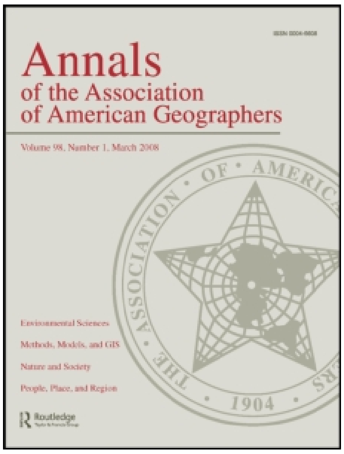

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Adapting to Climate Change: Retrospective Analysis of Climate Technology Interaction in the Rice-Based Farming System of Nepal

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The development of technological solutions to minimize risks of the current climate can lead to two possible outcomes: increase in agricultural productivity and insights about adaptation to future climate change. Drawing on the hypothesis of induced innovation, we investigate whether spatial variations in climatic resources prompted the development of location-specific technologies that led to increased rice productivity in Nepal. Using Nepal's district-level time-series data (1991–1992 and 2002–2003), this article examines the extent to which technological innovations have provided farmers with means to respond to climatic constraints to enhance rice productivity in climatically marginal regions of the country. Complementing this analysis with relevant case studies, we also investigate how and to what extent Nepal's research establishments have provided farmers with technological options to alleviate climatic constraints in rice cultivation across the country's climatically diverse terrain. The findings from both the empirical and 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 outcome of such commitment has been a series of technological innovations and changes in policies in agriculture. Together, this might 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. If the current trend of addressing the constraints of climate in agriculture through appropriate technological as well as institutional changes continues, then the prospect of adapting to further climate becomes more apparent in Nepal. *Key Words: adaptation, agriculture, climate change, induced innovation, Nepal.*

通过开发技术解决方案以减少当前的气候风险会导致两种可能的结果：增加农业产量，增进关于适应未来气候变化的见解。基于诱发创新的假说，我们探讨了气候资源的空间变化是否促进了与位置相关的技术进步，而这种进步增加了尼泊尔的水稻产量。利用地区级别的时间序列数据（尼泊尔 1991–1992 年和 2002–2003 年），本文探讨了在何种程度上的技术创新为农民适应气候的限制而提供了相应的手段，籍此提高了大米在该国气候边缘地区的产量。在相关的案例研究分析中，我们还研究了尼泊尔的研究机构如何以及在何种程度上为农民提供了技术方案，以减轻在全国范围内气候多样性的地域上气候对水稻种植的限制。基于实证和定性评估的结果显示，尼泊尔的研究机构从事并致力于发展位置相关的技术以应对气候的制约。这种投入的结果表现为技术创新和农业政策的一系列变化。总之，可能是由于气候边缘地区的提高产量的原因，最终导致了水稻产量在全国范围的增长。通过适当的技术和体制变化来解决气候对农业的制约，如果目前的这个趋势能够继续下去，那么，未来尼泊尔进一步适应气候的前景将变得更加明朗。*关键词：适应，农业，气候变化，诱发创新，尼泊尔。*

El desarrollo de soluciones tecnológicas para minimizar los riesgos del clima actual pueden conducir a dos posibles resultados: incremento en la productividad agrícola y a la generación de buenas ideas sobre adaptación a cambios climáticos futuros. Trabajando con based en la hipótesis de la innovación inducida, investigamos si las variaciones espaciales de recursos climáticos promovieron el desarrollo de tecnologías con especificidad locacional que llevaran a incrementar la productividad de arroz en Nepal. Utilizando los datos de series de tiempo a nivel de distrito en Nepal (1991–1992 y 2002–2003), este artículo examina la extensión con la que las innovaciones tecnológicas han dotado a los agricultores de los medios para responder a los avatares climáticos e incrementar la productividad del arroz en regiones climáticamente marginales del país. Complementando este análisis con estudios de caso relevantes, investigamos también cómo y en qué magnitud las entidades de investigación de Nepal han provisto a los agricultores con opciones tecnológicas para mitigar los efectos nocivos del clima para el cultivos del arroz por el abigarramiento climático del territorio nepalés. Los descubrimientos de esta evaluación tanto empírica como cualitativa indican que el establecimiento investigativo de Nepal

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está involucrado y comprometido con el desarrollo de tecnologías para localidades específicas con las que enfrenten los rigores del clima. El resultado de tal compromiso ha sido una serie de innovaciones tecnológicas y cambios de políticas en agricultura. En conjunto, esto podría ser responsable de los rendimientos más altos logrados en los distritos con climas marginales, que subsiguientemente han llevado a la convergencia de la tasa de crecimiento de productividad del arroz en el país. Si la tendencia actual de enfrentar los rigores del clima sobre la agricultura por medio de apropiados cambios tanto tecnológicos como institucionales continúa, entonces el prospecto de adaptarse a climas futuros se hace más aparente en Nepal. *Palabras clave: adaptación, agricultura, cambio climático, innovación inducida, Nepal.*

One of the challenges in estimating the potential consequences of climate change on agriculture anywhere in the world is gaining understanding of how farmers and their supporting institutions interact to adapt to changing climatic conditions. The crux of the problem is whether or not climate variability and change serves as a driver of appropriate technological change. In this study, we investigate the interaction of two closely related factors, climate and technology, in agricultural production in Nepal. More specifically, using Nepal's district-level time-series data for the period between 1991–1992 and 2002–2003, we examine the extent to which technological innovations have provided farmers with options to substitute for climate deficiencies to stabilize and enhance rice (*Oryza sativa* L.) productivity in districts with marginal climate. The goal of this article is to investigate whether variations in climatic resources (e.g., average rainfall) combined with regional environmental and socioeconomic features have prompted climate-sensitive technological innovations in the rice-based cropping system of Nepal.

Much of what is known about the process of technological innovation in agriculture has yet to be captured in discussions of climate change adaptation. We agree that technological innovation in agriculture does not evolve with respect to climatic conditions alone; nonclimatic forces, such as market and other social factors, clearly play a significant role (Brush and Turner 1987; Liverman 1990). Yet, research efforts in understanding the processes of technological change driven by climatic factors are pivotal to make any assertion about likely adaptation of agriculture to climate change (Glantz 1991; Rosenberg 1992). Although the characteristics of the future climate are unknown, exploring the ways in which technological innovations have provided farmers with the means to respond to specific climatic limits can offer insights about how society might be able to adapt to future climate.

The article begins by introducing the hypothesis of induced innovation as a basis for the theoretical argument of climate-induced innovation in agriculture. This is followed by a discussion of the value of climate-induced innovation in adaptation to climate change. Next is a brief presentation of Nepal's biophysical setting and the significance of rice in the country and then a discussion of the methodology of this article, followed by the unit of analysis. After presenting the findings of this article, there is a discussion on the manner by which resource endowments have influenced the evolution of technological innovations in Nepal. The article concludes with brief discussion of the implications of climate–technology interaction in gaining understanding of potential agricultural adaptation to climate change.

Theoretical Framework

The process of agricultural change has been a subject of interest in geography for a long time. Geographers have made important contributions to the understanding of various drivers of agricultural change (e.g., Brookfield 1984, 2001; Doolittle 1984; Blaikie and Brookfield 1987; Ali 1995; Turner and Ali 1996). Although farmers have practiced agriculture virtually everywhere on earth and have developed a rich tapestry of human–environment relations (Brush and Turner 1987), the role of climatic resources as a driver of innovation largely has been overlooked. Climatic factors such as temperature and precipitation are treated as marginal and their variability is reduced to an average (Denevan 1983). Given the significance of climate as a driver of agricultural systems, its marginal treatment as a factor of production is problematic. This research is in response to the challenge of developing a theoretical foundation needed to advance understanding of the process by which agricultural adaptation can occur in the future. In addition, using the hypothesis of induced innovation, we extend the boundaries of human–environment research to take into consideration the environmental inducements of technology in agriculture.

The hypothesis of induced innovation, as articulated by Hayami and Ruttan in the early 1970s, has earned wide recognition as an economic theory of agricultural development (e.g., Hayami and Ruttan 1971). The most fundamental insight of this hypothesis is that investment in the development of new technology is a function of the detection of change (or difference) in the resource endowments that are needed for agricultural production, whereby societies develop technologies that facilitate the substitution of relatively abundant (hence, cheap) factors of production for relatively scarce (hence, expensive) ones. In the short term, substitutions simply might involve using a large quantity of less expensive resources for a given amount of output. Unit production costs might 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.

