of the country. The RARS conduct research and outreach activities based on the climatic and socioeconomic needs of the farmers (Vaidya, 1998; Gauchan and Yokoyama, 1999). Responsibilities are decentralized to ensure that the individual RARS have flexibility to design and develop climatically appropriate cropping technologies. This includes engaging farmers as a part of an overall research design known as a participatory research approach. Promising technologies developed through the NARC systems are disseminated to the farmers' fields through the district-level government extension agents located in each of the 75 districts. These new technologies are first demonstrated in small plots with the active participation of farmers. The district level extension workers not only provide active supervision of these demonstrations, but also work as liaison between NARC and farmers. This feedback mechanism between the farmers and the research institutions allows researchers to incorporate specific needs of the farmers in their process of research and technology development.

In addition to the Outreach Programs through RARS, NARC also collaborates with international research institutions. For example the International Maize and Wheat Improvement Center (CIMMYT) in Mexico and the NARC farmer participatory research program are working on development of wheat and maize varieties that meets farmers' needs. Continued bilateral relationships between NARC and the International Rice Research Institute (IRRI) in the Philippines have fostered rice development activities in Nepal. The NARC Soil Science Division manages long-term soil fertility trials in collaboration with Cornell University in rice-wheat cropping patterns to study the impact of intensive cropping in soil quality in the region. Another example is the Farmers Field

Schools (FFS) of the Potato Research Program in integrated disease management. The Institute of Agriculture and Animal Science (IAAS) is the only institute that produces agricultural graduates who are most likely to be a part of the agricultural development experts in the country.

Furthermore, after the establishment of a democratic government in 1991, Nepal initiated a 20-year Agricultural Perspective Plan (APP) with the objective of alleviating poverty through the development of agriculture. The multiphase APP envisages a five percent increase in the annual growth rate of agricultural production and a doubling of per capita food availability (ADB/ HMG, 1995). The plan also aims to improve the supply of agricultural inputs (e.g., fertilizers, improved seeds and pesticides), increased availability of credit, improved irrigation infrastructure, generation of technology suitable for specific climatic niches, and creation of markets for agricultural products.

In recent times, APP has garnered growing importance in its ability to guide agricultural development policy in Nepal. For example, prior to 1997, the Agricultural Input Corporation (AIC), a public entity established in 1966, was the only institution for import, distribution, and sale of fertilizer in Nepal. Fertilizer was sold to farmers at a subsidized rate, which tended to benefit richer farmers more than poorer ones. The supply of fertilizer was erratic and often failed to achieve the desired objectives of increased access to fertilizer by the farmers. In 1997, the government deregulated the fertilizer sector. This was achieved by (a) removing the monopoly of the Agricultural Input Corporation (AIC) and allowing the private sector to import and distribute fertilizers, (b) phasing out fertilizer subsidies, and (c) removing the control over fertilizer prices. The new policy sought to enhance agricultural productivity through increased, efficient, and balanced use of fertilizers. This is in line with the goal of the APP for the development of the agricultural sector for the period 1995-2015 (MOAC 2002).

National rice development policies and practices

The focus of technological innovation in agriculture in Nepal has always been on rice. This is attributed to the Green Revolution's introduction of the new seed-fertilizer technology (Ashby and Pachio, 1987). To maintain and increase food security of the country, the government of Nepal for the past 30 years has made significant investment in the agricultural sector including development of improved rice varieties and crop management technologies. Agricultural scientists have developed new technologies and HYVs of rice that adjust to environmental constraints that have been adopted by farmers (NARC, 1999). New cropping technologies have offered better and more options to farmers. New varieties of rice recommended for different ecological zones have extended the choices for farmers to adapt to different climatic conditions, such as early or delayed rainfall or mid-season drought.

The Coordinated Rice Research Program (CRRP), which functions under NARC, is mandated to develop rice rowing technologies including improved agronomic practices and varieties with higher yield potential. At the international level, CRRP coordinates with IRRI for new genetic materials and at the national level conducts research through active involvement of RARS. In the last 30 years, CRRP has released and recommended about 40 MVs of rice appropriate for various climatic conditions of the country (HMG/MOAC, 2000). Although farmers are selective in accepting MVs of rice owing to risks associated with rainfall variability and grain quality, the area covered by these improved varieties of rice has increased steadily over time. In the early 1990s, the area covered by MVs of rice was estimated to be about 46 percent (Thapa, 1994), which had risen to 71 percent by the end of the decade (Goletti, 2001). Depending on their various characteristics, MVs of rice may offer possible stability and higher yields, which suggest resiliency under climate change.

Synthesis

In the past 50 years, the process of agricultural research and technology development in Nepal has evolved from conducting adaptive research in the 1950s and integrating farming systems research in 1980s, to the development of site-specific research to evaluate new technologies in multiple environments in the 1990s. To date, the research establishment responsible for generating technologies in agriculture has been actively engaged in the innovation of technologies sensitive to the needs of farmers operating in various climatic conditions (Subedi, 1998). New technologies continue to penetrate isolated communities in response to needs generated by socioeconomic conditions and physical climate (Brown and Shrestha, 2000). Scientific innovations have been deliberately targeted to encompass the needs of farmers in different agro-climatic conditions through crop improvement programs, such as development of varieties, improvement of irrigation infrastructure, and increased availability of improved seeds and fertilizers.

Do differences in climate across regions (districts), particularly differences in rainfall and other biophysical conditions, influence innovation in agricultural technology? Do local climatic limitations to crop growth and development provide incentives for farmers and their supporting institutions to invest in research and development of appropriate technologies to overcome those limitations?- need to be answered. The importance of these questions underscores the essence of this dissertation as it relates to the understanding of the impacts of climate change in rice-based cropping systems in Nepal.

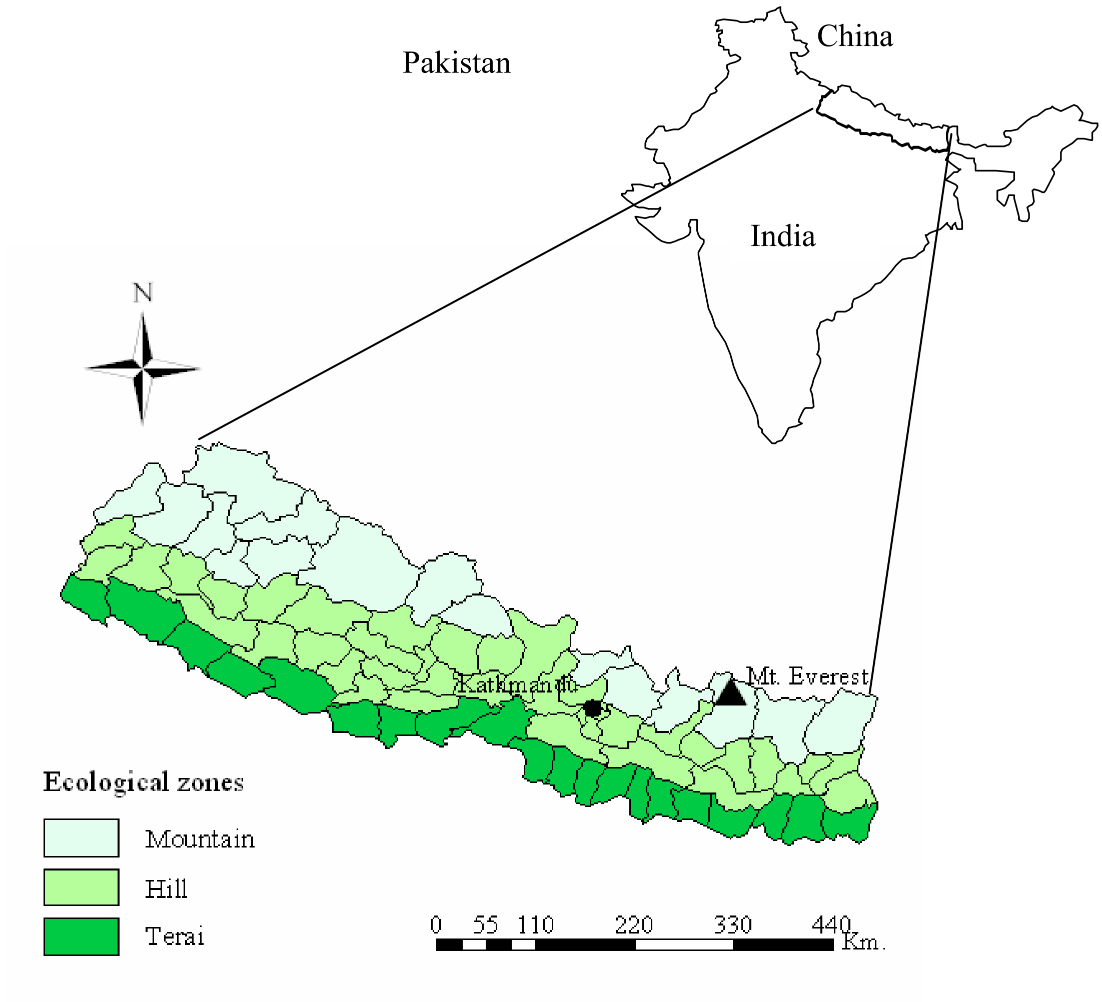


Figure 2.1: Map of Nepal showing three ecological zones

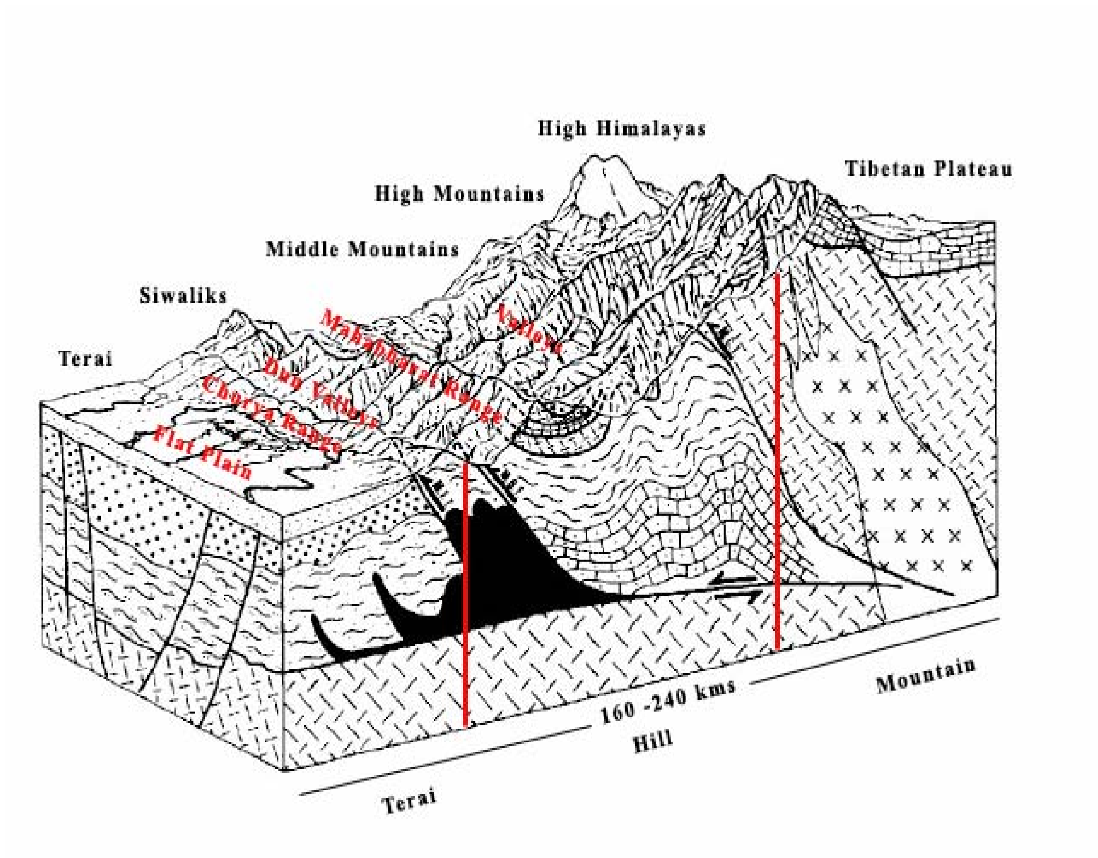


Figure 2.2: Physiographic regions showing microclimates within the broader ecological zones of the Terai, Hill, and Mountain of Nepal

Source: Agrawala et al., pp 10

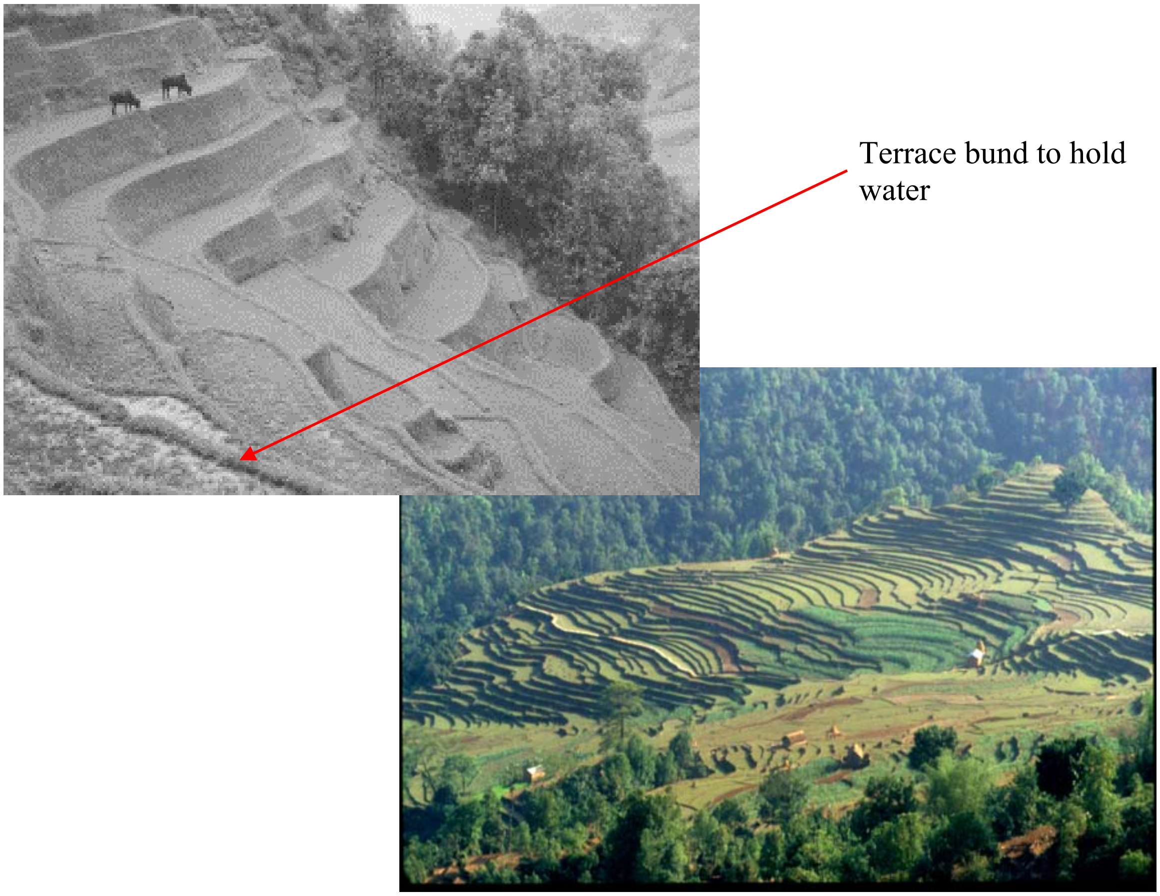


Figure 2.3: A typical representation of rice terraces in the Hills of Nepal

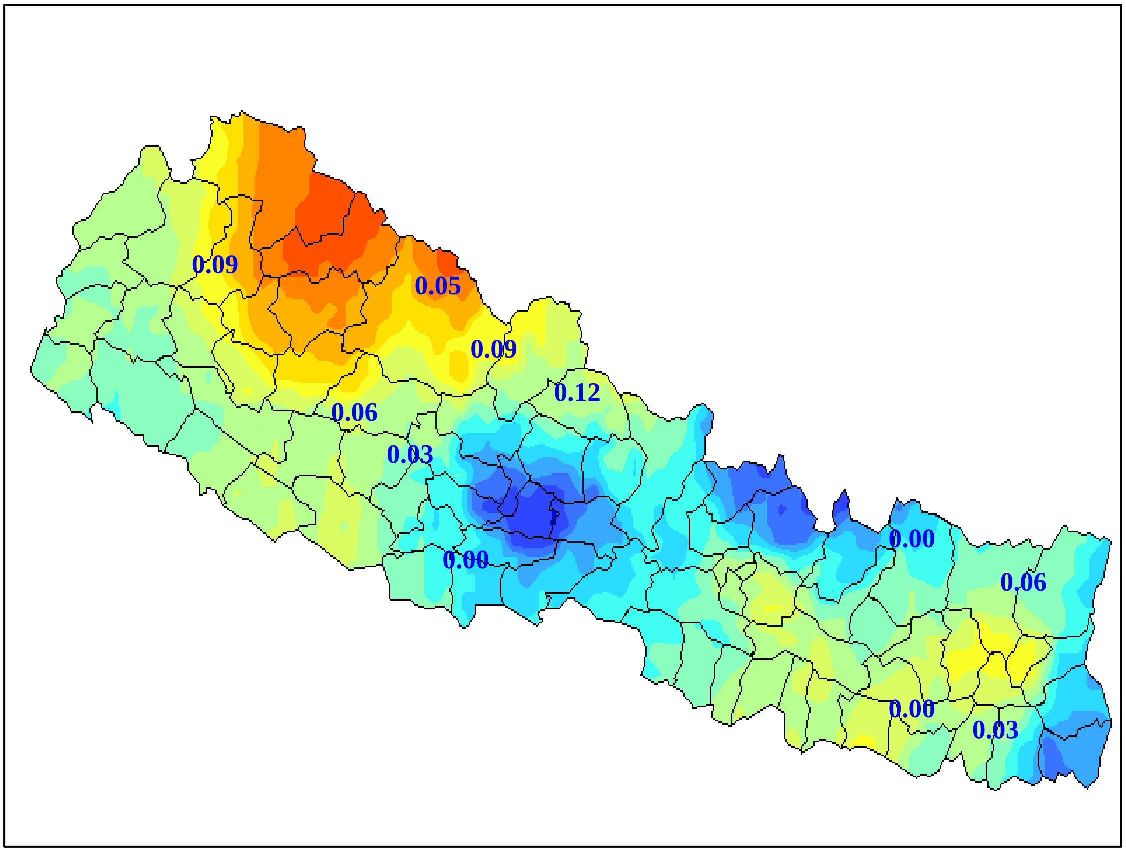


Figure 2.4: Observed trend in temperature change and rainfall surface in Nepal

Source: Temperature trend was derived from Shrestha et al., 1999 and rainfall surface was created through Kriging interpolation using average monsoon rainfall data from 196 meteorological stations across the country.

Year	Temperature change (^{0}C) Mean (standard deviation)			Precipitation Change (percent) Mean (standard deviation)		
	Annual	Winter	Summer	Annual	Winter	Summer
2030	1.2 (0.27)	1.3 (0.40)	1.1 (0.20)	5.0 (3.85)	0.8(9.91)	9.1(7.15)
2050	1.7 (0.39)	1.8 (0.58)	1.8 (0.29)	7.3 (5.56)	1.2(14.39)	13.1(10.2)
2100	3.0 (0.67)	3.2 (1.00)	2.9 (0.51)	12.6(9.67)	2.1(25.02)	22.9(17.8)

Table 2.1: Estimated change in temperature and precipitation for Nepal

Source: Agrawala et al., 2003:16. Estimated change in temperature and precipitation are derived from the output of seven General Circulation Models (GCMs) used for estimating the impacts of climate change in hydrology of the Himalaya region

GDP Component	Growth Rates Over Period			Percent Change
	1991-2000	1991-1995	1996-2000	
Agriculture, Fisheries, and Forestry	2.70	1.75	2.94	0.68
Mining and Quarrying	5.59	4.76	3.79	-0.2
Manufacturing	8.07	11.89	6.57	-0.45
Electricity	5.78	5.78	3.89	-0.33
Construction	5.55	6.01	4.87	-0.19
Tourism and Trade	5.39	6.72	4.78	-0.29
Transport and Communication	7.81	8.80	7.31	-0.17
Finance and Real State	5.63	5.56	5.25	-0.05
Community and Social Services	5.98	7.39	5.05	-0.32
Total GDP	4.72	4.83	4.47	-0.07

Table 2.2: Components of GDP and their growth rates

Source: Statistical Yearbook, 2000/01

Year	Events
1924	Establishment of the Department of Agriculture (DOA)
1947	Establishment of Agricultural Research Station (ARS) in the central Terai region of Nepal
1950s	More ARS established to test and modify exotic technologies for application in Nepalese conditions
1966	The institutional framework of the DOA was expanded by creating more divisions. For example, the creation of Division of Agricultural Education and Research (DAER), which was responsible for cereal crop research in Nepal
1971	A separate commodity-specific research program on major cereal crops (rice, wheat, maize) was initiated by the DAER
1972/73	The National Rice Improvement (NRI) program was created to test and develop new high-yielding rice technologies in the country
1985	Establishment of National Agricultural Research and Services Centre (NARSC) to strengthen and coordinate research activities of the DOA
1990	NARSC became the Nepal Agricultural Research Council (NARC), an autonomous institution governed by a board, headed by the minister for agriculture
1992	Nepal's government drafted a law to give NARC a greater flexibility and freedom to operate agricultural research and development in the country
1995	The government of Nepal initiated a 20-Year (1995-2015) Agricultural Perspectives Plan (APP) with the goal of developing agricultural sector by making fertilizer supply and irrigation as one of the principal priorities to improve household food security
1997	Government took the decision to deregulate the fertilizer sector

Table 2.3: Agricultural research and development in Nepal, 1924-1997

Source: APP (1995); Pokherel (1997); HMG/MOAC (2002)

CHAPTER THREE

ADAPTATION TO CLIMATE CHANGE: REVIEW OF LITERATURE

Introduction and definition

As the issue of climate change gained scientific and public attention in the early 1980s, interest in its potential impacts on agriculture intensified. The sensitivity of crop production to climate makes agriculture vulnerable to the risks associated with climate change. While it is generally acknowledged that climate change may not imperil the ability of world's agriculture to maintain food security, it does, however, challenge farmers to adapt in regions where it may be stressful or new climate-induced opportunities are unanswered. Therefore, interaction with climate, particularly in light of climatic adaptation, is considered an important policy option in climate change impact studies.

While the concept of adaptation is relatively new to the climate change research community, it has a longer history in other fields of natural sciences such as in evolutionary biology and ecology (Holling, 1973; Winterhalder, 1980). Adaptation, in the latter, refers to genetic and morphological abilities of individual species to survive and reproduce in the environment they inhabit (Slobodkin and Rappaport, 1974). In ecology, adaptation is consistent with the concept of resilience. For example, Holling, a systems ecologist (1973; 1997) defines it as the degree to which a system can withstand disturbances and still come back to steady state after the shock. He uses ecological concepts (e.g., resilience and stability) to describe the propensity of biological systems to adapt to changing conditions. Social systems, including agriculture, do adapt to changing climatic conditions in the same way that ecological systems do (Smithers and Smit, 1997). Unlike ecological systems, however, social systems have the ability to plan for adaptation in pursuit of social goals for meeting the demand of food.

More recently, the concept of adaptation has had wider application and is studied in many scholarly fields such as cultural geography, human ecology, natural hazards research, ecological anthropology, political ecology, and, more recently, climate change research (Blaikie and Brookfield, 1987; Chioti and Johnson, 1995; Smithers and Smit, 1997; Adger et al., 2000; Berkes and Jolly, 2001). In climate change literature, researchers have increasingly considered the notions of vulnerability and resilience to understand the potential impacts of climate change (e.g., Kasperson, 1991). Drawing on concepts from ecology, discussed earlier, scholars argue that the nature of response to climatic disturbance is influenced by the ability of a system to cope and withstand changes.

Some analysts, particularly from natural hazards research, have examined the ability of agricultural adaptation from the perspectives of social, political, and institutional forces that causes some regional variations in adaptation to climate change (e.g., Chiotti and Johnson, 1995; Adger, 1999; Kates, 2000; Eaiken, 2000). Others, particularly cultural geographers such as Blaikie and Brookfield (1987), Watts and Bohle (1993) and Bohle et al., (1994), argue that climate is one of the many factors that determine the adaptive capacity of the farmers. They use social issues, such as the issue of distribution, entitlement, and acquisition of knowledge, to model household level behavior on agriculture adaptation. In addition to its role in impact assessment, adaptation is also considered an important response strategy or policy option to manage the impacts of climate change (Smit and Skinner, 2002).

While the extent of impact of climate change on agriculture depends partly on the nature of climate change, it also depends on the ability of society to adapt or to exploit perceived opportunities (Smithers and Smit, 1997). Research shows that without adaptation, climate change is generally problematic for agricultural production (e.g., Reilly et al., 1996; Gitay et al., 2001). In general, adaptation may lessen future yield losses due to climate change or may improve yield in regions where beneficial climate change occurs. Figure 3.1 shows changes in yields with and without adaptation for the world in general, and in developed and developing countries in particular. Each vertical bar in the figure represents the range of percentage change by region, with and without adaptation. Although vulnerability of agriculture, *defined here as the extent to which change in climate may damage food production from climate change net of adaptation*, is greater in developing countries compared to the developed countries, in both cases adaptation clearly ameliorates losses in yield. Moreover, the general perception that developing countries will be inadequately prepared to avoid the impact of climate change has added the impetus to promoting adaptation.

Mitigation and adaptation represent the two main issues in the climate change literature (Smithers and Smit, 1997). Mitigation research focuses on measures to reduce the emission of green house gas, including sequestration of carbon. Scholarly work on adaptation assumes that climate change, to some extent, is inevitable and focuses on measures that reduce the threats from deleterious climate change (Kates, 2000). Therefore, adaptation in climate change literature is described as human actions taken in response to experienced or expected threats of changing climatic conditions to reduce impacts or to take advantage of the opportunities posed by new climate (e.g., Smit et al., 2001; Burton et al., 2002; Tompkins and Adger, 2003). In this dissertation, following Easterling et al. (2004), the term agricultural adaptation is used to mean *human adjustments in agricultural systems that enhance systems' abilities to cope with external stresses particularly due to climate change.* Hence, adaptation refers to all responses that may be used to reduce severity or actions designed to take advantage of new opportunities that may arise as a result of climate change. Agricultural adaptation, in this premise, is not a new concept and is a fundamental human trait (Burton et al., 1998; Redman, 1999). Most impact studies routinely make assumptions about the expected adaptation of the system in question (Tol et al., 1998). The main interest in the adaptation literature, therefore, is to predict the circumstances under which adaptation can be expected.

Historically, societies have shown a strong capacity for adaptation to social and climatic stimuli, which can be used as an analog of climate change due to global warming (Glantz, 1996). Agricultural systems have adapted to changing economic conditions, technology, and resource (climatic and non-climatic) availabilities, and have kept pace with growing population (Rosenberg, 1982). Society is capable of devising a wide range of technologies and social strategies to cope with variable climatic conditions. It has learned to thrive in a wide range of climatic conditions, spanning from extreme cold to hot and from very dry to a humid climate (Easterling et al., 2004). It is therefore reasonable to expect that farmers and their supporting institutions respond to new crop growing environments brought about by climate change the same way they have responded to climatic limitations in the past.

