

CLIMATE CHANGE SERIES

Climate Change and Agriculture

*A Review of Impacts
and Adaptations*

Pradeep Kurukulasuriya
Shane Rosenthal

June 2003

*Published jointly with the Agriculture
and Rural Development Department*



THE WORLD BANK ENVIRONMENT DEPARTMENT

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A Review of Impacts and Adaptations

Pradeep Kurukulasuriya
Shane Rosenthal¹

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The International Bank for Reconstruction
and Development/THE WORLD BANK
1818 H Street, N.W.
Washington, D.C. 20433, U.S.A.

Manufactured in the United States of America
First printing June 2003

Pradeep Kurukulasuriya and Shane Rosenthal are doctoral students at the Yale University's School of Forestry and Environmental Studies. We wish to thank Robert Mendelsohn (Yale University), Ariel Dinar (ARD, World Bank), and Ajay Mathur (ENV, World Bank) for helpful comments in earlier drafts. We are also grateful to Ian Noble (ENVCF, World Bank) and John Horowitz (University of Maryland) for their comments and suggestions in a review of this paper. We thank Pat Daly (World Bank) for editorial assistance and advice.

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Foreword

Climate change is widely agreed to be already a reality, and its adverse impacts on the vulnerability of poor communities are superimposed on existing vulnerabilities. Climate change will further reduce access to drinking water, negatively affect the health of poor people, and will pose a real threat to food security in many countries in Africa, Asia and Latin America. Consequently, the World Bank is moving towards mainstreaming climate risk in all its work, and integrating climate-change adaptation, where appropriate, in projects, strategies and policies. We believe this is necessary to ensure the effectiveness of our investments in poverty eradication and sustainable development.

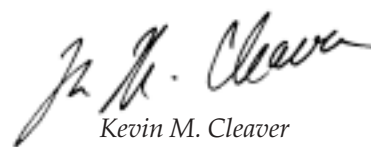
Agricultural outputs, as well as the livelihoods of people who depend on it, are particularly vulnerable to climate change, and it is important

that we assess adaptation mechanisms to reduce these vulnerabilities. Strategies to cope with current climate variability provide a good starting point for addressing adaptation needs in the context of poverty reduction. Learning from experience can help prevent the underachievement of sustainable development efforts, as well as avoid maladaptation.

As a first step in this direction, the Environment Department and the Agriculture & Rural Development Department asked Pradeep Kurukulasuriya and Shane Rosenthal, both doctoral students at Yale University, to review the impacts of climate on agriculture, and the adaptation mechanisms that farmers and countries have used to cope with these impacts. We are pleased to present their review as a joint working paper of the two Departments.



Kristalina I. Georgieva
Director
Environment Department



Kevin M. Cleaver
Director
Agriculture & Rural
Development Department

Abbreviations

AET	Actual evapotranspiration
ACRU	Agrohydrological model
CCCM	Climate and Carbon Cycle Modeling
FAO	Food and Agriculture Organization
GDP	Gross domestic product
GFDL	Geophysical Fluid Dynamics Laboratory (United States)
GISS	Goddard Institute for Space Studies (United States)
OSU	Oregon State University (United States)
PET	Potential evapotranspiration
UKMO	United Kingdom Meteorological Office (United Kingdom)
USDA	United States Department of Agriculture

Executive Summary

The vulnerability of the agricultural sector to both climate change and variability is well established in the literature. The general consensus is that changes in temperature and precipitation will result in changes in land and water regimes that will subsequently affect agricultural productivity. Research has also shown that specifically in tropical regions, with many of the poorest countries, impacts on agricultural productivity are expected to be particularly harmful. The vulnerability of these countries is also especially likely to be acute in light of technological, resource, and institutional constraints. Although estimates suggest that global food production is likely to be robust, experts predict tropical regions will see both a reduction in agricultural yields and a rise in poverty levels as livelihood opportunities for many engaged in the agricultural sector become increasingly susceptible to expected climate pressures.

While contemporary policy dialogue has focused on mitigating emissions that induce climate change, there has been relatively limited discussion of policies that can address climate impacts. First, climate variability is already a problem both in developed and developing countries. Second, even moderate climate change provides added impetus to promoting local adaptation options concurrently with the pursuit of global efforts on mitigation strategies. That is, adaptation to climate change and

variability (including extreme events) at the national and local levels is regarded as a pragmatic strategy to strengthen capacity to lessen the magnitude of impacts that are already occurring, could increase gradually (or suddenly), and may be irreversible.

Consequently, several key themes have emerged from the current literature on adaptations to climate change. First, given the range of current vulnerability and diversity of expected impacts, there is no single recommended formula for adaptation. Second, responsibility for adaptations will be in the hands of private individuals as well as government. Third, the temporal dimension of policy responses is likely to have a significant role in the effectiveness of facilitating adaptation to climate change. One set of measures will decrease the short-term vulnerabilities of the agricultural sector through adaptations to weather effects. These measures will therefore address concerns with climate variability. However, more often than not policies aimed at reducing vulnerability to short term climate variation will not reduce vulnerability to long term climate change. Another set of strategies that reduce vulnerability to climate change will thus be necessary. This second set of adaptation measures include options such as improving water management practices, modernization by adopting and utilizing new technologies, and changing crop types and location, including

migrating permanently away from the agricultural sector. Finally, a third set of adaptation options need to incorporate economic, institutional, political, and social policy changes that promote sustainable development. The pursuit of such “no-regrets” options through an interdisciplinary approach is fundamental to strengthening local capacity to adapt.

In conclusion, it is clear that in the short run, adaptation options in the agricultural sector need to reflect what is currently known about climate conditions. In contrast, in the long term it is necessary for national sectoral policy and assistance provided by international agencies to

developing countries to reflect expected changes in the future from climate change. The focus of policymakers should thus be on formulating and implementing policies that promote better adaptation. In particular, incentives that promote adaptation need to be formulated and incorporated into project designs. It is also clear that policymakers should promote dynamic adaptation, as it is unlikely that there will be one solution for all time. Finally, incentives that promote adaptation policies should be incorporated into poverty reduction and other sustainable development policies that in turn will also enhance the resiliency of the agricultural sector.

1 Background

1.1 Why is Climate Change a Concern in Agriculture?

Numerous factors shape and drive the agricultural sector. Market fluctuations, changes in domestic and international agricultural policies (such as the form and extent of subsidies, incentives, tariffs, credit facilities, and insurance), management practices, terms of trade, the type and availability of technology and extension, land-use regulations and biophysical characteristics (availability of water resources, soil quality, carrying capacity, and pests and diseases) are among the set of primary influences. Given its inherent link to natural resources, agricultural production is also at the mercy of uncertainties driven by climate variation, including extreme events such as flooding and drought.

Over the last decade or so, climate change (in terms of long-term changes in mean temperature or precipitation normals, as well as an increased frequency of extreme climate effects) has gradually been recognized as an additional factor which, with other conventional pressures, will have a significant weight on the form, scale, and spatial and temporal impact on agricultural productivity. The general consensus to emerge from the literature is that in the absence of adequate response strategies to long-term climate change as well as to climate variability, diverse and region-specific impacts will become more apparent. Some impacts are expected to be

adverse; others, favorable. At times, impacts will be slow to unfold, enabling local farmers and national governments time to respond. The distribution of impacts will vary as both the ability to respond to impacts and resources with which to do so vary across nations. In other cases, impacts will be unexpected, and appropriate responses may not easily be known or implemented in advance.

Impacts of climate variability and change on the agricultural sector are projected to steadily manifest directly from changes in land and water regimes, the likely primary conduits of change. Changes in the frequency and intensity of droughts, flooding, and storm damage are expected. Climate change is expected to result in long-term water and other resource shortages, worsening soil conditions, drought and desertification, disease and pest outbreaks on crops and livestock, sea-level rise, and so on. Vulnerable areas are expected to experience losses in agricultural productivity, primarily due to reductions in crop yields (Rosenzweig and others 2002). Increasing use of marginal land for agriculture (especially among smallholder farms) is anticipated as the availability and productivity potential of land begin to decline.² In contrast, climate change is also expected to result in some beneficial effects, particularly in temperate regions (Mendelsohn and others 1999). The lengthening of growing seasons, carbon fertilization effects, and improved

conditions for crop growth are forecast to stimulate gains in agricultural productivity in high-latitude regions, such as in northern China and many parts of northern America and Europe.

Consequently, the likely impacts of climate change on the agricultural sector have prompted concern over the magnitude of future global food production (Intergovernmental Panel on Climate Change (IPCC) 1996; Bindi and Olesen 2000). Early global estimates predict (without consideration of CO₂ fertilization effects or adaptation) a 20–30 percent reduction in grain production (Darwin and others 1995).³ Based on agronomic research in low latitude countries, Reilly and others (1994, 1996) approximate global welfare changes in the agricultural sector (without adaptations) between losses of US\$61.2 billion and gains of US\$0.1 billion. This is in contrast to losses of US\$37 billion to gains of US\$70 billion with appropriate adaptations in place. More recently, studies that reflect CO₂ fertilization impacts and adaptation suggest that global agricultural supply is likely to be robust in the face of moderate warming. Under the most severe scenarios of climate change, however, significant losses are expected worldwide (see also studies by Fischer and others (1993, 1996; see also Rosenzweig and others 1993; Rosenzweig and Parry 1994); Darwin and others (1995, 1996); Tsigas and others (1996); Adams and Hurd 1999; Reilly 1999; Rosenzweig 2000).

Given the range of warming predicted by the scientific community, regional and local variation in impacts on the agricultural production is likely to be high. However, a rapidly emerging consensus is that the worst impacts will be in tropical regions (Rosenzweig and others 1993; Mendelsohn 2000; IPCC 2001; Sachs 2003⁴ As a result, experts predict a spatial shift of crops and agricultural practices away

from the tropics toward the temperate and polar regions (IPCC 2001). Early estimates suggest 4–24 percent losses in production in the developed countries, and 14–16 percent losses in developing countries (IPCC 1996). Dryland areas (where rainy seasons are already short and significant water shortages are currently the norm) are likely to be among the most vulnerable. Declines in aggregate production are anticipated in most of Africa and South and East Asia (for example, Western India, Bangladesh, and Thailand), with increments in countries such as Indonesia, Malaysia, Taiwan, and parts of India and China. Murdiyarso (2000) highlights that rice production in Asia may decline by 3.8 percent of production levels of 2000 (estimated at 430 metric tons) under likely future climate regimes.⁵

The concern with climate change is heightened given the linkage of the agricultural sector to poverty. In particular, it is anticipated that adverse impacts on the agricultural sector will exacerbate the incidence of rural poverty. Impacts on poverty are likely to be especially severe in developing countries where the agricultural sector is an important source of livelihood for a majority of the rural population. In Africa, estimates indicate that nearly 60–70 percent of the population is dependent on the agricultural sector for employment, and the sector contributes on average nearly 34 percent to gross domestic product (GDP) per country.⁶ In the West African Sahel alone, more than 80 percent of the population is involved in agriculture and stock-farming in rural areas, and the two sectors contribute approximately 35 percent of the countries' GDPs (Mohamed and others 2002). With lower technological and capital stocks, the agricultural sector in such poorer developing countries is unlikely to withstand the additional pressures imposed by climate change without a concerted response strategy (Crosson 1997). According to some

estimates, the overall economic impact of climate change on the agricultural sector could be up to 10 percent of GDP (Hernes and others 1995; IPCC 2001).

As research on the spatial variation in climate change and its subsequent impacts mounts, it is becoming increasingly apparent that both across and within regions vulnerability to climate impacts will be diverse. Another expectation is the high cost of maladaptation, where policies to address climate change are not fully implemented or are poorly designed. In developing countries, the expansion of human settlements to marginal land and hazardous areas such as deltas and low-lying coastlines and other climate-sensitive areas has no doubt contributed to worsening the expected problems (Burton 2001). In short, it is apparent that some communities will be better equipped and positioned to deal with the many possible outcomes associated with sudden or gradual climate scenarios.