In theory, and given sufficient time, the process of agricultural adaptation should accommodate the characteristics of physical and human changes required for production in a sustainable manner. The hypothesis of induced innovation stresses qualitative changes in agricultural production, such as through the use of specialized inputs, improved varieties of crops, use of appropriate agronomic practices, or change in resource organization. It can be visualized as a continuum: One end indicates changes occurring through improvement of existing technologies and the other end shows new and more productive technologies that are developed with demand. Methodologically, the hypothesis of induced innovation has been substantiated with the establishment of a correlation between the measure of factor scarcity (resource endowment) and indicators of the direction of technical change. This has been used in explaining the process of technological and institutional change in agricultural development (Hayami and Ruttan 1985; Koppel 1995). Although the hypothesis has made important contributions to the understanding of the process of agricultural development, it has shed little light on the role of climatic factors in the innovations of technologies. It is in this connection that the hypothesis of induced innovation has been identified as a potential theoretical framework for understanding environmental inducements of technological change in agriculture as well as for shedding light on possible agricultural adaptation to climate variability and change in the future.

As mentioned earlier, the notion of environmental inducements is notably missing from studies conducted to analyze the agricultural impacts of climate change (Riebsame 1991; Easterling 1996; Gitay et al. 2001). Although climate is an integral part of agricultural production, unlike other factors of production (e.g., input of fertilizers and labor), it is not commonly exchanged in the organized market and the economies of the response to climate change have not been well documented (Abler et al. 2000). Given the significance of climate in agriculture, its valuation by farmers and public institutions during the process of technological innovation is crucial. In view of this discussion, reorientation of how society institutes agricultural research becomes necessary to understand and realize the opportunities for technical change associated with the new climate.

Studies show that farmers and the research institutions that support them have found new ways of detecting and managing changes driven by climate. For example, in response to a lengthening of the frost-free growing season, farmers have changed planting dates and varietal choices of wheat across much of Australia since the middle of the twentieth century (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, which has enabled them to diversify cropping systems and minimize risk from increasing drought spells and erratic rainfall patterns (Ngigi et al. 2000). Likewise, to escape the effects of drought, scientists in the African Sahel have developed cowpea cultivars, a major food crop, with varying phenological characteristics and an early maturity level. The ‘Ein El Gazal’ and ‘Melakh’ varieties, for example, take fifty-five to sixty-four days to mature, and can escape easily the effects of late-season drought (Elawad and Hall 2002). Another variety, Mouride, flowers in approximately thirty-eight days after planting and remains flowering over an extended period of time, thereby avoiding a midseason drought (Cisse et al. 1997; Hall 2004).

Notwithstanding the widely recognized examples of climate–technology interaction in agriculture, there is a dearth of research that investigates the role of climate as a stimulus for innovation of technologies (Pinstrup-Andersen 1982; Council for Agricultural Science and Technology 1992; Ausubel 1995; Ruttan 1996; National Research Council 1999). This study investigates whether climatic limitations have been

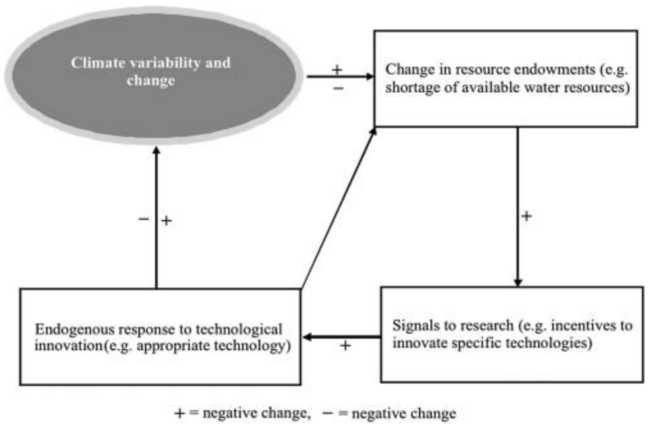

Figure 1. Conceptual framework: Climate–technology interaction.

considered in the research and development of agricultural technologies. Given this, we argue that the regions that have a long way to go to fulfilling production potential are more able to improve their agricultural productivity over time through targeted, climate-induced technologies than regions that have better fulfilled their potential. This is especially important in the case of Nepal; there is doubt that the country can maintain its food security even in the absence of climate change. Insights from this research will provide policymakers with process knowledge that could improve their leverage in managing the adaptation strategies that farmers and their supporting institutions need to adopt to ensure food security in the face of deleterious climate change.

As illustrated in Figure 1, change in resource endowment might solicit an adaptive response whereby farmers and their supportive institutions might adjust management techniques and the allocation of resources to offset the effect of climate change. More specifically, where arable land is already scarce (as in Nepal), the pressure to grow food on climatically less favored areas continues, and the marginal cost of production increases relative to the marginal cost of production via the application of technologies. Eventually, societies reach a stage where land augmentation through the use of new technologies, as opposed to bringing new land into production, becomes an appropriate means of increasing agricultural output. This ultimately leads to the development of new and improved human–environment relations for agricultural production. Based on this conceptual model, the hypothesis of induced innovation suggests an important pathway for understanding the human–environment relationship and, by extension, 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.

Climate-Induced Innovation in Agriculture

Climate-induced innovation occurs when location-specific climatic constraints produce new demands on technology. Two outcomes are likely in this process. First, climatic constraints could induce the development of new knowledge to optimize the use of available climatic resources, resulting in increased production. Second, such new knowledge 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 (Evenson and Gollin 2000; McCunn and Huffman 2000). Logically, in the case of Nepal's rice production, climate-induced innovation might provide opportunities for farmers to substitute for climate, allowing for increased productivity in climatically less favorable regions and leading to a convergence of productivity across climatically different regions of the country. 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 the existing region-specific human–environment conditions.

Following the thrust of the hypothesis of induced innovation, a priori it can be argued that technological innovation in response to scarcity of climatic resources provides potential for rice productivity to grow faster in districts with marginal climate relative to those with more favorable climate. This process is asserted ultimately to lead to a convergence in the yield of rice over time. Such processes of targeted technological innovation can be reflected through the development of higher yielding, location-specific rice varieties, the enhancement of land development activities (e.g., irrigation), the development of climate-specific agronomic practices, or a combination of all of these. The adoption of short-season rice varieties, for example, allows farmers to escape the late-season drought that occurs in some areas of the country. Similarly, the presence of irrigation alleviates the scarcity of water, a major constraint in the adoption of improved varieties of rice in Nepal.

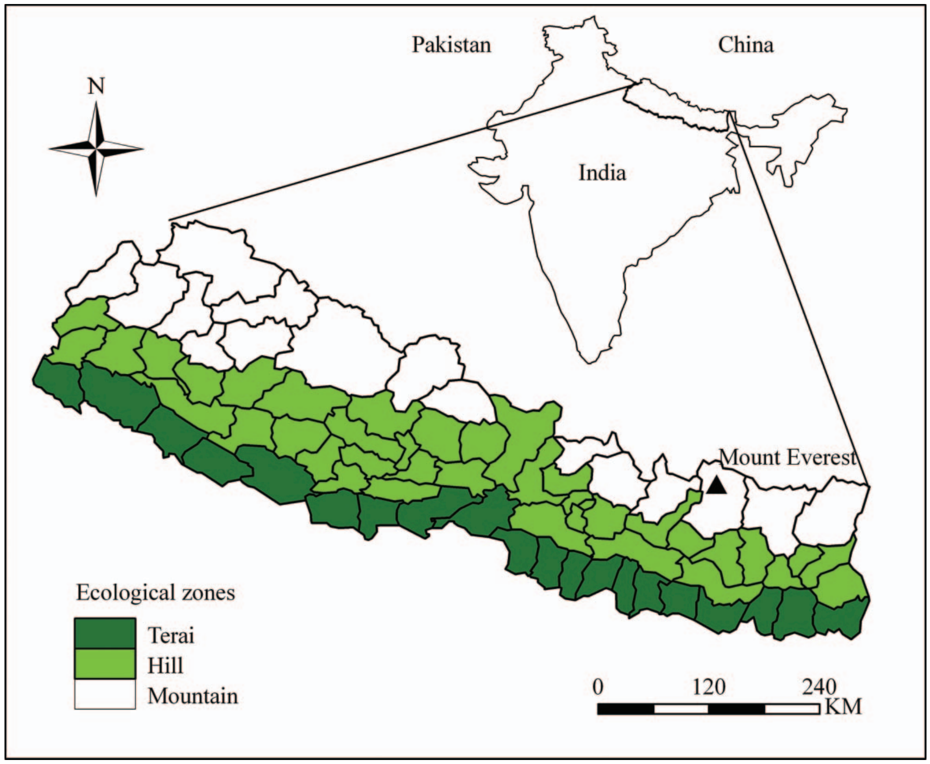

Figure 2. Map of Nepal showing three ecological zones (mountains, hills, and terai).