The role of adaptation in modern agriculture

Although a future climate caused by global warming may be very different from the one that society has experienced in the past, insights for agricultural adaptation that confront us today may well be found in the experience of how climatic challenges were handled in the past (Glantz, 1996). Case studies on technological substitutions in response to existing variability in climatic resources include crop translocation across different climatic gradients and development of new agronomic practices to deal with changing social and climatic conditions.

The development of cowpea cultivars in the African Sahel and the growth of soybean in Ontario, Canada illustrate the examples of technological substitutions in response to existing variability in climatic resources. To escape the effects of drought, scientists in the African Sahel have developed early maturing cowpea cultivars with different phenological characteristics. For example, to avoid the effects of late season drought, they have developed cowpea varieties (*Ein El Gazal* and *Melakh*) that mature between 55 – 64 days after planting (Elawad and Hall, 2002). Similarly, to avoid mid-season drought, scientists have also developed a cowpea variety (*Mouride*) that matures between 70-75 days after planting (Cisse et al, 1997). Unlike *Ein El Gazal* and *Melakh*, that begin flowering between 30-35 days from sowing and have synchronous flowering characteristics, the *Mouride* variety starts flowering in about 38 days after planting and spreads out over an extended period of time, thereby escaping the midseason drought. To enhance the chances of significant grain production, agriculturists in this region have developed cropping techniques where both types of cowpea (short and medium maturing) are planted together so that variable climatic input is optimized (Hall, 2004).

Although soybean was cultivated in Ontario throughout the 20th century, it was not a prominent field crop until the 1970s. Between 1970 and 1997, the total acreage planted to soybean increased by over 500 percent, with the expansion being attributed to a series of technological innovations made in response to the climatic condition of Ontario (Smithers and Blay-Palmer, 2001). A fundamental climatic constraint to soybean cultivation in Ontario was the prevalence of cold night temperature during flowering, confining soybean cultivation to the extreme southwestern portion of the province. A key innovation to address this constraint was the introduction of cold-tolerant genetic material (*Fiskeby63*) from Sweden that led to the development of *Maple Arrow* cultivar which played a vital role in eastward spread of soybean crop. According to Smithers and Blay-Palmer (2001), technological innovations were not only confined to development of cultivars but also to a range of agronomic activities including modification of planting time and crop rotation interrupted pest cycle enhancing the cultivation of soybean.

Example of crop translocation includes historical expansion of hard red winter wheat across climatic gradients of the North American Great Plains (Rosenberg, 1982). From 1920 to 1999, the northern boundary of hard red winter wheat expanded into a climatic region that was about 4.5^{0}C cooler and 20 percent drier than the climate for the wheat zone in the 1920. Interestingly, the southward expansion of hard red winter wheat has not been as extensive where annual average temperatures at the southern boundary are 2^{0}C greater than those of the 1920 southern boundary (Easterling et al., 2004). Thus hard red winter wheat has been adapted to cooler and drier climates in the last 80 years. In China, winter wheat planting has shifted from 38^{0}54′N to 41^{0}46′N. This shift was aided by introduction of freeze-resistant winter wheat variety from high latitude countries (Chen and Libi, 1997). In response to the reduction of a frost free growing season, farmers in Australia have modified their choice of cultivars in wheat (Minke et al., 2003). For example, in Central Queensland, the average frost period has shrunk from approximately 80 days at the end of 19th century to about 17 days at the end of 20th century. In response to such a change in growing season length, wheat in this region is sown earlier than in 1950s and 1960s, targeting flowering dates of early to mid August (Howden et al., in press).

Management of climatic risks is a critical aspect of economic survival. Farmers are understandably risk averse in their adoption of new technology (Pannell, 1999). An interesting example is seen in the adoption of canola in southern Australia. Saders et al. (2003) offers an analysis of a dynamic cropping strategy based on a putative association between start-of-season rain (April and May) and total seasonal rainfall. The study shows the advantage of long-term income when switching from a cereal only strategy in a year of low rainfall to a more risky strategy of canola and cereal based cropping systems in a year of high rainfall.

Features of adaptation to climate change in agriculture

Scholars have identified various characteristics by which adaptations to climate change in agriculture can be distinguished (Watson et al., 1996; Easterling, 1996; Smithers and Smit, 1997; Reilly and Schimmelpfennig, 2000; Smit et al., 2001; Smit and Skinner, 2002; Burton et al., 2002). Different features of adaptation have been identified in the climate change literature. In the following paragraphs I will provide a brief discussion of each of these features as a basis for understanding agricultural adaptation to climate change.

Adaptations by humans are categorized in different forms. They can be *reactive* or *anticipatory*. While the distinction between reactive and anticipatory adaptation is particularly a policy question, it is consistent with the concept of resilience discussed earlier. Reactive adaptations, also known as autonomous adaptation, occur naturally and spontaneously as a reaction to climatic stimuli or risks and require no direct interventions of public agencies (Watson et al., 1996; Easterling, 1996; Reilly and Schimmelpfennig, 2000; Smit et al., 2001). In essence, reactive adaptations form benchmarks against which the system's (agricultural) ability to adjust to external shocks can be judged. Reactive adaptation in agriculture may involve the utilization of the existing technological, social, economic, and political structure of society. These are adaptations that farmers and their supporting institutions have developed to deal with the risks of normal climate variability. Although reactive adaptation can provide resilience in the short term by restoring production to its previous condition, vulnerability to future climate change may increase in the long term as the agricultural system continues to increase its exposure to climate risk (Easterling et al., 2004).

Anticipatory adaptation also referred to as *proactive* adaptation moves beyond the concept of resilience and involves the reorganization of systems to improve their capacity to prevent damages due to future climate change (Holling, 1973). It requires deliberate policy decisions such as changes in production technologies, government policies and market mechanisms in response to climatic stimulus (Smit et al., 2001). Anticipatory adaptations are regarded as being the outcomes of conscious and deliberate responses to persistent stress in the systems of production (Smithers and Smit, 1997). An example of such adaptation is the investment by government and/or industry in the development of heat and/or drought resistant crop varieties through utilization of genetic resources that may be better adapted to new climatic conditions. Such policy action is based on the degree of awareness about changing climatic condition for crop growth and development and the action that is necessary to minimize yield losses (Pittock and Jones, 2000).

The distinction between reactive and anticipatory adaptation is not clear, particularly when attention shifts from adjustments made by individuals to a system-wide adaptation (Smit et al., 2000). Such blurred distinction is manifested in the following example. A farmer who, over many years, gradually phases out one crop variety in favor of another crop that seems to adapt better in the climatic conditions might be considered to have taken reactive action, but at the same time such decisions also appear to have been planned consciously (Bryant et al., 2000). Anticipatory adaptations also involve switching to more robust crop varieties that are better suited to the new environment, the development of new technologies that enable farmers to cope with various climatic conditions, and the development of infrastructure as substitutes for scarce climatic resources such as provisions of irrigation (Smit and Skinner, 2002).

Farmers' decisions to adapt are not likely to be made in light of climatic conditions alone though the latter may be a significant part of this process. Such decisions are made as a part of an on-going risk management strategy, and may occur at several levels ranging from an individual farm to the global level, and may involve interrelated but different actors. Schimmelpfennig et al., (1996) differentiated agricultural adaptation to climate change at three levels – *farm-level, regional* and/or *national level*, and *global level* adjustments.

Agricultural adaptation to climate change at the *farm-level* depends on the capabilities of farmers to detect climate change and technological potential to undertake any necessary actions. At the *national level*, government policies and programs such as crop insurance, disaster assistance, and level of agricultural research affect farmers' response to climate change. At the *global level*, tariffs and quotas affect the economic incentives for farmers to adapt and motivate them to seek technological options with which they can adapt. For example, farmer's decision to plant a crop variety that is more drought resistant is a farm-level adaptation. In the same manner governments may take a policy action at the national level by supporting research in development of drought tolerant crop varieties.

Timing and duration of adaptation distinguish responses according to the time frame during which they apply. This time frame could be *tactical* or short-term versus *strategic* or long-term (Smit et al., 1996). Tactical adaptations are made during a crop-growing season such as when dealing with drought by selling off liquid assets or undergoing temporary migration (Smit and Skinner, 2002). Strategic adaptations refer to structural changes in farm operation. For example, farmers experiencing frequent drought over recent years but expecting increased precipitation in the future, may adjust certain production practices to manage drought risks.

Agriculture is a sector of economy where the role of an individual is significant in adaptation to climate change, and that is assumed to be undertaken autonomously (Waggoner, 1992). Researchers have distinguished agricultural adaptation on the basis of whether they are undertaken *privately* or through *public agency*, and/or via *combination of both* (Tobey, 1992; Smit et al., 1996; Smit and Skinner, 2002). Given the impressive record of adjustments made by the farmers across different climatic regions of the world, this is not an unwarranted assumption (Smit et al., 2001; Tompkins and Adger, 2003). Although, for many situations, the role of public agency is not clear, it is an important part of the calculus of agricultural adaptation to climate change (Smithers and Smit, 1997). For example, as discussed earlier, the degree to which farmers take risks depends, in part, on government policies and programs (e.g., crop insurance, disaster assistance, price support, and international trade agreement) that encourage certain types of production but discourage others.

In the next section, I will discuss the major approaches applied in understanding agricultural adaptation to climate change with specific focus to their assumptions about adaptation and its relevance for policy decisions.

Conceptual approaches to understanding agricultural adaptation

To better understand the state of the literature on agricultural impact assessment and adaptation, it is useful to split them into four classes, and along two dimensions (see Figure 3.2). The *agro-economic approach* – associated with researchers such as Easterling et al. (1993) and Rosenzweig and Parry (1994) – employs site specific mechanistic model to simulate the response of agricultural systems over a series of 'representative' points in an area in response to climate change. The response from crop simulation models is then aggregated to regional and national scale to estimate the damage function through economic models. Using the terminology of Root and Schneider (1995), crop simulation models tend to take a 'bottom-up' approach to estimate the response of agronomic systems to climate change and variability.

The *Ricardian approach* – pioneered by Mendelsohn et al., (1994, 1996), estimates the statistical relationship between land values and climatic variables (precipitation, temperature, soil type) using cross sectional data, and employs the fitted relationship to predict the changes in land value as a consequence of change in the climatic variables. Mendelsohn et al. (1994) estimates the impact of climate change on the national economy as a quadratic function of temperature change. Again using the terminology provided by Root and Schneider (1995), such aggregate measures tend to take a 'top-down' approach.

Other approaches, although not explicitly used in estimating the impacts of climate change on agriculture, that have surfaced in the climate change literature are *natural hazards* and *induced technological innovation*. The *natural hazards* approach developed by Kates (1971), White (1974), Watts (1983), Jodha (1984), and Burton et al. (1993) is an area of inquiry that explores the interaction of human and environment by focusing on the impacts of and human response to extreme events such as floods and droughts. Emerging scholarship from natural hazards research, which studies farmers responses to extreme climatic events, demonstrates that technological adjustments made by farmers in both developed and developing countries are sources of resilience to climatic variability and can provide insights into how adjustments can be made in the face of climatic uncertainty due to global warming.

The *innovation of technology* as a means for adapting to climate change is associated with the hypothesis of induced innovation by Sir John Hicks (1932), Syed Ahmad (1966), and Hayami and Ruttan (1971), that posits that the development of new technologies in agriculture is a continuing process induced by differences in the relative scarcity of resources, signaled by change in relative price of the resources. Based on the historical evidence of technological responses to changing economic conditions and resource availabilities, scholars have put enormous faith in the ability of technology to continue to provide farmers with the needed strategic and tactical options for handling uncertainties related to future climate change (Ruttan, 1991; Rosenberg 1992; Ausubel, 1995). They strongly believe that technologies could be designed to substitute for future climate resource inadequacies as societies have done in the past.

As the role of technology continues to become more entrenched in strategic thinking of agricultural adaptation to climate change, there is a need to understand better the role that climate has played in innovation of technologies as fundamental to understanding potential future agricultural adaptations to climate change. Although consideration of technology as a means for agricultural adaptation to climate change began as early as the 1980s (Rosenzweig, 1985) with further consideration in the MINK study by Easterling et al., (1993), researchers engaged in climate change impact assessments admit that adaptation is not well developed and understood in impact studies (Easterling et al., 2003). Empirical analysis of the interaction between climate and technology, the thrust of this dissertation, is needed to understand the role of technology in future climate change. For the rest of the chapter, I will elaborate upon these approaches and also illustrate the methods by which adaptations have been considered.

Agro-economic approach

As stated earlier, the agro-economic approach typically involves the use of site-specific mechanistic models. The mechanistic model is a research tool usually applied in assessing the relationship between crop productivity and environmental factors. Models such as Erosion Productivity Impact Calculator, EPIC (Williams et al., 1987), Coalition for Environmentally Responsible Economics, CERES (Ritchie et al., 1989), General Purpose Formulation Model of the Soil-Plant Atmosphere System, GAPS (Butler and Riha, 1989), Soybean Crop Growth Simulation Model, SOYGRO (Jones et al., 1989), and International Benchmark Sites for Agro-technology Transfer (IBSNAT, 1989) have been shown to be sufficient in determining the response of crop plant to change in climatic conditions (Graves et al., 2002). Specifically, these process based models simulate agronomic response to climate change and variations over a series of representative points and extrapolate the findings to a larger geographic regions to further estimate the impacts of climate change. This method is similar to carefully controlled experiments where climatic parameters or other variables of interest (e.g., CO_2) are adjusted to study the sensitivity of a crop to changing climatic conditions and to the effects of CO_2 fertilization on crop yields (Tubiello et al., 1995; Rosenzweig and Hillel, 1998). Crop-simulation models may also include assumptions about adaptation, which can be evaluated within the framework of theoretical principles of crop growth (Tol et al., 1998; Smit et al., 1999).

The significance of this "bottom-up" approach of crop simulation models lies in their ability (a) to simulate the physiological effects of change in climate in crop yield across the regions in question, (b) to provide spatial implications of such changes, (c) to help understand the effects of CO_2 fertilization in crop yield, and (d) to hypothetically understand the role of adaptation in mitigating the impact of climate change. As illustrated in Figure 3.3, crop simulation models are first run for observed climatic and management conditions, and then for projected climate conditions such as with climate change and CO_2 enrichment, and with or without adaptation. Comparison of the results under these various scenarios allows analysis of the extent of the impact on crop yields, crop growing seasons, irrigation requirements, and evapotranspiration due to climatic factors. Most of these types of models use maximum and minimum temperatures, precipitation, wind speed, relative humidity, and solar radiation as climatic inputs.

A pioneering study on farmer's adaptation is the MINK study on climate change impacts in the Missouri, Iowa, Nebraska and Kansas region (Easterling et al., 1993). The study used the climate of the 1930s as an analogue to future climate and imposed a set of arbitrary adaptation such as change in planting dates and increased supply of irrigation water. With adaptation, Easterling et al. demonstrate that adaptation could reduce agricultural losses to MINK region by 30 to 60 percent. Other studies, such as by Rosenzweig and Parry (1994) show a similar picture. Rosenzweig and Parry conducted a global study using three arbitrary levels of adaptation – no adaptation, modest (Level 1) adaptation, and significant (Level 2). The no adaptation scenario considered farmers as 'dumb' and who continue to behave as the way they currently do. Under modest adaptation, farmers make small adjustment in their cropping behavior such as small capital investment and alteration of some agronomic activities. In significant adaptation, they imposed a scenario of substantial investment in agriculture development such as the development of crop varieties and investment in irrigation. In their global results, a change of -1.2 to -7.6 percent cereal productions without adaptation was reduced to 0 to -

5 percent with modest level adaptation. More comprehensive adjustment in agricultural management could offset practically all losses at the global level.

Although an increasing number of studies have investigated the impact of climate change using crop simulation models with scales ranging from local, national, regional to global, very few studies have compared the crop yield change using both with and without adaptation cases (Gitay et al., 2001). Even fewer such studies are available from developing countries, of which the study by Matthews et al. (1995), and Yates and Strzepek (1998) are of special significance. Comparisons of yields with and without adaptation from these studies reveals that adaptation clearly ameliorates yield losses in all cases as the median yield from adaptation shifts upward relative to the median yield with no adaptation.

Critiquing the agronomic approach: Impact assessment models were criticized for their lack of sensitivity to the adaptation of agriculture in the early eighties, (Smit et al., 1989; Mendelsohn et al., 1994; Mendelsohn and Dinar, 1999). Since then studies have routinely incorporated some form of adaptation in their impact studies. Typically, adaptation is simulated by making adjustments in tillage operations, planting dates, timing and amount of fertilizer applications, and irrigation schedules as agronomic countermeasures against climate changes. One of the shortcomings of the mechanistic model is that, while the benefit of agronomic adaptation is derived, the costs of adaptation are completely neglected. Adaptation involves some form of cost adjustment and ignoring it overestimates the benefit of adaptation from climate change.

In mechanistic models, adaptation is simulated by making adjustments in tillage operations, planting dates, timing and amount of fertilizer applications, and irrigation schedules as agronomic countermeasures against climate changes. These countermeasures are typically applied by adjusting parameter values for key variables in the model that control the agronomic processes in order to climatically optimize yields under the assumption of climate changes (Easterling et al., 2001). For example, the period from crop emergence to physiological maturity is often matched perfectly with a new growing season length observed in the scenarios of climate change. Therefore, they are performed with climatically optimized adaptations, which provide the best possible crop yields under a given scenario of climate change. Only a small subset of possible adaptation measures can be evaluated within crop models.

The main significance of crop simulation models with respect to adaptation is that agronomic adjustments are important and must be taken into consideration in order to assess the impact of climate change on crop yields. However, there are limitations in this approach of adaptation. The crop simulation models, which consider adaptation explicitly, assume that farmers have perfect insights about the climate, and are hence able to respond appropriately as climate changes. This may not be a realistic assumption. Unfortunately crop simulation models are not capable of examining the behavioral responses of individual farmers. Farmers' responses to climate change are therefore strictly hypothetical, although results demonstrate adaptation can significantly affect crop yield outcomes. The lack of a behavioral component that is sensitive to the role of climate in the inducement of technologies makes this approach less robust in considering the impact of climate change in agriculture (Ausubel, 1995).

Similarly, issues concerning the rate of adaptation of various technologies are ignored altogether in crop simulation models. The assumption of perfect adaptation is also problematic in crop simulation models. It assumes that all farmers accurately interpret the signal of climate change instantaneously and respond with the correct adaptation strategy, a very simplistic but inaccurate view of the real world. In the climate change literature, this is called an assumption of *clairvoyance* (Schneider et al, 2000). It is the polar opposite of the "*dumb farmer scenario*" – a metaphor where farmers are assumed to remain virtually unchanged in response to climate change (Rosenberg, 1990; Easterling et al., 1993). The agronomic approach models adaptation possibilities decided by the expert modeler. The adaptation possibilities are extrapolated from limited examples, often from laboratory settings, to the world as a whole.

Ricardian approach

As an alternative to crop simulation models, researchers have used the Ricardian approach to assess the impact of climate change (e.g., Mendelsohn et al., 1994; Sanhgi et al., 1998; Kumar and Parikh, 2001; Maddison, 2000; Molua; 2002; Kurukulasyriya and Ajwad, 2004). The Ricardian approach is primarily used in estimating structural relations between climate and agricultural land values under the presumption that such relations reflect a steady state level of adaptation of regional farming systems to local climatic characteristics. These relations are cross-sectional (i.e., units of observation are geographic areas) and the geographic variations in land values are assumed to be partly regulated by differences in the quality of climate inputs (e.g., Mendelsohn et al., 1994). The intuition here is that if climate conditions in region *X* become more like current climate conditions in region *Y*, then farmers in region *X* will adapt more like farmers are currently adapting in region *Y*.

The theoretical foundation for the Ricardian approach is rooted in neoclassical duality theory (Segerson and Dixon, 1999), which suggests that in competitive market economies, all else being equal, the land with the most suitable climate will generate the highest net revenues (rent) and that rent is derived from the most economically efficient use of land. Given that farmers receive appropriate signals of climate change, they can generate higher net revenues by adapting appropriately. Since potential revenues are proportionate to the market value of a farm, adaptation to climate change is logically reflected by land value. In essence, geographic variations in climate result in different modes of farming, and consequently in different land values.

The Ricardian approach, by relying upon how farmers and ecosystems have actually adjusted to varying local conditions, incorporates adaptation readily (Mendelsohn et al., 1994, 1999, 2001). In their seminal paper on the use of the Ricardian technique to value climate impacts, Mendelsohn et al. (1994) used county-level cross-section data from the United States to differentiate economic costs and benefits associated with climate change. They found that the effects of higher temperatures ranged from mildly harmful to unequivocally beneficial. The results suggest that warming will do less damage than predicted by the crop simulation models.

A number of studies have applied the Ricardian approach to model the economic impact of climate change in agriculture in various regions of the world. Using district level data on agricultural yields and land value from India and Brazil, Sanhgi et al., (1998) estimated a decline in agricultural net revenue of 12.3 percent in the former and 20 percent in the latter country. Using farm-level net revenues and climate variables, Kumar and Parikh (1998; 2001) estimated the economic impact of climate change in agriculture in India. They found that, even with adaptation – such as a change in cropping patterns, increased use of inputs, switching crops, and application of irrigation by farmers – there was significant negative impact created by the rise in temperature in the Indian economy.

Maddison (2000) estimated the marginal value of farmland in England and Wales and found that climate, soil quality, and elevation were significant determinants of farmland value. In a study of the southwestern region of Cameroon, Molua (2002) explored the impact of climate variability on agricultural production through the use of household level data. The study found that pre-season precipitation, tillage practices, and crop rotation had significant effect on farm returns. Results from the Ricardian analysis confirmed that farm-level adaptation including change in tillage, crop rotation, and change in planting and harvesting dates correlates positively with higher farm returns. In the same vein Kurukulasyriya and Ajwad (2004) estimated the effect of climate change on small farmers in Sri Lanka. They used household level data to test the sensitivity of farm revenue to climate change. Their results show that warmer climate may be harmful to the economy of the country, but net revenues are most sensitive to the complex interplay of precipitation across the two rainy seasons of the country. They found considerable variations in the impact of climate change across the country with losses up to 67 percent and gains of more than double the current revenue. The largest negative impacts were observed in the dry zones of the north-central region and southeastern region of Sri Lanka.

Critiquing the Ricardian approach*:* Two important insights emerge from the Ricardian model of climate impact assessment. First, it incorporates observed climatic data (which has a greater degree of reality than those derived from modeled scenarios); and second, as opposed to crop simulation models, it estimates the relationship between climate and land use across a climatically heterogeneous region based on current operating conditions rather than on an idealized view of farmers' response to climatic events. For example, the Ricardian approach of modeling the impact of climate change is embedded in the fact that farmers' decisions regarding land use are based on the existing climate and the socioeconomic environment. In order to optimize the benefits, farmers will choose the crop and/or cropping techniques based on the rent they will receive from the land.

The use of cross-section variation to predict time series behavior requires that many assumptions be satisfied. The Ricardian approach is typically viewed as a local (i.e., farm-level) process. Yet, farm-level decisions are determined by a myriad of factors operating at different levels (Easterling et al., 1998), and hence such decisions are not independent. Therefore, evolution of agricultural adaptation processes requires explicit consideration of large-scale forces (Polsky and Easterling, 2001). As noted by Meyer (1998), the relationship between climate and society is not pre-determined and formulaic. Rather the level of impact of climate change depends on the socioeconomic, political, and organizational context of the farmers facing threat from climate variability and change. This notion challenges the prescriptive nature of the Ricardian approach to study the impact of climate change, as Mendelsohn and others have done (Stewart, 1997), and urges creating a broad based understanding of how societies can be made more resilient to climate variability and change through adaptations, an area where research is lacking.

The Ricardian approach, as applied by Mendelsohn et al., (1994) assumes that agriculture will make a smooth transition in adaptation to climate change, thereby minimizing damage and maximizing output, so the assumption of smooth transition from one crop to the next becomes another shortcoming in the model (Schneider, 1997; Reinsborough, 2003). Moreover, the Ricardian approach does not explicitly model the agricultural economic system; instead it assumes that historical choices made in the market implicitly map the agricultural to climate variables (Morgan, 1999; Stewart, 1997. It sidesteps the problems of understanding explicit crops and farmers' responses to climate by implicitly assuming that the biophysical and economic adjustments imposed by climate change will be made automatically – an assumption that can be confirmed today by examining crops and behaviors in warmer climates.

A relatively small number of climatic variables (e.g. average temperature, precipitation, and perhaps a simple measure of variability) are assumed to capture all climatic phenomenon and its impacts on agriculture. Change in one climatic variable could create a series of changes in other climatic variables. Therefore, considering a few climate variables in the models is not enough. In fact, present estimates do not account for impacts due to extreme weather events, such as when frequency and intensity of extreme events is altered due to climate change (Hulme, 1999). A number of agronomic links – such as impact of climate change on behavior of pests and diseases – are still not very clearly understood and hence their economic implications are also not incorporated in the current estimates.

Researchers have also questioned the assumptions implicit in the statistical approach and the applicability of such with respect to adaptation to climate change (e.g., Cline 1996; Schneider 1997; Kaufmann, 1998; Quiggin and Horowitz, 1999; Lewandrowski and Schimmelpfennig, 1999; Timmins 2001). One of the many criticisms of this approach is centered on its failure to fully control the impact of other variables besides climate that could also explain the variation in farm income. The assumption of constant price is another drawback in this approach (Cline 1996; Schneider 1997). The Ricardian approach, as applied by Mendelsohn et al., (1994; 1996; 1999) has also been criticized for its statistical interpretations and inconsistency in model parameters. The lack of consistency implies that the models do not measure the effects of climate on the yield of individual crops, which creates biases in their crop revenues, and tends to overestimate the benefit of adaptation (Kaufmann, 1998). The inability of the Ricardian approach to incorporate the costs of adjustment to climate change is a serious flaw in the model, and credits more gain to the farmers than they would actually acquire (Quiggin and Horowitz, 1999; Lewandrowski and Schimmelpfennig, 1999).

In addition to the agro-economic and Ricardian approaches of analyzing the impact of climate change, case studies of managing the climatic risks, especially from natural hazards and cultural ecology, have begun to elicit the interest of scholars. In the next section, I will review some of the studies that offer examples of managing agriculture in climatically marginal regions of the world, shedding light on the relevance of such studies in the context of climate variability and change.

Adaptation: perspectives from natural hazards and cultural ecology

***Natural hazards*:** Emerging scholarship from natural hazards research offers an interdisciplinary view to the problem of agricultural adaptation to future climate change (Burton et al., 1992). Natural hazards are widely regarded as "extreme events involving the interaction of human activity with biological and physical systems" (Chiotti and Johnston, 1995:342). While the origin of 'modern' natural hazards research can be traced to human ecology (Burton et al., 1992), in geography, research on natural hazards are undertaken from the perspective of cultural and political ecology (Kates, 1985). Geographers involved in studying the impact of natural hazards in agriculture have provided important insight about the effects of climate variability in agriculture, in particular the impact of drought (e.g., Liverman, 1990; Eakin, 2000).