1.2 Addressing Climate Concerns Through Adaptation

In order to address the expected pressures on the agricultural as well as other economic sectors, policymakers have thus far largely focused on addressing climate change through mitigation of human-induced emissions of greenhouse gases and sequestration of carbon. However, it is becoming widely accepted that mitigation alone is unlikely to be sufficient as a climate policy (Pielke 1998). As understanding improves of the workings of ecosystems and socioeconomic systems' function and the extent of their likely resilience to climatic stimuli, there is an intensive push for contemporary policy dialogue to complement mitigation initiatives with adaptation policies as another key defense against climate change. The recognition that

some countries (especially the developing countries and, particularly, the poorest segments of society within countries), will not be able to avoid the impacts of climate change has added impetus to promoting adaptation (Burton 2001). In addition, under-preparedness to increased frequency or lengthening of periods of drought, higher temperatures, and climate variability (for example, extreme events) can be prohibitively costly and can severely undermine expensive long-term investments.

Numerous studies have consequently emphasized the need to pursue adaptation in addition to mitigation strategies.⁷ The Intergovernmental Panel on Climate Change (IPCC) notes that adaptability through changes in "processes, practices or structures" is a crucial element in reducing potential adverse impacts or enhancing beneficial impacts of climate change (IPCC 2001). Adaptation is regarded as a vital component of climate change impacts and vulnerability assessment (Skinner and others 2001). In the context of development, Burton (1996) asserts that a practical response strategy is to improve adaptation to climate variability, including extreme events.⁸ Smith (1997) maintains that adaptation is necessary to avoid impacts that can otherwise occur gradually and may be irreversible. That is, increasing the robustness of infrastructure designs and investments can reap immediate benefits through improved resilience to climate variability and extreme atmospheric events. Adaptation is viewed as a crucial step to strengthen local capacity to deal with forecasted and unexpected climatic conditions (Smith and others 1996; Smit and others 1999).

1.3 Objectives of Review

Given the growing urgency of adaptation of agriculture to climate change, numerous issues

need to be addressed. For one, what is the range of adaptation options based on experiences to climate issues in agriculture? Moreover, why has adaptation been successful in some instances and not in others? That is, what conditions determine the ability to adapt and successfully cope with the challenges that climate change will bring to bear? What underlying socioeconomic and institutional conditions are necessary to facilitate the adoption of various measures that scientific (field) and natural experiments have shown can cushion the adverse impacts of climate change?

This review contends that experiences in adaptation to current climate across the world's numerous agro-ecological zones hold much scope for providing crucial insights on the various options for dealing with future climate change scenarios. Consequently, in examining the above issues, a key objective of the review is to provide an overview of the typology of primary measures undertaken at the macro and micro level to adapt to climate change impacts in agriculture. The discussion that follows is aimed at improving understanding of the underlying processes and conditions necessary for successfully identifying and designing appropriate adaptive measures for dealing with future climate change impacts in the agricultural sector and their implementation in developing countries. The review focuses predominantly on the agricultural sector, although some examples from other sectors such as forestry and water are also highlighted. Both micro and macro level policy responses to climate change impacts are examined.

As a point of departure, this review begins with the assumption that human-induced changes in

climate will occur over the coming decades⁹ (IPCC 1996, 2001). Given the long lifetime of atmospheric greenhouse gases, the stock of these gases in the atmosphere will continue to accumulate for some time into the future, regardless of the rate at which mitigation policies at the international level are successful (IPCC 1996). Consequently, some level of human-induced climate change is inevitable even if uncertainty remains over the extent to which (and where, specifically,) impacts will be most acutely felt.

The review is organized in the following way: Section 2 discusses some of the primary literature on the impacts of climate change on agriculture in various parts of the world. Following a brief overview of the mechanism of climate change impacts on agriculture, results of impact studies on agriculture and forestry using different estimation techniques (agronomic and economic) are presented. Studies incorporating adaptation and those that are not are highlighted. Section 3 focuses on the scope and varieties of adaptation strategies. Private versus public adaptation as well as the temporal dimension of adaptations is discussed. Section 4 examines short- and long-run adaptations in greater detail. In particular, an attempt is made to develop a typology of the main response strategies that are highlighted in the literature. Moreover, constraints that may prevent such adaptations to be successfully implemented are discussed. Section 5 presents a summary matrix of the suite of response strategies based on materials in section 4, in addition to outlining necessary support policies and other prerequisites. Section 6 concludes and highlights key themes to emerge from the review.

2 Impacts of Climate Change on Agriculture

An extensive literature has developed on the impacts of climate change on agriculture, with the earliest focusing primarily on the vulnerability of the sector. The general message to emerge from this literature is that the degree of vulnerability of the agricultural sector to climate change is contingent on a wide range of local environmental and management factors. Key features include local biological conditions such as soil content, type of crop that is grown, extent of knowledge and awareness of expected changes in climate, type and objectives of the management regimes prevalent in agriculture (that is, maximizing output or revenues, and so on), the extent of support from government and other external (private) agencies, and the ability of key stakeholders (at the national, local, and household level) to undertake the necessary remedial steps to address climate concerns, to name a few. In a sense, the increased uncertainty of climate effects represents an additional problem that farmers have to address. For example, poor soil quality, financial constraints, and lack of access to markets can constrain agricultural productivity to begin with, regardless of climate effects. Climate change thus represents an additional burden that for farmers translates into production risks associated with crop yields, probabilities of extreme events, timing of field operations, and timing of investments in new technologies.¹⁰

2.1 Mechanism for Climatic Impacts on Crops

Hulme (1996) describes four ways in which climate would have a physical effect on crops.¹¹

First, *changes in temperature and precipitation* will alter the distribution of agro-ecological zones. Changes in soil moisture and content and the timing and length of growing seasons¹² will be affected in various ways in different parts of the world. Rosenzweig and Hillel (1995) state that in middle and higher latitudes, higher temperatures will lengthen growing seasons and expand crop-producing areas pole-ward, thus benefiting countries in these regions. While less fertile soils in higher latitudes will temper some of the gains of an extended growing season, it is not clear to what additional extent soils will be a real constraint given that numerous other factors (such as changes in precipitation levels, fertilizer use, irrigation availability, and so on) will also have a significant influence on the final outcome. In contrast, in lower latitudes, it is expected that higher temperatures will adversely affect growing conditions,¹³ especially in areas where temperatures are close to or at the optimal level for crop growth to begin with. Irrigation availability and demand will also be affected by both changes in temperature and precipitation. Reduction in precipitation is likely to intensify further aquifer exploitation for agriculture and place additional burdens on other surface and groundwater resources from non-agricultural use (such as industrial and municipal needs). An increase of potential evapotranspiration is likely to intensify drought stress, especially in the semiarid tropics and subtropics (Hillel and Rosenzweig 1989).

For example, temperatures in Africa are expected to rise at less than the global average, and will have varying impacts depending upon the underlying type of agro-ecological zone. That is, impacts will depend on initial temperatures. Fischer and Velthuizen (1996) and Downing (1992) explore the impact of climate change on Kenya, and find that higher temperatures would have a positive impact in highland areas. Downing (1992), relying on a model of land use to estimate changes in availability of land suitable for cropping, has shown that in highland areas of western Kenya, there is likely to be a 67 percent increase in “high potential” land in response to a 2.5° C rise in average temperature. In contrast, rising ambient temperatures may have a detrimental effect in many lowland areas, particularly those that are semiarid. For some crops, plant metabolism begins to break down above 40°C, and a reduction in growing periods due to accelerated growth can reduce the yields (Hulme, 1996).

Second, *carbon dioxide* effects are expected to have a positive impact due to, for example, greater water use efficiency and higher rate of photosynthesis. Numerous publications dealing with the agronomic effects of climate change offer the following explanation concerning carbon dioxide concentrations, which are expected to rise by as much as 57 percent by 2050 (Ringius and others 1996; Hulme 1996). Rising carbon dioxide concentrations in the atmosphere are important to agriculture because they increase the rate of photosynthesis and water use efficiency. These effects are strongest for plants with the C₃ photosynthetic pathway,¹⁴ which include crops such as wheat, rice, and soybean. Carbon dioxide enrichment is also positive—though not by as much—for C₄ plants such as maize, millet, and sorghum, and many grasses (and thus weeds). IPCC (1996) and Reilly et al. (1996) estimate that a doubling of carbon

dioxide concentrations would lead to yield improvements ranging from 10–30 percent. Ringius and others (1996) suggest that water use efficiency will increase in the same range. However, while higher atmospheric concentrations of CO₂ will, by reducing evapotranspiration, improve water use efficiency of crops and increase the rate of photosynthesis (Darwin 2001), the net result may be moderated by costly pest and weed infestations (Rosenzweig and Hillel 1995).¹⁵

At the same time, there is a debate on whether expected increments in productivity due to CO₂ have been overestimated. Horowitz¹⁶ argues that while increases in global temperature occur with a lengthy lag (after the increased concentration of greenhouse gases), fertilization should happen virtually instantaneously. Thus, given the increase in CO₂ concentration that has occurred, Horowitz claims that the fertilization effects in crop yields should already be apparent. Of course, carbon fertilization effects may be responsible for some of the rapid increases in production observed throughout the world.

Several papers have examined effects of carbon fertilization in forests. In natural forests, there is reason to believe that carbon fertilization effects may be limited by shortages in other nutrients (citation). Clearly this is less of a problem with agriculture where farmers regularly supplement nutrients through fertilizers. Berry and Roderick (2002) examine the relationship between the observed 20 percent increase in CO₂ over the last two hundred years and land-use effects on Australian vegetation and conclude that the seasonally green leaves of annual and ephemeral herbaceous plants vegetation cover is roughly the same over this period. In addition, their results highlighted that the increase in evergreen cover is likely to have been caused by the increase in CO₂ concentrations, but it alone is

unlikely to be the sole cause of the change. In another paper, Lutze and others (1999) report that crop growth under elevated CO₂ led to spring frost damage in field-grown seedlings of snow gum (*Eucalyptus pauciflora* Sieb, ex Spreng), a usually frost-tolerant eucalyptus. Their result suggests that an increase in frost susceptibility may lower likely gains in productivity from CO₂ fertilization. This result clearly will be less important as frost risk is reduced from higher temperatures.

Third, *water availability* (or *runoff*) is a critical factor in determining the impact of climate change in many places, particularly in Africa. A number of studies suggest that precipitation and the length of the growing season are critical in determining whether climate change positively or negatively affects agriculture (Hulme, 1996; Fischer, 1996; Strzepek and Smith 1995; Sivakumar 1992). However, as outlined earlier, constraints abound on the scientific ability to predict trends in rainfall with much certainty. For other parts of the world too, there is less confidence about precipitation than other climatic changes. A lack of comprehensive regional and sub-regional precipitation models limit researchers' ability to reach firm conclusions about related impacts on agriculture.

Fourth, agricultural losses can result from climatic variability and the increased frequency of *extreme events* such as droughts and floods or changes in precipitation and temperature variance. As outlined in Rosenzweig and Hillel (1995), a higher frequency of droughts is likely to increase pressure on water supplies for numerous reasons ranging from plant transpiration to allocation. In contrast, increases in rainfall intensity in other regions can lead to higher rates of soil erosion, leaching of agricultural chemicals, and runoff that carries

livestock waste and nutrients into water bodies. While current climate forecasts are not clear about how extreme events and variability will change across agro-climatic zones, it is expected that adjustment costs are likely to be higher with greater rates of change (Adams and others 1999). One area that has received substantial attention in recent years is El Niño/Southern oscillation (ENSO). ENSO has been responsible for considerable variation in both temperature and precipitation. Of particular concern are areas such as Southern Africa where these effects are important.¹⁷

The expected variability of temperature, precipitation, atmospheric carbon content, and extreme events are forecast to have profound effects on plant growth and yields, crops, soils, insects, weeds, diseases, livestock, and water availability in Africa (Adams and others 1998; see also IPCC (1996) for a wide-ranging overview of the likely impacts on the agricultural sector). Burton (2001) suggests that expected impacts in dryland areas include reduction in rainfall, rise in temperature, and increased rainfall variability. Some arid areas such as Mauritania, Mali, and Niger may even get higher levels of rainfall. Highland areas are also expected to benefit, since the growing season would be lengthened and the incidence of frost diminished. In contrast, other, more subhumid zones, such as Burkino Faso, Mali and Ghana are expected to suffer from reductions in rainfall.