Nepal's Biophysical and Climatic Characteristics

Nepal's diverse terrain is made up of distinct ecological regions including the flat plains, or the terai, in the southern part of the country, rising to higher elevations categorized sequentially as the hills in the middle, and the mountains in the north (see Figure 2). The mountains region that lies above the altitudes of 5,000 m includes 35 percent of Nepal's 147,181 km^2 of land. The hills lie between altitudes of 600 and 5,000 m and account for 42 percent of the total land area. The flat terai region, a northern extension of the Gangetic plain, is located below 600 m elevation and makes up 23 percent of the total land area. Each of these regions represents a well-defined geographic area with distinct biophysical characteristics that are significantly different from each other, demanding location-specific technological innovations.

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) occurs in the summer season, and it is during this phase that the country receives over 75 percent of its annual precipitation (Shrestha et al. 2000). The monsoon, which is highly variable across space and time, is first experienced in the eastern part of the country. The monsoon gradually moves westward with diminishing intensity. The amount of summer monsoon and the number of days with rainfall decrease substantially as it moves to the west and northwestern part of the country (Chalise and Khanal 1996) and the precipitation pattern becomes more varied with the diverse terrain within each physiographic belt (Chalise 1994). Whereas the temporal and spatial variability of monsoon rainfall and its social relation to rice production are well recognized, the specific role it plays in the innovation of technology remains understudied. The risks and impacts arising from monsoon variability are site specific and require development of technology that reflects local conditions.

Studies reveal that the average temperature in Nepal has increased at the rate of approximately 0.06°C per year during 1977–2000 (Climate Change National Policy 2009; Jianchu, Shrestha, and Erikson 2009). The temperature differences are most pronounced during the winter season and least after the summer monsoon begins (Shrestha et al. 1999). Consistent with the global trend, temperature is increasing at a faster rate in the higher elevations compared to the lower elevations. Notably, the rate of warming is greater in the western half of the country compared to the eastern half. Also, the former is significantly drier than the latter. Unlike temperature trends, no

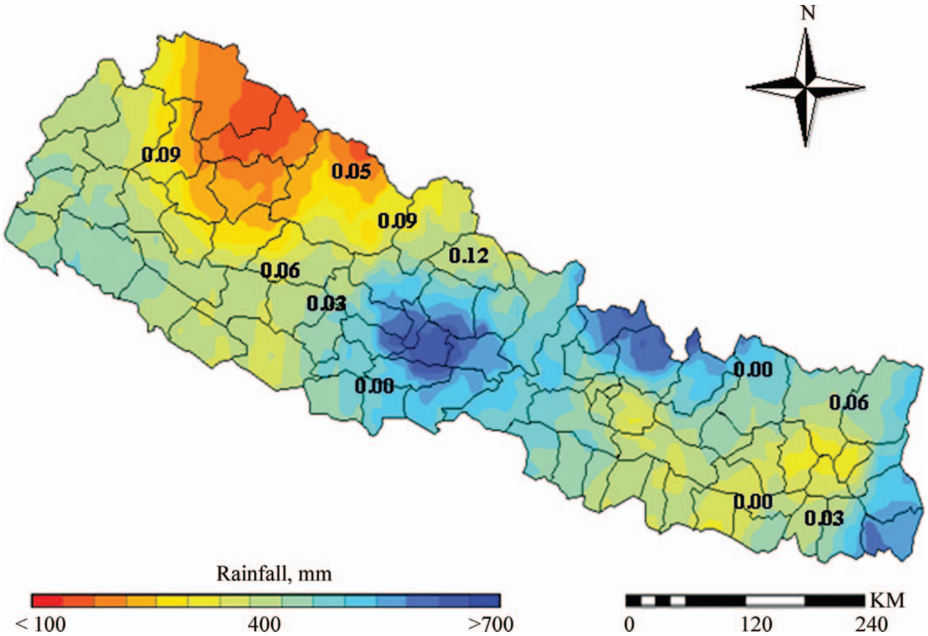

Figure 3. Observed pattern of mean annual temperature change in Nepal, 1971–1994 (*Source:* Shrestha et al. 1999) superimposed on mean monsoon rainfall surface created using average monsoon rainfall data (1968–1997) from 196 meteorological stations across the country.

evidence of change in aggregate precipitation has been noted, although studies do point to an increased variability and intensity of rainfall in some regions of the country (Shrestha et al. 2000).

As illustrated in Figure 3, if the observed trends of temperature change are overlain on the prevailing patterns of rainfall in the country, a negative association between the amount of rainfall and general trends of warming is revealed. For example, the hills and mountains 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 mountains, which are comparatively wetter. Theoretically, if this trend continues in the foreseeable future, the drier regions of the country will become even drier due to the projected increase in temperature. For farmers, such a prognosis poses a further challenge to their efforts to ensure increased rice productivity. A recent study using general circulation models also projects a consistent warming of the Himalaya region (Agrawala et al. 2003). The study also estimates an overall increase in precipitation, mostly during the monsoon season, but it is not clear how these changes will affect the timing and period of monsoon rainfall.

Along with maize, millet, wheat, and barley, rice is an important staple crop, accounting for about 50 percent of both the total agricultural area and production in the country (Pokhrel 1996). Rice is grown in all agroecological zones, from the subtropical climatic region of the terai and the valleys to the higher altitudes of 1,500 and 3,050 m above sea level—the highest elevations in the world known to grow rice. Most rice-growing areas of the country have relatively optimal temperatures for rice cultivation, except the high hills and the mountains. In Nepal, the total area under rice is estimated to be about 1.55 million hectares (His Majesty's Government/Ministry of Agriculture and Cooperatives [HMG/MOAC] 2002a). 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. Where there are irrigation facilities, rice fields can be irrigated during the rice-growing season to supplement the rainfall. Areas under irrigated rice are extremely limited, however, so rainfed cultivation is the dominant practice for about 66 percent of the rice area (Pokhrel 1996). The consequences of an adverse climate change could, therefore, have a significant negative effect on rice production.

Methodological Approach

Because an optimal cultivation of rice is possible only when climatic conditions are favorable, invariably an inadequate supply of climatic resources (e.g., rainfall) adversely affects productivity. For example, Kung (1971) showed that an estimated 1,300 mm of field water is required during the rice-growing season for optimal production. For this reason, regions with drier climate either need to be compensated through irrigation or provided with low-water-demanding varieties of rice that are able to produce comparatively equivalent yields even when climatic conditions are not favorable. Therefore, examining rice yield performance over the period from 1991–1992 to 2002–2003 across the districts of Nepal can be instructive to test the thrust of climate-induced innovation. The test of yield convergence provides evidence that research and development of technologies can overcome differences in rice yields arising from such factors as climate. This is vital to assess the adaptive capacity of rice farming systems to changing climatic conditions.

Following Barro and Sala-I-Martin (1992), convergence can be understood in two ways: convergence in terms of level of productivity across time, or *sigma* (σ) *convergence*, and the rates of productivity growth across space and time, or *beta* (β) *convergence*. Conceptually, the two measures used in the literature to test for convergence are related and provide alternative ways to examine similar phenomenon (Sala-I-Martin 1996). In agriculture, researchers have expanded it to test for the existence of convergence in total factor productivity (TFP) in agriculture (e.g., McCunn and Huffman 2000; Mukherjee and Kuroda 2003). In this context, TFP convergence is a function of best practices brought about by technological change. Theoretically, convergence in agricultural productivity occurs if and when location-specific technologies are available to the farmers (Thirtle et al. 2003; Rahman 2005).