The body of scholarship that has emerged from natural hazard literature has made a valuable contribution towards our understanding of human adjustment to extreme natural events. Recent debates focusing on the relationship between climate change and agricultural adaptation recognize that climate change not only includes change in average climatic condition, but also includes change in year to year variability in crop growing environments including the extreme climate such as drought, flood, and frost (Hulme et al., 1999). Impact studies discussed earlier in this section address adaptation as an adjustment to risks associated with change in average climatic conditions and do not include climate variability in their analysis. The main contribution of this approach lies in its focus on the strategies applied by small farmers to adjust to extreme climatic conditions to avoid risks of crop failure.

The dependence of smallholder agriculturists on specific environmental conditions for the production of food and fiber has made management of climatic risks an integral part of agriculture. Adjustments made by smallholder agriculturists to adapt to climatic risks have evolved over centuries and are widely implemented. Emerging scholarship from natural hazards research, which studies farmers' response to extreme climatic events, demonstrates that technological adjustments made by small farmers in developing countries are a source of resilience to climatic variability and can provide insights on how adjustments can be made in the face of climatic uncertainty due to global warming. Retrospective studies conducted in smallholder farming communities have offered an exhaustive list of response strategies applied by farmers to cope with environmental shocks, such as drought, floods, and frosts (Jodha, 1978).

***Cultural ecology*:** Researchers using cultural ecology approaches provide evidence of adaptive strategies applied by the farmers living in fragile environments of Asia and Africa (Watts, 1983; Rosenzweig and Wolpin, 1993; Kinsey et al., 1998; Fafchamp et al., 1998; Jalan and Raavallion, 2001; Rockstrom et al., 2002). Perhaps the most commonly referenced examples of traditional approaches to dealing with climatic uncertainty are (a) use of water harvesting techniques, (b) managing risks and uncertainty through agronomic practices, and (c) technological substitutions in response to climatic resources.

Water harvesting techniques, broadly defined as the concentration of surface runoff for production purposes, have ancient roots and still form an integral part of many farming systems worldwide (Evanari, 1971; Frasier, 1985; Agarwal and Narain, 1997). They imply the collection and storage of rainy season precipitation that would have otherwise seeped into the soil or run off into stream channels. For resource-poor farmers in a water scarce area, even a small volume of stored water for supplemental irrigation can significantly improve crop yield. Although earlier rainwater harvesting systems were designed primarily to meet domestic needs for water, in recent decades, scientists in many areas, such as Sub-Saharan Africa, Southeast Asia, South Asia, and Latin America, have made efforts to design and develop a wide variety of techniques to collect, store, and use natural precipitation for agricultural purposes (Richards, 1972; Boers and Ben Asher, 1982; Cater and Miller, 1991; Kronen, 1994; Tabor, 1995; Agarwal and Narain. 1997; Gunnell and Krishnamurthy, 2002). In regions with inadequate and or unreliable precipitation, such water harvesting techniques have eased the constraints of water scarcity and helped improve crop yields.

Building upon China's long history of rainwater harvesting techniques (Frasier, 1985), scientists in the Gansu province of China have since the mid 1980s developed a newer approach to dry land agriculture (termed rainwater harvesting agriculture) to cope with erratic rainfall. They are promoting small water harvesting tanks to collect surface runoff for supplemental irrigation in wheat and maize. Research shows a significant wheat yield increase (average 35 percent) in areas with supplemental irrigation from such water harvesting tanks compared to areas with no such irrigation (Li et al., 2000). In another study at the same site, Li et al. (2000) observed similar results with maize, recording yield increases of 20 percent with supplemental irrigation.

Inspired by the Chinese example, similar systems are presently being developed and promoted in Kenya, Ethiopia, and Burkina Faso to irrigate vegetable gardens to enable farmers to diversify sources of income from the land. During 1998-2000, on-farm research in the semi-arid climates of Kenya and Burkina Faso indicated a significant scope of enhancing crop yield in rain-fed farming through water harvesting, especially when combined with soil-fertility management (Barron et al., 1999, Fox and Rockstrom, 2000). Low-tech, on-farm water harvesting ponds from a small catchment (1-2 hectare) provided an average 70 mm (range of 20-220 mm) of water per growing season. This is substantial in an area where seasonal rainfall ranges around only 196–557 mm in Kenya and 418–667 mm in Burkina Faso. In Burkina Faso, dry spell mitigation through water harvesting combined with fertilizer application resulted in the tripling of average yields for the farmer's normal practice of 460 kg/ha to 1400 kg/ha. The corresponding figures from Kenya show an average yield increase of approximately 70 percent from 1100 to 1900 kg/ha.

In semiarid southern India, *tank* irrigation has been a significant feature of rural landscape over the centuries. Tank irrigation, with a command area that can vary from 1.5 to 50 hectares, is considered as a key strategy against water scarcity (Agarwal and Narain 1997). In 1950, the storage capacity of irrigation reservoirs defined as tanks was estimated to be 15×10^9 m^3 – only second to medium and large reservoirs (Gunnell and Bourgeon. 1997). Discharge from the tank to command area also helps recharge the ground water, thereby ensuring a sustainable pattern of water management involving partial recycling (Gunnell, and Krishnamurthy, 2003). Such examples are also commonly found in Latin America. In the semiarid region of Tlaxcalam, Mexico, farmers mitigate the effects of drought through the creation of farmer-managed small irrigation systems, water harvesting ponds, and development of bench terraces as strategies to adapt to climate variability. For small farmers operating in water scarce areas, even such simple technology can make significant improvements in the household economy (Eakin, 2000).

Managing risks and uncertainty through agronomic practices is a critical aspect of economic survival in smallholder farming communities. Traditional approaches to crop management such as multiple cropping, crop diversification, conservation tillage farming, and conservative cropping are regarded as the most important strategies to avoid complete crop failure due to uncertain climate. Multiple cropping, commonly observed in many traditional farming systems, is not only considered as a means to avoid risk of crop failure, but also is pivotal in achieving yield stability, maintaining soil fertility, and attaining a constant supply of human and animal food. By growing a range of crops with different climatic response characteristics, farmers in climatically sensitive regions iron out fluctuations in crop yields under a broad spectrum of seasonal conditions. Case studies from the African Sahel suggest that farmers have adapted to changes in rainfall regimes by switching to different crop varieties and by using a range of water saving techniques such as bench terrace construction, mulch farming, multiple cropping, and organic manure increases. Research shows that through more efficient use of nutrients, soil moisture, and light, yields from multiple cropping are relatively higher than the proportional area planted with a single crop (Tiffin and Mortimore, 2002).

Through seemingly rationale decisions, at a time of increasing aridity and population growth in the last three decades of 20^th^ century, smallholder agriculturists of northern Nigeria have demonstrated resilience through continued increase in per-capita agricultural production. Although initial impacts of drought were severe, farmers in this region deployed adaptive strategies to remain productive in the face of climatic stress due to a reduction of precipitation of about 30 percent (Mortimore and Adams, 2001). The adaptive strategies employed by small farmers include techniques to improve soil fertility, conserve water, increase cropping diversity, manage trees, increase livestock, and take advantage of a changing market. In Diourbel, Senegal, farmers substituted longer-season varieties of sorghum and millet with short-season millet and better adapted varieties of groundnut. From 1960 to 1995, farmers were able to increase production of millet, both per hectare and per unit of rainfall (Tiffin and Mortimore, 2002).

In Bangladesh, farmers have established self reliance in food production despite increasing population pressure and high environmental constraints and have applied new and efficient irrigation techniques, introduced early maturing variety of rice, and improved crop management techniques to escape the consequence of drought. For example, farmers from drought prone areas of the Surjapur districts in the western region of Bangladesh increased land productivity by about 60 percent to sustain an ever increasing food demand brought about by population growth (over 225 percent). This is largely attributed to a shift from rainfed *aman* rice to irrigated *boro* rice, increased use of chemical fertilizers, and efficient use of water resources (Ali, 1996).

Other techniques applied by smallholder farmers include conservation tillage. It covers a range of practices including minimum tillage, mulch farming, and cover cropping. While the conventional approach to conservation tillage farming was mainly focused on the reduction of soil erosion from agricultural field, recent successes in reducing moisture stress in crop in low rainfall region as in Brazil (Derpesch, 1998), has inspired research and development efforts in sub-Saharan Africa and Asia. Although confined to commercial farming, examples of successful conservation tillage farming, where crop yields have significantly increased due to reduction of soil erosion and improvement of water conservation, can be found in several countries in sub-Saharan Africa like Ghana, Nigeria, Zimbabwe, Tanzania, South Africa and Zambia (Elwell, 1993). There are reports of water productivity improvements using conservation tillage farming in low-rainfall areas of Asia. For example, zero tillage of wheat in Pakistan using drill planting shows water savings of 15-20 percent (on average an estimated 100 mm per ha) through reduced evaporation and runoff and through deep percolation, while increasing yields (Hobbs et al., 2000).

Crop management strategies such as multiple cropping (growing two or more crops in the same plot at a time), crop diversification (planting different crops at a time to avoid total failure of harvest), and conservative cropping (growing traditional varieties that copes better in harsh climate) are regarded as the most important strategies to avoid complete crop failure due to uncertain climate in developing countries (Subedi, 1997; Sadras et al., 2003). These tactics are usually explained as risk-minimizing devices providing household food security by diversifying sources of food and extending its period of availability (Walker and Jodha, 1986). These are evidence of deliberate choices by the farmers to safeguard a minimum supply of food during periods of climatic uncertainty. The full array of strategies applied by small farmers to mitigate the effects of climatic hazards is seldom captured by the current generation of impact assessment studies.

Multiple cropping, commonly observed in many traditional farming systems in Nepal and India, is not only considered as a means to avoid risk of crop failure, it is pivotal in achieving yield stability, maintaining soil fertility, and attaining a constant supply of human and animal food (Jodha, 1981; Subedi, 1997). By growing a range of crops with different climatic response characteristics, farmers in climatically sensitive regions iron out fluctuations in crop yields under a broad spectrum of seasonal conditions (Willey et al., 1987; Moris, 1989).

Critiquing the natural hazards and cultural ecology perspectives: In developing countries, adjustments made by farmers to climatic extremes have evolved over centuries, been widely implemented, and have been primarily household based (Ribot, 1996). Yet greater understanding of current interactions between agriculture and climate is necessary for developing strategies to adapt to future climate. Given the uncertainty associated with future climate, efforts to assess adaptation to current climate may be a crucial step in reducing vulnerability from changed climate in the future (Bohle et al., 1994; Burton, 1997). The main contribution of this approach lies, perhaps, in its focus on the strategies currently applied by the farmers.

Severe climatic conditions, such as the consecutive droughts of West Africa in the 1980s, may render crop management strategies discussed earlier ineffective in preventing total crop failure. In the case of less extreme courses of events, crop management strategies applied by farmers in developing countries can ease the risk of crop failure (Walker and Jodha, 1986; Swinton, 1988; Fafchamps et al., 1998; Kinsey et al, 1998; Jalan and Raavallion, 2001; Rockstrom et al., 2002). The primary objective of most traditional strategies of crop management is to minimize year-to-year fluctuations in crop yield, and that may exact a price in terms of potential yield foregone (Nix, 1985). For example, during the summer seasons, farmers in the Mallee region of southeastern Australia still opt for lower risks cropping strategy (low-input cereal crops) to reduce the risk from inadequate summer rainfall over the potential profits from higher yielding oilseed crops that require more water (Sadras et al., 2003).

However, successful adaptation depends upon technological advances and institutional arrangement. With few exceptions, most of the traditional approaches of managing climatic risks are autonomous, i.e., spontaneous responses to climatic extremes. The inherent question with this approach is whether such strategies are adequate enough to handle climatic extremes associated with future climate change. Kates (2000) argues that vulnerability in the developing world is increasing because successful traditional methods applied by farmers to cope during the period of climatic stresses are no longer implemented and the social institutions that support them are not available. Therefore, the abilities of the farmers in developing countries to make smooth and cost-effective adjustments to climate extremes caused by global warming are by no means assured (IPCC, 2001).

In the previous paragraphs I elaborated upon the two conventional approaches (agro-economic approach and the Ricardian approach) used in understanding the potential impacts of climate change in agriculture. I highlighted the method by which adaptation is considered in these approaches. In addition, I provided a brief literature review from natural hazards and cultural ecology to demonstrate evidence of traditional approaches of managing climatic risks in developing countries. It is clear from the review that studies conducted to understand the impacts of climate change in agriculture have not examined the process by which climate change may prompt adaptation in agriculture. In the next section, I will take the discussion further to include the role of technological change in climatic adaptation through the conceptual framework of the induced innovation hypothesis.

Induced technological innovation

Agricultural adaptation to climate change can be viewed as a dynamic process of adjustment in technology, the understanding of which requires some concept of the driving forces of changes in technologies. The hypothesis of induced innovation, articulated by Hayami and Ruttan in the early 1970s, is such a concept and has earned wide recognition as a predominant economic theory of agricultural development. Furthermore, this hypothesis has emerged as a basis for understanding potential future agricultural adaptation to climate variability and change. I begin this section by examining the theoretical foundation of this hypothesis. I will also provide some examples of its application, in addition to discussing its significance in understanding agricultural adaptation to climate change.

Theoretical foundation of the induced innovation hypothesis

The hypothesis of induced innovation refers to the process by which societies develop technologies that facilitate the substitution of relatively abundant factors of production for relatively scarce factors in the economy. In the short term, the substitutions may simply involve using a large quantity of less-expensive resources over more-expensive ones for a given amount of output. Unit production costs increase, but this increase is less than it would have been without the substitution. Eventually, when substitution possibilities are exhausted, farmers and public institutions are stimulated to undertake new research to develop technologies to overcome such situations. The hypothesis of induced innovation has been substantiated through establishing a correlation between a measure of factor scarcity and an indicator of the direction of technical change (Hayami and Ruttan, 1985) For example, the constraints imposed on agricultural development by an inelastic supply of land have, in countries such as Japan, Taiwan, Korea, and several south Asian countries, been offset by the development of high-yielding crop varieties designed to facilitate the substitution of fertilizer for land. Similarly, the constraints imposed by an inelastic supply of labor, in countries such as the United States, Canada, and Australia, have been offset by technical advances leading to the substitution of mechanical power for labor.

Modern interest in the effect of factor endowments on technical change in agriculture goes back to the early 1960s when Syed Ahmad (1966) introduced the concept of the *innovation possibility curve* (IPC).[3] Ahmad argued that at a given time there exists a set of potential production processes, determined by a basic state of knowledge, available to be developed. Each process in the set requires that resources be devoted to research and development before it can be actively employed in the production.

Figure 3.4 illustrates the concept of IPC. While it deals with only two-factors of production (fertilizer and land), inclusion of other factors would not change the principles

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[3] IPC is defined as envelop of alternative isoquants, each representing a given output on the surface of production function. An equivalent term in the work of Hayami and Ruttan (1971) is *meta-production function* (MPF), which forms the basis of the application of the induced innovation hypothesis, hence the thrust of this dissertation.

involved. In this figure, the slope P_0 represents the price of fertilizer relative to the price of land, and the most efficient production function is shown by the tangent *a* in curve Q_0. An efficient rice farmer, for example, will combine *OL* ha of land with *OF* kg of fertilizer to produce a given amount of rice. Over time, due to growth in population, demand for rice increases putting pressure on the land and leads to a rise in the price of land relative to the fertilizer. This situation leads to the development of a new price ratio represented by price line P_1. Initially farmers increase the use of fertilizer as an appropriate substitution for land, as the latter is more expensive. In the figure, this is represented by OL_1 ha of land and OF_1 kg of fertilizer. The most efficient combination of fertilizer and land is shown by tangent *b*.

In the short term, the substitution of fertilizer for land profits both the farmers and consumers more than if the substitution had not occurred. However, a further increase in population and income puts more pressure on farmers to grow more rice, thereby creating greater scarcity of rice if it results in unsatisfied demand. This situation, according to the hypothesis of induced innovation, stimulates the demand for technological change in rice production. Farmers convey their distress through extension agents and/or political representatives to the institutions responsible for managing agricultural research. Eventually, if the political and economic institutions are receptive and able, they respond to the pressure by allocating more resources to the development of technologies, which substitutes for scarce land.

In Figure 3.4 this situation is demonstrated through the shift of the isoquant from Q_0 to Q_1, where the new tangent is *c*. This is the new production possibility curve representing the new technology developed in response to rising land scarcity. This concomitant adjustment of the isoquant reflects technological change that is biased with regard to saving land and the use of more fertilizer. This is made possible through the development of rice varieties by the research establishment that is responsive to more fertilizer compared to traditional varieties.

In the figure, it is assumed that the relative prices of fertilizer and land have not changed since price lines P_0 and P_1 have the same slopes. But, with the innovation of fertilizer and responsive high-yielding rice varieties, the efficient combination of fertilizer and land is OL_i and OF_i. The curve Q_1 is described as an envelope of alternative isoquant where dynamic production function operates. The figure illustrates how a difference in price creates an environment for farmers and their supporting institutions to move to the dynamic path of technological development. In the following section, I present the empirical evidence of the application of the induced innovation hypothesis.

Empirical test of the induced innovation hypothesis

The hypothesis of induced innovation gained prominence with the publication of Yujiro Hayami and Vernon Ruttan's book, *Agricultural Development: An International Agricultural Perspective in 1971 and 1985*. In their work Hayami and Ruttan (1985) claim impressive empirical support for the induced innovation hypothesis, noting that it has been tested against the historical record of agriculture development in the United States, Japan, Taiwan, Korea, the Philippines, Denmark, France, Germany, and Great

Britain. They argue that their "model provides powerful insight into the development process in both developed and developing countries" (pp, 92). An important entry point into their analysis is the decomposition of changes from output per unit of labor to change in output per unit of land and change in land available per unit of labor (Olmstead and Rhode, 1993). These two factors of production are seen as "relatively independent" and associated with two different paths – one typified by the experience of the United States where progress in mechanical technology "facilitated the substitution of other sources of power for human labor," and the other typified by the Japanese experience, where the progress in biological technology increased the productivity of land (pp. 171). The use of biological technologies (e.g., high yielding varieties, chemical fertilizers, and pesticides) did not become significant until 1930 when, according to Hayami and Ruttan, an increasing scarcity of land and decline in commercial fertilizers prices made such innovation profitable.

In their work, Hayami and Ruttan (1985) argued that the different paths of technological change in agriculture of the U.S. and Japan were shaped by differences in relative scarcity of labor and land. Throughout the period of 1880-1980 the Japanese farmers used more fertilizer per hectare than the U.S. farmers. Similarly the U.S. farmers used more machinery per worker than the Japanese farmers. In Japan, where land is relatively scarce, it was progress in biological technologies that led to increased response of rice varieties for higher level of fertilizer application. But in the U.S., where labor is the relatively scarce factor, it was the process of mechanization, first with animal and later with farm machinery (e.g., combine harvester), which facilitated the expansion of agricultural production by increasing the area operated per worker. In both cases, a process of dynamic adjustment to changing relative factor price was achieved, and the appropriate innovation was induced successfully by the price signals.

There is now a substantial body of literature documenting the process of induced technological change in both developed and developing countries. Literature shows the development of alternative technological trajectories to facilitate the substitution of relatively abundant factors for relatively scarce ones (Thirtle and Ruttan, 1987; Islam and Taslim, 1996; Thirtle et al., 1998). Studies on land and labor productivities across and over time for a broad group of counties and major geographic regions are broadly consistent with the hypothesis of induced innovation. In these studies, technical changes are represented as movement around the IPC, and change in factor ratios are induced, to a significant extent, "by the long term trend in relative factor prices" (Hayami and Ruttan, 1985:181). The authors reinforce the argument of the role of resource endowments in inducing both technological and institutional changes in agricultural development.

Islam and Taslim (1996) provided a more systematic study of the relationship between population growth and the adoption of HYVs in Bangladesh covering the period of green revolution (1960-1991). As the amount of cultivable land remained fixed, the increased population pressure led to the use of land more intensively by means of increased cropping frequency and the adoption of green revolution technologies. The study indicates that the switch from traditional to modern technologies, which raised agricultural output substantially, was indeed prompted by the population pressure. Although the growth in population had a positive effect on the inducement and adoption of HYVs, it did not prevent per capita agricultural output from declining. It may be that failure of the non-agricultural sector to grow at a sufficiently rapid pace has meant that the sheer weight of increased population had to be absorbed by the agricultural sector alone.

Lin (1991) tested the hypothesis of induced innovation to estimate the effects of decentralized research systems in the allocation of resources to the development of agricultural technologies at the provincial level. Lin carried a questionnaire survey on research resource allocation in each provincial academy after the end of cultural revolutions in 1988. The research reveals that allocation of research resources in China's decentralized research systems has responded effectively to market demand and factor scarcity in each locality. Even in rural China, where the market factor is nascent, the allocation of resources for research is consistent with the hypothesis of induced innovation.

Similarly, Burmeister (1995) tested the hypothesis of induced innovation and found a strong influence of policy-laden inducement in Korean rice production. The case of the "green revolution" in India, Bangladesh and other South Asian countries consistently supports the assertion of the induced innovation hypothesis (see Koppel, 1995; Islam and Taslim, 1996; Turner and Ali, 1996). In case after case, researchers who tested the induced innovation hypothesis found strong evidence to support it.

Methodologically, there has also been significant development in the measurement of the direction of technical change in agriculture (Thirtle et al., 2002). In the earlier stages studies were directed towards measuring partial productivity ratios such as output per worker and per hectare. For example, Hayami and Ruttan (1971) regressed the logarithms of the factor ratios (land/labor, fertilizer/land, and machinery/labor) on the logarithms of the factor price ratios. If the coefficient of the relevant price ratio is negative and significantly different from zero, the result is considered to corroborate the inducement hypothesis. However, the test was entirely ad hoc, and the distinction between factor substitution and induced innovation was not clear (Thirtle et al., 1998), and was limited to establishing a correlation between a measure of factor scarcity and the direction of technical change.

The revised edition of the Hayami and Ruttan (1985) work includes two-stage tests based on constant elasticity of substitution (CES) production function. The two-stage CES is estimated, with time-dependent factor augmentation coefficients, to produce estimates of the Allen elasticities[4] of factor substitution and the biases of technical change (Thirtle and Ruttan, 1987). This approach is more robust, and the functional form itself gives rise to estimating equations that allow direct testing of the inducement hypothesis. Subsequent work by other authors extended the induced innovation hypothesis in the analysis of institutional changes ranging from property rights to the development of public sector agricultural research systems. Most of these studies have employed the frontier (Malmquist) productivity approach rather than the fixed coefficient production function used in the earlier stage (Ruttan, 2002). Using the pooled data of 22 countries from Sub-Saharan Africa, Thirtle et al., (1995) found a significant role for

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[4]Allen elasticity of substitution measures the percentage change in factor proportions due to a change in marginal rate of technical substitution and has been used as standard statistics in empirical studies.

policy in inducing technological change. Later, Thirtle et al. (1998) tested the induced innovation hypothesis using historical data from South African agriculture for 1947-1991. They found factor prices to be a strong signal of inducement of technological change in commercial agriculture.

In the most fully developed form of the induced innovation hypothesis, technological change is treated as being induced by institutional change (Koppel, 1995). Institutionalized research is the key factor for producing innovation leading to advanced agricultural technology, especially the ones leading to the development of biological technologies in developing countries. Institutional change, in turn, is treated as induced by changes in factor supplies (e.g., land) and product demand (e. g. food) and by technological change (e.g., high yielding varieties). Therefore, innovation in agricultural technologies depends on the sensitivity of public research institutions to local climate (Chiotti and Johnston, 1995; Huffman, 1998).

Insights to be gained for agricultural adaptation to climate change

The hypothesis of induced innovation has been used to explain the relationship between resource endowment and the development of new technologies. Over time it has been substantiated through many examples involving technical change in food production. The premise of the hypothesis of induced innovation concerning the role of climate as a stimulant for technological innovation has gone largely unquestioned because it is a difficult assumption to test. Although climate is an integral part of agricultural production, unlike other factors of production in agriculture (e.g., input of fertilizers and labor), it is not commonly exchanged in the organized market (Abler et al., 2000). Given that climate is unaccounted for by the market, the need for its valuation by the public institutions during the process of technological innovation is pivotal so as to address the constraint imposed by scarcity of climatic resource. Therefore, insights about the role of climate as a stimulus to technological innovation in agriculture are likely to be useful for a number of reasons including its implication for agricultural adaptation to climate change.

The economic value of climate may be reflected indirectly in the price of land or the revenue generated by the land. As argued by Mendelsohn et al. (1994 and 1996), the revenue generated by a piece of agricultural land encapsulates the value of land, which is in part determined by climate. The critical question with regards to agricultural adaptation to climate variability and change, therefore, is *whether substitution of technologies for climate would be employed in the future?* Advances in knowledge can permit the substitution of more abundant resources for increasingly scarce resources to reduce the constraints for agricultural production. For example, innovation of early maturing cultivars has the greater potential of escaping the effects of drought which would be increasingly important to address the limitation of water scarcity due to a change in rainfall pattern. In light of this discussion, reorientation of the way society institutes the agricultural research will be necessary to adapt and/or realize the opportunities for technical change provided by new climate. Therefore, a research effort along the path induced by climatic stress is an essential step if meaningful insights are to be obtained with regard to agricultural adaptation to climate change.

To identify the effects of climate on the adoption of HYVs, McKinsey and Evenson (1998) built a technology-climate model to measure how the green revolution affected net revenue from agriculture in India. They investigated whether district level climate differences conditioned the regional pattern of investment and technology adoption as the green revolution unfolded in India. The study found that the Green Revolution in India increased farm net revenue substantially but that technology had a neutral impact on climate sensitivity. The districts with favorable rainfall were found to be associated with higher HYV adoption and irrigation intensity, hence significantly higher net revenue. Also the intensity of irrigation tended to be greater in the districts with a lesser gradient of slope. They argue that the green revolution did not try to move crops to new climate zones, but merely attempted to increase productivity in regions with ideal climates.

Even if new technology has not historically tried to move crops into new climate zones, technology could affect climate sensitivity by changing the production function (Antle, 1996). The interaction between climate and technology depends upon whether new technology encourages capital to be a complement or a substitute for climate (Mendelsohn et al., 2001). For example, if the marginal productivity of technology is higher for farms in an ideal climate, technology and climate could complement each other. In this case, technology is targeted to the ideal climate, making farmers in this environment more productive than farmers in marginal locations. However, if the marginal productivity of technology is equal or better in a relatively unfavorable climate compared to the favorable climate, then technology is said to substitute for climate. Following the assertion made by the hypothesis of induced innovation, this is a desired condition if agriculture is to adapt to changing climatic resources in the future.

Synthesis

Although future climate is uncertain, the critical issue is how the research establishment has perceived the scarcity of climatic resources so as to integrate them into their attempts to innovate technology needed for farmers to respond to evolving climate. Thus, the perception of resource scarcity, in this case climate, enters the R&D process through interaction between farmers and the public institutions responsible for generating technologies. In the context of climate, mechanical innovations include irrigation, conservation tillage, leveled terracing, and integrated drainage systems – all of which are essential to widen agricultural activities that existing climatic resources would have otherwise permitted. Biological innovations, on the other hand, also have significant roles in enabling agriculture to adapt to a wider range of climatic conditions. For example, through investment in crop-improvement programs, societies can develop varieties that are resistant to pest and diseases or tolerant to heat and drought, all pivotal in ameliorating the impact of climate change.