2.2 Quantitative Studies on Impacts of Climate Change

2.2.1 Estimation Methods

The quantitative estimates on impacts of climate change have been based predominantly on experimental and cross-sectional studies. The experimental approach includes *agro-economic simulation models*, as applied in early studies by

Parry and others (1988), Adams and others (1989). The method is similar to a carefully controlled experiment where climate levels or other variables of interest (such as CO₂) are adjusted (rather than the more likely transient climate scenarios driven by gradual increments in greenhouse gas forcing—see Reilly 2003), and impacts on crop productivity are estimated. A very similar approach is the *agro-ecological zone analysis*, a technique where predicted yields, based on the initial assignment of crops to specific agro-ecological zones, are utilized in crop simulation models that track the changes that take place in the agro-ecological zones and crops as climate changes. In turn, the results are incorporated in economic and general circulation models (GCM) to predict the scale and range of impacts.

Mendelsohn and others (1994) and Mendelsohn and Dinar (1999) outline several criticisms of the agronomic (or production function) approach. One serious criticism is that such models tend to overestimate damages. The underlying constraint is that yield estimates from controlled experiments (for effects of temperature, precipitation, and carbon dioxide) that, by definition, do not incorporate adaptations in the form of modified farming methods, remained at the heart of model specification.¹⁸ That is, estimation models are based on the unrealistic assumption that farmers would not adapt, or take into account, the effects of government interventions to offset climate impacts.¹⁹ Moreover, given the high cost of controlled experimentation, estimates of impacts were limited primarily to grains (an exception being Adams and others 1998) and to a few locations around the world (Mendelsohn 2000). Others also argue that crop models have focused on agricultural productivity in marginal lands in tropical climates²⁰ (Rosenzweig and Parry, 1994; Reilly and others 1996).

Dinar and Beach (1998) cast doubt on the accuracy of predictions made by agro-economic models given that price effects cannot be satisfactorily included in domestic-level models. They assert that since agricultural markets are characteristically worldwide, agricultural prices can only be reliably predicted using global models. Despite the efforts made by agro-economic models employed in studies by Rosenzweig and Parry (1994), Darwin and others (1994) and Reilly and others (1994), which Dinar and Beach (1998) suggest represent some of the best attempts to measure global prices, accurate measurement of climate-induced supply changes remains problematic. The magnitude of the errors is compounded in light of data limitations in the case of developing countries.

In addition, while agro-ecological zone analysis makes use of established data on the distribution of zones in developing countries, there are some drawbacks. Mendelsohn and Dinar (1999) point out that the large temperature categories reflected in the climate zones make it difficult to capture subtle changes within a zone. That is, a subtle shift between climatic zones is likely to result in a dramatic change in crop production in contrast to no effect when there are changes within a zone. In addition, they also point out that in early models (as applied in studies by Darwin and others 1995), the calibration of price effects is crude and the effects of soils and climate have to be analyzed separately.

In contrast, recent studies have begun to focus on efficient adaptation. One way this has been done in economic research is through the application of the *Ricardian approach*, which attempts to capture the influence of economic, climatic, and environmental factors on farm income or land values (Mendelsohn, Nordhaus, and Shaw 1994). This approach is preferred to the traditional estimation methods, given that instead of ad hoc

adjustments of parameters that are characteristic of the traditional approach, the Ricardian technique automatically incorporates efficient adaptations by farmers to climate change. That is, so long as the costs and benefits of agricultural production²¹ have a market value, they will be included in the analysis.

The primary criticism of the Ricardian approach is its failure to fully control the impact of important variables that could also explain the variation in farm incomes. Incomplete specification can result in an underestimation of damages and overestimation of benefits. The assumption of constant prices is another drawback (Cline, 1996). With regard to the latter, Mendelsohn and others (1994) agree that the inclusion of price effects is problematic and the Ricardian approach is weaker for it. However, this weakness also applies to all agronomic models which are confronted with the same difficulty of predicting domestic price changes when changes in agricultural prices due to climate change are determined at the global level. Although the Ricardian approach does not address this problem, Mendelsohn and others (1994) contend that the bias is less than 7 percent.

Furthermore, Quiggin and Horowitz (1999) argue that the Ricardian approach assumes that adjustment is costless, which will also bias the final outcome. The authors state that the primary costs of climate change will be costs of adjustment and that both natural capital and long-lived physical capital stocks will be reduced in value as a result of climate change. The magnitude of loss will depend on the variability and stochasticity of climate change.

More recently, Timmins (2001) concludes that the traditional Ricardian approach may yield

biased results when land within locations (such as at the district or county level) is heterogeneous and land owners behave optimally. Consequently, the conditions under which such a bias will occur are underlined, and an empirical model that controls for it is suggested. Based on results from its application to data from Brazil, Timmins highlights the importance of the bias and shows (among other things) that the agricultural implications of global climate change may not be as favorable as the application of the traditional Ricardian models suggested.

While research has provided important information on the likely impacts of climate change, there is an ongoing debate on the appropriateness of various types of models that are used to estimate impacts. Smit and Pilifosova (2001) emphasize, as others such as Tol and others, (1998) have also done, that many of the assumptions of impact models may not match with actual behavior. Yohe and others (1996) and Yohe and Neumann (1997) make the distinction between rational behavior under perfect information and rational behavior under uncertainty. It is argued that efficient adaptation techniques are only theoretically possible and not without uncertainty, as individuals may not necessarily behave rationally nor be willing to act with imperfect information.

2.2.2 Results from Agronomic and Agro-Ecological Zone Analysis Studies

(a) Agriculture

In one of the earliest agronomic studies, Newman (1980) undertook a crop production study of the United States and concludes that the U.S. cornbelt would shift northeast for every 1° C rise in temperature. Similarly, Rosenzweig (1985) finds that climate change would increase winter

wheat production in Canada, and regional shifts in wheat cultivars in the United States. Eswaran and Van den Berg (1993) use geographic information systems (GIS) to examine shifts in crop production and find that higher latitude regions are likely to benefit as areas become more appropriate for agricultural production through climate change. Parry and others, (1988), while not taking into account CO₂ effects or adaptation, also conclude, based on evidence from a number of agricultural case studies, that warmer temperature in high-latitude countries will by the lengthening of the growing season increase crop production. Higher evapotranspiration, however, is found to lead to adverse impacts on crop yields.

Early studies from developing countries also predominantly relied on agronomic models with limited adaptation. Recent research on climate impacts on Indian agriculture by Tata Energy Research Institute (TERI) highlights results from some studies undertaken in India.²² For example, in one of the earliest studies, Seshu and Cady (1984) estimate a decrease in rice yield in India at the rate of 0.71 ton per hectare given an increase in minimum temperature from 18° C to 19° C. The authors also associate a decrease of 0.41 ton per hectare with a temperature increase from 22° C to 23° C. Similarly, Sinha and Swaminathan (1991) find that a 2° C increase in mean air temperature could decrease rice yield by about 0.75 ton per hectare in the high-yield areas and by about 0.06 ton per hectare in the low-yield coastal regions. Further, a 0.5° C increase in winter temperature would reduce wheat crop duration by seven days and reduce yield by 0.45 ton per hectare. In particular, the increase in winter temperature is estimated to account for a 10 percent reduction in wheat production in the high-yield states of Punjab, Haryana, and Uttar Pradesh. In a crop

simulation study, Rao and Sinha (1994) estimate that wheat yields could decrease by 28–68 percent. Similarly, Aggarawal and Sinha (1993) show that in North India, a 1° C rise in mean temperature would have no significant effect on wheat yields, while a 2° C increase would reduce yields in most places.

A number of publications (Downing, 1992; Rosenzweig and others 1995; and Desanker, 2002) focus on the “vulnerability” of African countries to climate-induced reductions in agricultural production, and on the impact on individual farmers. Downing (1992) examines the impact of climate change on food security in three countries in Africa (Zimbabwe, Kenya, and Senegal). A variety of methods are employed, and careful attention is given to the definition of vulnerability. Data on numerous non-climatic factors such as the socioeconomic setting, trade issues, institutional structures, and geography are drawn on to examine “*current vulnerability, risk of present and future climatic variations and responses to reduce present vulnerability and improve resiliency to future risks.*”

Hulme and others (1999) examine actual and predicted continent-wide changes in temperature and rainfall in Africa during 1900–2100, drawing on data related to diurnal temperature range and rainfall variability. Using emissions scenarios prepared for IPCC’s Third Assessment Report and other models, the study presents four new scenarios, or “*futures*” of regional temperature, rainfall, carbon dioxide concentrations, and sea-level changes. The results of the scenarios are consistent with the IPCC conclusion, indicating that warming will continue and in most cases will accelerate. While the authors assert that in 100 years the continent could be 2–6° C warmer on average, they are less confident about future changes in rainfall due to

two primary reasons. Firstly, ENSO-type climate variability, a key determinant of rainfall variability in Africa, has not been represented satisfactorily in most global climate change models. In addition, the failure of GCMs to account for the dynamic land cover-atmosphere interactions and dust and biomass aerosols, important interactions in explaining climate variability, including recent desertification of the Sahel region, reduce the confidence of estimates on future precipitation levels.

Research on the agronomic impacts of climate change in Africa has largely focused on southern Africa. Hulme (1996) describes three models for maize that have been used for impact analysis in this region. The CERES-Maize site model was used to examine sites in Zimbabwe. Research reported in publications by Eid (1994), Muchena (1994), and Makadho (1996) is based on this model. The Agrohydrological (ACRU) model with CERES-Maize is described in Schulze and others (1993) and Schulze and others (1996). The monthly crop-climate model uses the Food and Agriculture Organization (FAO) water requirements satisfaction index (WRSI) to assess the sensitivity of maize to moisture deficits at certain times of year. Conclusions from these studies appear to be consistent. In most areas of southern Africa, the benefits from increases in carbon dioxide (higher water use efficiency, higher rates of photosynthesis) would outweigh adverse effects of lower rainfall and higher temperatures. The window for planting is also lengthened, which can have a positive effect. This research is applied in a number of country- and region-specific studies of the wider impacts of climate change, which are described in publications reviewed further below.

Sivakumar (1992) focuses on changing rainfall patterns and production of Pearl millet, the main

staple crop in Niger. He finds that previous studies on the implications of declining rainfall for agriculture in western Africa (which used monthly data) were too arbitrary an interval as a realistic index of crop responses. Using data on daily precipitation from 21 stations from the Niger rainfall database at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center, the author establishes patterns over the period 1921–1990 and explores correlations with millet yields and aggregate production. His conclusions indicate that shifts in the patterns of rainfall during the 1965–1988 period (relative to the 1945–1965 period) reduced the growing season by 5–20 days across various locations in Niger, making cropping more risky. Sivakumar notes that the implications for agriculture are important, not only because the absolute amount of rainfall has decreased, but also because its timing has changed. In particular, a decrease in the August rainfall is troubling for millet producers because of the lack of adequate water supply during the sensitive reproductive growth stage. The author notes that in times of drought farmers will sacrifice cash crops in order to save food crops, a finding that may partially explain a decline in groundnut production over a 10–15 year period beginning in the mid-1960s. This type of climatic change is thought to have important implications for sustainable agriculture, since continuing low rainfall can result in accelerated environmental degradation. A failure to intensify production has led to cropping in marginal lands that are more susceptible to rainfall variability and wind erosion.