An 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. β convergence refers to the tendency of countries or regions with comparatively low initial productivity levels to grow relatively faster. It 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 on innovation of technologies appropriate to the region-specific socioeconomic and climatic needs. If this scenario holds, there should be a negative correlation between the initial productivity level and the subsequent growth rate (Barro and Sala-I-Martin 1992).

From a conceptual perspective, two methods for the test of β convergence are prevalent—absolute and conditional convergences. *Absolute convergence*, also known as *unconditional convergence*, is defined as a tendency toward equalization of productivity, where regions with low productivity at the initial stage will grow faster to catch up with the regions with greater initial productivity (Islam 2003). It is absolute because all factors of production are assumed constant across regions (Barro and Sala-I-Martin 1992; 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 term. In convergence literature, this is attributed to inherent differences in underlying conditions that could have a direct effect on productivity (Mukherjee and Kuroda 2003), giving rise to the concept of conditional β convergence. Conditional β convergence emphasizes the inclusion of appropriate independent variables to control for differences these variables might exert on productivity growth rates (de la Fuente 1997; Islam 2003; McErlean and Wu 2003).

The test of conditional β convergence is particularly important in rice production systems of Nepal where the climatic gradient presents a uniquely different resource condition for rice cultivation. By testing the conditional β convergence, one can explain the significance of specific factors 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 this consequently implies conditional β convergence (McErlean and Wu 2003). Although conditional β convergence also requires a negative coefficient for initial productivity, regions with lower productivity at the initial stage might exhibit greater growth rates after controlling for the effects of conditioning variables.

This article analyzes the σ convergence by examining a measure of spread of the rice productivity at aggregate (national) and disaggregate (ecological region) levels. It occurs when the dispersion of rice productivity across seventy-three 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 and σ_{it+T} is the dispersion of rice yield across districts at subsequent periods.

Convergence of σ might be a necessary condition, but it is not a sufficient condition to generate β convergence (Islam 2003). The analysis of σ convergence does not reveal whether there is a tendency for districts with relatively low initial rice productivity to catch up with districts that have relatively higher initial rice productivity. For this reason, investigating whether Nepal's rice productivity over time demonstrates the presence of β convergence would be desirable. As discussed earlier, the rationale for absolute β convergence lies with the relative homogeneity of the factors of production. In agriculture, where productivity is determined by myriad factors including biophysical and climatic condition, absolute β convergence is not sufficient (McCunn and Huffman 2000), and hence the scenario for conditional β convergence. For example, the terai region of Nepal is endowed favorably for rice production compared to the hills and mountains regions. 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 necessarily just at the same level of rice productivity as those districts with favorable climates. For this reason, a conditional convergence model with a dummy variable (terai = 0, otherwise = 1) of the following form is estimated:

$$(1/T)\ \ln(y_{it+T}/y_{it0}) = \alpha + \beta \ln(y_{it0}) + \gamma H + \delta \mathrm{M} + \varepsilon_{i0,T} \quad (2)$$

where $(1/T)\ \ln(y_{it+T}/y_{it0})$ is 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 the base year of 1991–1992. 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, and γH and δM represent the hills and the mountains dummy variables, where the terai is considered the reference region. The sign of the β coefficient indicates either convergence or divergence. A negative and significant β coefficient indicates convergence, whereas a positive coefficient indicates divergence. Absence of either with respect to 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 limitation of the dummy variable model is that it cannot account for the role of district-specific factors, climatic and otherwise, that might have influenced rice productivity from converging to the same growth trajectory. More important, such models fail to incorporate the basic policy and behavioral rationale for a decision to invest in technological changes in marginal climate. For example, if districts with favorable climates (e.g., optimum rainfall) have increased their advantage over the districts with less favorable climates, intuitively it shows complementarities between technology and climate (Mendelsohn, Dinar, and Singh 2001). It also rejects the notion that scarcity of desired climatic resources acts to spur technological innovation to substitute for climatic resources, hence providing no support for the climate-induced innovation discussed earlier. 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:

$$(1/T)\ \ln(y_{it+T}/y_{it0}) = \alpha + \beta \mathrm{l}(y_{it0}) + \kappa_i X_i + \lambda_i K_i + \psi_i Z_{it+T} + \gamma \mathrm{H} + \delta \mathrm{M} + \varepsilon_{i0,T} \quad (3)$$

where $\kappa_i X_i$ is a vector of the biophysical variables (average monsoon rainfall and slope), $\lambda_i K_i$ is a vector of the socioeconomic variables (built-up area and population growth rate), and $\psi_i Z_{it+T}$ is a vector of the average growth rate of irrigated area as a percentage of the total rice cultivated area between 0 and T. A positive and significant value of the coefficient of biophysical variables indicates that districts with relatively better resource endowments (e.g., higher monsoon, less slope) produce significantly higher amounts of rice compared to those districts with lesser resource endowments. The opposite is true if the sign of the coefficient is insignificant, implying that technology is substituting for climatic deficiencies.

In convergence literature, it is customary to measure the rate of convergence, which is estimated with the β coefficient obtained by computing growth-initial level regression (Barro and Sala-I-Martin 1995). Following McErlean and Wu (2003) the speed of convergence (commonly referred to as *implied* β) across the districts of Nepal is computed as:

$$\hat{\beta} = -\ln(1+\beta)/T \quad (4)$$

where the implied $\hat{\beta}$ 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. In this research, $\hat{\beta}$ convergence provides an impartial test of convergence that is judged by the sign of the coefficient. A positive and significant value of estimated $\hat{\beta}$ (i.e., $\beta < 0$) in growth-initial level regression is a necessary condition for rice productivity convergence. 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 in the initial year must exhibit greater rates of growth compared to those districts with higher initial levels of productivity.

Unit of Analysis, Data and Variables, and Their Sources

Unit of Analysis

The districts for which data on rice productivity and irrigation acreage are available are the primary spatial units of analysis in this study. Of the seventy-five districts of Nepal (thirty-nine in the hills, twenty in the terai, and sixteen in the mountains), seventy-three districts are included. Two districts in the mountains (Mustang and Manang) are not included because rice is not grown there. The choice of the district as the unit of spatial analysis is further justified because it is the smallest administrative unit that contains the full complement of government services. For example, in the agriculture sector, every district has a government-run agricultural development office that employs agricultural extension workers responsible for promoting improved technologies. Each district also is supplemented by the office of the Agricultural Input Corporation and the Agricultural Development Bank (ADB), government subsidiaries established to market agro-technologies to the farmers. In addition, the Department of Irrigation has its offices at the district level, which are 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.

Data and Variables

Table 1 presents a list of variables included in this study and their sources. Average rice yield is the dependent variable. Climate, biophysical, and socioeconomic factors determine the productivity of rice and make up the independent variables. In the following sections, each of these variables is discussed separately.

Table 1. Variables included in the convergence models

Variable	Definition	Dimensions
Dependent: Rice yield	Net yield (kg/ha)	Time-series
Independent:		
Average monsoon rainfall	Arithmetic average	30 years average
Ecological zone	Terai, hills, and mountains	Biophysical
Gradient of slope	Area with >45% slope	Biophysical
Irrigation	% of net rice area under irrigation	Time-series
Built-up area	% of total area with infrastructure	Cross-section
Population	Rate of population growth between 1991 and 2001	Time-series

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). During the 1990s, the average yield of rice in Nepal grew by 1.33 percent. In some parts of the country, it rose by as much as 3.6 percent, whereas in others the growth was nominal (Goletti, Bhatta, and Gruhn 2001). This growth is largely attributed to a combination of factors, including 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 (His Majesty's Government/Agricultural Development Bank [HMG/ADB] 1995; Gruhn, Poudel, and Goletti 2003).

Rainfall. Although rice production in Nepal is restrained by several climatic factors, the amount, timing, and duration of monsoon rainfall significantly affect rice production in Nepal. Monsoon rainfall is defined as the average precipitation that occurs during the period of June, July, August, and September. The average cumulative monsoon rainfall over a thirty-year period from 1968 to 1997[1] has been taken to represent Nepal's rainfall variable. Although this variable is derived from a long-term average, it has no time-series variation and has one value per district.