In Nepal, for example, climate change may reduce the supply of soil moisture during the growing season by altering monsoon precipitation. As water becomes scarce, its value increases and this provides a signal to the farmers and their supporting institutions to conserve such scarce resources by developing efficient irrigation systems. Following the logic of induced innovation, it is reasonable to hypothesize that new technologies will be developed that are more efficient in the use of scarce water. This may be done through the development of crop varieties that can perform even better with short supplies of water; through employment of water conserving techniques, such as conservation tillage farming; and/or through the development of efficient irrigation techniques, such as drip irrigation that maximizes the use of available water. In response to inadequate and or unreliable precipitation, it is reasonable to assume the same responses from farmers and their supporting institutions (Glantz and Ausubel, 1988). This assumption implicates the null hypothesis of this dissertation: that climatic limitations cannot be shown to provide incentives to farmers to urge their supporting institutions to invest in research and development of location-specific rice production technologies that substitute for climate scarcity.

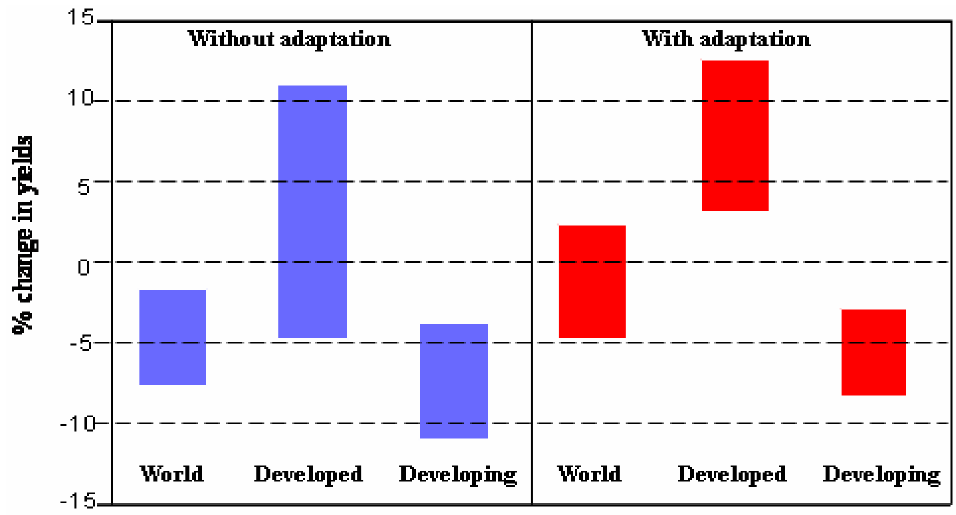

Figure 3.1: Change in grain yield due to the effects of climate change

Source: Grain yield summarized for the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) by Reilly et al, 1996.

Note: The extent of the vertical bars represents the percentage change in average yield due to the effects of climate change when simulated using process based crop simulation models – considering CO2 fertilization effects and the assumption of with and without adaptation by the farmers.

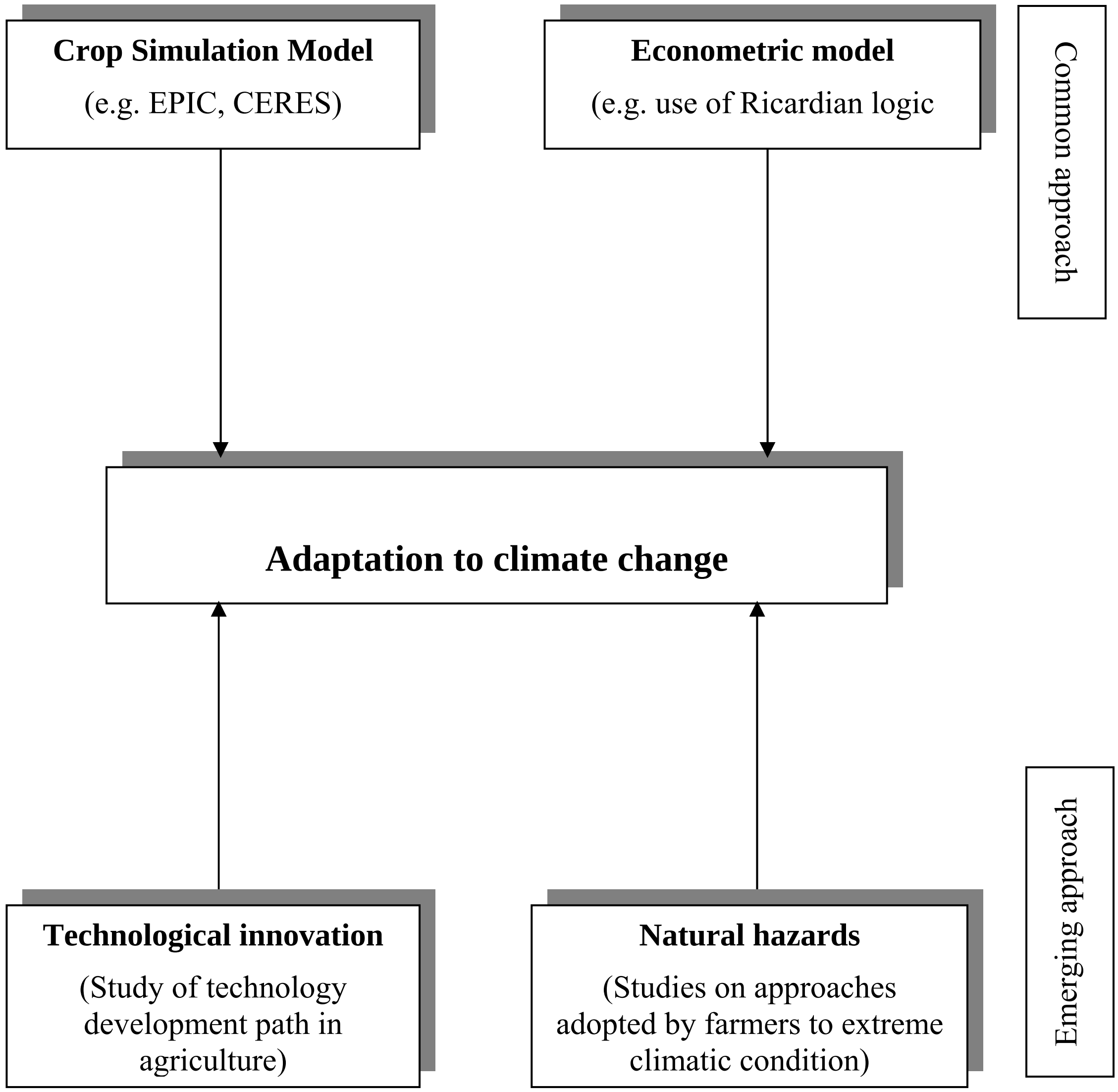

Figure 3.2: Analytical protocol: climate change and agricultural adaptation

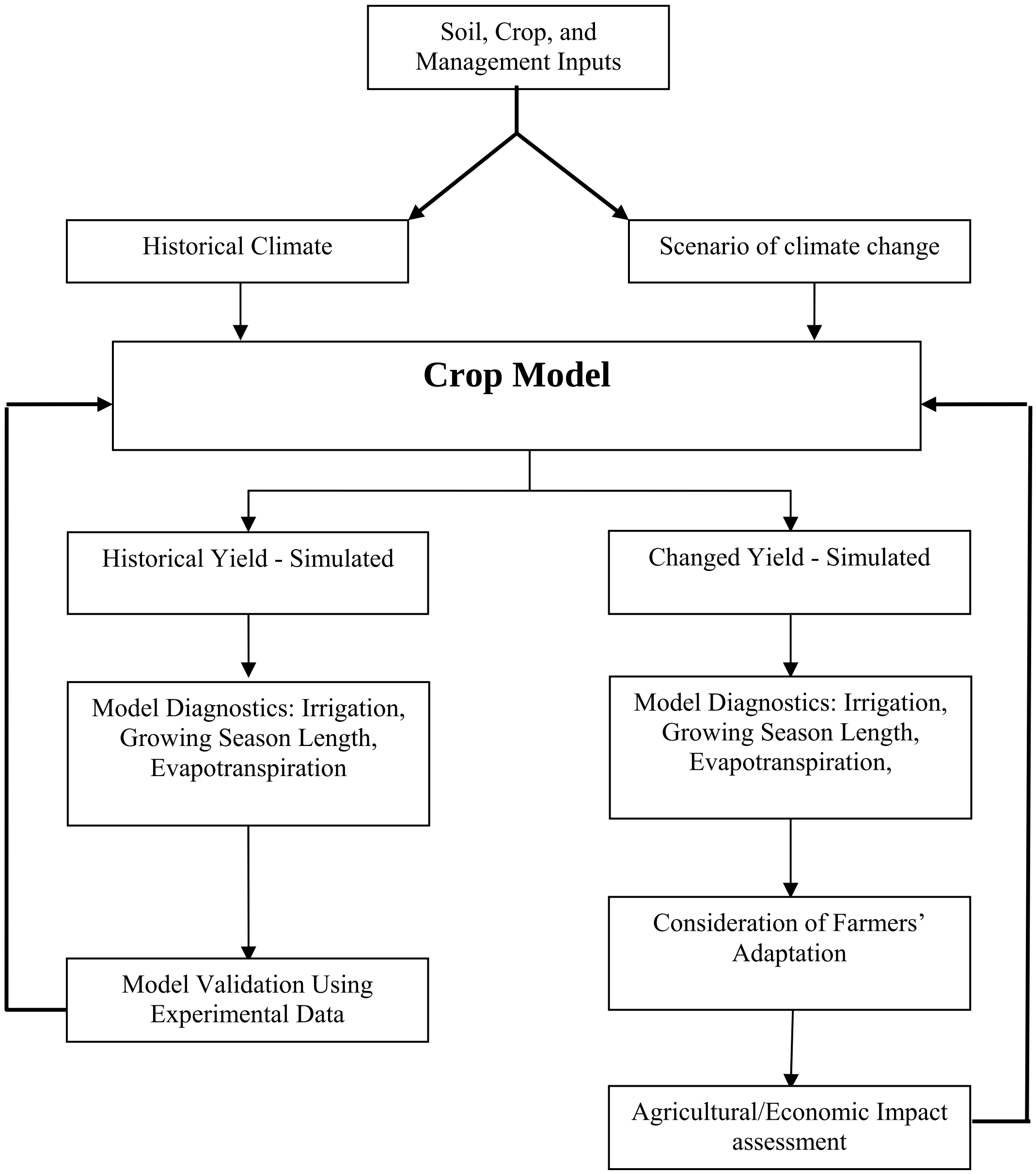

Figure 3.3: Parameterizations of crop simulation models to assess the impacts of climate change in agriculture

Source: Smith et al., 1996

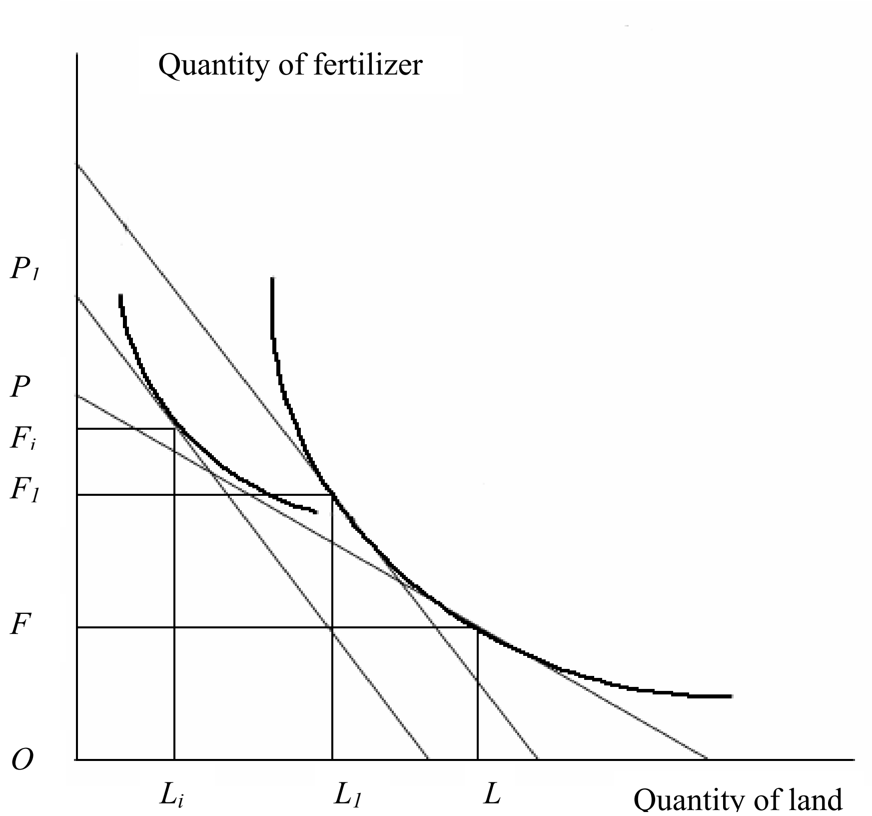

Figure 3.4: Trajectory of technological substitution: the concept of innovation possibility curve (IPC)

Source: Hayami and Ruttan, 1985:275

CHAPTER FOUR

CLIMATE-TECHNOLOGY INTERACTION IN AGRICULTURE: METHODOLOGICAL PERSPECTIVE

The purpose of this chapter is to justify the rationale of the assertion that variability in climatic resources prompts the innovation of appropriate technologies that substitute technology for climate. In the next section, I discuss the role of climate-induced innovation in the rice production system, which will then be followed by a discussion of the use of the measure of productivity growth as an indicator of climate-induced innovation. In the third section, I will define and discuss the concepts of productivity convergence, a methodological approach used in this study. A detailed account of the data and variables, their sources, and the unit of analysis are discussed in the fourth section. Finally, I present the methodology employed for testing the null hypothesis of this dissertation.

Climate-induced innovation in agriculture

Climate-induced innovation occurs when location-specific technologies are delivered to and adopted by farmers to address climatic limitations or opportunities in crop growth and development. This interaction is vital because greater rice yield is desired by all farmers regardless of the range of climatic conditions in which they grow rice. Since an optimal cultivation of rice is possible only when climatic conditions are favorable that invariably means an inadequate supply of climatic resources (e.g. rainfall) adversely affects productivity. Kung (1971) showed that an estimated 1300 mm of field water is required during the rice growing season, for optimal production. For this reason, regions with drier climate need to be either supplemented through irrigation or provided with drought-resistant varieties of rice, which are able to produce equivalent yield even in water-stressed conditions. It is in this premise that the comparison of rice productivity growth across the districts of Nepal with contrasting climates can be instructive to test the null hypothesis of this dissertation that *climatic limitations cannot be shown to provide incentives for farmers to urge their supporting institutions to invest in research and development of location-specific rice production technologies that substitute for climatic scarcity*. The implication of this hypothesis is that regions that do not have location-specific technologies and/or infrastructure in place would not be able to cope and adapt to the changing future climate. As discussed in Chapter Two, rice productivity in Nepal is affected by climatic factors such as rainfall. Although the mean annual rainfall for the entire country is 1767.5 mm, with 80 percent of rainfall occurring during the summer monsoon (Shrestha, 2000), the diverse topography and dominance of monsoonal flows induce considerable variability in rainfall patterns across the districts of Nepal (Chalise, 1994).

Districts with higher monsoon rainfall have a climatic advantage in that they are favorably endowed to produce more rice than those that receive less rainfall. However, if Nepal's research establishment is rational in allocating resources to overcome the limited supply of rainfall, such as through innovation of technology, then over time, rice productivity in the districts with less favorable climates will be able to compensate for such constraints, and even be on par with districts with favorable climate. Either farmers can compensate for inadequate supply of monsoon rainfall through the development of irrigation systems, or, as discussed earlier, through the adoption of appropriate rice varieties that can thrive even with limited amount of water.

Following the thrust of the induced innovation hypothesis, *a priori* it can be argued that relative biases in the innovation of technology in response to scarcity of climatic resources provide an opportunity for rice productivity in regions with less favorable climate to converge with those with more favorable climate. In Nepal's rice production system, such bias may be reflected either through the development of location-specific rice varieties that have higher yields potential despite climatic constraints or through the enhancement of land development activities (e.g., irrigation) or a combination of both. For example, the planting of short-season rice varieties allows farmers to escape the late-season drought that occurs in some areas of the country. Also, with the innovation and adoption of drought-resistant rice varieties, the crop is able to withstand the stress of intermittent drought that can occur any time during the growing season. Similarly, the presence of irrigation alleviates the scarcity of water, a major constraint in the adoption of improved varieties of rice in Nepal. If investment in technological innovation is emphasized in districts with less favorable climate, the productivity of rice, which would otherwise be marginal in such areas, may increase. Given that climate is unaccounted for by the market, the need for its valuation by the public institutions during the process of technological innovation is pivotal so as to address the constraint imposed by scarcity of climatic resource.

Productivity convergence: proxy for measuring climate-induced innovation

The fundamental – and perhaps the more difficult – issue in the analysis of productivity is how to explicitly characterize the impact of technological change. In agriculture, empirical analysis of the impact of technological change in productivity resorts to indirect measures such as area covered by a new crop variety, amount of chemical fertilizers and pesticides applied, and the number of machineries used (Huffman 1998; Mudlock, 2000). In order to quantify these technologies utilized by the farmers, economists have developed an index of measure commonly known as the total factor productivity (TFP) index that measures change in total output relative to the change in the usage of all inputs used. Coelli et al. (1998) provide exposition to various approaches to calculate TFP indices that are relevant in the context of measuring productivity changes over time and space.

Conceptually, TFP indices may be used to capture the effects of technological innovation and investment in infrastructure such as irrigation (Mukherjee and Kuroda, 2003) as higher TFP not only means higher output from the adoption of technologies and better utilization of resources, but also indicates increased food security (Fan et al., 2000). For example, if regional difference in TFP growth rates narrow over time owing to the innovation of location-specific technologies, then the new technology is considered to be an important source for reducing intra-regional disparity in agricultural productivity.

Using the Tornqvist-Theil index of TFP growth for the period of 1973-1993, Mukherjee and Kuroda (2003) studied whether there is convergence of agricultural productivity growth across fourteen major agricultural states of India. The study found evidence of convergence across the states of India and is attributed to the innovation of region-specific technologies. Similarly, using the Malmquist index to calculate TFP indices in the across sixteen regions of Bangladesh, Rahman (2005) found a gradual convergence of agricultural productivity during the period of 1964-1992. Unlike the study from India and Bangladesh, the study from Botswana paints a different picture. Using the same index as Rahman (2005), Thirtle et al. (2003) found widening of gap in agricultural productivity across the eighteen districts between 1981-1996. Primary region for divergence, as shown by the study, is that the government tends to under-invest in regions that are climatically less favorable, which are hence not able to increase their productivity as those with favorable climate. From a policy perspective, it is important to examine the long-term trends in the regional pattern of agricultural productivity to address this situation.

The formulation of TFP indices, though useful, is an abstract concept and may not be practical in every situation. It is also evident that a careful aggregation of inputs and outputs is important to obtain accurate measures of TFP which can be used as a proxy for technological change (Coelli et al., 1998). There are two basic problems associated with the measurement of TFP indices. First, there is a general lack of acceptable data on factor inputs needed for the construction of TFP indices. Second, there are few widely accepted conversion factors for the various inputs that farmers use for production of desired outputs (Acelus and Arocena, 2000). This is especially true in the context of small-holder agricultural societies where factors of production in agriculture come from different sources, often impossible to quantify (Thirtle et al., 2003). For example, in integrated crop and livestock farming systems in Nepal, farm animals not only provide draft power but also manure as a source of fertilizer.

A recent study conducted by the HMG/MOAC shows that although over 90 percent of the farmers apply both manure and inorganic fertilizers, smaller farmers are likely to use the manure as their major source of input for soil fertility (HMG/MOAC, 2002). However, despite the significance of manure in Nepal's agricultural production, the item is difficult to quantify and consequently no data exists for this resource. Similarly, another commonly used source of fertilizer is the leaf litter from the forest that small farmers use to maintain soil fertility. As with manure, no data exists as leaf litter is difficult to quantify. The problem worsens when major inputs for agricultural production are heavily subsidized to promote high-intensive agricultural activities. Additionally, the process is complicated by the existence of multicollinearity between technological variables that have important bearing in crop productivity (e.g., use of HYVs and irrigation availability). In the absence of quantifiable data, accounting for the impact of technological change in productivity is difficult. Given the limitations posed by the lack of data and problems of multicollinearity, there is a need to compensate for these shortcomings by applying theoretically grounded, generalized approaches such as the test of convergence. Divergence (opposite of convergence) in rice productivity is often caused by various factors, including climate, and is a signal to farmers and their supporting institutions that new technologies on demand are needed to compensate for climatic limitations. One plausible explanation for convergence of rice yield over time, *ipso facto*, is the response of the research establishment to the specific needs of farmers, specifically brought about by regional differences in climate and other factors. Convergence is not causal evidence of innovation inducement but is a necessary condition.

According to McCunn and Huffman (2000), in agriculture, when climate-induced innovations occur, two outcomes are likely. First, such innovations may advance knowledge to optimize the use of available climatic resources across different regions. Second, it has the potential to enhance the ability of a region to compensate for the constraints imposed by climate and become self-sufficient in agricultural production. The potential for convergence of productivity across different climatic regions can only be realized if and when farmers and research establishments devise and adapt technologies appropriate to climatic as well as societal need of a region in question. In the case of Nepal, this process will allow climatically less favorable regions to increase rice yield relatively faster eventually letting them catch-up in productivity alongside the regions with favorable climate. I assert that society, through the innovation of location-specific technologies, would provide opportunity for farmers to substitute for climate allowing for increased rice productivity in climatically less favorable regions. It is in this premise that I investigate whether spatial variations in climatic resources condition the regional patterns of investment in rice technologies, and conversely if the process that constituted the adaptation to existing climate might ameliorate the negative effects of future climate change.

Concept and definition of productivity convergence

While convergence in the economic literature generally refers to the convergence of labor productivity, mostly in industrial sectors, in recent time researchers have expanded to testing for the existence of TFP convergence in agricultural productivity (e.g., Lusing et al., 1998; McCunn and Huffman, 2000; Mukherjee and Kuroda, 2003; Thirtle et al, 2003; Coelli et al, 2003; Rahman, 2005). Additionally, productivity convergence in itself is a function of best practice brought about by technological change, especially adoption of improved technologies and corresponding improvement in irrigation and rural infrastructure (Rahman, 2005). Theoretically, the hypothesis of induced innovation and yield convergence are not the same; convergence in agricultural productivity occurs if and when location specific technologies are delivered to the farmers by the research establishment. Less frequently, yield convergence can be explained by relative differences in environmental determinants of yield. It is in this premise that the test of convergence provides descriptive information about whether the technological innovations made routinely by the public research establishment is an endogenous response to the relative resource endowments in the regions in question.

Following Barro and Sala-I-Martin (1992), convergence can be understood in two different ways – convergence in terms of level of productivity and growth rates – and are referred to as *sigma (σ) and beta (β) convergence*, respectively. Sigma (σ) convergence refers to decreasing productivity dispersion over time (Barro and Sala-I-Martin, 1992). In agriculture, analysis of the standard deviation of the productivity (e.g., TFP) across unit of observation is used for the test of σ-convergence (McCunn and Huffman, 2000; Mukherjee and Kuroda, 2003). The presence of σ-convergence in agriculture therefore suggests a tendency toward reduction of productivity gap across regions. A frequent approach to observe the occurrence of σ-convergence is to plot the evolution of standard deviations over time. For example, McErlean and Wu (2003) show the evolution of σ-convergence by plotting the standard deviations of productivity across the three geographic regions of China from 1985 to 2000. The study indicates divergence of productivity during the first half (1985 – 1992) but convergence in the second half (1992 -2000) of the study period. The existence of convergence in the period of 1992-2000 was attributed to major agricultural policy reform by the government of China in 1992.

Beta (β) convergence refers to the tendency of countries with comparatively low initial productivity levels to grow relatively faster. Convergence occurs when regions with a low productivity level during the initial period grow more rapidly than regions with a high initial level of productivity implying that the low producing regions are "catching-up." In agriculture, this is contingent upon innovation of technologies appropriate to the region specific socioeconomic and climatic needs. If this scenario holds, there should be *negative* correlation between the initial productivity level and the subsequent growth rate (Barro and Sala-I-Martin, 1995).

From the conceptual perspective, two methods for the test of β-convergence are prevalent in the literature and are termed as *absolute* and *conditional* convergence. Absolute convergence, also known as unconditional convergence is defined as the tendency towards equalization of productivity, where countries with low productivity at the initial stage will grow faster to catch-up with the countries with greater initial productivity (Islam, 2003). It is absolute because all factors of production are assumed constant across regions (Barro and Sala-I-Martin 1995; de la Fuente, 1997). In reality, factor inputs do not necessarily remain constant. Hence, a high degree of inequality among countries (regions) could persist, even in the long run. In the convergence literature, this is attributed to inherent differences in underlying conditions that may have direct effect on productivity (McCunn and Huffman, 2000; Mukherjee and Kuroda, 2003)). This gives rise to the notion of the concept of conditional β-convergence. The conditional β-convergence emphasizes the inclusion of appropriate independent variables on the growth-initial level regression in order to control for the differences these variables may exert on productivity growth rates (Durlauf, 1996; de la Fuente, 1997; Rassekh et al., 2001; McErlean and Wu, 2003; Islam, 2003; Mulder and de Groot, 2004).

The test of conditional β-convergence is particularly important if the countries/regions within which the productivity difference is being tested are heterogeneous, such as in Nepal where each of the three ecological regions presents a unique resource condition for rice cultivation. By testing the conditional β-convergence one can explain the significance of specific factor in productivity convergence. Therefore, if the regions across which convergence is being tested are heterogeneous, the inclusion of independent variable(s) to control for the apparent differences would be necessary, and consequently implies conditional β-convergence (McErlean and Wu, 2003). While conditional β-convergence also requires a negative coefficient on initial productivity, regions with lower productivity at the initial stage may exhibit greater growth rates after controlling for the effects of the conditioning variables.

Data and variables

Table 4.1 presents a list of variables included in this study and their sources. The primary purpose of this analysis is to examine whether districts with initially low rice productivity are converging with those with higher rice productivity. Average rice yield is the dependent variable. In a country like Nepal, absolute convergence (discussed earlier) is very unlikely. In this analysis, climate and biophysical condition are the main determinants of rice productivity convergence. These independent variables are represented by average rainfall of the rice growing season, irrigation, and ecological zones of Nepal. It would have been highly desirable to use other variables that have significant bearing on rice productivity, such as fertilizer application and HYVs. However, for reasons explained earlier, the data for such variables are not available at the district levels and are, hence, not included in the study.