Other publications reporting on research in Africa apply agronomic research to investigations of the wider impacts of climate change for a particular country or region. These include Phillips and McIntyre (2000) on Uganda,

Fischer and Velthuizen (1996) on Kenya, Schulze and others (1993) on southern Africa, and Makadho (1996) on Zimbabwe.

According to Downing's outlook (Downing 1992) for Kenya in 1992, potential food production would increase with higher temperatures and greater rainfall. However, those in semiarid areas, particularly "vulnerable socioeconomic groups," could face serious difficulties when their already low yields decrease further as a result of insufficient rainfall. Similarly, Fischer and Velthuizen (1996) suggest that the overall impact on the sector may be positive, but that results will vary by region. Kenya has a wide range of agro-ecological conditions, from hot and arid lowland areas to cool, humid highlands. Increases in concentrations of carbon dioxide are expected to have a positive effect overall, as would additional rainfall, to the extent they occur. The authors warn, however, that if rising temperatures are not accompanied by increases in precipitation (to make up for higher rates of evapotranspiration), then large decreases in agricultural production could result. This is a particular concern in low-lying areas of eastern and southern Kenya. In the highlands of the central and western parts of the country, higher temperatures could increase production due to larger areas becoming suitable for cropping. Furthermore, due to higher cropping intensities in these places, higher production would more than outweigh any effects of lower moisture. In some areas, reduced moisture could diminish the potential impact of pests and disease. The authors conclude that "the national level food productivity potential of Kenya may well increase with higher levels of atmospheric carbon dioxide and climate-change-induced increases in temperature, provided this is accompanied by some increase in precipitation as predicted by several global circulation models."

Makadho (1996) shows this to be a likely outcome for maize in Zimbabwe, with decreasing yields of up to 17 percent in drier areas. Using climate data from four agro-ecologically representative stations in Zimbabwe, the author bases his analysis upon two climate change models, the Geophysical Fluid Dynamics Laboratory model (GDFL) and the Climate and Carbon Cycle Modeling Group model (CCCM). Under both irrigated and non-irrigated conditions, in some regions maize production is expected to decrease significantly (by approximately 11–17 percent). Increments in temperature that shorten the crop growth period, especially the "grain-filling period," are underlined as the primary cause of the crop reductions.

Downing (1992) also confirms that shifts in agro-climatic potential would affect national food production and land use in Zimbabwe. With a 2° C increase in temperature, the core agricultural zone decreases by a third. The semiextensive farming zone is particularly sensitive to small changes in climate. Farmers in this zone, already vulnerable in terms of self-sufficiency and food security, are expected to be further marginalized due to increased risk of crop failure. A subsequent report by the Government of Zimbabwe,²³ follows closely the analysis and results found in Downing (1992) and Hulme (1996).²⁴

The focus of the analysis for Senegal is on population growth in the face of climate change. A carrying-capacity model is applied that compares consumption requirements with food production. The findings for 1990 suggest that of the country's 93 *arrondissements* (that is, precincts), two-thirds have rural populations exceeding their rainfed carrying capacity. While recognizing the limits of the model, the author

believes these results should be of concern, particularly if climate change were to increase the number of areas that are not food self-sufficient.

The Senegalese Government's Initial Communication on Climate Change (Government of the Republic of Senegal, 1997) provides a detailed account of the same research reported in Downing (1992). The report devotes significant attention to the implications of climate change for food security, and emphasizes the pressure that a 2.7 percent per year population growth rate places on the economy in light of the climate change that has taken place since 1966 – mainly in the form of much-reduced rainfall.²⁵

Hulme (1996) suggests that the droughts of 1984/85 and 1991/92 in southern Africa showed how vulnerable the southern Africa region is to climate and the impact that changes can have on food security and water resources. Both droughts had a significant impact on maize production in the southern Africa region. Problems of desertification are attributed more to human impacts, particularly demographic change. Moreover, analyses of vulnerability center on national food balances, food production, and dependence on food imports and food aid. Hulme (1996) also constructs an index of vulnerability based on these variables and GNP, and rates eight countries. According to the model, South Africa is the least vulnerable and Angola is most vulnerable. Downing (1992) characterizes vulnerability as (a) referring to a consequence as opposed to a cause, (b) implying an adverse consequence, and (c) a "relative term" rather than an absolute measurement of deprivation.

Yates and Strzepek (1998) explore how climate-induced changes in water resource availability,

crop yields, crop water use, land resources, and global agricultural markets affect Egyptian agriculture.²⁶ The authors point out the uniqueness of the agricultural sector in Egypt, namely, that all agricultural land is irrigated with water from the Nile River. Although Egypt's population is not growing quickly as compared with many other developing countries, an expected doubling by 2060 requires efforts to increase agricultural production. The authors emphasize the country's high dependence on natural resources make it especially vulnerable to climate change.²⁷

The paper confirms previous suspicions that Egypt is vulnerable to global warming, fluctuations in agricultural markets (local and global), and changes in agriculture and water and land resources. Specific conclusions that are made include: (i) population and economic growth scenarios are significant factors; (ii) a country adaptation to climate change is important; (iii) water resources availability and crop water use are important to consider in assessing vulnerability; (iv) water is a limiting factor; (v) economic, trade and social policies greatly affect the potential integrated impacts of climate change. Finally, emphasis is placed on the value of an integrated, economy-wide approach to assessing impacts and vulnerability.

Benson and Clay (1998) explore the impact of droughts on national economies in southern Africa. Using data from countries including Namibia, Zimbabwe, South Africa, Mozambique, Malawi, Lesotho, and Botswana, they maintain that industrial economies may be more vulnerable to such shocks than the developing countries of Africa. While developing economies would appear to be more vulnerable because of their dependence on agriculture, "weak inter-sectoral linkages, a high degree of self-

provisioning, relatively small non-agricultural sectors, and often poor transport infrastructure” have the effect of containing the impact of the drought. Evidence presented in the report suggests that the relationship between the level of complexity of an economy and its vulnerability to drought take the form of an inverted U.

(b) Forestry

Assessing the impact on forests is clearly a challenging task, as socioeconomic forces are critical and must be taken account of in order to get meaningful results. Smith and others (1995) provide an excellent overview of research on the impact of climate change on forestry, and include many useful references. They estimate the impacts of climate change on the distribution of global vegetation and identify and evaluate adaptive strategies for reducing vulnerability of forested ecosystems.

The Southern Africa Savanna/Woodlands Pilot Project assessed potential impacts at a regional and country level, looking at effects on vegetation structure, woody biomass, and nature reserves. It was conducted for the entire subequatorial region, with an emphasis on the Southern African Development Cooperative Council member nations of Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, Swaziland, Tanzania, Zambia, and Zimbabwe. Country studies analyzing the potential impacts on fuelwood provision, surface erosion due to vegetation loss, and protected areas were conducted for Zimbabwe and Malawi.

Regional impacts were predicted by coupling the Holdridge Life Zone Classification system²⁸ with four major global climate change models. The Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), and

United Kingdom Met Office (UKMO) scenarios show mesic forest declining anywhere from 18 to 63 percent from current coverage, while the Oregon State University (OSU) scenario projects an increase by 46 percent. The OSU model predicts a significant increase in precipitation relative to evapotranspiration, showing the sensitivity of the projections to rainfall. Results for the first three models reflect an overall drying predicted for the region. A major conclusion is that changes in forest cover by forest type are largely determined by the relationship of actual evapotranspiration (AET) and potential evapotranspiration (PET) to precipitation. The authors caution that the approach they use is somewhat static, since the Holdridge classification system does not take into account temporal constraints in the transition from one vegetation type to another.

Results from the study of Zimbabwe are consistent with the regional analysis, in that the UKMO, GFDL, and GISS models show an increase in the aridity of forests, and a concomitant decline in production of woody biomass. However, the OSU model, due to its’ more optimistic predictions concerning precipitation, show no change in these and other measures related to the production of fuelwood.

Matarira and Mwamuka (1996) report on research on the impact of climate change on the forest resources of Zimbabwe. The authors also use the Holdridge Life Zone Classification System and the GISS general circulation model scenarios of global climate change to assess likely changes in forest cover by type. Under the GISS scenario, almost one-fifth of the total land area is projected to shift from subtropical thorn woodland and subtropical dry forest to tropical very dry forest. The authors conclude that this likely trend is attributable to “a future decline in

precipitation patterns and an increase in ambient temperature.”

Dixon and others (1996) report on results of a comparative assessment of current and future forest distribution in Cameroon and Ghana that considers the impact of human-induced land use changes and global climate change. Using the same Holdridge classification system employed by Smith and others (1995) and Matarira and Mwamuka (1996), the authors apply four general circulation model scenarios of climate change (GISS, OSU, UKMO, and GFDL).

The GISS, Oregon State University (OSU), and UKMO scenarios predict an expansion in coverage for evergreen and deciduous forests. The magnitude of change differs depending on the GCM used. In contrast to these results, the GFDL scenario projects a possible decrease in forest area. The authors point out limitations of the analysis, including that the Holdridge system is static and does not take into account the carbon dioxide enrichment impacts on water-use efficiency or seasonality of precipitation. The analysis assumes that vegetation changes can occur as quickly as changes in climate. The inclusion of anthropocentric land-use factors in the analysis is not made clear.

Schulze and Kunz (1995) map the spatial distributions of areas in South Africa, Swaziland, and Lesotho climatically suited to optimum growth of two commercially cultivated tree species (*Pinus patula* and *Eucalyptus grandis*) and two subtropical fruit crops, avocado and pecan nut. This is done for present climatic conditions and for a future climate scenario for southern Africa. The authors used a series of climate change scenarios on temperature and precipitation applicable to southern Africa that were based on IPCC publications and data.

The results suggest that the impacts of future temperature increases on spatial distributions are species-dependent. The future scenario favored *E. grandis* and the two horticultural crops – both cultivated for the export market – but were unfavorable for *P. patula*. *E. grandis*, a timber species, and the two crops were likely to find new suitable areas in a westward shift. Avocado and pecan nut were expected to fare even better than timber species, and thus may out-compete commercial tree species for land use.

Eeley and others (1999) examine the potential impact of climate change on forest distribution in KwaZulu-Natal province in South Africa. The authors define bioclimatic “profiles” for eight forest subtypes, and compare the distribution of these with climatic and geographic variables. Five models are developed to predict the distribution of each forest subtype on the basis of their bioclimatic profiles. These are used to project changes in forest distribution under future climatic conditions expected with a doubling of global atmospheric carbon dioxide.

Under projected climatic conditions, forest shifts in altitude and latitude to occupy an area similar to its current *potential* distribution, but more extensive than its *actual* present distribution. The authors believe that these results show considerable sensitivity of these forest subtypes to climate change. They believe that anthropocentric factors have limited the “radiation potential” of forest and its “ability to track environmental change.”

In a study based on the United States, Sohngen and Mendelsohn (1998) emphasize the role of information in eventual impacts by examining several scenarios. In one scenario, assuming foresters have information on climate impacts

and the most efficient response (for example, in terms of which trees to plant), then the results point out that if foresters are caught unaware of the occurrence of the climate impacts in terms of diebacks, net present benefits of climate change will range from \$2.2 billion to \$16.2 billion. In contrast, when impacts are foreseen in advance, enabling adaptation, the estimated benefits range from \$4.9 billion and \$17.3 billion. In contrast, assuming foresters do not have sufficient foresight, then net present benefits range from -\$4.3 billion to \$11.7 billion (when caught unaware) and -\$0.4 billion to \$13.9 billion (when timely adaptations are made). The results suggest, as Tol and others (1998) outline, whether or not the impacts are known or not appears to not matter significantly given that timber can be salvaged after dieback and markets shift to areas that are least vulnerable to impacts.

2.3 Estimates of Impacts of Climate Change With Adaptation

The estimated net impacts from the above studies provide limited information on the extent of actual vulnerability to climate effects (Mendelsohn and others 1994). Consequently, numerous studies have emerged that affirm that adaptation has the potential to negate a significant amount of the vulnerability associated with climate change.