Slope Gradient. The gradient of slope is an important biophysical factor that creates different underlying conditions for rice production. The higher the gradient, the less favorable it becomes for rice cultivation. Although the farmers of Nepal have, for centuries, carved out the hill slopes to form rice terraces primarily to retain water, the higher gradient makes it difficult to establish terraces that can hold water for long periods of time, a necessary condition for rice production. We argue that areas with lesser gradient are not as vulnerable to climate change and are therefore likely to take advantage of technological choices. The gradient of land is measured as the fraction of area with greater than 45 percent slope.

Ecological Regions. Nepal's three ecological regions (terai, hills, and mountains) provide a standardized framework for characterizing biophysical conditions of the country and have traditionally been used to plan the 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), discussed earlier, 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 macrolevel policy, according to HMG/ADB (1995), has remained largely unchanged and continues to be the core strategy of the recent Twenty-Year Plan (1995–2015). For this reason, the ecological zones of Nepal are used as a proxy for biophysical conditions, and have been identified through the creation of dummy variables (terai = 0, hills and mountains = 1).

Irrigation. In the drive to increase agricultural production, Nepal's government has incorporated multiple strategies, including the development of irrigation systems. Irrigation mediates the relationship between climate and agricultural production and has become a widely used substitute in areas where soil moisture is inadequate for crop growth and development (Easterling, Hurd, and Smith 2004). Irrigation is not an innovative technology per se, but the presence of irrigation alleviates the problem of water scarcity and is expected not only to facilitate adoption of improved technologies such as high-yielding varieties (HYVs) and the use of chemical fertilizers but also to provide greater capacity to adapt to climatic shocks in the future. For the past twenty-five years, the government of Nepal has made major investments in irrigation with significant focus in the 1990s (HMG/MOAC 2002b). In this study, *irrigated land* refers to areas with access to irrigation facilities, including those that have water throughout the year as well as those having guaranteed irrigation during the rice-growing season. To make interpretation of the results more practical, we 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.

Built-Up Area. *Built-up area*, defined here as an area covered by building and manmade infrastructure such as roads and airports, is the indicator of general development of the region in question. The importance of good infrastructure for agricultural development is widely recognized. In Nepal, as anywhere in the world, growth in rice productivity depends on the existence of rural infrastructure, a well-functioning domestic market, and access to appropriate technology. Although the state of infrastructure varies widely across the country, most districts in the mountains and the hills regions have very low levels of built-up area. In the case of Nepal's rice farming system, this translates to lack of inputs, little or no spatial and temporal integration, and weak internal competitiveness, all of which are pivotal in productivity growth. For this reason, built-up area is included to represent the economic environment of the districts in question.

Population Growth Rate. Following Boserup (1965), research on demographic change and agricultural development centers around the issue of the pressure of population on resources in agrarian societies. In the short term, population growth simply might involve using more labor per unit area, but increased use of labor alone does not meet the ever increasing demand for food. Eventually, this signals the farmers and research institutions to innovate technologies to overcome such situations. For this reason, the population growth rate between the censuses of 1991 and 2001 for each district has been included to help explain the role of population growth in the convergence of rice productivity in Nepal.

Source of Data

This study is based on secondary data obtained from the various agencies of the government of Nepal. The data concerning rice yield (productivity and yield are used interchangeably to indicate mean output per unit of land) and irrigation were obtained from the Nepal Agricultural Database of the Ministry of Agriculture and Co-operatives (MOAC). The average monthly rainfall data were obtained from the Department of Hydrology and Meteorology, which has compiled the average monthly precipitation for the period between 1968 through 1997 from the records of various meteorological stations throughout the country and has used the data to represent the monsoon rainfall in this analysis. Data from Global Land Cover Characterization (GLC 2000), which provides global and regional land cover classification at approximately 90 × 90 m grid cell scale, were extracted to calculate the percentage of slope gradient and built-up area of a district. The data on population growth are calculated using the absolute change in population between the two nationwide censuses of 1991 and 2001.

Results

Summary Statistics

Figure 4 displays the spatial pattern of rice productivity for the year 1991–1992, 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 hills region (Kathmandu, Lalitpur, and Bhaktapur) rank among the highest rice-producing areas in the country, with over 5.00 tons/ha yields. They are followed by four districts in the central terai region (Bara, Parsa, Rautaht, and Chitwan), with yields of a little over 3.0 tons/ha. In contrast, over 50 percent of the other districts, most of them in the western half of the country, produce less than the national average of 2.00 tons/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 shows rice productivity patterns for the year 2002–2003, the end of the study period. The spatial patterns of rice productivity during this time indicate that the number of districts with darker shades of brown has increased considerably, indicating that more districts are now producing greater than average rice yields compared to 1991–1992. Although the previously high-yielding districts in the central Hills 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 and the other is in the mideastern part of the country. Both clusters also are ranked as regions with low monsoon precipitation. Emerging patterns of rice productivity growth in climatically marginal regions might be the outcome of conscious policy decisions to invest more heavily in regions that are not well endowed agroclimatically.

Figure 6 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 1991–1992 to 2,497 kg/ha in 2002–2003, 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 1991–1992 to 2,718 kg/ha in 2002–2003, averaging an annual growth rate of 2.19 percent, the highest among the three ecological

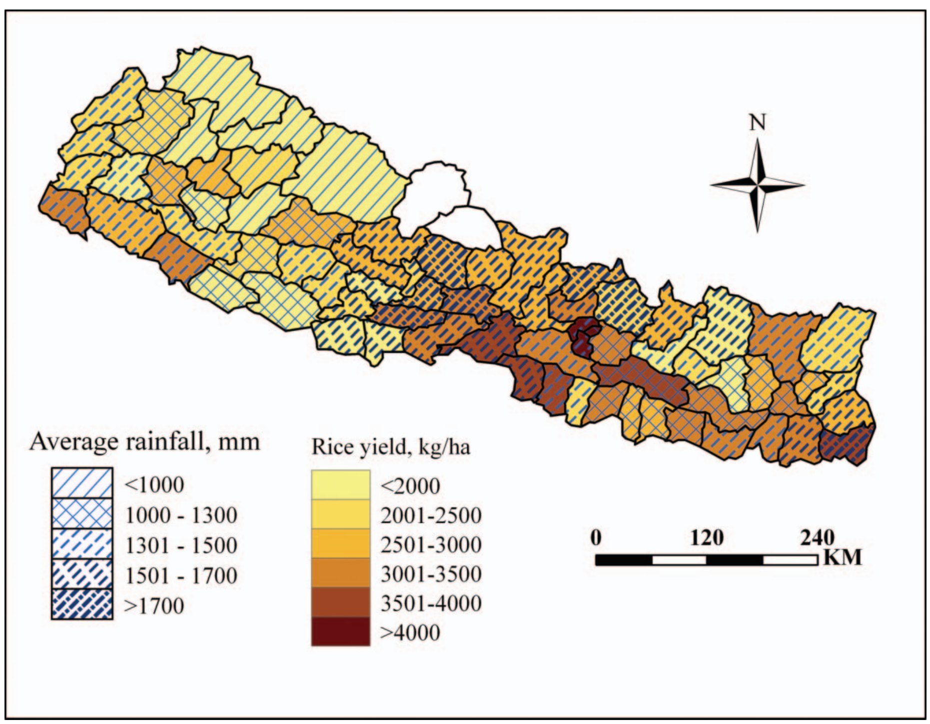

Figure 4. Average rice yield during the calendar year of 1991–1992 overlaid with average monsoon rainfall (1968–1997) across the seventy-three districts of Nepal.