Rice yield: The test of convergence using rice yield is justified on the basis that rice has always been a focus of innovation, primarily because of the introduction of Green Revolution techniques in neighboring India (Thapa, 1994). Also, in the last 40 years, Nepal has made significant progress in rice production. In 1961, the average rice yield was less than 2000 kg/ha, but rose to about 2700 kg/ha in 2001 (FAOSTAT, 2002). Figure 4.1 reveals that until the late 1980s, rice productivity grew slowly and at times even plunged dismally, indicating that the benefits of the Green Revolution had bypassed Nepal. However, after the early 1990s, productivity began to grow at a relatively faster rate than the preceding decades. Such growth is largely attributed to the adoption of a new generation of rice varieties, the improvement of farmers' crop management practices, and the increased use of irrigation, fertilizer, and other agrochemicals in rice production (HMG/ADB, 1995; MHG/MOAC, 2003). It is also attributed to the adoption of policies that are favorable to increased production of rice.

During the decade of the 1990s, average yield of rice in Nepal grew by 1.33 percent. In some parts of the country, it rose as much as 3.6 percent, while in others the growth was nominal (Gilloti et al., 2000). The important question, however, is whether the districts with relatively less favorable climates for rice production lagged behind or showed signs of catching-up with those with comparatively favorable climates. Whether or not the relative yield differences narrows or amplifies depends on several factors, with innovation and adaptation of location-specific technology being the most important ones.

Following the thrust of the hypothesis of induced innovation, it is reasonable to expect a reduction in yield difference in rice across the districts of Nepal, even if they are endowed with different climatic resources. For example, after the endorsement of the APP (discussed in Chapter Two) in 1995, there has been a significant effort in the development of irrigation infrastructure particularly in dry regions of the country (HMG/ADB, 1995). Additionally, when NARC, through its network of RARS, undertakes research and development activities with a regional focus, technologies that optimize the resource endowment of the geographic region in question are expected to be devised. Such combined efforts should lead to an increase in rice yield across regions, leading to productivity convergence.

Rainfall: Though rice production in Nepal is constrained by several physiographic factors, such as altitude, aspect, and soil type, inadequate precipitation is considered to be the most serious constraint (HMG/ADB, 1995; HMG/MOAC, 2000). For successful rice production, rainfall is as important as other inputs, such as fertilizers and pesticides. Disruption in the supply of rainfall, as in the case of a drought year, may lead to a significant decrease in rice productivity. Continuous disruption in the supply of climatic resources, such as rainfall, increases the scarcity of soil moisture – an important input to agricultural production. But over time, as argued by Barnett and Morse (1963), a society will substitute scarce resources through the innovation of appropriate technologies. This substitution process may even lead to increased agricultural production in a sustainable manner. In the case of Nepal's rice-based cropping system, such innovation may come through in three ways: (a) through the development of short-season rice varieties that can escape the effect of early or late season drought; (b) through the development of efficient irrigation systems, and (c) through the development of specific agronomic practices that can harness the negative effects of monsoon rainfall.

Even though farmers have developed risk reduction strategies to cope with the vagaries of the monsoon climate in their farming systems, the amount, timing, and duration of monsoon rainfall still significantly affect their rice production. For this reason, I have identified *a priori* that monsoon rainfall is a major determinant of rice productivity in Nepal and defined it as the average rainfall that occurs during the period of the monsoon (June, July, August, and September). In this analysis, the average[5] cumulative monsoon rainfall from 196 meteorological stations has been taken to represent Nepal's rainfall variable (see Figure 4.2). Although this variable is derived from the long-term average, it has no time series variation, and has one value per district.

As discussed in Chapter Two, interannual variability is also a distinguishing feature of the monsoon rainfall and, consequently, has direct effect in rice productivity. The date of its onset at a given location is highly variable during any given monsoon period. Such variability has negative impact on productivity. Bliss and Stern (1982) report that a two-week delay in the onset of monsoon during the rice planting season can lead to as much as a 20 percent decline in rice yield. However, this analysis will not consider the interannual variability of the average summer monsoon.

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[5] According to World Meteorological Organization (WMO), an average of 30 years of continuous records is considered normal. Unfortunately only 89 meteorological stations in Nepal have rainfall records for such a long period of time. Therefore, to have spatially normal climate, many other stations having records for less than 30 years have had to be included.

The rainfall data are measured daily at meteorological stations distributed sparsely across Nepal (see Figure 4.2). Based on the daily value recorded at each meteorological recording station, the Department of Hydrology and Meteorology calculates the monthly sum of rainfall and makes it public. Average monsoon rainfall data for each meteorological station is calculated by using the monthly total rainfall. This average value forms the normal rainfall of the recording station in question. Unlike other data that are actual district averages, the rainfall data are available at point locations. In order to create a continuous precipitation surface across Nepal, I used a technique of spatial interpolation.[6] There are several interpolation methods available such as inverse distance weighting (IDW), kriging, and splines (O'Sullivan and Unwin, 2003). Each method has its merits and choice of method depends on density of data points, variability of the field under consideration, and the purpose of interpolation (Shen et al., 2000). Following Shrestha et al. (2000), I used ordinary kriging to create spatial surface of monsoon rainfall.

Kriging is similar to inverse distance weighting in that it uses a weighting mechanism that assigns more influence to the nearer data points to interpolate values at unknown locations. If applied properly, kriging allows the user to derive weights that result in optimal and unbiased estimates. It attempts to minimize the error variance and set the mean of the prediction errors to zero so that no over- or under-estimates are observed (Oliver and Webster, 1990; Deutsch and Journel, 1998). The unique feature of

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[6] Spatial interpolation is a statistical method of predicting the values at unobserved sites based on the measurements made at point location within the same area or region. This technique uses the location and

kriging is that it provides an estimation of the error at each interpolated point, providing a measure of confidence in the modeled surface. The accuracy of interpolation is assessed by cross-validation for both observed points and interpolated values of the same point. Although far from perfect, cross-validation results through correlation between the values observed at each climate station and the value that is derived through kriging (correlation = 0.74) demonstrate that the ordinary kriging used for interpolation of rainfall data point location is adequate to represent rainfall surface of monsoon rainfall in Nepal (see Figure 4.3).

To obtain an average monsoon climate at the district level, I first created rainfall surfaces for each month (June, July, August, and September) of the monsoon season using kriging (see Figure 4.4a, b, c, and (d) in ArcGIS 8.3. With the use of zonal statistics function in ArcGIS, I then calculated the mean value from the value generated in the raster cell through the kriging interpolation for each month. These values were then summed for all the districts to make an average monsoon value. The mean rainfall value of the district represents the monsoon climate for this study. Figure 4.6 shows the average monsoon rainfall created using zonal statistics in ArcGIS. The figure also shows four distinct clusters of rainfall patterns across the country. The districts with the least monsoon rainfall (<1000mm) are concentrated in the western part of the country and include both the Mountain and the Hills districts. The middle section of the country receives the most rainfall (>1500 mm), which is most favorable for rice production. The

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magnitude of the values at known points to estimates the values at unmeasured locations.

Terai and the Hills districts situated in the eastern part of the country experience low precipitation (<1300 mm), and these regions are generally considered to be marginal for rice production. The western Terai and Hills districts receive a modest amount of rainfall (between 1300 to 1500 mm), which is regarded to be adequate for rice production.

Irrigation: Irrigation mediates the relationship between climate and agriculture production and has become a widely used substitute in areas where soil moisture is inadequate for crop growth and development (Easterling et al., 2004). Irrigation is not an innovative technology *per se,* although increases in irrigation efficiency are derived of innovative technologies. For example, the efficiency with which nutrients from fertilizers are delivered to the plant depends significantly on the presence of soil moisture. The presence of irrigation alleviates the problem of water scarcity, a major constraint in the implementation of improved technologies, such as high yielding varieties (HYVs) and the use of chemical fertilizers. In the past 25 years, the government of Nepal made major investments in irrigation development, from barely NRS 9.2 millions in 1974/75 to NRS 5,035 million in 2001/02. During the 1990s, investment in irrigation accelerated notably, reaching an all time high since 1974/75 (HMG/MOAC, 2002).

Reliable access to irrigation not only attracts farmers to take advantage of the supply of water by the adoption of advanced agro-technologies (e.g., HYVs, fertilizer, and pesticides), it also helps them plan their cropping activities. For example, in Nepal, where there is reliable irrigation, farmers adopt a system known as *Pareli* – a traditional labor exchange system whereby members of a community exchange labor with participating households. It is a system primarily designed to alleviate labor scarcity during peak agricultural activities such as rice planting and harvesting season. This system provides an added advantage given the highly labor-intensive nature of rice cultivation.

In the data set, the variable measuring irrigation is reported as *net irrigated area,* which is a measure of the total geographic area that has received irrigation during the crop calendar year. Irrigated land refers to areas with access to irrigation in a given district either throughout the year or part of the year (e.g., the irrigation system activated only after the onset of the rainy season). To make interpretation of such results more practical, I have transformed the net irrigated area as a percentage of the total rice cultivated area by dividing the total irrigated area by the total rice area. One of the assumptions in this study is that all irrigated area is utilized for rice cultivation, an acceptable notion given the importance of an abundant supply of water for growing the crop (Thapa, 1994).

Biophysical factors: Nepal's three ecological zones (Terai, Hills, and Mountain) provide a standardized framework for characterizing climate, soil, and terrain conditions of the country. Biophysical conditions, such as soil type and slope aspect, vary among the three ecological regions, creating different underlying conditions for rice production. Hence, technology appropriate for one ecological region may not be suitable for another, imposing limitations on the transferability of agricultural research due to the existence of several regional climates. On the other hand, opportunities for borrowing and adapting research from neighboring India is likely to be advantageous in rice production in the

Terai region, as the latter is largely on extension of the same large agro-climatic sub-region of the Gangetic Plains (Yadav, 1987). Thus, improvement of rice productivity in a country that is climatically diverse as Nepal depends more on development of technologies that are location specific.

From the policy perspective also, the three ecological zones have traditionally been used to evaluate and plan crop production potential of the country. For example, the four objectives outlined by the first comprehensive agricultural development plan of the country (the Ten-Year Agricultural Plan, 1975-1985) prioritized the fertile Terai and the valley bottoms for high input agriculture, such as grain production; the Hills for fruit and vegetable production, and the Mountains for livestock development (Yadav, 1987). This macro-level policy, according to HMG/ADB, 1995 has remained largely unchanged and continues to be the core strategy of the more recent twenty-year plan (1995-2015). For this reason, the ecological zones of Nepal are used in this dissertation as a proxy for the biophysical condition of the rice cultivation, and have been identified by creating dummy variables (Terai = 0, Hills and Mountain = 1).

Source of data

This study is based on secondary data obtained from the various agencies of the government of Nepal. The data concerning rice productivity (yield) and irrigation is obtained from the Nepal Agricultural Database (NAD) of the Ministry of Agriculture and Co-operatives (MOAC). The data on agricultural productivity and irrigated area by district begins from 1991/92. For the purpose of the dissertation, the data on rice productivity and irrigation use for the year of 1991/02 and 2002/03 are drawn from this source. The data on average monthly rainfall is obtained from the Department of Hydrology and Meteorology (DOHM). The DOHM has compiled average monthly precipitation for the period of 1968 through 1997 recorded at various meteorological stations throughout the country. This data has been used to represent the monsoon rainfall in this analysis.

Unit of analysis

The district (i.e., the smallest Nepalese administrative unit, comparable to a county in the United States) is the primary spatial unit of analysis in this study. It is the smallest level for which data on rice productivity and irrigation acreage are available. Of the total 75 districts of Nepal (39 in the Hills, 20 in the flat Terai, and 16 in the Mountain regions), 73 districts are included in this study. The districts of Mustang and Manang within the Mountain region are not included since no rice is grown in these districts.

The choice of the district as the unit of spatial analysis is further justified because it is the smallest level that contains the full complement of government administrative services. For example, in the agriculture sector, every district has a government run Agricultural Development Office (ADO) that employs subject matter specialists and extension workers responsible for promoting location-specific technologies. Each district is also supplemented by the office of the Agricultural Input Corporation (AIC) and the

Agricultural Development Bank (ADB), government subsidiaries established to market agro-technologies to the farmers. In addition, the Department of Irrigation (DOI) has its offices at the district level which is responsible for developing irrigation infrastructure. All these agencies are pivotal in the development of specific agricultural technologies needed in various agro-climatic regions of Nepal. Also, the Regional Agricultural Research Stations, discussed in Chapter Two, conduct research and outreach activities appropriate to the local climate and socioeconomic needs of the farmers in a district.

This study involves the use of annual time series data on rice productivity and irrigated area starting from 1991/92 to 2002/03, and provides a temporal dimension to the analysis of the relationship between climate and rice production technologies. As mentioned earlier, the year 1991/92 was the first time that the MOAC made district level data available on an annual basis, thereby setting the timeframe for this study. While one may argue that the 12-year period chosen for this study may not be a long enough to observe technological changes in agriculture, it is a reasonable period for observing the impacts of ongoing agricultural R&D activities in the highly dynamic rice-based cropping system of Nepal.

The period of 1990s, covered by this study, is marked by major policy changes that greatly affected production in the agricultural sector of Nepal. Some of the important changes include: (a) the establishment of the Nepal Agricultural Research Council (NARC) in 1992; (b) the implementation of the 20-year Agricultural Perspective Plan (APP) in 1995; and (c) the deregulation of the fertilizer policy in 1997.

NARC is an apex national level agricultural research body entrusted to develop an effective and dynamic agriculture research system to increase the food security of the people of Nepal. The APP sets strategic priorities for the development of the agricultural sector for 1995-2015. It has identified increased supply of fertilizer and the development of irrigation infrastructure as the principal factors that contribute to the achievement of accelerated agricultural growth and improved household food security in the country. In line with the policy priority set by the APP, in 1997 the government de-regulated the fertilizer policy. As discussed in Chapter Two, this was achieved by (i) removing the monopoly of the AIC and by allowing the private sector to import and sell fertilizers, (ii) phasing out fertilizer subsidies to the farmers, and (iii) by decontrolling the fertilizer prices (HMG/MOAC 2002). Although agricultural transformation through innovation and development of appropriate technologies has always been a policy priority, in the 1990s, Nepal pursued a comprehensive rice-based technological packages mainly composed of high-yielding varieties of rice, chemical fertilizer, pesticide, and irrigation development (HMG/ADB, 1995), all of which were pivotal in achieving self sufficiency in food production. In addition, starting in the mid 1990s, the government began to partner with non-governmental organizations (NGOs) and the private sector.

Analytical protocol

Earlier I noted that the differences in climatic and biophysical characteristics (e.g., soil type and topographic condition) account for a significant amount of variation in rice productivity in Nepal. For example, with higher temperature and better soil type, the

Terai region of Nepal is favorably endowed for rice cultivation and has always exceeded the Hills and the Mountain regions in average rice production. Likewise, poor soil quality combined with low temperature pose a significant constraint in rice productivity in the high Hills and the Mountain regions. Therefore, productivity growth in these regions is contingent upon the development of high-yielding varieties of rice that can harness the temperature effects. If the Hills and the Mountain regions are to catch up with the Terai region, where biophysical conditions for rice cultivation are more favorable, then technology has to compensate for climatic constraints of the less favorably endowed regions. Against this backdrop, the existence of climate-induced innovation in Nepal is assessed through analysis of both σ and β convergence.

First, I will analyze the σ-convergence by examining measure of spread of the rice productivity at aggregate (national) and disaggregate (ecological region) scales. Analysis of the evolution of σ-convergence across the different scales is especially informative to see whether the pattern of σ-convergence observed at the aggregate scale, for example, is also found within the disaggregate scale of ecological regions. Second, I will investigate whether there is emerging tendency for districts with low initial rice productivity to grow relatively faster compared to those having greater initial rice productivity. This will be achieved through the test of β-convergence.

As discussed earlier there are two methods for the test of β-convergence, (a) absolute β-convergence and (b) conditional β-convergence. As a convention, I will begin with the test of absolute β-convergence at the aggregate scale to examine whether there is general tendency for districts with low initial rice productivity to grow relatively faster compared to those with greater initial productivity. The ability of absolute β-convergence to explain productivity growth rates across the diverse districts of Nepal, however, is rather small. This is not surprising since the specification of absolute β-convergence implicitly builds upon the assumption that rice productivity among regions will converge into similar growth trajectories. Therefore, a subsequent analysis using a dummy variable model is performed. In the dummy variable model, the Terai is taken as a reference region where the coefficients of the regional dummy variables (i.e., Hill and Mountain) provide estimates of difference with reference to the Terai region. The dummy variable model helps determine how close or far apart the Hills and Mountain regions are from approaching the most favorable region – the Terai. Nepal's 73 districts included in this study are characterized by unique climatic characteristic where the amount of average monsoon rainfall that each district receives is different. In order to control for the effects of monsoon rainfall on rice productivity, an additional model with irrigation along with the average monsoon rainfall is included.

Methods of analysis

Based on the analytical protocol presented in the previous section, the evolution of both σ and β convergence will be examined. However, prior to this analysis, I will provide an illustrative example of spatial patterns of average rice productivity across the 73 districts of Nepal. Using two separate maps constructed respectively for 1991/92 and 2002/03, which mark the beginning and the end of the study period, I will demonstrate the change in productivity across the districts of Nepal during these time periods. These yield maps will then be overlain on the average rainfall map to demonstrate the evolution of rice productivity in response to average monsoon rainfall, an important climatic variable, during each of these time periods. The purpose of the map is to demonstrate how regional patterns of rice productivity have evolved over time, and whether there is a significant growth in rice productivity in the districts with lower than average monsoon rainfall. Higher rice productivity growth during 2002/03 compared to 1991/92 in districts with lower rainfall would indicate that climate induced innovations are at work, thereby signifying convergence.

Study of σ-convergence: In this study, σ-convergence provides the measure of spread of rice productivity from the mean of all the districts in the country. Following Sala-I-Martin (1996), σ-convergence occurs when the dispersion in rice productivity across 73 districts of Nepal tends to decrease over time.

That is, if

$$\sigma_{it+T} < \sigma_{it} \qquad (1)$$

where, σ_{it} is the dispersion of rice yield (y_{it}) across districts $_i$ at the initial period (1991/92) and σ_{t+T} is the dispersion of log of rice yield across districts at subsequent periods.

As discussed earlier convergence of σ may be a necessary condition but it is not a sufficient condition to generate β-convergence. For this reason, along with the study of the evolution of σ-convergence, I investigate whether Nepal's rice productivity over time demonstrates the presence of β-convergence as well. The test of β-convergence is important because it may reveal whether or not there is a tendency for districts with relatively low initial rice productivity to catch up with districts that have relatively higher initial rice productivity.

In this analysis, I examine both absolute and conditional β-convergence. As the first step in quantifying convergence, I investigate whether there is the presence of absolute β convergence across the districts of Nepal. Following Barro and Sala-I-Martin (1995), absolute β convergence in this study refers to the tendency towards equalization of rice productivity across 73 districts of Nepal, where districts with low productivity at the initial stage grow faster to catch-up with the districts with higher initial productivity. It is absolute because all other factors of production are assumed constant across 73 districts. Absolute β convergence can be tested on the basis of ordinary least squares estimation of the following approximation to eq. (2) discussed earlier.

$$(1/T)\ \ln(y_{it+T/}\, y_{it0}) = \alpha + \beta \ln(y_{it0}) + \varepsilon_{i0,T} \qquad (2)$$

where, $(1/T)\ \ln(y_{it+T/}\, y_{it0})$ defines the natural logarithm of district *i's* average rice productivity growth from 0 to T, in which $y_{i,t+T}$ measure average productivity in district i between 0 and T and y_{it0} measures the rice productivity at district i during base year of 1991/92. The parameter, α, is the intercept term and $\varepsilon_{i0,T}$ represents the average of the error term, ε_{it}, between time 0 and T. In this case, the dependent variable is the natural logarithm of the average growth rate of rice productivity between 1991/92 – 2002/03 and the independent variable is the natural logarithm of the rice productivity of the base year 1991/92.

The sign of the β coefficient indicates either convergence or divergence. Negative and significant sign of the β coefficient indicates convergence whereas a positive sign indicates divergence. Absence of either signs on β coefficients indicates that neither convergence nor divergence has occurred. If there is an occurrence of β convergence it implies that over time, districts with comparatively lower initial rice productivity have increased their rate of production relatively faster than districts with higher initial productivity.

The rationale for absolute β-convergence lies on the relative homogeneity of the factors of production across the districts of Nepal. In agriculture where productivity is determined by biophysical and climatic condition, absolute β-convergence is not sufficient (McCunn and Huffman, 2000), hence the scenario of conditional β-convergence. As discussed earlier the Terai region of Nepal is favorable endowed for rice production compared to the high altitude region of the Hills and the Mountain. If the districts with less favorable climates receive appropriate responses from the public institutions responsible for devising technologies, then there should still be convergence to the same growth trajectories, not just necessarily at the same level of rice productivity as those of districts with favorable climates. For this reason a conditional conversion model with dummy variable (Terai = 0, otherwise = 1) of the following form will be estimated:

$$(1/T)\ \ln(y_{it+T/}\, y_{it0}) = \alpha + \beta \ln(y_{it0}) + \delta\mathrm{H} + \delta\mathrm{M} + \varepsilon_{i0,T} \qquad (3)$$

where, δH and δM represent the Hills and the Mountain dummy variable and where the Terai is considered as the reference region. The dummy variable model allows for control of possible differences across districts such as that due to different biophysical conditions. The question then is whether the Hills and the Mountain regions are significantly different from the Teari or not. If the answer is no then the notion of absolute convergence is accepted and if the answer is yes then convergence is conditional. In short, conditional convergence leads to the assertion that Nepal's regions can have different equilibrium levels, but as long as technological innovation is induced by differences in climate resource, they should eventually grow at the same growth trajectory. Conditional convergence can help to explain why districts can converge to the same growth trajectory, albeit with different equilibrium levels.

If districts with favorable climate have increased their advantage over the districts with less favorable climate, intuitively it shows complementarities between technology and climate (Mendelsohn et al., 2001). It also rejects the notion that scarcity of climatic resource acts to spur technological innovation to substitute for climatic resources, hence providing no support for the climate-induced innovation discussed earlier. In order to test for the existence of climate-induced innovation, a subsequent conditional β convergence model with additional explanatory variables of the following forms is estimated:

$$(1/T)\ \ln(y_{it+T/}\, y_{it0}) = \alpha + \beta \ln(y_{it0}) + \gamma_i X_i + \psi_i Z_{it+T} + \delta\mathrm{H} + \delta\mathrm{M} + \varepsilon_{i0,T} \qquad (4)$$

where, X_i represents the districts i's average monsoon rainfall and Z_{it+T} represents the growth rate of irrigated area as a percentage of total rice cultivated area between 0 and T, $\gamma_i X_i$ is the average monsoon rainfall, and $\psi_i Z_{it+T}$ represent the average growth rate of the irrigation rice land during the 12 year of study period.

The variable rainfall is used as the proxy for climate, where each district is represented by a unique value of climatic characteristics. A positive and significant value of the coefficient indicates that districts with higher monsoon produce significantly higher amounts of rice compared to those districts with lower monsoon rainfall. In other words, there is a direct complementary between climate and technology. However, the opposite is true if the sign of the coefficient is insignificant, implying that technology is substituting for climate.

In accordance with the hypothesis of induced innovation, research and development effort should generate conditions that ease out the resource constraints that may be inhibiting growth in rice productivity. In areas where water resource is limited due to inadequate rainfall, research effort should focus on innovation of technologies that substitute for climate (e.g., drought resistant rice varieties) and/or development of infrastructure (irrigation) that alleviates the deficiency of rainfall. Therefore, to a large extent, the influence of rainfall is mediated by the presence of irrigation, hence it is used as an activity interacting closely with climate and acting as a substitute for scarcity of rainfall. So, the possibility of productivity convergence is also conditioned by the existence of irrigation. I expect to find a positive and statistically significant coefficient of irrigation and possibly a positive, but not significant coefficient of rainfall. Such findings would imply that districts lagging in rice productivity during the initial period are benefiting from targeted intervention made in response to existing climatic limitations. Thus, such findings would cause rejection of the null hypothesis that *climatic limitations cannot be shown to provide incentives for farmers to urge their supporting* *institutions to invest in research and development of location-specific rice production technologies that substitute for climatic scarcity*.

Speed of convergence

In convergence literature, it is customary to estimate the speed of convergence which is estimated by making use of the coefficient of β obtained by running growth of initial level regression (Barro and Sala-I-Martin, 1995). Following McErlean and Wu (2003) the speed of convergence across the districts of Nepal is computed as:

$$\hat{\beta} = -\ln(1+\beta)/T \qquad (5)$$

where $\hat{\beta}$ is the estimated coefficient that shows the rate of convergence, β is the coefficient of growth-initial level regression, and T represents the length of the study period. A positive and significant value of estimated $\hat{\beta}$ (i.e., $\beta<0$) in growth of initial level regression is a necessary condition for rice productivity convergence. If the estimated β is negative (i.e., $\beta>0$) and significant then divergence is accepted. Likewise when the coefficient of estimated β is insignificant, neither convergence nor divergence is accepted (McErlean and Wu, 2003). If convergence in rice productivity across the districts of Nepal is to occur then districts with low rice productivity at the initial year must exhibit greater rates of growth compared to the growth rates of those districts with higher initial level of productivity.

Synthesis

If the β convergence coefficient, obtained by regressing the measure of rice productivity growth rate on the initial productivity, is negative and significant, then the assumption of convergence holds. That is, if the rice productivity across the districts of Nepal is converging, then districts with low levels of rice productivity in the initial period are exhibiting greater rates of productivity growth relative to the districts with higher initial rice productivity. Districts with favorable climate that have increased their advantage over the districts with less favorable climate are believed to have exhibited complementarities between technological innovation and climate. In such cases, the notion that scarcity of climatic resources spurs technological innovation would be rejected, causing acceptance of the null hypothesis of this dissertation. If, on the other hand, investment in research and the development of technologies favors districts with harsher climate for rice production, then the marginal productivity of the crop would increase more rapidly in these districts compared to the districts with more favorable climate. Such development would ultimately lead to the convergence of rice yield across the districts of Nepal over time, leading to the rejection of the null hypothesis. The next chapter will analyze the results based on the methodology presented in this chapter.

Variables	Definition	Dimension
1. Dependent variable i) Rice yield	Net yield kilogram (kg) per hectare	Time series
2. Independent variables		
i) Average monsoon rainfall	Average monsoon rainfall	30 years average
ii) Irrigation	Percent of net rice area under irrigation	Time series
iii) Ecological zone	Regions to differentiate the resource endowments	Ecological characteristics

Table 4.1: Variables included in the convergence models.