2.3.1 Agronomic Studies

In contrast to the early studies cited above, others such as Adams and others (1990, 1993, 1999), Kaiser and others (1993), Easterling and others (1993) have emerged that examine farm alternatives and the most efficient adaptation choices under various climatic scenarios. Studies on climate impacts on agriculture incorporating CO₂ fertilization effects and adaptation in the United States and other temperate regions

suggest that adaptation of input choice, production practices, and outputs to suit the changing climatic conditions will reduce much of the expected damages.

For example, Adams and others (1990) examining simulations using atmospheric, plant science, and agro-economic models outline that irrigated acreage in the United States will increase. Their results show that as climate change increased in severity, the contribution of U.S. production into export markets declined. Adams and others (1993) analyze the effects of climatic conditions on farmer input and output choices. With CO₂ fertilization and trade effects, the authors suggest net gains of \$9–10.8 billion. In another study based on the United States, Darwin and others (1995) estimate impacts to range from -\$4.8 billion to \$5.8 billion. Their study also shows that climate change results in 38.9–55.3 percent of U.S. land assigned to a new land class—reflecting the new length of the growing season. Net changes in land classes reflect increments in land allocated to crop production, while in many scenarios, land in pasture also increases by 0.7–7.4 percent. The implication is that climate change will increase the total amount of land in agricultural production in the United States, even with 8.6–19.1 percent of cropland abandoned for production. While it is acknowledged that some communities will be severely affected by climate change (for example, in some scenarios, area in the Midwest/Southeast of the United States are likely to shift to a land class with a shorter growing season), in other areas climate change will favor wheat production and reduce the production of other grains and livestock. The authors find that production of oil crops (except soybeans), pulses, fibers, vegetables, and temperate region fruit are likely to increase, while production of corn and roots and tubers fall.

Of the more recent studies, Southworth and others (2002a) investigate the impacts of climate change and changing climate variability due to increased atmospheric CO₂ concentration on soybean yields in the Midwestern Great Lakes Region. Based on nine representative farm locations and six future climate scenarios, their results indicated that earlier planting dates produced soybean yield increases of up to 120 percent above current levels in the central and northern areas of the study region. In the southern areas, comparatively small increases (0.1 to 20 percent) and small decreases (-0.1 to -25 percent) in yield are observed. The latter is attributed to greater warming, and the doubled climate variability scenario – a more extreme and variable climate. The authors find that CO₂ fertilization effects (555 -parts per million) are significant for soybean, increasing yields around 20 percent under future climate scenarios. Beneficial impacts are estimated in terms of mean soybean yield increases of 40 percent over current levels

In another study, Southworth and others (2002b) examine winter wheat yields under increased levels of CO₂ concentrations in five US states (Indiana, Illinois, Ohio, Michigan, and Wisconsin). These regions are selected given that they are currently considered as marginal areas in terms of wheat production, but have the potential to become a more important under a warmer climate. The authors find that under the same CO₂ fertilization effects (555 parts per million), wheat yields increased 60 to 100 percent above current yields across the central and northern areas of the study region when modeled for 2050–59 climate change scenarios. The southern states were observed to be the worst affected, as expected, even with CO₂ fertilization effects factored in the model. The authors conclude that postponing planting to early September was optimal.

Using a dynamic crop model, Rosenzweig and others (2002) simulate the effect of heavy precipitation on crop growth, and plant damage from excess soil moisture in order to estimate the impact on U.S. corn production. The authors find that damages of approximately \$3 billion per year are likely to result from climate variability. The authors highlight that the burden of these losses is likely to be borne directly by those impacted or transferred to private or governmental insurance and disaster relief programs.

Recent research in the United States also suggests that early predictions of the beneficial impacts of climate change on agriculture in temperate regions may have been overly optimistic. Lobel and Asner (2003) suggest a 17 percent decrease in both corn and soybean yields in the United States for each degree increase in growing season temperature, indicating a higher observed sensitivity of agriculture to temperature than studies had previously predicted. Similarly, Antle and others (2002), treating adaptation as an endogenous economic response to climate change in a study of dryland grain production systems of the Northern Plains region of the United States, find that climate change would induce a shift in the use of production systems towards a winter wheat-fallow system and grass and away from spring wheat and barley systems. Moreover, they find that the most adverse changes occur in the areas with the poorest resource endowments and when mitigating effects of CO₂ fertilization and adaptation are absent. The authors conclude that vulnerability is a function of how it is measured, and conditional on multifaceted interactions between climate change, CO₂ level, adaptation, and economic conditions such as relative output prices.

However, Reilly and others (2003) conclude that, in general, the agricultural production in the

United States will largely be positive. Their results, based on examining shifts in the location of crops and trends in the variability of U.S. average crop yields of maize, wheat, and potatoes from 1866 to 1998, suggest that non-climatic forces account for the north- and westward movement of crops and observed trends in yield variability. The authors argue that the observed climate change over the last 100 years had a negligible impact on the national aggregate measures of crop variation and location. Instead, changes in production technology, the introduction of hybrid crops, and economic factors are highlighted as likely explanations for the northward movement of crops. Changes in observed yield variation are explained by factors such as ability of farmers to adopt technologies that reduce yield losses (such as irrigation, grain drying, and impact of federal farm programs on production choices) and concentration in areas better suited to production. The authors also point out that government policies to limit financial losses may have been an important factor in the willingness of farmers to accept the risk of losses through a northern movement of production.

Estimates of economic welfare changes in the Reilly and others (2002) study range from \$0.8 billion to \$12.2 billion.²⁹ The gains in welfare were distributed across domestic and foreign consumers and domestic producers, with gains to consumers accruing through lower commodity prices. The results also revealed losses in income to U.S. producers (due to lower prices) between \$0.1 billion and \$5 billion. Although simulations of impacts on the agricultural economy under various climatic scenarios suggested production increments overall, substantial variation in production was also observed. Substantial production losses in soybean, wheat, rice, and tomato yields were

observed in the hot and dry Southern and Plains area of the United States. In addition, the authors suggest an increase in expenditure on pesticides (although the additional expenditure is projected to reduce the benefits of climate change by only \$100 billion). At the same time, the results revealed a decline in the number of irrigated acres and in water demand for irrigation of between 5 and 35 percent. According to Reilly and others, this “reflects the fact that on net, climate change was productivity enhancing and the definition of an increase in productivity in economic terms is that the same amount of output can be produced with fewer total inputs” (page 58). The implication of the latter is that, at least in the United States, the competition for water with urban demands would reduce.

Similar micro level studies based on other countries have also been completed. Rosenzweig and others (1993) use crop models to simulate effects of warming on four different types of grains in a cross-section of countries and ecological regions. Depending on the forecasted rate of growth in the economy, population and trade, and level of adaptation and effect of projected CO₂ fertilization, net climate change impacts were modest to negligible in temperate countries, but persistent in developing countries.

Numerous agronomic studies have also focused on African countries. Muchena (1994) explored the impact of climate change on maize production in Zimbabwe, and in simulations found that a 2° C rise in ambient temperature led to unacceptably low yields. A similar result was observed even when the positive effects of a concomitant rise in CO₂ levels were included in the analysis. More recently, Phillips and McIntyre (2000) describe results from a study of historical climate data aimed at understanding the effect of ENSO events on agriculture in

Uganda. They show that sea surface temperatures associated with these events bring about different changes in unimodal (one peak in rainfall per year) and bimodal (two peaks in rainfall per year) areas. In unimodal zones, “the El Niño events are associated with a depression of the August peak in rainfall, but a lengthening of the season, potentially providing an opportunity for growing later-maturing crops. In bimodal areas, there is little change in the first peak in August, but the second peak in November is enhanced in El Niño years and depressed in La Niña years.” The authors discuss implications for the choice of crops and the timing of planting, and point out that making use of this information may depend on the existence of an effective extension service. Cropping changes may require inputs of various types such as fertilizer.

Schulze and others (1993) apply the CERES-Maize model used in a study of Zimbabwe, while Muchena (1994) and Makadho (1996) apply it to South Africa, Lesotho, and Swaziland. The analysis simulates yields and productivity under present and future climatic conditions, taking into account the effects of increasing carbon dioxide concentrations and resultant expected increases in temperature. Changes in precipitation are not considered given the uncertainty of predicted changes.³⁰ The results show a large dependence on the intra-seasonal and inter-annual variation of rainfall. Results from the primary productivity model indicate that a decline in productivity is likely to marginal. Soil water availability is a key variable and accounts for a fair amount of geographic variability. Results from yield analysis show that for nitrogen-unlimited simulations in areas yielding at least 8 tons per hectare, elevated temperatures and carbon dioxide concentrations fail to increase yields significantly. In more

variable conditions (4–8 tons per hectare), there is an expansion into areas previously yielding below 4 tons per hectare. In areas with marginal rainfall for maize production, climate change has little impact on the already low yields. Overall, the results point to a general increment in potential maize production.

Onyeji and Fischer (1994) consider the impacts of climate change on Egypt. They use estimates of potential changes in agricultural production under conditions of global climate change to provide insights on the economy-wide implications for Egypt. The analysis takes account of wider impacts of climate change on world commodity trade, and the consequent effect on Egypt’s economy. The study examines scenarios with and without adaptation, and compares results with a reference scenario of no climate change.

Estimates of changing crop yields are centered on maize and wheat, based on International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) crop model simulation experiments at two sites in Egypt. The data are coupled with production data from the crop modelers, FAO, and the United States Department of Agriculture (USDA) to get changes in national yield. Yield changes for crops other than wheat and maize were estimated “based on their similarities to the modeled crops.” Estimates were made for three scenarios under each of the GISS, GFDL, and UKMO models, with and without the effects of carbon dioxide enrichment. The first scenario assumes no investments in adaptation; the second, only small investments; and third, the large investments. The projected changes in yield were then applied to the Basic Linked System (BLS) of National Agricultural Models, a model developed by the International Institute for

applied Systems Analysis. Impacts for the period 1990–2060 were simulated. The BLS is a world level general equilibrium model, with 35 national and regional models; individual models are linked via a world market module. Among the results, the authors find that large investments in adaptation are required to make significant gains in avoiding the adverse impacts on the economy. Changes in GDP range from –6.2 percent (with no adaptation) to +0.7 percent (with large investments in adaptation).

Mohamed and others (2002) examine the impact of inter-annual rainfall variability over the previous 30 years and future climate change scenarios on millet production in Niger. Results from the study indicate that sea surface temperature anomalies; the amount of rainfall in July, August, and September; the number of rainy days, and the wind erosion factor were significant determinants of millet productivity. The authors estimate that production of millet will be about 13 percent lower by 2025, as a consequence of reduction of the total amount of rainfall for July, August, and September, combined with an increase in temperature. Similarly, Van Duivenbooden and others (2002) assess the impact of climate variability and change on groundnut and cowpea production. Their estimates suggest that by 2025, production of groundnut will be between 11 and 25 percent lower, while cowpea yield will fall maximally 30 percent.

Rosenzweig and Parry (1994) find that a rise in temperature of 4° C could result in grain yields in India reducing by 25–40 percent. Achanta (1993), simulating irrigated yields for Pantnagar District (in Uttar Pradesh State in northern India) under doubled CO₂ and increased temperature, concludes that the impact on rice production would be positive in the absence of

nutrient and water limitations. See also Luo and Lin (1999), who review numerous studies that focus on climate impacts on agriculture based on Asian countries prior to 1999. The main conclusion to emerge from those, besides early estimates of impacts, is that countries in the tropical zones (essentially South and Southeast Asia) are among the most vulnerable.

More recently, Murdiyarto (2000) estimates the potential impact of climate change and variability on rice production in Asia, taking into account CO₂ effects, to be a decrease of 7.4 percent of rice potential per degree increase in temperature. In addition, the author highlights that constraints in land availability will lead to the increasing use of marginal lands for agriculture, thereby depressing production. The author also states that the risks to production from climate variability and uncontrolled land-use planning are likely to pose a much larger threat to sustainable food production.