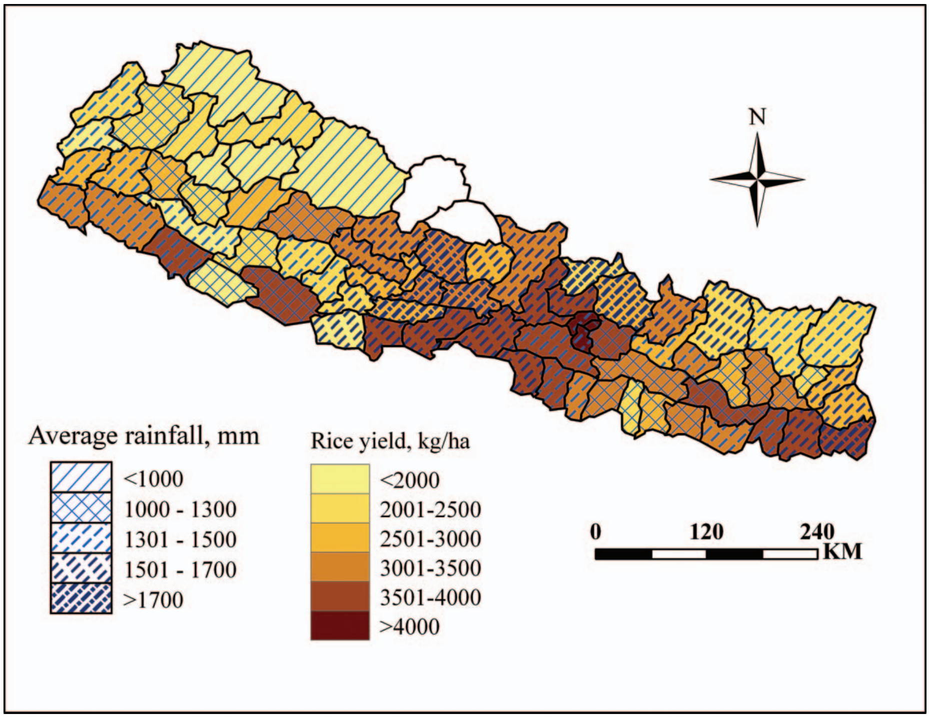

Figure 5. Average rice yield during the calendar year of 2002–2003 overlaid with average monsoon rainfall (1968–1997) across the seventy-three districts of Nepal.

zones. In the hills region, where rice is the second most important crop after maize, the yield increased from 2,229 kg/ha in 1991–1992 to 2,615 kg/ha in 2002–2003, an average of 1.57 percent annual growth rate. Although small, during the same period, the growth rate in the mountains region increased by 0.31 percent per year.

Although concerted efforts in the research and development of agricultural technologies began after the establishment of research stations and farms in the 1960s (Yadav 1987), the establishment of a twenty-year Agricultural Perspective Plan (APP) in 1996 provided much needed policy directives. With the APP underway, the importance of site-specific research for evaluating new technologies in multiple environments became evident (Gauchan and Yokoyama 1999). Among other goals, the APP established a firm commitment to doubling per capita food availability by the end of the plan (HMG/ADB 1995). This was to be achieved by improving the supply of agricultural inputs (e.g., fertilizers, improved seeds, and pesticides), irrigation infrastructure, availability of credit, markets for agricultural

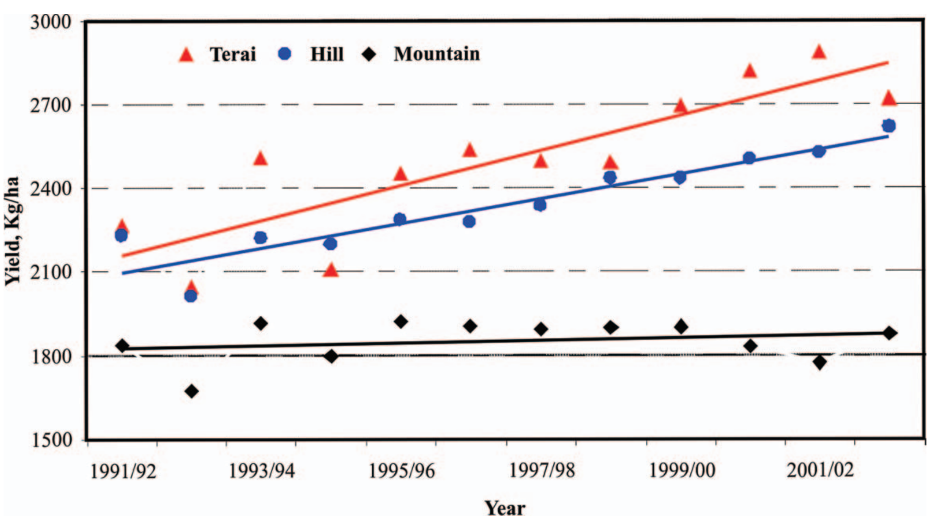

Figure 6. Rice productivity trends across the three ecological zones of Nepal, 1991–1992 through 2002–2003.

products, and target innovations to capitalize on the climatic niches of the country. Specific plans such as these might have been partly responsible for the increased rice yield.

Test of σ Convergence

In general, there have been no distinct patterns to suggest the occurrence of σ convergence in rice productivity because the coefficients of variation (CVs), defined as the ratio of standard deviation to the mean, has not reduced substantially across the districts of Nepal during the twelve years of the study period. In aggregate, the CV in 1991–1992 was 31.7 percent, which continued to decline until 1996/1997, with a record low in 1995–1996 (22.6 percent). The trend reversed thereafter, reaching an all time high of 33.9 percent in 2002–2003. The finding at the aggregate level does not preclude the fact that σ convergence might not have occurred within a specific ecological region. It is therefore important to assess the evolution of CVs at the scale of ecological regions to see if the pattern observed at the aggregated level is also found within the ecological (finer scale) regions.

Figure 7 presents the general trends of the evolution of CVs over time in the three ecological regions. Although exhibiting fluctuations, the CVs have declined in twenty districts of the terai region. From a high of 26.3 percent in 1991–1992, they declined to a low of 7.6 percent in 1996–1997. With the exception of 2002–2003, all other years show relatively lower CVs, hovering around 10 percent. At the same time, CVs in thirty-six 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 1996–1997 to a high of 29.8 percent in 2001–2002, shows no apparent sign of σ convergence.

There are several factors that farmers have to consider to make crop production decisions (Eakin 2000; Leichenko and O'Brien 2008), and their ability to interact with factors such as market risk, varying costs, availability of critical inputs, and other environmental risks makes some farmers (as well as regions) more productive than others. There could be several factors at play in the apparent lack of σ convergence. The push toward implementing the goals of APP might have been constrained by widespread inaccessibility due to difficult geographic terrain, especially in the hills and the mountains. At this level of abstraction, however, the trend does provide insights about the unfolding of climate–technology interaction; hence the need for further analysis.

Test of β Convergence

Although σ convergence and β convergence are related, it is possible to observe β convergence without the presence of σ convergence (Bernard and Durlauf 1996; Sala-I-Martin 1996). In this research, β convergence provides an impartial test of convergence that 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.

We begin this analysis by presenting the β convergence coefficient of the dummy variable model. The

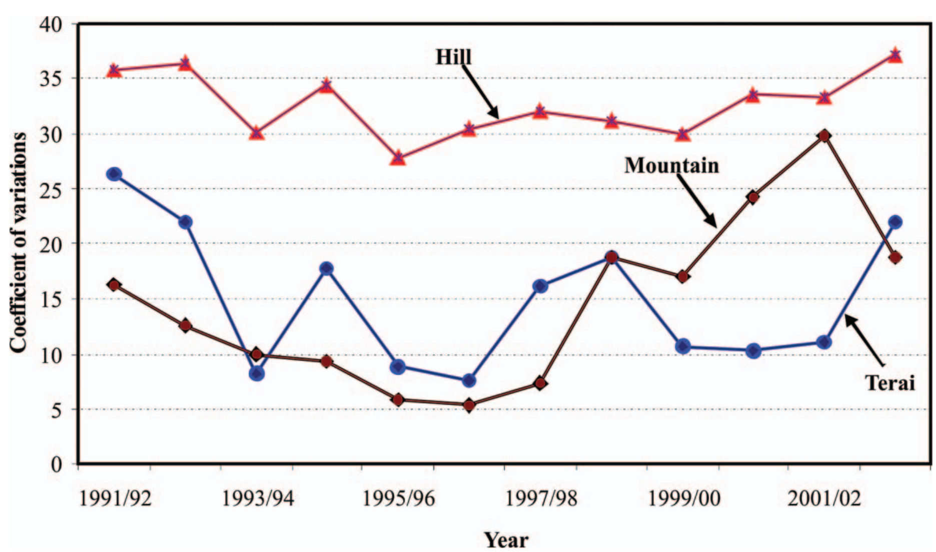

Figure 7. Distribution of sigma as measured by the coefficient of variation across the three ecological regions of Nepal, 1991–1992 to 2002–2003.

qualitative variables such as the three ecological zones (terai, hills, and mountains) are quantified by converting them into simple binary values and used as predictors in the regression analysis. This provides a way to characterize spatial differences for the time-series of rice productivity across the districts that share some common characteristics. For example, the hills and the mountains are differentiated from the terai by biophysical characteristics. If these differences in biophysical characteristics equate with differences in regional resource endowments, irrespective of the district in which they are grown, then, theoretically, rice productivity among regions should approach a common growth trajectory.