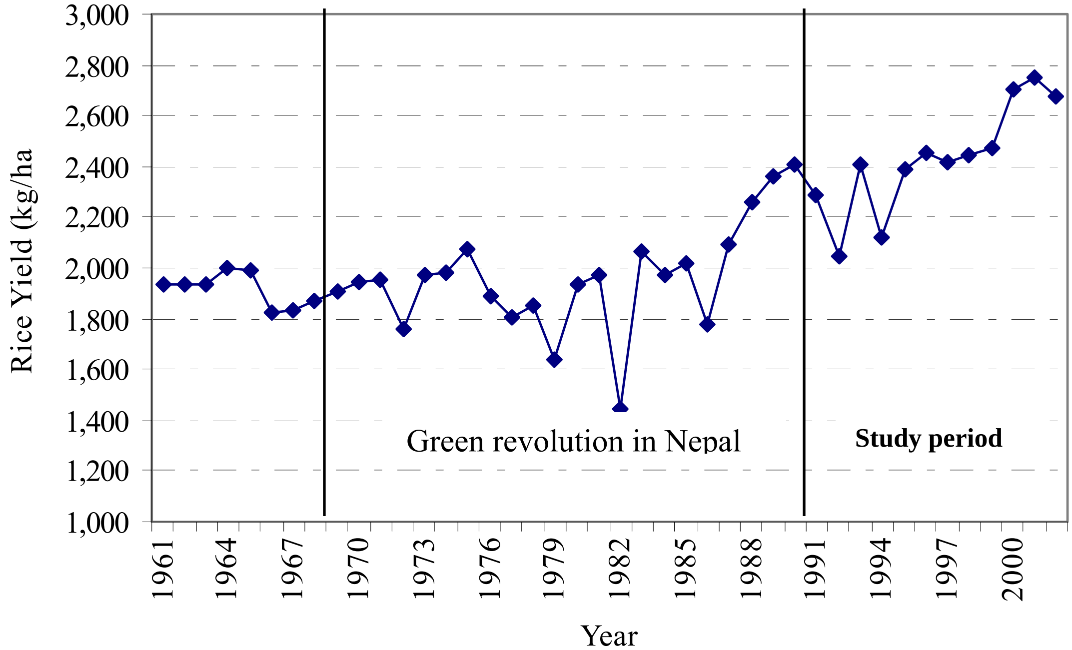


Figure 4.1: Annual time series of rice yield in Nepal, 1961 – 2001

Source: FAO STAT, Accessed 2002, July

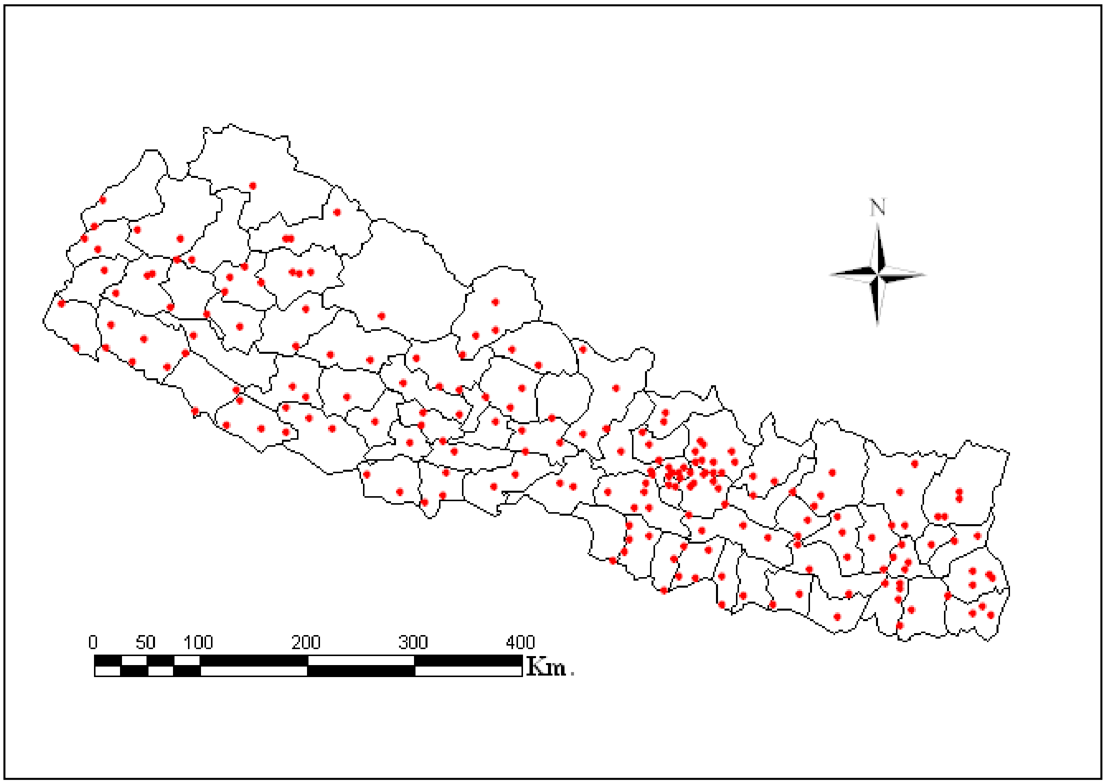


Figure 4.2: Meteorological stations across the districts of Nepal

Source: Department of Hydrology and Meteorology of the Government of Nepal

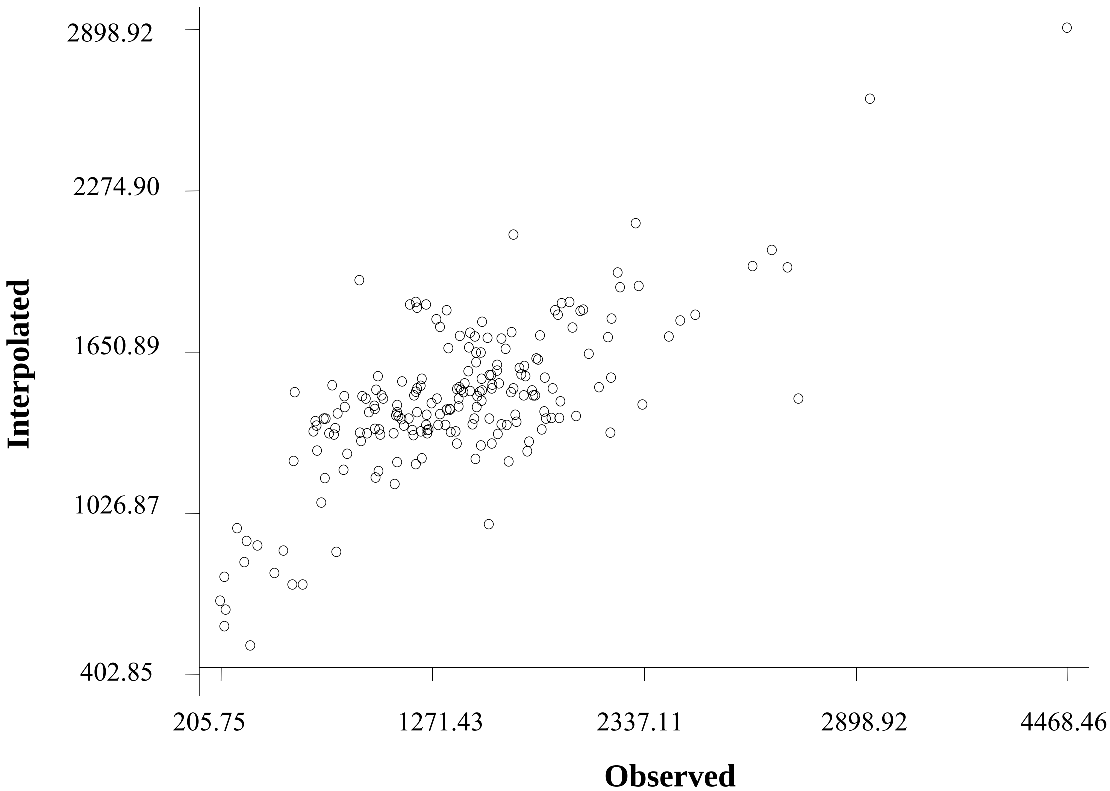
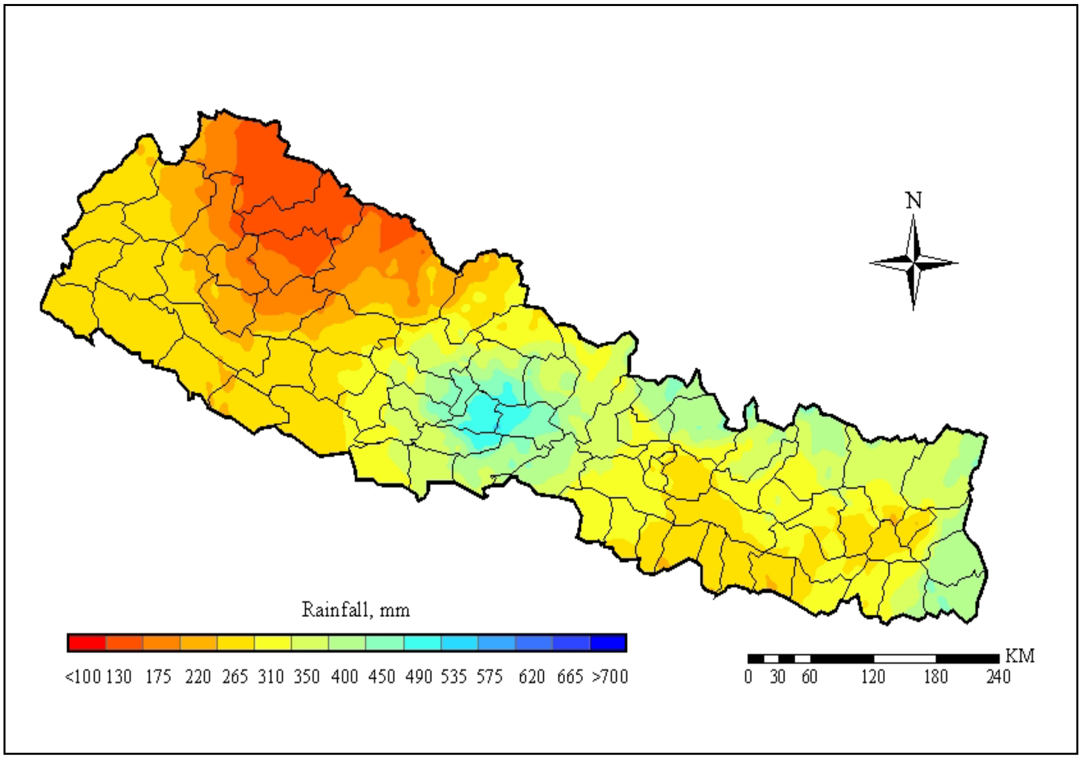


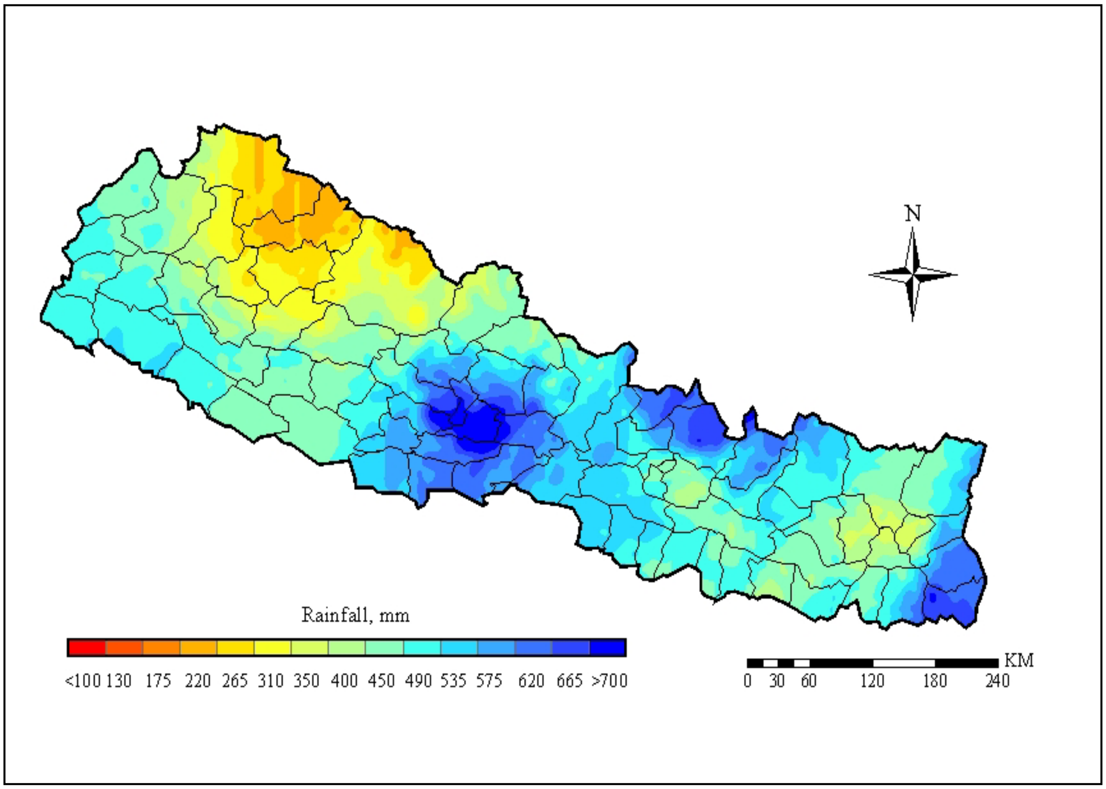
Figure 4.3: Correlation between observed and estimated value of rainfall

Note: The pairwise correlation (r=0.74, p <0.5) indicates that the average value of rainfall created using Kriging interpolation is robust



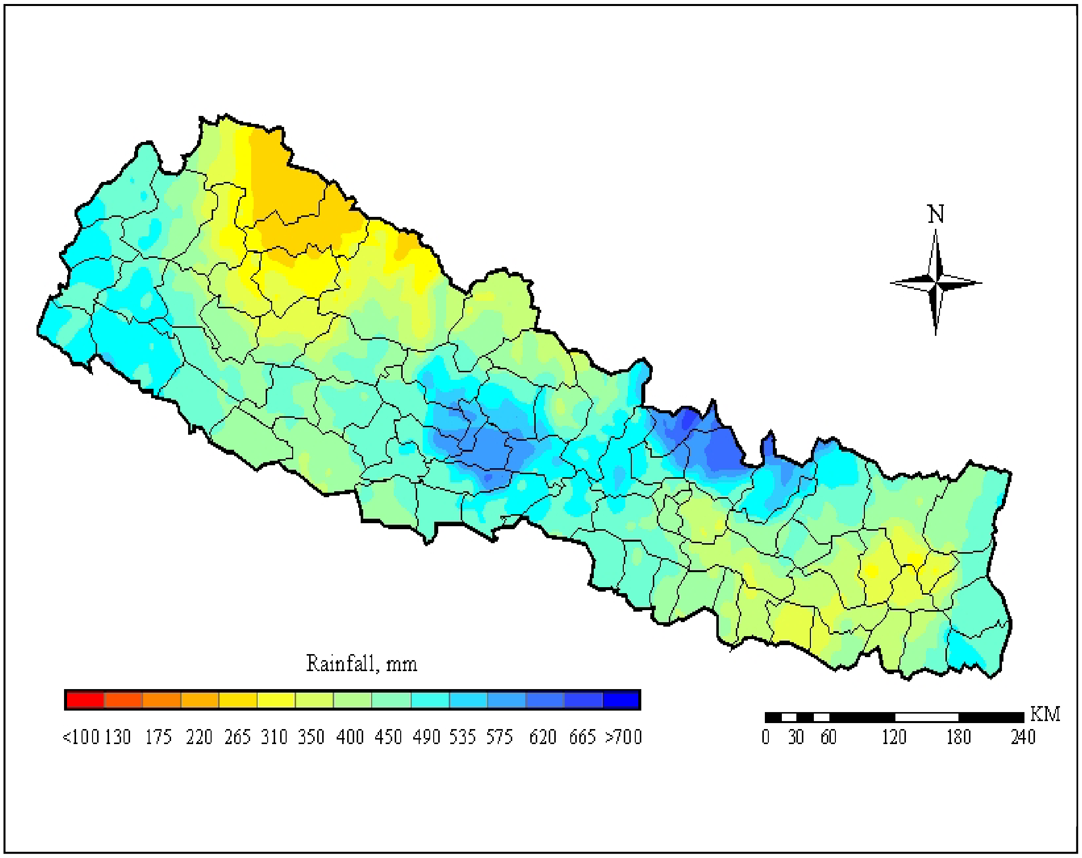
Map 4.4a: Average precipitation surface for the month of *June*

Note: The precipitation surface is obtained through Kriging interpolation techniques (Method = Gausian, Search radios = 12 nearest point). Average rainfall data obtained from the Department of Hydrology and Meteorology from 196 meteorological stations were used to create the rainfall surface.



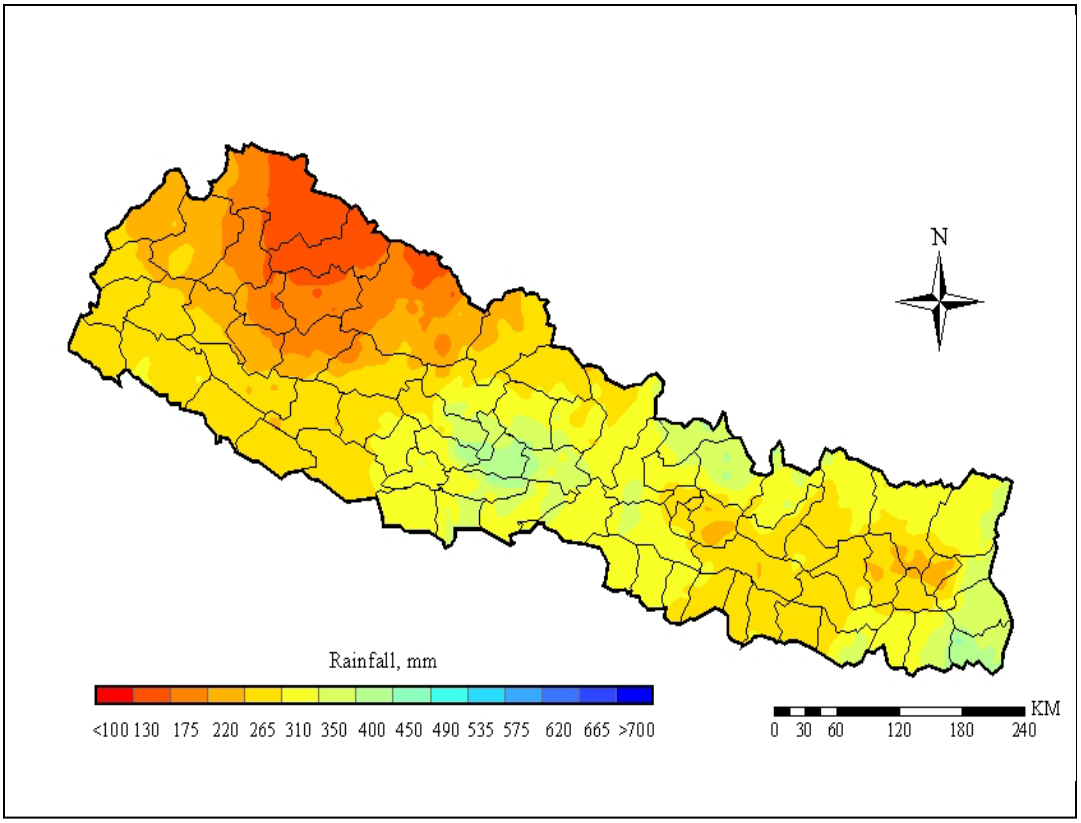
Map 4.4b: Average precipitation surface for the month of *July*

Note: The precipitation surface is obtained through Kriging interpolation techniques (Method = Gausian, Search radios = 12 nearest point). Average rainfall data obtained from the Department of Hydrology and Meteorology from 196 meteorological stations were used to create the rainfall surface.



Map 4.4c: Average precipitation surface for the month of *August*

Note: The precipitation surface is obtained through Kriging interpolation techniques (Method = Gausian, Search radios = 12 nearest point). Average rainfall data obtained from the Department of Hydrology and Meteorology from 196 meteorological stations were used to create the rainfall surface.



Map 4.4d: Average precipitation surface for the month of *September*

Note: The precipitation surface is obtained through Kriging interpolation techniques (Method = Gausian, Search radios = 12 nearest point). Average rainfall data obtained from the Department of Hydrology and Meteorology from 196 meteorological stations were used to create the rainfall surface.

CHAPTER FIVE
RESULTS AND DISCUSSIONS

In the preceding chapter, I provided the methodological approach in light of the hypothesis of this dissertation that *the research establishment in Nepal has devised location-specific technologies to reduce the climatic risks in rice production in climatically less favorable areas*. This chapter presents the results of the empirical analysis of σ-and β-convergence in rice productivity growth in Nepal. To complement the findings of this analysis, I also present specific examples of climate-induced innovations in rice production. I begin with the description of the spatial patterns of rice productivity across the districts of Nepal. Higher rice productivity growth in districts with lower rainfall than in districts with higher rainfall, *ceteris paribus*, may indicate that climate induced innovations is at work, signified by yield convergence. This is followed by summary statistics that show the overall trend of productivity growth during the study period from 1991/92 to 2002/03.

Spatial patterns of rice productivity in Nepal

In this section, I use two maps to illustrate the change in spatial patterns of rice productivity across the 73 districts of Nepal. The two points in time that I have used to construct the map correspond with the beginning and end of the study period. These maps are overlain on the average monsoon rainfall across the country, an important consideration given that rice production is directly influenced by the amount of monsoon rainfall. The darker shades of brown in the maps indicate higher average rice yield and *vice versa*.

Figure 5.1 displays the spatial pattern of rice productivity for the year 1991/92, the beginning of the study period. It is apparent from the map that there is a wide variation in rice productivity across the districts of Nepal. Three districts in the central Hill region (Kathmandu, Lalitpur, and Bhaktapur) rank among the highest rice-producing areas in the country, with yields of over 5.0 t/ha. They are followed by four in the central Terai region (Bara, Parsa, Rautaht, and Chitwan), with yields of little over 3.0 t/ha. In contrast, over 50 percent of the districts, most of them in the western half of the country, produce less than the national average of 2.0 t/ha of rice. Districts with low productivity also correspond with areas that receive lower average monsoon precipitation, indicating a direct association between rainfall (an important climate variable) and rice productivity.

Figure 5.2 shows rice productivity patterns for the year 2002/03, the end of the study period. The spatial patterns of rice productivity during this time reveal an increase in the number of districts with darker shades of brown indicating that more districts are now producing greater than average rice yield compared to 1991/92. Though the previously high yielding districts in the central Hill region have maintained their overall lead, more districts are now catching up. This trend is particularly noticeable in two clusters of districts. One of the clusters is in the western part of the country and the other is in the mid-eastern part of the country. Both clusters are also ranked as regions with low monsoon precipitation. The emerging patterns of rice productivity growth in climatically marginal regions are consistent with a general tendency toward policy makers' increasing investment in regions that are not well endowed agro-climatically. Based on the observed spatial patterns of increased rice productivity in areas with less rainfall, it is clear that districts with low rainfall are also making headway in terms of greater rice production, closing the gap with districts with high rainfall.

Rice productivity trends across geographic scales

This section analyzes the rice productivity trends across different scales during the study period. I begin by examining the overall trends of productivity at the aggregate scale (i.e., national) followed by a more disaggregated analysis at the ecological levels as discussed earlier in this dissertation. Such an analysis of trends summarizes the growth of rice productivity across geographic regions that are characterized by different resource endowments.

Figure 5.3 displays the average rice productivity trends across different geographic scales. At the national level, on average, rice productivity increased from 2,164 kg/ha in 1991/92 to 2,497 kg/ha in 2002/03, with an average annual growth rate of 1.49 percent. In the Terai, where over 70 percent of rice is produced, the yield increased from 2,268 kg/ha in 1991/92 to 2,718 kg/ha in 2002/03, averaging an annual growth rate of 2.19 percent, the highest among the three ecological zones. In the Hill region, where rice is the second most important crop after maize, yield increased from 2,229 kg/ha in 1991/92 to 2,615 kg/ha in 2002/03, an average of 1.57 percent annual growth rate.

During the same period, the growth rate in the Mountain region was fairly small, averaging only 0.31 percent per year, the lowest among the ecological zones.

Though the country has yet to meet the South Asian standard of about 4000 kg/ha of rice production (Pingali et al., 1997), this upward trend is encouraging. One possible explanation of such growth in rice productivity could be the use of improved technologies, including high yielding varieties (HYVs) developed by the National Rice Improvement Program (NRIP). Local-level studies also corroborate the explanation that productivity growth in rice is powered by the use of improved technologies (e.g., Thapa et al., 1992; Goletti et al., 2001). Expansion in the delivery of modern inputs (e.g., fertilizers and pesticides), irrigation facilities, and other infrastructural support may also have contributed significantly towards this growth.

While the overall increase in rice productivity is impressive, disaggregated analysis at the ecological level (Terai, Hill, and Mountain) shows a substantial regional variation. To explain these differences, I pursue an empirical analysis of productivity convergence. As discussed in the previous chapter, convergence in this dissertation is broadly defined as the tendency of districts with low rates of rice productivity growing more rapidly than those with high initial productivity in order to catch-up. Although analysis of productivity convergence is not a direct test of the hypothesis of induced innovation, the existence of convergence is a precondition for it. For example, if Nepal's research establishment is rational in allocating resources to alleviate climatic constraints faced by low-yielding districts through innovation of technologies, then over time, rice productivity in such districts will grow more rapidly than those districts with a favorable climate. In the following section, I use the results from the analysis of σ-and β-convergence, both of which are impartial tests of convergence, to show whether districts with different resource endowments have maintained similar growth trajectory in rice production or not.

First, I analyze the σ-convergence by examining changes in the evolution of the coefficient of variation (CVs) over time at aggregate (national) and disaggregate scales (ecological regions). Analysis of the evolution of σ-convergence across the different scales is especially informative to see whether the pattern of σ-convergence observed at the aggregate scale is also found within the disaggregate scale (e.g., ecological regions). Secondly, I perform the empirical analysis of β-convergence to understand whether there is an emerging tendency for districts with low initial rice productivity to grow relatively faster compared to those with greater initial rice yield.

Analysis of σ-convergence

The analysis of σ-convergence provides a measure of variability of rice productivity. It occurs when the variability of rice productivity across the districts decrease over time. Conversely, increase of variability implies in σ-divergence.

In general, there have been no distinct patterns to suggest the occurrence of σ-convergence in rice productivity because the CVs have not reduced substantially across the districts of Nepal during the 12 years. The CV in 1991/92 was about 32 percent and continued to decline until 1996/97, with a record low in 1995/96 (23 percent). The trend reversed thereafter, reaching an all time high of 40 percent in 2002/03. The finding at the aggregate level does not preclude the fact that σ-convergence may not have occurred within a specific ecological region. In the next section, I analyze the evolution of CVs at the scale of ecological regions to see if the pattern observed at the national (coarse-scale) level is also found within the ecological (finer-scale) regions.

Figure 5.4 present the general trends of the evolution of CVs over time in the three ecological regions of Nepal. Although fluctuating, over time the CVs have declined in 20 districts of the Terai region. From a high of 26.3 percent in 1991/92, the CVs have declined to a low of 7.6 percent in 1996/97. With the exception of 2002/03, all the other years show relatively lower CVs, hovering around 10 percent. At the same time, CVs in the 36 districts of the Hills have remained constant (at around 30 percent), and present no evidence of either σ-convergence or σ-divergence. In the Mountains, however, the evolution of the CVs, from a low of 5.3 percent in 1996/97 to a high of 29.8 percent in 2001/02, show an overall σ-divergence and indicate that rice productivity became more variable across the 14 districts of this region during that time.