Mirza and others (2003) examine the impact of climate change on river discharges in Bangladesh, including possible changes in the magnitude, extent, and depth of floods of the Ganges, Brahmaputra, and Meghna (GBM) rivers. Using a sequence of empirical models and the MIKE11-GIS hydrodynamic model, together with various climate change scenarios, indicated that future changes in the peak discharge of the Ganges and Meghna rivers are expected to be higher than those for the Brahmaputra River. As a result, faster changes in inundation are expected at low temperature increases than at higher temperature changes. Changes in land inundation will have significant implications on rice agriculture and cropping patterns in Bangladesh.

Studies from other parts of the world provide similar interesting conclusions. For example, Jin

and others (1994) find that the effect of new rice cultivars and changing planting dates for rice production in southern China increased yields in several of the sites. In another study, You (2001) notes that switching from rice to corn has the potential to have significant savings in water use. You's research estimates also suggest savings in water in agriculture of more than 7 billion cubic meters. In contrast, Chang (2003) finds, through an analysis based on yield response regression models for sixty crops, a significant potential impact of climate change on Taiwan's agricultural sector. The welfare analysis that is undertaken suggests that both warming and climate variations will have a significant but non-monotonic impact on crop yields, and while society is unlikely to suffer from warming, increments in precipitation could be adverse to farmers.

Naylor and others (2001) highlight ENSO-related fluctuations in rice production on the island of Java, where more than half of Indonesia's rice is grown. Examining data from 1971 to 1998 on area planted, harvested, and yields, reveals that El Niño and La Niña events significantly affect the timing of planting and result in fluctuations in production. The authors point out that the consequent domestic price instability has an adverse impact on food security for the lowest income groups, who are net purchasers of rice and who spend 50 percent or more of their household budgets on food.

The cost of climate variability on rice production is again underlined in a study by Lansigan and others (2000) based on the Philippines. According to the authors, climate variability in the form of typhoons, floods, and droughts have resulted in 82.4 percent of the total Philippine rice losses from 1970 to 1990. The cost of domestic losses in 1990 alone from climatic

events had amounted to US\$39.2 million (including losses of US\$11 million due to floods and typhoons and losses of US\$28.2 million from drought). The authors find that the occurrences of El Niño events are associated with periods of drought in the Philippines and delaying of sowing. In addition, data suggest that rice yield losses of 65 percent, 81 percent, and 52 percent (in 1973, 1983, and 1990, respectively) are a result of reductions in wet season cropping due to El Niño.

Planting dates were varied and new varieties of maize introduced in a study on agriculture in Greece by Kapetanaki and Rosenzweig (1997). Their results suggest that adjusting to earlier planting dates increased yields by nearly 10 percent while the introduction of new varieties also helped mitigate negative impacts. In another study, Iglesias and Minguez (1997) report on the effect of other adaptations such as using hybrid seeds, altering the sowing dates and practicing double cropping for wheat and maize, as well as using short-cycle maize varieties as a second crop in Spain. The authors examined the effect of combinations of these adaptation strategies and found that not only did yields increase despite higher temperatures but also led to more efficient use of water (nearly from 1 to 10 percent in southern regions and 40–80 percent in northern regions) and land.

More recently, in a study conducted in the Eastern European region, Stuczyński and others (2000) conclude that Polish agriculture could change from -5 percent to +5 percent of current levels with adaptations, while without adaptations, production is likely to reduce by 5–25 percent. In a study of climate impacts on agriculture in Kazakhstan, Mizina and others (1997) find a range of impacts depending on the predicted climate scenario, from 70 percent

reductions in yields (in a doubling of CO₂ scenario) to possible yield increments (see Mizina and others (1999)). Similarly, Alezandrov and Hoogenboom (2000) find that current CO₂ levels of 330 parts per million resulted in yield reductions of winter wheat (especially maize) in Bulgaria. The authors ascribe the reduction to a shorter crop season due to higher temperature and reduction in precipitation. However, their GCM simulations also indicated that the inclusion of the direct effects of CO₂ resulted in an increase in winter wheat yields.

2.3.2 Ricardian Studies

The Ricardian technique has been applied to the United States (see also Mendelsohn, Nordhaus and Shaw (1994, 1996,)), and Mendelsohn and Dinar (2002)), England and Wales (Maddison 2000), India and Brazil (Kumar and Parikh, 1998), Sanghi (1998), Sanghi, Mendelsohn and Dinar (1998), McKinsey and Evenson (1998), Sanghi and Mendelsohn (1999), Timmins 2001), Cameroon (Molua, 2002) and recently, Tunisia (Etsia and others 2002).

In their seminal paper on the use of the Ricardian technique to value climate impacts, Mendelsohn, Nordhaus and Shaw (1994) differentiate between economic costs and benefits associated with climate change depending on the time of year the impacts occurred.³¹ Their estimates from the cross-sectional approach method indicate more conservative estimates (relative to contemporary agronomic studies) of likely impacts in the United States that range from -\$5.8 billion to +\$36.6 billion (excluding CO₂ effects), contingent on the type of model and climate scenario used in the analysis.³²

Sanghi, Mendelsohn, and Dinar (1998) apply the Ricardian technique using district level data on agricultural yields and land values in Brazil.

Their results demonstrate that the net impact is negative, with substantial damages in the center-west region of the country, while the southern areas (currently the most fertile) benefit moderately. The authors estimate, given a 2° C increase in temperature and an 8 percent increase in precipitation by 2100, a reduction in expected agricultural net revenue of 12.3 percent in the case of India, and 20 percent in Brazil (without carbon fertilization effects). As noted by the authors, this is a higher estimate of net impacts relative to earlier estimates. In general the authors find that temperature changes have an adverse impact, whereas an increase in precipitation is beneficial. Significant regional variation is observed in the impacts from a 2 degree increase in temperature normals and a 7 percent increase in precipitation normals. Moreover, coastal and inland regions of India are shown to have the most harmful impacts, whereas high-value agricultural regions suffer limited damage. In response, the authors highlight the need to develop heat-tolerant high-value crops, as well as minimizing runoff in order to take advantage of increased rainfall during the winter season. Mitigation of pest infestations during the warmer winter climates is also advocated to be necessary.

Kumar and Parikh (1998) examine adaptation options while estimating the agricultural impacts. The relationship between farm level net revenue and climate variables is estimated using cross-sectional data in India. The authors demonstrate that even with adaptation by farmers of their cropping patterns and inputs in response to climate change, losses would remain significant. The loss in farm-level net revenue given a temperature rise of 2°C–3.5°C is estimated to range between 9 percent and 25 percent. Kumar and Parikh (1998) projected a 30–35 percent reduction in rice yields for India given a similar temperature increase (or losses in

the range of US\$3–4 billion). Moreover, the authors conclude that controlling for yearly weather deviations did not appear to make a significant difference, thereby suggesting that various other factors, such as government policy and prices, were having a major influence on variations in net revenues.

McKinsey and Evenson (1998) employ a model specification that is similar to the Ricardian model developed by Mendelsohn and others (1994). In particular, they utilize a net revenue specification of the model, and using two-stage least squares, examine the processes of technological and infrastructural change that characterized India's *green revolution*. In contrast to earlier studies, McKinsey and Evenson (1998) examine the primary technological variables of the green revolution—namely, that of adoption of high-yielding varieties, and expansion of multi-cropping and irrigation, within a framework that also incorporate detailed data on soils and climate, public and private investment variables, and prices. Their results highlight that climate affects technology development and diffusion. The authors also find that the converse—where technology development affects the impacts of climate on productivity. Furthermore, the authors assert that technology development and diffusion and climate has a significant impact on net revenue in agriculture in India.

Maddison (2000) employs the Ricardian technique to estimate the marginal value of various farmland characteristics in England and Wales. His findings reveal that climate, soil quality, and elevation, in addition to the structural attributes of farmland, were significant determinants of farmland prices. Maddison also finds that landowners are constrained by their inability to costlessly repackage their land (given that the size of the

plot has a considerable influence on the price per acre).

In a forthcoming paper, Mendelsohn and Dinar (2002) revisit (using recent data) the U.S. case study examined earlier by Mendelsohn and others (1994) to test whether surface water withdrawal can help explain the variation of farm values across the United States, and whether adding these variables to the standard Ricardian model changes the measured climate sensitivity of agriculture. The paper concludes that the value of irrigated cropland is not sensitive to precipitation, and increases in value with temperature. The authors find that sprinkler systems are used primarily in wet, cool sites, whereas gravity, and especially drip systems, help compensate for higher temperatures. These results indicate that irrigation can help agriculture adapt to global warming.

In a study of the southwestern region of Cameroon, Molua (2002) explores the impact of climate variability on agricultural production through an analysis at the farm household level. The results suggest that precipitation during growing, and adaptation methods through changes in soil tillage and crop rotation practices have significant effects on farm returns. Results from the Ricardian analysis confirm that farm-level adaptations including change in tillage and rotation practices and change in planting and harvesting dates positively correlate with higher farm returns. In addition, Molua finds that irrigation in the growth period, especially during dry spells, is very important for productivity.

Etsia and others (2002) examine the economic impact of climate change on agriculture in Tunisia using cross-sectional regional data over an 8-year period. Assuming CO₂ doubling, as

well as increase in temperature of 1.5 degrees (C), and 7 percent increase in rainfall, their results point out that Tunisia is likely to suffer losses in agricultural production of 7–22 percent.

The authors submit that primary crop-producing areas in the non-coastal regions are likely to experience a reduction in revenues.

3 Adaptations to Climate Change

Adaptation to climate impacts in general, and in the agricultural sector in particular, is not a new phenomenon. Natural and socioeconomic systems have continuously been adapting autonomously, or in accordance with a plan, to a changing environment throughout history (albeit with various natural and socioeconomic constraints that required surmounting³³ (Rosenzweig and Liverman 1992; Rosenberg 1992). In fact, as argued by Burton and others (1996), the complexity and interrelationship of various sectors and systems suggest that adaptations “made by one particular system may not have necessarily transpired by accident but could have occurred either in part, or as a whole, and in association with other sectors that it is inherently linked with.”

As studies cited above highlight, the right mix of adaptations have the potential to significantly reduce (or enhance) the magnitude of potential adverse (or beneficial) impacts on agricultural productivity. Research has shown that the agricultural sector is especially adaptable given that technological, resources, and management changes can be undertaken relatively quickly (Mendelsohn 2000).³⁴ However, as Smit and Pilifosova (2001) stress, in order to formulate effective adaptation policies, an understanding of the processes involved in adaptation decisions is necessary. This includes information on steps in the process, decision rationales, uncertainties, choices of adaptation types and timing, conditions that stimulate or dampen adaptation,

and consequences or performance of adaptation strategies or measures (Burton, 1997; Tol and others 1998; Basher 1999; Klein and others 1999; Smit and others 1999). It is also apparent from the empirical literature that while adaptation options are numerous, they must be site- and sector-specific and reflect numerous decision rules. Schneider and others (2000), for instance, suggest these should include the extent of belief that the climate is actually changing; awareness of the type and form of change; knowledge of technology, not only today but in years to come; and assumptions about what governmental policies will be in various regions and over time.

3.1 Addressing Climate Variability and Climate Change

With impacts on the agricultural sector manifesting from both climate variability and long-run climate change, the type of adaptation option that is implemented is clearly crucial. While climate variability impacts will be essentially local in scale, climate change will affect long-term trends. The literature reflects this distinction in terms of studies that focus on the impact of adaptations to changing average climate conditions as opposed to others that concentrate on adjusting to inter-annual variations and extremes. It is also this distinction that underscores the necessity (as argued below) of different policies to address climate variability and climate change impacts.