Table 2 presents the estimates of the dummy variable model. The sign of the implied β coefficient in the model is consistent with the overall expectation; that is, negative and statistically significant ($p < 0.001$). The amount of variation explained by R^2 is 50 percent and the F statistic is 25.1, $p < 0.001$. The estimated β convergence coefficient implies that, on average, the speed of convergence across the districts of the mountains and the hills is greater by about 5 percent as compared to the districts in the terai region. Net of other factors, estimates of implied β reveal that rice productivity growth rates across the districts of the hills and the mountains are greater, indicating that districts with unfavorable climate are catching up with the reference region of the terai. Despite this increased growth rate, however, the hills and the mountains still lag behind in closing the gap with the reference region. Average rice productivity growth rates across the thirty-nine 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 mountains remains 19 percent below the reference region, and is statistically highly significant ($p < 0.001$).

Table 2. Estimates of β convergence coefficient for rice productivity across districts of Nepal, 1991–1992 through 2002–2003

	Estimates of the β convergence coefficients	
Parameters	Dummy variables	Explanatory variables
Implied β	−0.43 (−8.27)***	−0.69 (−13.42)***
Hills (Yes = 1, No = 0)	−0.07 (−2.28)**	0.008 (1.18)
Mountains (Yes = 1, No = 0)	−0.19 (−4.75)***	−0.11(−2.06)
Average monsoon rainfall		0.00006 (1.39)
% of irrigated rice land		0.002 (2.44)*
Gradient of slope >45%		0.001 (1.25)
Built-up area		0.015 (5.58)***
Population growth rate		0.05 (2.83)**
Estimated β	0.047	0.097
Number of observations	73	73
Constant	3.45 (8.54)***	5.02 (13.35)***
F ratio	25.11***	25.99***
R^2	0.50	0.74

Note: Numbers in parentheses are the t values.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

The second column of Table 2 reports the estimates of β coefficients with additional explanatory variables. The amount of variation explained by R^2 is 74 percent and the F statistic is 25.9 ($p < 0.001$), and the signs of the coefficients are as expected. After controlling for both biophysical and socioeconomic variables, the results show a greater rate of β convergence. The estimate of the conditional β convergence coefficient implies that the rate of rice productivity growth across the districts of the hills and the mountains is higher when compared with the terai, indicating that the districts with lower rice productivity at time t_0 increase their growth rate by about 10 percent per year.

Net of other factors in the model, irrigation is a strong predictor of rice productivity. However, the relationship is monotonic and concaves (i.e., diminishing marginal returns). As discussed earlier, rice productivity in Nepal is inherently sensitive to monsoon climate and 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 might have committed more production inputs (e.g., fertilizers), leading to increased production in climatically less-endowed regions. Likewise, climate variability, as translated in the form of variations in the amount of monsoon rain, is insignificant in explaining the variations in rice productivity growth rates across the districts of Nepal. Inadequacy of monsoon rainfall might have been compensated by means of irrigation, which is an expected outcome of induced innovation.

Interestingly, the degree of slope is a weak predictor of rice productivity across the districts of Nepal, but the two socioeconomic variables, built-up area and population growth, show a strong influence on productivity growth rates. A 1 percent increase in built-up area contributed a 1.5 percent growth rate in rice productivity ($p < 0.001$). Likewise, the population growth rate had a positive contribution to rice productivity ($p < 0.01$). These findings are consistent with the study by McKinsey and Evenson (1998), which measured intracountry agricultural productivity differentials in India. Although the Green Revolution increased farm net revenue substantially, their study showed that technology had greater impacts on more developed areas. For example, districts connected with infrastructure were associated with higher productivity. The authors argued that the differences have persisted over a long period and are associated with the discrepancy of investment in research and development activities in marginal areas. 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 the regions with higher research investment.

When controlling for both biophysical and socioeconomic variables, 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 (−0.11 percent, $p < 0.001$), however, shows that this region lags behind. One of the principal characteristics of the mountains, in addition to the 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. Better soil quality and the warm climate of the valley bottoms of the hills and the terai also offer a greater potential for rice production, making investment of infrastructure and technology more efficient. This might explain the inherent difference in rice productivity in the mountains region of Nepal. The convergence of rice productivity as seen across the districts of Nepal was likely driven by several factors, including the development of varieties targeted to specific climatic conditions. These factors are more thoroughly discussed in the next section.

Explaining Observed Convergence

Rice has always been the focus of technological innovation in Nepal. Over time, researchers have developed location-specific technologies (agronomic and cultivars) that reflect local conditions. The Coordinated Rice Research Program (CRRP), which functions under the National Agricultural Research Council (NARC), coordinates with the International Rice Research Institute for new genetic materials. In the last thirty years, CRRP has released and recommended more than forty improved varieties of rice for a wide range of climatic conditions of the country (HMG/MOAC 2001). Although farmers are selective in accepting them, owing to risks associated with rainfall variability and grain quality, the area covered by these improved varieties has increased steadily over time. The new cultivars recommended for different climatic conditions have extended the technological choices for farmers, even in areas with marginal climate. In the early 1990s, the area covered by improved varieties of rice was estimated to be about 46 percent (Thapa 1994), but it increased to 71 percent by the end of the decade (Goletti 2001). We believe that greater rice productivity in climatically marginal areas can be linked to three overlapping interventions: (1) introduction and adoption of location-specific rice varieties; (2) adoption of climate-appropriate management practices; and (3) institutional changes that led to technological innovation in marginal areas.

Introduction and Adoption of Location-Specific Rice Varieties. Agricultural research institutions in Nepal have released more than forty new varieties of rice since the early 1960s (Table 3). Although most of these varieties were developed for high-potential irrigated land (e.g., thirteen for the terai and the fertile valleys and eleven for the hills), a number of them were developed for climatically marginal areas. About 25 percent of these forty varieties were recommended specifically for rainfed regions having intermittent drought periods, of which three were for the rain-fed condition of the mid- and far-western terai region, four for the drought-prone regions of the hills, and three developed as cold-tolerant varieties for high-altitude regions of the mountains. In the rain-fed rice-growing area of the mountains and the hills, participatory plant breeding has led to a successful intervention and adoption of improved rice varieties.

A good example if this was the release of two high-altitude rice varieties, Machhapuchre-3 and Machhapuchre-9, in the mid-1990s. Studies show that 'Machhapuchre-3' was significantly superior to local varieties, producing a 42 percent higher yield in rice-growing areas situated between 1,500 and 2,200 m above sea level (Sthapit, Joshi, and Witcombe 1996; Joshi and Witcombe 2003). Similarly, 'Machhapuchre-9' was found to be doing well in areas located at altitudes greater than 2,200 m above sea level. Likewise, 'Rampur Masuli,' another improved rice variety, has been replacing local low-yielding varieties due to its ability to

Table 3. Improved varieties of rice released by the agricultural research systems of Nepal in the last thirty-five years

Recommended ecological domain	No. of varieties released	Crop characteristics	Yield potential (Mt)
Terai under irrigated condition	3	Medium maturity (145–160 days)	4.0–4.5
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 condition	3	Late maturity (165–180 days)	4.2–5.0

Source: HMG/MOAC, Agri-Business Promotion and Statistical Division, 2001–2002.

mature ten to fifteen 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 2003).

In Nepal, centralized research and development policies of the past also could imply that research and development policy could be assessed and planned without much consideration of particular climatic or other conditions at the local level. It is at the local level that availability of technology and other information determines the production choices of farmers (Liverman 1990). Understanding how location-specific needs are addressed by farmers and their supporting institutions is the first step toward identifying options for potential agricultural adaptation in a changing context.