Many factors may have been responsible for the apparent lack of σ-convergence across the districts of Nepal, including variability of the monsoon rainfall. Monsoon precipitation normally enters Nepal in early to mid-June when the majority of Nepalese farmers plant rice. If it is delayed, then rice productivity may decline significantly. Also, interruption of monsoon precipitation during the active rice planting time (the third and fourth weeks of June) can cause significant losses in yield. Where irrigation facilities are lacking, farmers have to depend on monsoon precipitation and time their planting cautiously. The timing of rice planting is even more crucial in the Hills and the Mountains due to temperature constraints brought about by topography. If farmers are unable to utilize the narrow window of planting date due to inadequate supply of water, then rice productivity declines substantially. Once the rice is transplanted in the main field, it requires adequate temperature for the growth and development of ear heads. A dry spell during the rice planting season will cause further delay in planting, thereby leading to a negative consequence in rice yield. In order to gain better insight of the likely cause of the observed variability, I further analyze whether the observed pattern of CVs is directly associated with the annual variability of average monsoon rainfall or not.

Although the correlation between the variability of average monsoon rainfall and average rice productivity (as measured by their standard deviations) over the period of 12 years is far from perfect (r= 0.71, p= <0.05), it is an important factor in explaining observed patterns of CVs in rice yield. For example, 1994 is marked as a monsoon anomaly year in Nepal when most climatic stations recorded lower than average rainfall (see Figure 5.4). While a few districts in the central Hill region of Nepal demonstrated an increase in rice yield, more than half of Nepal's rice growing districts show a reduction when compared to the previous year. Lower monsoon rainfall in 1994 has not only had a negative consequence in rice productivity it has also had a noticeable impact in increasing the variability.

Variable monsoon pattern may have been partly responsible for increasing CVs across the districts of Nepal. During the year of 2002/03, for example, rice planting was delayed by two to three weeks in the eastern part of the country due to delayed rainfall.

At the same time, districts in the central Terai region suffered from flooding due to excessive precipitation during the critical growth stage of rice (Joshi et al., 2003). Likewise, due to weak monsoon in June of the same year, farmers in many low-rainfall region of the country (especially mid- and far-western regions) could not begin their rice planting activities at the normal time. However, the Hill region in the central part of the country received timely and favorable monsoon rains. The analysis of *σ*-convergence shows no apparent sign of decreasing variability in rice productivity across the districts of Nepal.

As discussed in the preceding chapter, although *σ*-convergence and *β*-convergence are related, it is possible to observe *β*-convergence without the presence of *σ*-convergence (Sala-I-Martin, 1996). In other words, *β*-convergence is necessary but is not a sufficient condition for *σ*-convergence (Bernard and Durlauf, 1996; Bernard and Jones, 1996). McCunn and Huffman (2000) investigated the convergence in TFP for agriculture in forty-two U.S. states. While they found no evidence of *σ*-convergence characteristics of conditional *β*-convergence existed in the data. Likewise, a recent study in Indian agriculture by Mukherjee and Kuroda (2003) demonstrated no evidence of reduction in productivity gap (i.e. *σ*-convergence) but found signs of *β*-convergence across the states of India. Their conjecture is that in the long run, elimination of differences in infrastructure, research and development, and extension services may have contributed to the apparent convergence of agricultural productivity across the states in India, a finding that is similar to that of McCunn and Huffman (2000).

In this dissertation, β–convergence provides an impartial test that asserts that over time, districts with comparatively lower initial productivity levels have increased their rate of production relatively faster than those with higher initial productivity. Existence of convergence is judged by the sign of the β coefficient – a negative and significant sign of the β coefficient obtained by running *growth-initial level* regression is a condition for convergence. However, researchers such as Quah (1993) and Friedman (1994) hold the view that a negative relationship between growth rate and initial level of productivity does not guarantee a reduction of dispersions. According to this view, instead of making prognosis based on the sign of β coefficient, convergence should be assessed directly by examining the level of dispersion of the productivity across observations over time. Despite this debate, researchers have continued to be interested in β-convergence, in part because it is an impartial test to assess whether there is a significant convergence or not (Islam, 2003).

Empirical test of β convergence

This section deals with the notion of convergence in terms of rice productivity growth rates. The rationale behind this analysis is that those districts falling behind in rice productivity can benefit from technological innovation made in response to the existing climatic conditions.

The most common approach for analyzing β-convergence is by developing a general linear model with productivity growth rates (t_{0+1}) as the dependent variable and the productivity of base year (t_0) as the independent variable, and is termed as *growth-initial level regression* (Islam, 2003:314). In this dissertation, the dependent variable is the average growth rate of rice productivity for the period of 1991/92-2002/03 and the independent variable refers to the rice productivity for the base year of 1991/92. One issue to be considered when testing convergence using time series data is the choice of base year (Bernard and Jons, 1996). The year 1991/92 was selected as the base year for the analysis of the test of β-convergence since it is the earliest in which observations of rice productivity by districts were available in the government database. As indicated earlier, Nepal's rice production is highly sensitive to monsoon rainfall, and the base year of 1991/92 also did not experience any specific climatic shocks. Similarly, by taking an average growth rate as opposed to the growth rates of the final year of study period, I also isolated the effects of climatic fluctuation in rice productivity.

I begin this analysis by presenting the coefficient of absolute β-convergence. The ability of absolute β-convergence to explain productivity growth rates across the diverse districts of Nepal, however, is rather small because the justification for absolute β-convergence is founded on the relative homogeneity of the factors of production. As discussed in the previous chapter, rice productivity in Nepal is determined by several factors including climate. Convergence is, therefore, contingent upon policy decisions geared towards increasing productivity in climatically less favorable regions, hence the scenario of conditional β-convergence.

The qualitative variables such as the three ecological zones can be transformed into quantitative ones and used as predictors in the regression analysis. For example, the qualitative variable that distinguishes physiographic regions (Terai, Hills, and Mountain) may be represented by a dummy variable of the Terai's physiography versus physiographies of the other two regions – i.e. Terai vs. non-Terai – with the respective numerical value of 0 and 1. So the three ecological zones of the country could be represented as three dummy variables – Terai vs non-Terai, Hills vs non-Hills, and Mountain vs non-Mountain. Therefore, a subsequent analysis using a dummy variable model with the Terai as the reference is performed. The dummy variable model helps determine how close or far apart the Hills and Mountain regions are from approaching the reference region – the Terai. Nepal's 73 districts included in this study are characterized by unique climatic characteristics where the amount of average monsoon rainfall that each district receives is different. In order to control for the effects of monsoon rainfall on rice productivity, an additional model with irrigation and with the average monsoon rainfall is included.

Following the hypothesis of induced innovation, research and development (R & D) efforts should alleviate the constraints that may be inhibiting growth in rice productivity. Climatically marginal regions can increase their rice productivity more rapidly compared to the more endowed regions by implementing technologies that are targeted to substitute for climatic deficiencies. For example, in a region where optimum rice productivity is limited due to inadequate rainfall, R&D efforts could be expected to focus on innovation of technologies that substitute for lack of rainfall (e.g., drought resistant rice varieties) and/or on the development of infrastructure (irrigation) that alleviates the deficiency of rainfall. Therefore, to a large extent, the influence of rainfall is mediated by the adoption of drought resistant varieties and/or the presence of irrigation. Irrigation in this dissertation is used as an activity interacting closely with climate and acting as a substitute for the scarcity of rainfall. So, the possibility of productivity convergence is also conditioned by the existence of irrigation.

Absolute β-convergence: The first column of Table 5.1 shows the estimates of the absolute β-convergence across the 73 districts of Nepal. The signs of the implied β-convergence coefficient is in tandem with the overall expectation, i.e., negative and statistically significant (p<0.001). The amount of variation explained by R^2 is 37 percent and that the model's fit as described by F statistics is 40.8 (p<.001). While the larger F statistics show that the model is a best fit, the presence of smaller R^2 indicates that there are other factors that have significant roles in rice productivity growth. The estimated $\hat{\beta}$ convergence coefficient calculated from equation (5) as discussed in the previous chapter shows that districts with lower rice productivity at time t_0 increased their yield by about 3.7 percent per year. This is an indication that rice productivity is taking a definitive growth trajectory where districts with lower rice productivity are catching up.

While the study of absolute β-convergence can be informative in knowing the overall trajectory of rice productivity, it is of limited use in understanding the dynamics of β-convergence across the districts of Nepal. As discussed earlier, the assumption of absolute β-convergence rests on the relative homogeneity of the observations in question (Barro and Sala-I-Martin, 1995; de la Fuente, 1997; Areculus and Arocena, 2000). In the case of Nepal, where rice productivity is determined by climatic conditions, among others, the estimates of absolute β-convergence do not fully explain the effects of these factors in convergence. An understanding of region-specific differential in productivity convergence explains how these factors complement technological innovation in production (Siriopoulos and Asteriou, 1998; Rassekh et al., 2001). In subsequent analysis, by introducing dummy variables, I intend to explore how rice productivity convergence is unfolding across the ecological regions of the country,

Conditional β-convergence with dummy variable model: Conditional β-convergence, as opposed to absolute β-convergence, provides a way to analyze rice productivity across the districts that share some common characteristics. For example, the Hills and the Mountains are differentiated from the Terai because they have different biophysical characteristics. If differences in regional resource endowments should determine the direction of technological change in rice-based cropping systems, irrespective of the district they are grown in, then theoretically rice productivity among regions should approach a common growth trajectory. The theoretical argument behind conditional β-convergence is that technological innovation in climatically marginal district is driven to augment the constraints imposed by limited supply of climatic resources so the rice productivity is improved relatively faster in such districts as compared to climatically better endowed district.

By estimating the conditional β-convergence coefficient using the dummy variable model, I also test whether Nepal's rice productivity has approached a single growth trajectory or not. With the Terai as the reference region – due to its favorable biophysical condition for rice cultivation – the assumption of single equilibrium state is accepted if, and only if, the estimated coefficient of the Hills and the Mountains regions show no significant difference in rice productivity growth. The second column of Table 5.1 presents the estimate of conditional β-coefficient from the dummy variable model. The sign of the implied β-coefficient in the model is in tandem with the overall expectation, i.e., negative and statistically significant ($p<0.001$). The amount of variation explained by R^2 is 50 percent and the F statistics is 25.1, $p<.001$. The estimated β-convergence coefficient implies that the rate of rice productivity convergence across the districts of the Mountain and the Hills is 4.7 percent per year. Although the rate of convergence as shown by the estimated β-convergence coefficient is greater in the dummy variable model than in the absolute model, net of other factors, average rice productivity growth rates across the 39 districts in the Hills remains about 7 percent below that of the Terai and is marginally significant ($p <0.05$). The corresponding figure in the Mountain region remained 19 percent below the referenced region, and is statistically highly significant ($p<0.001$).

Overall, the estimates of β-convergence coefficient reveals that rice productivity growth rates across the districts of the Hills and the Mountain regions is greater indicating that the districts with the unfavorable climate are catching up with the reference region of the Terai. Despite this increased growth rate, however, the Hills and the Mountain regions are still lagging behind in closing the gaps with the reference region. These findings suggest that there may be significant regional differences in the technological response to rice productivity. Biophysically marginalized regions may always lag behind better-endowed ones in terms of applying new climate-oriented (or any other) technologies because the rate of return to investment in agriculture may not be as great as the region with favorable climate.

The findings from the dummy variable model are consistent with the study by McKinsey and Evenson (1998), which measures the intra-country agricultural productivity differentials in India. Although the Green Revolution increased farm net revenue substantially, the study shows that technology had a neutral impact on climate sensitivity. For example, districts with favorable biophysical conditions were associated with higher productivity. The authors argue that the differences have persisted over a long period and are associated with the discrepancy in investment in agricultural research and development. This is an indication that regions with little or no research aimed at addressing the constraints posed by the limited supply of climatic resources have lagged behind.

A recent study by Mukherjee and Kuroda (2003) explores the question of Total Factor Productivity (TFP) convergence in agriculture across the 14 major states of India and they also reveal findings similar to that of McKinsey and Evenson. According to Mukherjee and Kuroda, climatically favorable states of India demonstrated substantial growth in agricultural productivity (over 2 percent per year during 1973-1993), while states with less favorable climate showed marginal improvement in agricultural productivity. Two of the 14 states (Gujarat and Kerala) even showed divergence in TFP growth rates over time. Although the agriculture sector in general performed admirably after the introduction of Green Revolution in 1960s, the authors argue that there is no evidence of the reduction in the productivity gap among the major agricultural states of

India. In line with the findings from McKinsey and Evenson (1998) as well as Mukherjee and Kuroda (2003), Thirtle et al. (2003) reports a widening of gap in agricultural productivity across the 18 districts of Botswana from 1981-1996 despite an overall growth of TFP indices by 1.7 percent per year. They argue that the growth in agriculture was powered exclusively by technological change in cattle ranching resulting in a skewed growth because only a few districts enjoyed the increased comparative advantage of this change.

If agricultural productivity diverges due to the lack of location-specific technologies to address the climatic constraints, then new innovation in resource-rich regions could become a significant source of inter-district variability in agriculture production. In the subsequent model with the additional explanatory variable of climate (average monsoon rainfall), I explore whether climatic constraints contributed to the differential rate of convergence across the ecological regions of Nepal. If climatic limitations in rice cropping have been addressed through technological innovations, the coefficient of average monsoon rainfall will be insignificant. Even though monsoon rainfall is a predominant climatic factor, irrigation may substitute for lack of rainfall. For this reason, I also include percentage of irrigated area as an explanatory variable to explain the relationship between climate, irrigation and rice productivity convergence.

As discussed earlier, irrigation mediates the relationship between climate and crop production (Mendelsohn et al., 2001) and has become a widely used substitute in areas where rainfall is inadequate. For example, presence of irrigation alleviates the problem of water scarcity, a major constraint in the implementation of HYVs of rice in

Nepal. If the districts with greater than average monsoon rainfall have increased their advantage over the districts with less than average precipitation it intuitively shows complementarities between monsoon rainfall and rice productivity. In such a case productivity across the districts of Nepal would show a sign of divergence, implying lack of climate-induced innovation. By the same token, if the districts with less than average rainfall have increased their advantage over the districts with greater than average monsoon rainfall over time, then rice productivity across the climatically diverse districts of Nepal would eventually converge, indicating the occurrence of climate-induced innovation. This suggests (but does not prove) the existence of a condition required to accept the hypothesis of this study: that *farmers and the research establishment in Nepal have devised location-specific cropping technologies to reduce the climatic risks in rice production leading to the convergence of rice productivity across climatically diverse districts of Nepal*.

Conditional β convergence with additional explanatory variables: The third column of Table 5.1 reports the conditional *β*s estimated by using additional explanatory variables. The signs of the coefficients are in tandem with the overall expectation. The amount of variation explained by R^2 is 54 percent and the F statistics is 17.8 (p<.001). After controlling for average monsoon rainfall and irrigation, the results show a greater rate of β-convergence. The estimate of the conditional β-convergence coefficient implies that the rate of convergence is 5.7 percent per year, indicating that the districts with lower rice productivity at time t_0 increases their growth rate by over 5 percent per year.

Net of other factors in the model, the relationship between increased percentage of rice growing areas under irrigation and rice productivity is positive and the coefficient is significant ($p < 0.01$), indicating that a one percent increase in area under irrigation will enhance rice productivity growth by about 7 percent. This may explain why the districts with greater average monsoon rainfall do not necessarily have a comparative advantage over the districts with lower precipitation. It is also the indication that climate variability, particularly the amount and the timing of the onset of monsoon rains in these districts, was addressed by supplying additional water through irrigation. This is consistent with the studies conducted by the International Rice Research Institute (IRRI) which examined the rice productivity patterns in a number of Asian countries (e.g., Rosengrant et al., 1993; Evenson, 1993; van der Eng, 2004), with particular focus on water availability. They found that access to water (either through irrigation or natural rainfall) to be the most important factor in explaining differential productivity patterns in rice. Although rice productivity in Nepal is inherently sensitive to monsoon climate, its vulnerability to uncertainty in monsoon rainfall depends on many factors, including whether or not irrigation is in use. It is possible that with assured irrigation, farmers may have additionally committed more production inputs (e.g. fertilizers) leading to increased production in climatically less endowed regions. This may explain why average monsoon rainfall is not a significant predictor of rice productivity in Nepal.

When controlling for monsoon rainfall and irrigation and using a dummy variable as a proxy to represent region specific biophysical factors, the results suggest that growth in rice productivity across the districts of the Hills and the Terai are statistically the same.

The corresponding figure of the Mountains (-0.17 percent, p <0.001), however, shows that this region lags behind. One of the principal characteristics of the Mountain region, in addition to its overall marginal climate with low temperatures, is the relatively small fraction of arable land available for rice cultivation. In contrast, the Terai and the Hills have a more favorable climate with higher temperatures and a higher percentage of arable land under rice. The better soil quality and warm climate of the valley bottoms of the Hills and the Terai offer a greater potential for rice production, making investment of infrastructure and technology more efficient. This may explain why the rate of rice productivity growth is less in the Mountain than in the Hills and the Terai regions.

Discussions

Although definitive conclusions regarding climate-induced innovation cannot be made from this dissertation, observed rate of rice productivity growth in climatically marginal districts indicate that research establishments in Nepal are sensitive to climatic limitations as appropriately as financial conditions and basic knowledge permit. This is not only important for reducing climatic risks, but equally essential for growth in rice productivity in districts with marginal climate. Such location-specific technological response to address the constraints of climate in rice production is in line with the general expectation of the hypothesis of induced innovation.

In this study I have used only rainfall as a climate variable and have used ecological regions to represent biophysical conditions of a district in question. Perhaps the inclusion of other climatic and biophysical variables, such as temperature, soil types, and slope of the cultivated land may provide additional dimensions to the analysis. Lack of data on the adoption of specific technological innovations made in response to climatic constraints also limited the analysis of climate-induced innovations. This constraint meant that productivity convergence had to serve as a generalized marker for climate-induced innovation. It is, at best, an indicator of the deeper processes of induced innovation and may also reflect other yield-enhancing factors that have little to do with climate.

Based on the findings from this study it can be concluded that rice productivity across the districts of Nepal has increased steadily during the period from 1991/92 to 2002/03. The increase in productivity is not just skewed towards climatically favorable regions but is also observed in drier western and the mid-eastern parts of the country. The emerging patterns of rice productivity growth in climatically marginal regions may have been the autonomous response to the increasing demand for rice production, but it may also have been facilitated by conscious decision to develop technologies that are location specific

The analysis of σ-convergence, which measures variability in production, reveals different patterns of convergence. For example, the Terai region showed signs of convergence, the Hills region neither convergence nor divergence, and the Mountains region displayed signs of σ-divergence. Thus the patterns of convergence differed according to the ecological regions, implying a wider gap in rice productivity between the three ecological regions of the country. The implication of this finding at the policy level is that despite the effort to increase food security in the climatically impoverished regions, the districts in the Mountains appear to be falling behind in productivity.

The empirical analysis of β-convergence, which measures the growth rate, however, shows signs of productivity convergence over time. While the lack of quantifiable data precludes the establishment of a causal link between the roles of climate in technological innovation, there are indications that climatic scarcities as experienced by farmers in the climatically marginal areas are addressed appropriately. For example, irrigation (although not a direct measure of climate-induced innovation) seems to have a significant role in substituting for inadequate supply of monsoon rainfall in the districts that receive lower average monsoon rainfall. The analysis reveals that the districts with greater average monsoon rainfall do not have a greater advantage over districts with lower average monsoon rainfall. There are likely many factors that could have contributed to the observed growth of rice productivity across climatically diverse districts of the country. Farmers may have utilized a combination of agronomic practices to address the limitations imposed by climate on rice production. However, it is reasonable to believe that districts with less than average monsoon rainfall would attempt to improve their rice productivity by alleviating this constraint by increasing the delivery of water through irrigation. To compensate for the lack of such empirical data, I provide a qualitative assessment of climate-induced innovation through review of relevant case studies.

Based on these reviews, I find that the research establishment in Nepal has shown considerable commitment in the development of appropriate technologies that target specific climatic zones. Since the beginning of the rice research program in Nepal in 1967, the government has released over 40 new varieties of rice. A shown in Table 5.2 over half of these varieties were developed for high potential irrigated land (e.g., 13 for the Terai and the fertile valleys and 11 for the Hills) (HMG/MOAC, 2001), a number of varieties were also developed for climatically marginal areas. About 25 percent of these 40 varieties were specifically recommended for rainfed regions having intermittent drought periods of which three were for the rainfed condition of mid and far-western Terai region, four for the drought-prone regions of the Hills, and three were developed as cold tolerant varieties for high altitude regions of the Mountains. For example, *Rampur Masuli*, an improved rice variety, is replacing local low yielding varieties due to its ability to mature 10-15 days earlier, an important consideration for farmers in regions with intermittent drought. The additional features that have led to a wider adoption of this variety include better tillering, high yielding capacity, and tolerance against foliar diseases (Joshi and Witcombe, 2002).

During the 1990s, Nepal made significant changes in agricultural research and development, one of which is the decentralization of its research activities (Biggs and Gauchan, 2001). Along with NARC (the only public research establishment entrusted to devise appropriate technology for farmers of Nepal), many new actors such as non-governmental organizations (NGOs) and private enterprises emerged to take active roles in Nepal's agricultural research and development (Sthapit et al., 2002). Decentralization of its research program provided the mandate for NARC to play a strategic role in coordinating and supporting all actors involved in innovation of agricultural technologies in Nepal. As a result an alternative institutional model in research and development known as Participatory Technology Development (PTD) emerged. The main appeal of PTD has been its promise to improve the adoption rates of appropriate technologies in climatically marginalized regions to increase food security and alleviate poverty, through better partnership with all stakeholders in agricultural development including farmers (Witcome et al., 1996).

By bringing the formal technological innovation process closer to farmers, and by combining the sub-disciplines of agriculture such as crop breeding, insect and pest management, agronomy, and traditional farmer's knowledge, PTD has facilitated the government's effort to transfer agricultural technologies to farmers in a more efficient manner (Witcombe et al., 1998). This new institutional framework has enabled researchers to receive feed-back from farmers about their preferences and perceptions of the technology more directly and frequently. This strategy has improved communication to tailor the technology with farmers' collaboration much more intensively thereby increasing the chances for successful adoption of new innovations (Sperling and Ashby, 1999). The new institutional framework of PTD has enhanced the relationship between NARC and other actors in agriculture thereby enhancing the process to devise location-specific technologies in agriculture. In recent time non-governmental organizations (NGOs) have grown into strong research bodies, an unlikely configuration a decade ago. For example, NARC is jointly working with the Local Initiative for Biodiversity Research and Development (LI-BIRD), an NGO experienced in participatory approach to innovation of technologies in agriculture. One of the important characteristics that distinguish PTD from conventional approach of R&D is that researchers work on objectives established by the farmers (Sperling et al., 2001).

In Nepal, PTD is used as a complement for popularizing varieties that are appropriate for climatically marginal regions (Witcombe et al., 1996). For example, through their joint undertaking, LARC and LI-BIRD have developed cold tolerant and disease resistant rice varieties that are also high yielding (Sthapit et al., 1996). Two high altitude rice varieties (*Machhapuchre-3* and *Machhapuchre-9*) were released in the mid 1990s (Sthapit et al., 1996). A recent study found that *Machhapuchre-3* rice variety was significantly superior to local varieties producing 42 percent greater yield in rice growing areas situated between 1500 to 2200 meters above sea level (Joshi et al, 2001). Similarly, *Machhapuchre-9* was found to be doing well in areas located at altitudes greater than 2200 meters above seal level. Although both of these varieties are prone to seed shattering compared to the local ones (tendency for grains to drop during harvesting), this trait has not prevented farmers from widely adopting the new varieties because the disadvantage is outweighed by the higher yield and better quality (Joshi et al., 2001). According to Shah et al., (2004), other varieties (*Lumle 1-9-1*, *LR 93002*, and *Lumle1-1-1*) have also been found to tolerate cold temperature better during anthesis than local ones. While these varieties are yet to be released, preliminary results indicate that they have been found to be most appropriate for low rainfall areas in the western mountain regions of the country.

Crop improvement has also led to a relatively new approach that has been driven by recent focus on Participatory Plant Breeding (PPB), another important element of PTD

(Sperling and Ashby, 1999). One of the important characteristics that distinguish PPB from conventional approach of developing crop varieties is its emphasis on breeding objectives established by the farmers (Sperling et al., 2001). Farmers take the major responsibility of selecting, experimenting, and disseminating new innovations, and scientists are expected to take a more supportive and facilitative role (Witcombe et al., 1996). This kind of participatory approach is in contrast to the conventional and centralized crop breeding programs with a top-down approach that have traditionally been the hallmark of research establishments. To date, in most developing countries PPB has been applied as a crop improvement strategy primarily in response to improving food security in climatically stressed regions (Sperling et al., 2001). The impact of PPB is reported to be highly positive especially in the marginal climates of Nepal (Sthapit et al., 1996; Joshi et al., 2001).

Researchers in Nepal also collaborate with international research bodies in devising varieties for marginal climate. For example, with the support of the International Rice Research Institute (IRRI) of the Philippines, researchers in Nepal are engaged in developing appropriate varieties for low-rainfall regions of the western Terai (Shah et al., 2004). The partnership with IRRI has been beneficial in producing varieties suitable for the rainfed environment of tropical and sub-tropical regions of the country. Four new cultivars have been recommended for the rainfed environment of the western region of Nepal (Dutta et al., 2004). These varieties were selected based on the performance ranking by the farmers, which is encouraged by IRRI.

Aside from work on varietal improvement discussed above, researchers in Nepal are also engaged in devising agronomic practices that alleviates the constraints posed by climate. For example, in order to maximize yield potential of HYVs farmers must follow a complex set of recommendations, one of which is the timing of planting. Failure to do so may result in substantial loss of yield. HYVs are very sensitive to the planting dates and age of the seedling at time of transplantation from the seed beds to the main field. Studies shows that improved varieties of rice must be transplanted from the see bed to the main field between 24-28 days in order to achieve maximum yield potential (Mahato and Pathic, 1997). In a country where the timing and intensity of monsoon precipitation is highly variable, such a stringent condition may be problematic.

In order to address the constant dilemma associated with the uncertainty of the onset of monsoon, researchers are improvising traditional method of "direct seeding" often practiced in risk prone environments (Pandey and Velasco, 2002). According to Pandey and Velasco, the development of suitable varieties, availability of modern tools (e.g., power tiller drill), and increased access to herbicides has made this traditional technology more profitable in risk prone environment of many Asian countries including Nepal. This method has not only reduced the demand on labor but has thrived in areas of erratic rainfall especially during the early stages of crop development. According to Tripathi et al. (2004), economic analysis of direct seeding yielded an additional net return of 33 percent compared to the conventional method of transplanting.

Parallel to the government's effort in developing technologies for improving production in agriculture, there has been a significant policy change that may have contributed to the observed growth in rice productivity. One of the most important policy changes with regard to rice productivity has been the decision by the government to deregulate the fertilizer policy in 1997. This change in policy has (i) allowed the private sectors to import and distribute fertilizers; (ii) phase out a fertilizer subsidy, and (iii) deregulate fertilizer prices. In the absence of detailed data it is difficult to precisely assess the impacts of the deregulation policy on the fertilizer use by the farmers. Nonetheless, a recent study based on the analysis of household level data collected from 986 farmers indicated a significant growth in the application of fertilizer by the farmers of Nepal (MOAC, 2003). According to this study, almost all households surveyed showed application of some type of soil additive to increase crop productivity. Eighty-one percent of the farmers applied both inorganic and organic fertilizers during the 2001/02 crop year. All farmers surveyed reported that they not only experienced increased supply of fertilizer but also indicated the availability of wider selection of fertilizers in recent times, an option that they had not experienced previously.