The importance of adapting to climate variability in addition to changes in mean climate has been highlighted in numerous studies. (Besides those highlighted in the previous section, see also Schneider and others 2000; Polsky and Easterling 2001; Brumbelow and Georgakakos 2001.) Smit and Pilifosova (2001) argue that climate change-related stimuli are not only limited to changes in average annual conditions, but also include variability and associated extremes. The impact of variable climate and extreme events has been noted to be significant in poorer developing countries (Huq 2002; Hay 2002).³⁵ Similarly, studies based on industrial countries, for example, Reilly and others (2001) contend that the consequences of climate change in the United States pivot on changes in climate variability and extreme events. In another study based on crop yields in the United States, Brumbelow and Georgakakos (2001) find higher irrigation demands in southern regions and decreased irrigation demands in the northern and western areas for both higher means and extremes in climate. The importance of considering climate variability in addition to changes in mean climate when estimating adaptation has also been highlighted in numerous studies in developing countries (Robock and others 1993; Mearns and others 1997; Alderwish and Al-Eryani 1999; Alexandrov 1999; Qunying and Lin 1999; and Murdiyarto 2000). IPCC states “the key features of climate change for vulnerability and adaptation are those related to variability and extremes, not simply changed average conditions” (IPCC 2001; Chapter 18). The report argues that communities are generally more adaptable to gradual changes in average climate conditions given the time dimension, but clearly less so to changes in the frequency or magnitude of variable climate conditions, especially extremes.

Recent research, however, by Mendelsohn and others (2002),³⁶ based on cross-sectional county-level data of agricultural productivity in the United States, Brazil, and India, reveals that while climate variance is important, it explains only a very limited portion of the observed variation in net revenue in cross-sectional analysis. Results have repeatedly shown strong evidence that climate normals relative to climate variance, specifically for those months that are crucial for agricultural productivity (including post planting, growth, and harvesting periods) are more significant and explain a large proportion of the variance in net and gross revenue and fraction of land under agriculture. The economic studies undertaken to date consistently reveal this result—a finding in contrast to studies using alternate methods of impact estimation.

The need to address climate variability and long-term climate change does, therefore, raise the question of when to adapt, particularly given that some impacts are more difficult to adapt to than others. For example, in the case of infrastructure, there is limited need to undertake costly investments to address climate variability concerns. Such types of investments in (especially capital-intensive) adaptations become less attractive when sudden or dramatic changes in climate can render the investments inappropriate and costly. Some of the investment literature has outlined that there is value in not investing in new technologies at present given that it preserves the option of investing at a better time in the future (Schimmelpfening 1995). Studies on climate impacts on agriculture in the United States, for instance, have lent support by establishing that costly adaptations and mitigation options are not warranted as yet. Instead, limited modifications to farm production methods are viewed to be more effective (such as water conservation in

agriculture and restructuring crop insurance and disaster assistance programs to counter potential risks). In contrast, in terms of recent results, such as Quiggen and Horowitz's³⁷ finding that the main market-based effects of climate impacts will be on very long-lived infrastructure whose value is associated with its location (for example, dams, roads, grain storage facilities, food processing facilities, and so forth), then it is necessary to make investments to ensure that vulnerability to anticipated climate change is reduced. That is, there is greater benefit from adaptation options in socioeconomic sectors and systems where the turnover of capital investment and operating costs is shorter, rather than where long-term investment is required (Yohe and others 1996; Sohngen and Mendelsohn, 1998; and Smit and Pilifosova 2001). In the case of the latter, given that the pace of climate change is slow, there is time to make the necessary adjustments in a dynamic way over time (Mendelsohn and Nordhaus 1999).

A key message that is thus emphasized in this paper is that climate variability and climate change need to be treated separately in that each will require a different set of policies. Some have argued that given the linkages between these two drivers of climate impacts, the distinction between adapting to short-run concerns as opposed to long-term issues is sometimes blurred.³⁸ However, the fact remains that some types of adaptations are simply designed to address short-term impacts from variable climate. These typically have little or no benefit for reducing vulnerability in the long term. Others are more appropriate for reducing susceptibility to climate change impacts in the long run, but clearly have limited effect or functionality in the short term. This does not, however, preclude the fact that there are some

adaptations that will be successful regardless of the temporal dimension of climate impacts. Nevertheless it is important that policy is appropriately targeted to address the exact nature of climate concerns.

3.2 Ex-Post and Ex-Ante Adaptations

In theory, the literature discusses two types of likely responses to address climate impacts, namely, those that are reactive or, alternatively, anticipatory adaptations. Measures made in anticipation of a coming change are ex-ante. They require that the decision maker be able to predict what is coming. Reactive (or autonomous) adaptations consist of coping strategies that agents and institutions are likely to make in response to climate impacts after the fact (*ex-post*). These strategies merely require the decision maker to be aware of changes that have occurred. The question that arises is thus when should adaptations be pursued? Both ex-ante and ex-post strategies have strengths and weaknesses.

The effectiveness of reactive measures is dependent on resources at hand to cope with an event. The capacity to adapt autonomously depends on, among other things, institutional support, manpower, financial and technological resources (see Ausubel, 1991; Yohe and others 1996; Mendelsohn, 1999; Mendelsohn and Neumann 1999). However, Barnett (2001) argues that focusing policy on such autonomous adaptations is likely to be futile because there is no guarantee that the necessary processes that trigger adaptation, which are essentially governed by the "respective influences of biology and culture on human behavior" (page 980) will occur. On the other hand, Mendelsohn (1999) emphasizes that sectors that can adjust quickly to climate change can adapt to climate as it unfolds. In this respect, sectors such as

agriculture do not generally have long-lasting capital and thus the early depreciation of capital to adjust to climate change would not be necessary.

An alternative response strategy encompasses precautionary or planned (*ex-ante*) adaptations to climate change. Mendelsohn (1999) asserts that this type of adaptation should be more appropriately aimed at capital-intensive sectors (coastal sector, forestry). These sectors either take time to respond or are currently under stress due to other pressures such that any further exposure to climate change will help push them over critical threshold boundaries. As Burton (1996) and Smit and Pilifosova (2001) outline, a planned approach to address climate impacts is sensible given that it can increase the efficiency and effectiveness of reactive measures.³⁹ In general, planned adaptations are called for through dynamic public policy⁴⁰ (Bryant and others 2000) and formulated on the basis of robustness, flexibility, and net benefits (Lewandrowski and Brazee 1993; World Bank 1998).

Both *ex-ante* and *ex-post* adaptation measures can be implemented at numerous levels, including at the global, regional, or national level. They can also be incorporated in response strategies adopted by individuals or local communities. In addition, both direct and indirect response strategies aimed to negate concerns about predicted impacts of climate change are included in the possible mix of *ex-ante* strategies (Benioff and others 1996; Fankhauser 1996; Smith 1997; Pielke 1998; UNEP 1998). Such adaptations have been recognized to have the potential to reduce long-term vulnerability as well as realize opportunities associated with climate change, regardless of autonomous adaptation (Smith 1997; Burton and others 1998; Fankhauser and others 1999).

3.3 Private versus Public Adaptations

At the outset, it is important to differentiate between private and public adaptations. Private adaptations are those undertaken only for the exclusive benefit of the individual decision maker. The adoption of various measures will be driven purely by self-interest and underlying welfare-maximizing objectives (including profit maximization, output maximization, and so forth). Mendelsohn (1999), for example, argues that adoption is likely to be a function of the farmer's own discount rate for undertaking adaptations. The higher the discount rate, the less likely that *ex-ante* adaptations will be undertaken. In such instances, it is probable that only short-term, ad hoc, *ex-post* adaptations are to be adopted.

Consequently, there is little evidence to suggest that only private adaptations will be adequate to counter climate impacts on agriculture. That is, reliance on the adjustments made by private agents to protect resources that have essentially the characteristics of a public good⁴¹ (such as, for instance, managing water resources for irrigation, maintaining soil quality, forecasting climate, research on adaptation initiatives) will typically lead to the classic problem of under-provision⁴² by the market (Leary 1999). Conflicting objectives among multiple stakeholders are likely to complicate matters.⁴³

In light of high information requirements or equity requirements,⁴⁴ or other externalities associated with adaptation, some types of government-sponsored adaptive measures therefore become necessary. While self-interest will encourage the adoption of efficient private adaptations, public adaptation will be efficient only with government intervention. The latter will in turn be determined by factors such as the institutional environment, community structure,

and existing public policies.⁴⁵ Moreover, policy designs will need to accommodate a series of subtle changes over time as there is unlikely to be one solution that will be adequate for all time. For example, Mendelsohn (1999) stresses the need for public (or joint) adaptation to be dynamic, particularly in capital-intensive sectors or where there are long-term assets.

Potential strategies include adaptation options introduced at the national or local level as well as those adopted by agents in the field (for example, farmers) as part of ongoing adjustments in agricultural practices (Dolan 2001). Clearly, numerous conditions will dictate the extent and means of adaptation. It is evident that given the diversity of interests, risks, and resources faced by various stakeholders in agriculture, there is likely to be an extensive typology of adaptive responses that are appropriate for each agricultural zone. At the micro level, adaptability to climate change will also be contingent on the ability of farmers or other primary decision makers to negate impacts (or capitalize on opportunities) associated with a changed climatic environment. This in turn is likely to be dictated by numerous key factors, including the type of local farming system, tenure system, access to financial resources, level

of skills, extent of support (that is, extension), and market conditions. The success of many of the micro level adaptation options will also depend on household risks being independent (Skees and others 2002). When there are covariate risks (as in the case of extreme climatic events), options to reduce vulnerability are limited to insurance.

At the macro level, effective adaptation to climate change in agriculture demands a combination of adjustments in the ecological, social, and economic systems. In particular, the institutional environment, as well as the prevalent economic, social, and political forces will play a significant role (Chiotti and Johnson (1995); IPCC (1996); Chiotti and others (1997); Smit and others 1999). Kelly and Adger (1999) maintain numerous local factors, including economic and social considerations, human capital limitations, and institutional capacity, will have a significant role in facilitating or constraining the development and implementation of adaptation measures. Variations in these key local factors across countries mean that it is unlikely that the suite of response strategies will be the same or applied uniformly.

4 Typology of Adaptations in Agriculture

The following sections focus on the typology of adaptation options in agriculture.⁴⁶ The discussion is categorized within the following framework. First, several *micro level* adaptation options are examined. These include farm production adjustments such as diversification and intensification of crop and livestock production; changing land use and irrigation; and altering the timing of operations. Second, there are numerous *market responses* that have emerged as potentially effective adaptation measures to climate change. They include development of crop and flood insurance schemes, innovative investment opportunities in crop shares and futures, credit schemes, and income diversification opportunities. A third subset of adaptation options encompasses *institutional changes*. Many that fall within this category require government responses. The latter comprise pricing policy adjustments such as the removal of perverse subsidies, development of income stabilization options, agricultural policy including agricultural support and insurance programs; improvement in agricultural markets, and broader goals, such as the promotion of inter-regional trade in agriculture. A fourth (and final) set of adaptation options considered in this paper are *technological developments*. These consist of the development and promotion of new crop varieties and hybrids and advances in water management techniques (for example, irrigation, conservation tillage).

The remainder of this paper examines some of the primary adaptation options to emerge from the literature. The discussion will attempt to highlight some of the underlying constraints and conditions that need to be addressed for their successful adoption. Following Dolan (2001),⁴⁷ the discussion of adaptation options is based on measures that are appropriate for the short and long term. Measures that are likely to produce benefits irrespective of the time dimension are discussed in section 4.3. In this following section, key short-term adaptations that emerge in the literature are highlighted.

4.1 Short-Term Adaptations

From the existing literature, it is clear that some types of adaptations are more appropriate to address short-term concerns. Most often, though not exclusively, these measures primarily address weather effects (that is, climate variability).