Adoption of Climate-Appropriate Management Practices. Varietal improvement alone will have limited impacts on rice productivity, especially in marginal climatic areas. Low soil fertility and lack of water are other major constraints that are difficult to overcome. Researchers in Nepal have been devising improved agronomic management practices that alleviate constraints posed by climatic factors. For example, to address the constant dilemma associated with the uncertainty of the onset of the monsoon, researchers have been improvising traditional methods of "direct seeding" that are often practiced in risk-prone environments (Pandey and Velasco 2002). According to Pandey and Velasco (2002), the development of suitable varieties, availability of modern tools (e.g., power tiller drill), and increased access to herbicides have made this traditional technology more profitable in risk-prone environments of many Asian countries, including Nepal. This method has not only reduced the demand on labor, but it 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 when compared to the conventional method of transplanting.

In another example, researchers working with farmers have helped them maximize the yield potential of HYVs. To do so, farmers were required to follow a set of recommendations, one of which was adhering to a specified timing of planting because delayed action could result in substantial loss of yield. A study also showed that improved varieties of rice must be transplanted from the seed bed to the main field at between twenty-four and twenty-eight days to achieve maximum yield potential (Shah and Yadav 2001). In a country where the timing and intensity of monsoon precipitation is highly variable, such a stringent condition can be problematic. Therefore, it becomes mutually beneficial for both researchers and farmers to understand and implement agronomic practices that will result in higher production. Evidence also suggests that farmers are quite capable of adopting complex technological interventions as long as there is a reciprocal relationship between them and the researchers (Witcombe et al. 1996; Joshi and Witcombe 2003).

Institutional Changes That Led to Innovation of Technology in Marginal Areas. Parallel to the government's effort in developing technologies for improving production in agriculture, there has been a significant policy change that could have contributed to the observed growth in rice productivity. One such policy change was the deregulation of fertilizer subsidy by the government of Nepal in 1997. This change in policy (1) allowed the private sector to import and distribute fertilizer, (2) phased out a fertilizer subsidy, and (3) deregulated fertilizer prices. In the absence of detailed data, it is difficult to assess precisely the impacts of the deregulation policy on the use of fertilizer by the farmers. Nonetheless, a 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 (Gruhn, Poudel, and Goletti 2003). According to this study, 81 percent of the farmers applied both inorganic and organic fertilizers during the 2001–2002 crop year and reported an increased supply of fertilizer, something they had not experienced previously.

In the early 1990s, NARC instituted a significant change in agricultural research and development. One of the outcomes was the setting up of Participatory Technology Development (PTD), a program that focuses on development of technologies that are appropriate to the climatically marginalized regions of the country. This is achieved through collaborative efforts among all stakeholders in agricultural development, including farmers (Witcombe et al. 1996; Sperling and Ashby 1999). The PTD approach incorporates indigenous knowledge so that new technologies are best adapted to local social and environmental conditions. The PTD also provides a clearer strategy for coordination of new players (e.g., private enterprises and nongovernmental organizations [NGOs]) involved in innovation of agricultural technologies in Nepal (Biggs and Gauchan 2001; Gauchan, Joshi, and Biggs 2003), an unlikely configuration a decade ago.

A new institutional setting for innovation of technology is no doubt complex, involving plural systems and multiple sources of innovation. Nevertheless, such an environment provides space for a wide range of actors in technological innovation including farmers, the private sector, and NGOs (Sthapit, Joshi, and Witcombe 1996) and allows for better interaction and learning. Whereas earlier work on varietal development lay only within the governmental research institutions, this new institutional arrangement has been able to seek wider partnership among the various stakeholders who are focused on agricultural development for marginal areas. This partnership has encouraged NGOs and other organizations to become stronger research institutions, contributing significantly to technological innovations in agriculture. The role of farmers in research and development of technology has grown significantly, so that they are now able to set their agendas based on their own resource endowments, which is facilitated by NARC and NGOs. This new institutional approach has not only improved the relationship between farmers and researchers but has created a dialogue that has benefited both partners. The impact of PTD is reported to be especially positive in rice production in climatically marginal regions (Sthapit, Joshi, and Witcombe 1996).

Conclusions

The theoretical foundation for this research is derived from the work of Hayami and Ruttan (1971, 1985), who argued that research and development of technology in agriculture is a function of the resource endowments of the geographic regions in question. They tested their model against the history of agricultural development in the United States and Japan and argued that the different paths of technological change in agriculture in these countries were shaped by differences in resource endowments. For example, the constraint imposed on agricultural development by an inelastic supply of land in Japan was offset by development of fertilizer-responsive, high-yielding crop varieties that compensated for limited arable land. Similarly, the constraint imposed by an inelastic supply of labor in the United States was substituted by technical advances leading to greater mechanical power in agriculture. Throughout the period of 1880 through 1980, Japanese farmers have used more fertilizer per hectare than U.S. farmers have. Likewise, U.S. farmers have used more machinery per worker than have Japanese farmers.

It is a challenge to make a compelling case for technological innovation as being driven solely by climatic factors because Nepal's rice production is framed within the context of other changes that are part of its agricultural development. Yet, this study recognizes that climate is one of the most important factors to which farmers in the country have to adjust their rice production system. More important, this research uncovers recent changes in rice production technology made at the local level that signify the thrust of the development of location-specific technologies. Lack of data has been a major shortcoming in the effort to establish an unambiguous empirical relationship between climate and technologies. This is an open research issue that can be addressed with time. 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.

The findings from both the empirical and the 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 development of technological innovations accompanied by changes in agricultural policies might have been responsible for higher rice productivity among the districts with marginal climate. This assertion is supported both by the results of the empirical analysis, showing evidence of productivity convergence, and by the assessment of policies related to research and development. The empirical analysis of productivity convergence, even 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. With respect to policy assessment, the new institutional framework exhibits change in policies that facilitate greater engagement of relevant stakeholders in the development and application of new technologies in rice cultivation (e.g., PTD approach).

The cost of devising location-specific technologies is greater for a country with a wide range of climatic variation than for a more geographically homogenous one. In a country such as Nepal, where climatic resources are far from uniform, the strategies needed for farmers to produce rice can be considerable. Furthermore, the cost of devising technologies appropriate for all agro-ecosystems is enormous and could hinder desired growth in agricultural productivity. Therefore, involving multiple actors in the development of agricultural technologies in the country is necessary to mitigate this cost. The recent institutional change in Nepal's research establishment, which has favored partnership with NGOs, farmers, and the private sector, has worked to everyone's advantage. The new institutional framework created by Nepal for research and development of technology is in line with the argument made by Hayami and Ruttan (1985). 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.

The theoretical basis that we have adopted for this research asserts that climate variability and change create conditions of insufficient climate resources, which prompt the development of appropriate technologies that substitute for and ameliorate the negative impacts of climate. Nepal's research establishment has used climate as one of the drivers of research and development of technologies in rice production, and multiple stakeholders, including farmers, have worked together to develop technologies that consider local needs and climatic conditions. This has resulted in a more complex and sophisticated human–environment relationship in rice production. Our analysis shows evidence of this climate–technology interaction, which provides support for climate-induced innovation in rice-based cropping systems in Nepal.

Based on these findings, we assert that farmers and their supporting public institutions in Nepal will continue to modify their cropping activities to new climatic conditions, thereby mitigating potentially negative effects in much the same manner that they have demonstrated to date. This finding should not, however, lead to complacency because innovations in agriculture have always depended on continued investment in agricultural research and infrastructure. Yet the current trend of weaning resources away from agricultural and climate research, especially in developing countries, corrodes the vital support provided by public institutions for farmers as they adapt to climate change. Therefore, agricultural adaptation to future climate is contingent on continued investment in agriculture as well as on the active engagement of public institutions responsible for developing and disseminating appropriate technologies for farmers operating in specific climatic regions.

Research on climate–technology interaction is important for at least three reasons. First, climate–technology interaction in agriculture represents a classic example of the human–environment interface, an area of long-standing interest within geography. Second, a productive and sustainable human–environment system is necessary for providing livelihood security to an ever-growing population. This is especially true in the case of developing countries, where agriculture is an important source of rural employment and occupies a significant role in the local and national economies. Finally, if farmers and their supporting institutions are engaged, they will be able to respond to climatic challenges much more readily, making them prepared to minimize the negative consequences of changing climate.

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Note

1. According to the World Meteorological Organization (http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/fn5.htm#1 [last accessed 6 October 2010]), an average of thirty years of continuous records is taken as normal. Only eighty-nine meteorological stations in Nepal have rainfall records for such a long period of time. Therefore, many other stations having records for less than thirty years had to be included.

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