Although the lack of data confined the analysis of this dissertation to the test of convergence and the discussion of case studies, significant trends are discernible in the data, and these are drawn upon, in tandem with the assumption of the hypothesis of induced innovation, to gauge (conservatively) the likelihood that farmers and public institutions in Nepal may be able to respond appropriately to the emerging future climatic conditions. In fact, the finding offers insights for refining our existing understanding of process and likelihood of agricultural adaptation to climate variability and change more generally.

Analysis of case studies shows that Nepal's research establishment is committed to and actively engaged in the development of location specific technologies that addresses the constraints of climate, either directly or indirectly. The outcome of such commitment has been a series of technological innovations and changes in policies in agriculture. Together, this may have been responsible for higher yields among the districts with marginal climate, which have subsequently led to convergence of the rice productivity growth rate in the country. These findings support the second hypothesis of this dissertation that the research establishment in Nepal has been actively involved in addressing the climatic constraints on agricultural production by responding appropriately to the location-specific needs of the farmers.

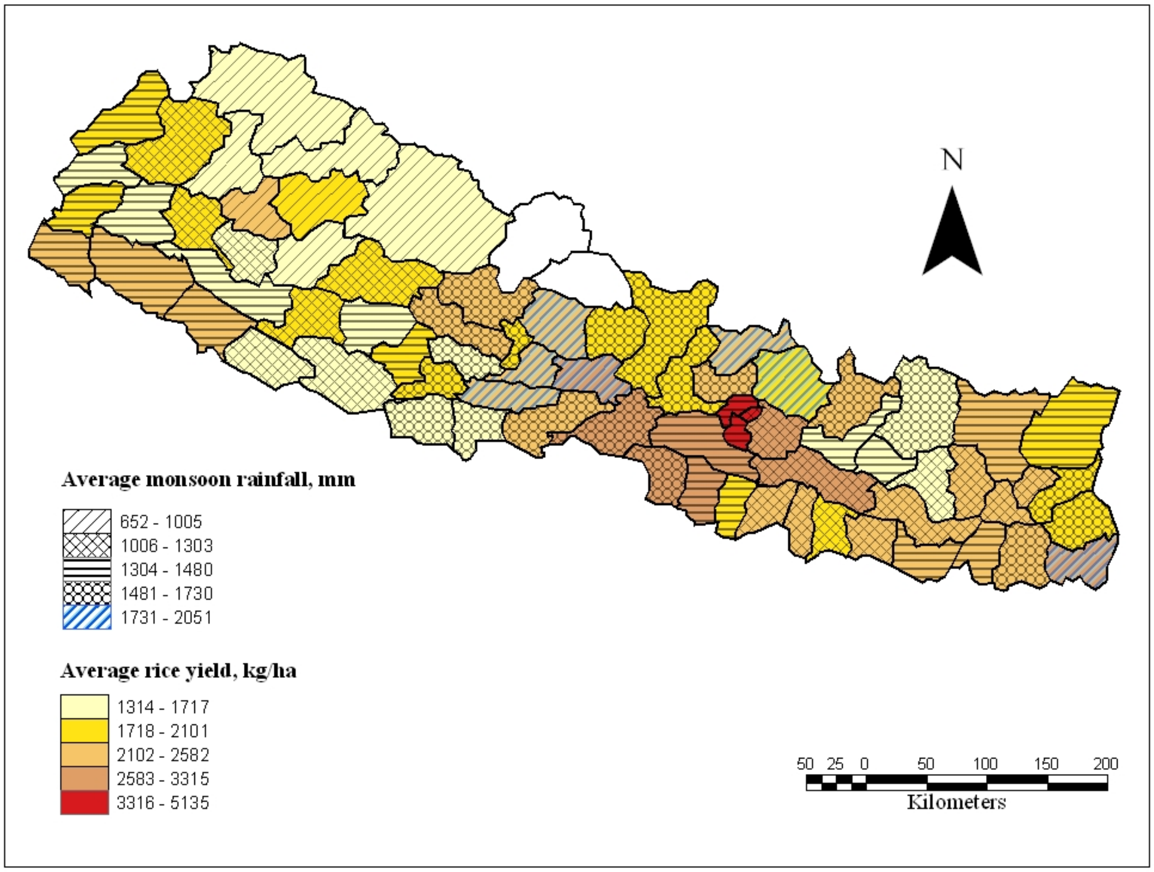


Figure 5.1: Rice productivity patterns across Nepal, 1991/92

Note: Rice productivity patterns are overlain on the average monsoon rainfall across the country. The darker shades of brown in the maps indicate higher average rice yield and *vice versa*.

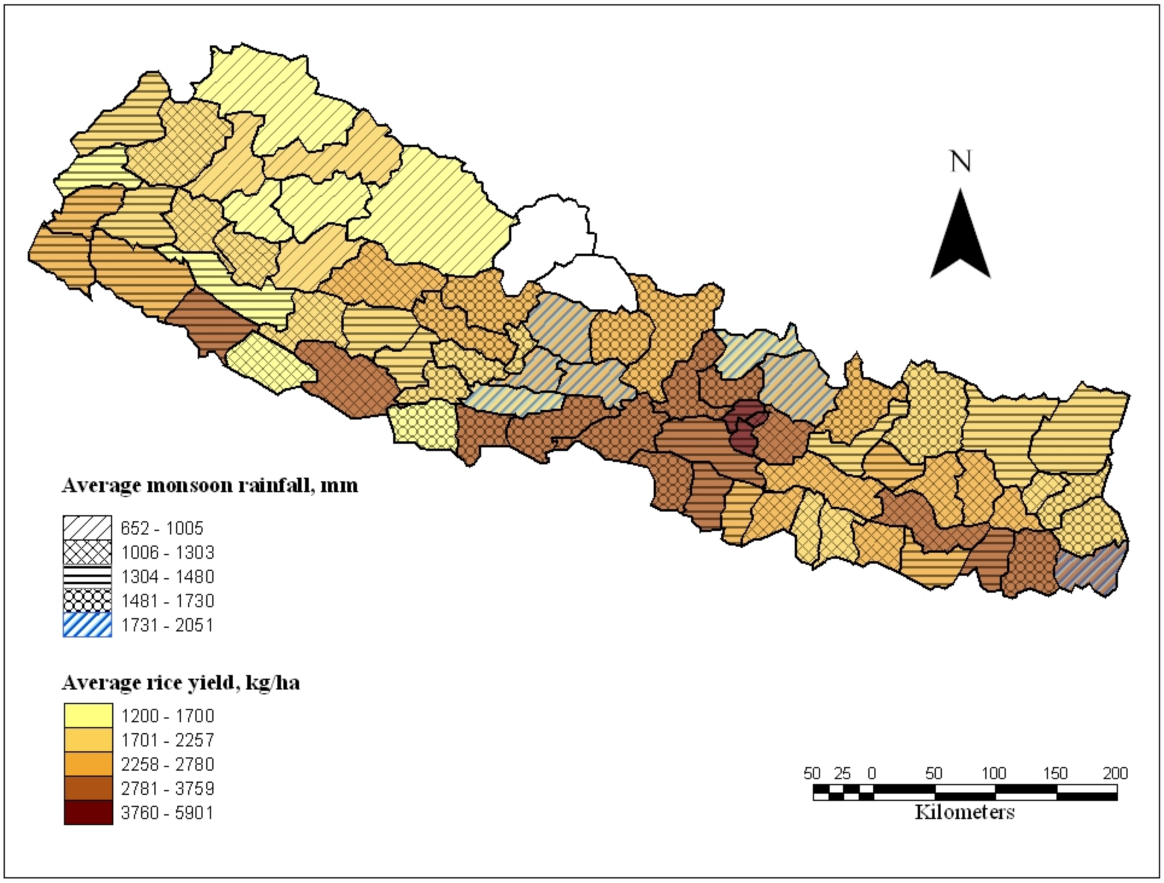


Figure 5.2: Rice productivity patterns across Nepal, 2002/03

Note: Rice productivity patterns are overlain on the average monsoon rainfall across the country. The darker shades of brown in the maps indicate higher average rice yield and *vice versa*.

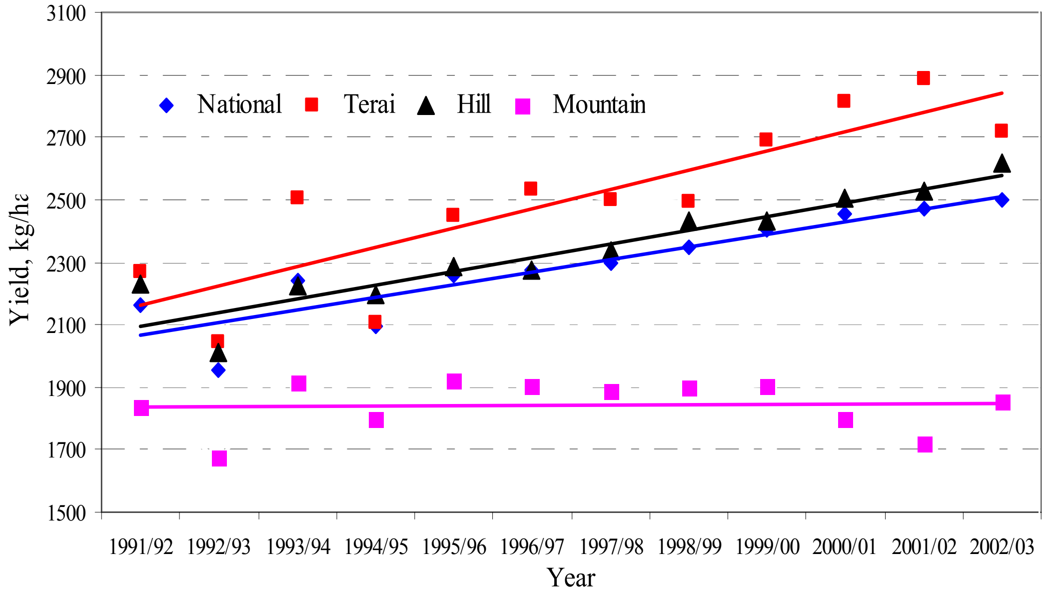


Figure 5.3: Rice productivity trends across scale, 1991/92-2002/03

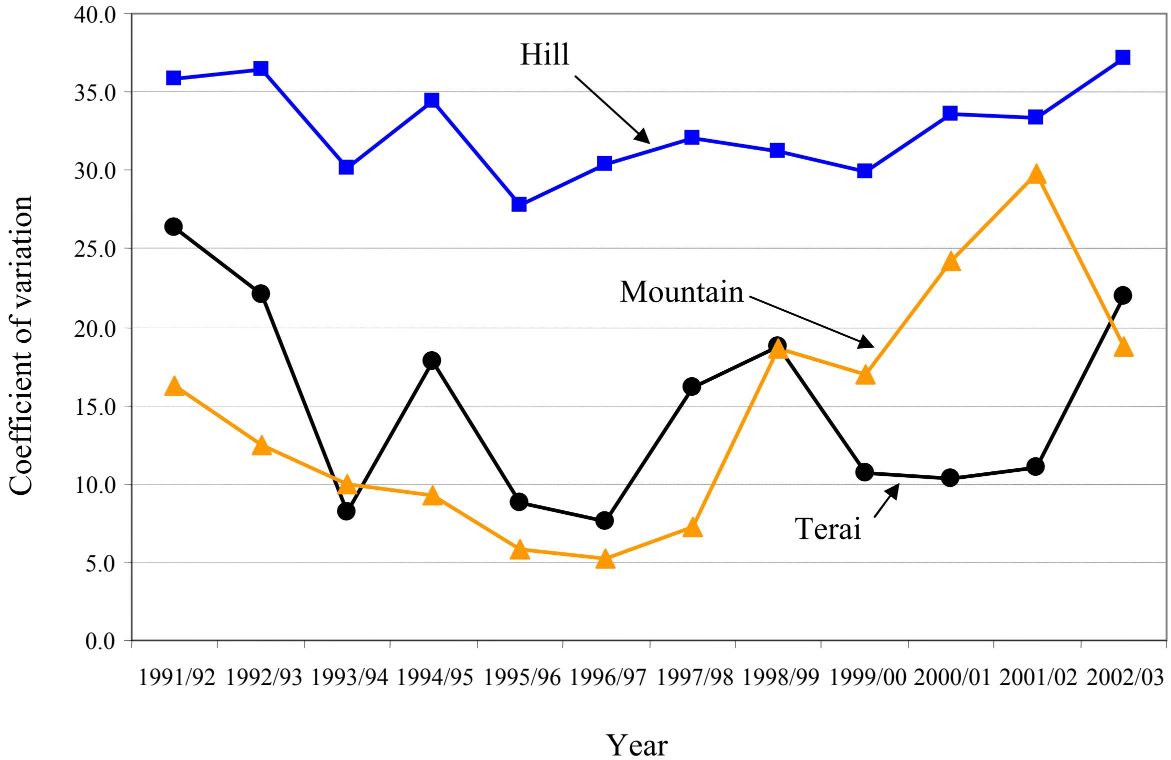


Figure 5.4: Distribution of the coefficient of variation: a measure of σ-convergence

Parameters	Estimates of the β–convergence coefficients		
	Absolute	Conditional	
		Dummy variable	Explanatory variable
Implied β	-0.36(-6.39)***	-0.43(-8.27)***	-0.49(-9.00)***
Hill (Yes=1, No=0)		-0.07(-2.28)*	-0.01(0.037)
Mountain (Yes=1, No=0)		-0.19(-4.75)***	-0.17(0.041)***
Average monsoon rainfall			-0.01(0.069)
% of irrigated rice land			0.07(0.026)**
Estimated $\hat{\beta}$	0.037	0.47	0.056
Number of observations	73	73	73
Constant	2.86(6.54)***	3.45(8.51)***	3.67(0.609)***
F ratio	40.8***	25.10***	17.83***
R^2	0.37	0.50	0.53
Cook-Weisberg test for heteroskedasticity	1.51	12.22	4.58

*=p <0.05 **=p<0.01 ***=p<0.001

Table 5.1: Estimates of absolute and conditional β-convergence coefficients

Note: t-values in the parenthesis.

Recommended ecological domain	# of varieties released	Crop characteristics	Yield potential (Mt)
Terai under irrigated condition	3	Medium maturity (145-160 days)	4.0-4.5
Terai and valleys under irrigated condition	10	Early maturing (118-135 days)	3.5-4.8
Mid hills under partially irrigated condition	11	Early/mid maturity (130-155 days)	3.5-4.9
Terai and valleys under rainfed condition	3	Medium maturity (145-160 days)	4.5-5.6
Hill under rainfed condition	4	Medium maturity (145-160 days)	3.2-4.5
High hills, cold tolerant, under rainfed	3	Cold tolerant, late maturity (165-180 days)	4.2-5.0

Table 5.2: Improved varieties of rice released by the agricultural research systems of Nepal in the last 35 years

Source: HMG/MOAC, Agri-Business Promotion and Statistical Division, 2001/02

CHAPTER SIX

CONCLUSIONS

I began this dissertation by asking two key questions about Nepal's capability to address climatic constraints in agricultural production, particularly rice: *1) do local climatic limitations, such as patterns of rainfall and other biophysical factors, provide incentives for public institutions to invest in research and development of technologies to overcome those limitations? 2) is the degree of rice productivity differentials across climatically diverse districts of Nepal narrowing overtime?* These questions were answered in the subsequent chapters with a series of empirical analyses and qualitative assessment of case studies.

The theoretical basis that I have adopted for this research is derived from the hypothesis of induced innovation and states that the direction of technological innovation in agriculture is induced by differences in relative resource endowments. Drawing from this hypothesis I asserted that climate variability and change prompt the development of appropriate technologies that substitute for and ameliorate the negative impacts of future climate change in rice production in Nepal. In other words, in this dissertation I proposed that climate which is an unpriced production factor is subjected to the hypothesis of induced innovations in order to understand the process by which agriculture might adapt to changing climatic conditions. I argue that successful adaptation involves a dynamic process of adjustment to resource endowment created by a new and changing climate.

The induced innovation hypothesis was examined empirically by analyzing the rate of productivity growth in rice across the climatically diverse districts of the country to determine the degree to which they were converging to a common mean. Convergence would be a general indication that technical efficiencies were changing unequally across the regions. Time-series data (1991/92 to 2002/03) on rice production in Nepal were used to conduct the convergence analysis. Case studies of climate-induced technological innovations in the rice-based cropping system were also reviewed to provide examples of changes that have been driven by climatic limitations. In the rest of the chapter, I synthesize the findings of this dissertation and analyze their implications with regard to Nepal's capacity to adapt to future climate. I conclude with a discussion on the adequacy of the hypothesis of induced innovation in explaining the role of climate in technological innovations, the foundation upon which this dissertation is based.

In general, my analysis shows that rice productivity increased steadily across the districts of Nepal showing a definite growth trajectory during the 12-year study period. However, this growth masked disparities in productivity caused by apparent differences in climatic resources of different regions of the country. For example, districts across the Hills and the Mountains showed an overall σ-divergence indicating increased variations in productivity of rice in these two regions, while districts of the Terai region showed a decline in disparity indicating reduction of variations in rice productivity. The patterns of convergence differed among the ecological regions, implying that despite the effort to increase food security in the climatically impoverished regions, some districts in the Mountains and Hills regions appear to be falling behind in productivity.

Many factors may have been responsible for the σ-divergence, including variability of monsoon rainfall. For example, a weak monsoon in the year 2002/03 delayed rice planting by about two weeks in parts of the relatively more arid mid- and far western districts (Joshi et al., 2003). The timing of planting is an important determinant of rice productivity and is even more crucial in the high altitude belts of the Hills and the Mountains due to narrow window of optimal temperature required for grain setting. If farmers are unable to plant rice on time due to delayed monsoon then productivity declines substantially. Therefore, variability in the onset of monsoon rains may have been partly responsible for the apparent lack of σ-convergence in this region. Distinguishing the effects of climate variability from technology on convergence of rice yield was a challenge in this research.

Although σ-convergence is widely applied to study convergence, it is not the only test to do so (Sala-I-Martin, 1996). The convergence of β, which measures growth rate over time, can also be used to understand the apparent direction of convergence – an appropriate test given the climatic diversity of Nepal. My findings of the analysis of β-convergence shows that rice productivity across the 73 districts of Nepal is converging to a common growth trajectory indicating that the districts with lower rice productivity are catching up. A closer examination of districts with comparatively lower initial productivity levels shows that they have increased their rate of production relatively faster than those with higher initial productivity, and are therefore catching up.

The overall finding from the test of β-convergence indicates that there is a tendency towards greater rate of growth among districts with marginal climate, thus suggesting that innovation of technologies appears to have substituted for climatic constraints in these areas. Climate variability, particularly the timing of the onset of monsoon rains in these districts, was eliminated as an alternative explanation of β-convergence by informal inspection of rainfall trends. Close examination of the coefficient of β-convergence reveals that rice productivity across the districts of the Hills and the Mountain regions are converging at a greater rate than the Terai region. The results of β-convergence, however, cannot be interpreted to mean that the rates of rice productivity convergence are uniform across all districts. For example, conditional convergence analysis shows that rice productivity growth in the Mountain region is significantly lower than the Hills and the Terai. Such apparent disparity suggests that there are significant regional differences in the technological responses to rice production. The implication of this finding at the policy level is that despite the effort of the government to boost food security in marginal areas such as the Mountains, this region has not been able to close the productivity gap with either the Terai or the Hills. It may be that such climatically marginal regions lack the comparative advantage of return to investment in agriculture and may remain vulnerable to changing climatic conditions.

The fact that the Mountain districts have not been able to fully catch up with the Hills and the Terai regions does not mean, however, that climate-induced innovations for this area have not been effective. In fact, some of the best examples of climate-induced innovations are demonstrated in this region. They include the development and adoption of cold-tolerant rice varieties in the higher-altitude belt and of traditional methods of "direct seeding" often practiced in risk-prone environments. As discussed in the previous chapter, newly developed cold-tolerant high-altitude rice varieties show 42 percent more yield than the traditionally grown varieties (Joshi et al, 2001). Similarly, direct seeding technology recommended for risk-prone environment shows a 33 percent increase in net economic return than conventional methods of transplanting (Tripathi et al., 2004). The expanding use of these technologies in the Mountain districts demonstrate that farmers and their supporting institutions in resource deprived regions are driven to improve efficiency in rice productivity to compete with farmers in the relatively better endowed region of the Terai.

Many factors may have been responsible for the observed growth of rice productivity across the diverse climatic regions of Nepal. The challenge of separating climate variability from technical change is one factor that was mentioned above. Another is the conscious policy decisions made by research establishments to allocate necessary resources for research in climatically marginal regions of the country. Lack of relevant data did not permit establishment of unambiguous empirical relationships between spatial differences in climate and spatial differences in the innovation and application of new technologies—this is an open research issue that requires improved data and more research. Lack of data has been a major shortcoming to establish a causal relationship between the concept of climate-caused opportunity costs to rice farmers and their subsequent demand for appropriate technical substitutions to reduce those costs. To partially compensate for this shortcoming, a detailed review of case studies was provided as a qualitative assessment of the development of climate-induced innovations over the period of the study. Based on this review, I find evidence that the research establishment in Nepal has developed technological innovations through a novel multilevel institutional partnership as a buffer against the deleterious effect of climatic risks. The partnership specifically includes collaborating with farmers and other non-governmental organization in all stage of technological innovation including goal setting, sharing of knowledge between various stakeholders including farmers, and development of farmer-preferred varieties suitable to local production environment.

This partnership has been enhanced over the last decade through an approach called the Participatory Technology Development (PTD). In the case of Nepal's rice production PTD is seen as a rice improvement strategy jointly implemented by farmers and other stakeholders in response to improving productivity in climatically stressed growing environment. This approach maintains an ongoing dialogue among farmers, researchers, and agricultural policy makers allowing them to draw up research agenda, choose appropriate technologies, and decide upon a range of partnership patterns (Gauchan et al., 2003). Nepal's research and development activities in agriculture have increasingly become more interactive and better coordinated with more focus on farmers' needs. More than ever, Nepal's research establishment is becoming focused on devising technologies that addresses the needs of farmers in climatically marginal regions (Witcombe et al., 1996; Joshi, 2000). The partnership between farmers and researchers has also improved because participatory research program requires a collegial relationship between them.

Another important stakeholder in this partnership has been the non-governmental organizations (NGOs), which have grown into strong research and development institutions, an unlikely configuration a decade ago (Gauchan et al., 2003). Through joint undertaking, public research institutions (e.g. National Agricultural Research Council (NARC) and Local Initiative for Biodiversity Research and Development (LI-BIRD), an NGO experienced in participatory approach to innovation of technologies in agriculture, have developed rice varieties for the high altitude region, which suffers perennially from poor production due to low temperature during anthesis and grain-fill, that are not only cold tolerant and disease resistant but are also high yielding (Sthapit et al, 1996; Sthapit et al., 2002). Both NARC and LI-BIRD are also working on developing drought resistant varieties with specific geographic focus on the low rainfall areas of the western Terai regions of the country (Joshi et al., 2003). Such collaborative efforts to devise location specific technologies suggest the inevitable role of climate in motivating farmers and public institutions to invest in research and development to overcome climatic constraints in rice production.

This new institutional arrangement illustrates the fact that technological innovations in rice-based cropping systems have been driven by conscious policy choices to allocate resources for research in climatically less endowed regions of Nepal. It is apparent that climate and its effect on agriculture have stimulated technological innovations that best address specific climatic constraints. For instance, in the drier western region where frequent recurrence of droughts has resulted in declining yield of traditional rice varieties, farmers have switched to a more drought tolerant ones as recommended by Nepal's research institution. Likewise farmers' managed irrigation systems have been actively promoted in the drier regions of the Hills and the Terai to compensate for the inadequate supply of water especially during the growing season (HMG/N, 1995). If the current trend in limiting the deleterious effects of climate through appropriate technological as well as institutional changes continues then the prospect of adapting to further climate becomes more apparent in Nepal.

Though the uncertainty associated with climate change and reliance on mechanistic assumptions limits our ability to understand how farmers may adapt (Easterling et al., 2004), by assessing climate-technology interaction in Nepal's rice farming system this dissertation provides a new dimension by which adaptation to climate change should be examined. It emphasizes the process by which climate-related innovation is stimulated. Analysis of productivity convergence, even if only indirectly, implies that technological changes can be represented by examining the direction of productivity over time and is an attempt to approximate the *ultimate* impacts of climate-induced innovation in agriculture. It is also a standard approach used for assessing the performance of agriculture in developing countries (Evenson, 1993). In the following paragraphs, I synthesize the major findings of this dissertation in light of the climate-induced innovations in rice production.

- I find a significant shift in the operational mandate of the research establishment. For example, the PTD approach within the institutional framework of Nepal's premier public research institution in agriculture such as NARC has created an environment that allows others non-state actors, such as NGOs, to participate in research and technology development.

- The role of farmers in technological innovation has also grown significantly whereby they are now able to set their agendas based on their own resource endowments, which is facilitated by NARC and NGOs. This has not only improved relationship between farmers and researchers, but has created an environment of dialogue that has benefited both partners.
- The recent institutional change in Nepal's research establishment, which has favored partnership with NGOs, farmers, and private sectors, has worked to everyone's advantage. It has been cost-effective, location-specific, and intensive as it involves both farmers and researchers every step of the way in developing technological innovations. This is in line with the argument made by Hayami and Ruttan (1985). They postulated that the cost of devising location-specific technologies is greater for a country with a wide range of climatic variation than for a more geographically homogeneous one.
- As a climatically diverse and yet economically challenged nation, the cost of devising technologies appropriate for all agro-ecosystems is enormous and may hinder desired growth in agricultural productivity in Nepal. Therefore, involving multiple actors in the development of agricultural technologies in Nepal is necessary to mitigate this cost.
- The findings from both the empirical and the qualitative assessment indicate that Nepal's research establishment is engaged in and committed to the development of location-specific technologies that address the constraints of climate. The development of technological innovations accompanied by change in policies in

agriculture may have been responsible for higher rice productivity among the districts with marginal climate.

- While the finding does not explicitly support a *climate-induced innovation hypothesis*, but does suggest a strong connection between climate deficiency and focused research to alleviate this deficiency. This tendency of targeted innovations bodes well for the future of the country's agricultural development despite the constraints placed by climate, and also offers insights into agricultural adaptation to future climate change.

Based on these findings, I assert that, in response to future climate change, farmers and their supporting public institutions in Nepal will modify their cropping activities to the new climatic conditions, thereby mitigating potentially negative effects in much the same manner that they have demonstrated at present. This finding should not, however, lead to complacency as innovations in agriculture have always depended upon continued investment in agricultural research and infrastructure. Yet, the current trend of weaning resources away from agricultural and climate research, especially in developing countries, endangers the vital support provided by public institutions for farmers to adapt to climate change. Therefore, agricultural adaptation to future climate is contingent upon continued investment in agriculture, as well as active engagement of public institutions responsible for developing and disseminating appropriate technologies for farmers operating in specific climatic regions. I argue that if research establishment and farmers have made appropriate responses to improve their capacity to respond to climatic constraints then they are generally better prepared to adapt to changing climate.

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