4.1.1 Farm Responses

(a) Crop and Livestock Diversification and Changes in Timing of Farm Operations

Among the most important and direct current adaptations to climate variability are a variety of farm level responses. Diversification of crop and livestock varieties, including the replacement of plant types, cultivars, hybrids, and animal breeds with new varieties intended for higher drought or heat tolerance, have been advocated as having the potential to increase productivity in the face

of temperature and moisture stresses (Benioff and others 1996; Smit and others 1996; Chiotti and others 1997; Downing and others 1997; Baker and Viglizzo 1998). Diversity in seed genetic structure and composition has been recognized as an effective defense against numerous factors, including disease and pest outbreak and, importantly, climate hazards. In a study of adaptations in Nigeria by Mortimore and others (2000), it was found that farmers used 3–12 types of pearl millet, 6–22 varieties of sorghum and 14–42 varieties of other cultivars. Seed inventories were from multiple sources including inheritances, own selections from planted material, and imported types with recognized advantages over indigenous ones for the new climate. According to the authors, direct transfers of seeds from extension agents were rare although some were traced to originate to those developed in agricultural stations within Nigeria or neighboring Niger. The primary mode of transfer appears to have been outcrossing—where farmers select from types grown in neighboring farms or even in the wild and store the seeds for planting in consequent years. Evidence from the selection of millet seeds, for example, indicates that farmers manage their own genetic pool by selecting and storing the best seeds from each year's crop.

Other options include changes in the timing and intensity of production. Delcourt and Van kooten (1995) note several options for addressing impacts on yields and soils from climate impacts. Changing land-use practices such as the location of crop and livestock production, rotating or shifting production between crops and livestock, and shifting production away from marginal areas can help reduce soil erosion and improve moisture and nutrient retention. The latter includes not only changes in land allocation for different uses, but also the abandonment of land altogether and the cultivation of new land

(Kaiser and others 1993; Lewandrowski and Brazee 1993; Reilly 1995; El-Shaer and others 1996; Erda 1996; Easterling 1996; Iglesias and others 1996; Mizina and others 1999; Parry 2000).

Brklacich and others (2000) suggest that altering the intensity of fertilizer and pesticide application as well as capital and labor inputs can help reduce risks from climate change in farm production.⁴⁸ Adjusting the cropping sequence, including changing the timing of sowing, planting, spraying, and harvesting, to take advantage of the changing duration of growing seasons and associated heat and moisture levels is another option. Altering the time at which fields are sowed or planted can also help farmers regulate the length of the growing season to better suit the changed environment. Farmer adaptation can also involve changing the timing of irrigation (de Loe and others 1999) or use of other inputs such as fertilizers (Chiotti and Johnston 1995). In a study on Tanzania, O'Brien and others (2000) report that farmers undertake several of such adaptation measures in response to information from climate forecasts.

In addition, Baker and others (1998) highlight several adaptation measures for livestock and rangeland management that have emerged to offset climate impacts. Possibilities include shifts in biological diversity, species composition and/or distribution. The options also include change in grazing management (timing, duration, and location) or in mix of grazers or browsers; varying supplemental feeding; changing the location of watering points; altering the breeding management program; changes in rangeland management practices; modifying operation production strategies as well as changing market strategies. In temperate climatic areas, planned adaptation measures in livestock management

that are advocated include the use of vegetative barriers or snow fences to increase soil moisture, or windbreaks to protect soil from erosion. In warmer climates, adverse climatic conditions such as heat stress can be moderated by the adoption of appropriate technology such as the use of sprinklers in livestock buildings or feedlots (Chiotti and others 1997). Other measures based on recommendations in IPCC (1996) include adjusting livestock stocking rates (see also Reilly and others 1996); implementing feed conservation techniques (see also Smit and others 1996) and fodder banks to moderate the consequences for animal production during periods of poor crops; changing the mix of grazing or browsing animals; altering animal distribution by the use of mineral blocks, watering points, and fences; implementing weed management programs; restoring degraded areas; and increasing native rangeland vegetation or plant-adapted species.

However, numerous constraints can make even these farm level adaptations difficult. For one, short term adaptations are not costless. The most significant problem to overcome is that diversification is costly in terms of the income opportunities that farmers forego (that is, switching crop varieties can be expensive, making crop diversification typically less profitable than specialization—Skees and others 1999). Moreover, traditions can often be difficult to overcome and will dictate local practices. For example, if a local region has a long and rich tradition of planting a particular crop variety, the transition to newer and more suitable varieties can be difficult.

(b) Improved Nutrient and Pest Control Management

Increased CO₂ levels and higher temperatures are likely to induce a need for increased plant

protection in light of likely pest and disease outbreaks (Chen and McCarl 2001). Downing and others (1997); and Parry and others (2000) highlight that changes in the application of pesticides and integrated pest and disease control may be necessary to negate such impacts. Alternative production techniques and crops, as well as locations, that are resistant to infestations and other risks can also be relied upon as effective response strategies. For example, it has been emphasized that this is one reason why pearl millet is a primary crop in the Sahel, a region where poor soils, variation in rainfall, and high evapotranspiration make other grains too risky to produce (Fafchamps 1999). FAO (2000) reports that farmers diversify output through mixed farming systems of crops and livestock to spread the risk of infrequent, and uncertain, pest and disease infestations.⁴⁹

A range of management practices have also emerged that can assist farmers adapt to loss of soil moisture and organic carbon contents and increased soil erosion as a result of changing climate conditions. Erda (1996), and Parry and others (2000) discuss improved nutrient management techniques to maintain soil fertility and prevent erosion. Smit (1993) and Easterling (1996) note that changing land topography through land contouring and terracing and construction of diversions and reservoirs and water storage and recharge areas can help reduce vulnerability by reducing runoff and erosion and promoting nutrient restocking in soils (see also de Loë and others 1999). Abidtrup and Gylling (2001) report on the establishment of agro-forestry to mitigate increased risk of soil erosion in some European countries.

In light of the increased frequency of droughts, farmers can further adapt by changing the selection of crops. Inevitably, this will lead to

shifts in the distribution of agricultural land use, which in itself will have impacts on soils. Alternatively, the introduction of other management techniques that conserve soil moisture, such as reduced or no tillage, in order to maintain soil organic carbon contents can result in improved soil structure and fertility. Mahboubi and others (1993) reveal that soil organic carbon contents increased by 85 percent after eight years on clay loam soils following the introduction of reduced tillage. Kern and Johnson (1991) report that increasing the area of non-tillage cropland in the United States from 27 percent to a potential 76 percent is estimated to result in gains of soil organic carbon of 0.43 Gt after 30 years.⁵⁰ Fallow and tillage practices (such as the planting of hedges to reduce evaporation together with the introduction of drought-resistant crop varieties) as well as alternative drainage methods have also been found to assist in reducing water runoff and improving water uptake.⁵¹ Carter (1993) provides a synthesis of existing research and practices of present conservation tillage practices in a wide variety of temperate agro-ecosystems and a discussion of methods to overcome soil, climatic, and biological constraints. For example, conservation tillage practices, which can include maintaining crop residues from previous harvests on the soil surfaces are seen as likely to help maintain soil quality and provide protection against wind erosion.

Alternative farm strategies include increasing production per unit of evapotranspiration with the use of new and improved varieties, reducing water use in land preparation as well as loss (through seepage and percolation) during the crop growth period, and adopting efficient water use methods. The diffusion of appropriate technology to enhance greater water use

efficiency (drip-irrigation and so on) is therefore imperative.

While the above discussion highlights that many microlevel adaptation options exist, it is important to take into account the various factors that influence the adoption of these options. Country- and site-specific studies have considerable importance in this respect and must be encouraged. For example, Adesina and Chianu (2002) examine the determinants of farmers' adoption and adaptation of agro-forestry in Nigeria. The authors find that gender of the farmer, extent of contact with extension agents, years of experience with agro-forestry and tenancy status in the village are important factors. In addition, the extent of land pressure, erosion intensity, fuel wood pressure, the importance of livestock as an economic activity in the village, and the distance of the village locations from urban centers were also significant variables. Human capital variables were significant in explaining farmers' decisions to adapt and modify the technology.

In addition, enabling farmers the options to adapt also requires that other factors first be in place. In particular, investment in institutional support to promote the dissemination of knowledge through extension, is important. This should be supported by appropriate land reforms that establish property rights as well as measures that enhance farmers' financial ability to undertake the necessary adaptation (for example, by improving access to credit and banking facilities in rural areas).

4.1.2 Temporary Migration

That migration is an important form of risk diversification has been made clear in the literature (see for example, Ellis 1998; Alderman and Paxson 1992). Migration is treated as either

a transient phenomenon, or as a permanent feature that is necessary for achieving long-term well-being⁵² (Saith 1992; Locke 2000).

Temporary (or “circular”) migration in agriculture includes seasonal migration where workers undertake off-farm or non-farm activities for part of the year, and return during harvest time. The movement of labor from one agricultural area to another area, or across sectors, as well as migration between and within urban and rural areas due to environmental, economic, or demographic reasons,⁵³ is central to a household’s ability to ensure security in livelihood (De Haan 1999).⁵⁴ It has the potential to enhance social resilience of households through temporary diversification of sources of livelihood.

However, it is not clear from the literature to what extent climate change per se can be attributed as the primary factor in the decisionmaking process of households engaged in agriculture on whether or not to migrate. Some evidence does exist, such as for instance, Tyson and others (2002) who find a significant relationship between climate patterns in equatorial Africa and subtropical southern Africa⁵⁵ and the southward migration and settlement patterns of the Sotho-Tswana speaking people from equatorial East Africa. The authors indicate that changes in rainfall in the two regions influenced migratory patterns. In addition, it has been the case that movement is often provoked by difficult environmental conditions (including harsh, sudden climatic events or series of climatic events) that intensify living conditions. There are numerous case studies, for instance, of pastoral migration, often seen as an intentional adaptation for managing a seasonally varying resource base. Desanker (2002) draws attention to nomadic societies that migrate in response to annual and seasonal

rainfall variations in the semiarid areas such as the Sahel and the Kalahari. It is suggested that the nomadic pastoral systems are intrinsically able to adapt to fluctuating and extreme climates—provided they have sufficient scope for movement and that other necessary elements in the system remain in place. Similarly, based on a study of households in dryland areas in northern Ethiopia, Meze-Hausken (2000) finds that a range of coping strategies can delay impacts after the onset of drought. While socioeconomic standing and resource endowments (such as animal holdings, non-farm income remittances, and so forth) play an important part, migration is often the only recourse at the point that critical thresholds governing habitability within an area are infringed.

However, in cases that do not involve seasonal pastoralists, some authors⁵⁶ maintain that climate is rarely the primary force behind the migration decision. Political, economic, gender, ethnic, social, and institutional considerations also play an important role.⁵⁷ For example, in a study of Pakistan using household data, Gorla (1999) examines the role of environmental factors as determinants of migration among rural people. The author concludes that higher expected income from non-farm sources and property assets influence the likelihood of migration, a result consistent with the process of migration from rural to urban areas and rural environmental degradation. In addition, it is argued that migration occurs among the poorest, with the primary motive being an expected gain from natural resources and other sources of income. Moreover, as expected, a higher density and quality of *natural* assets in the place of origin decrease the likelihood of migration. Locke (2000) provides evidence from Vietnam and India that individual cultivator responses to

climate risk have included, among other adaptations, employment in new areas that necessitates temporary migration. However, it is rarely one factor (such as climate) that results in migration. Institutional and government policy (including incentives) have a major influence as well.

The impact of temporary migration on agricultural productivity has received some attention, and the results have been mixed. Some studies conclude that remittances during periods of migration contribute to improve farm productivity by enabling the purchase of improved inputs and technology. Remittances also help to overcome capital and credit constraints that otherwise persist (Conway and Cohen 1998). Adger and others (2002) indicate that remittance flows are invested in human or physical capital to enhance household production. However, the literature also indicates that temporary migration may have harmful impacts on agricultural productivity. For example, Jokisch (2002) reports on numerous studies that indicate that household labor that remains behind is often overstretched during migratory periods, resulting in land degradation. Zimmerer (1993) discusses labor shortages caused by seasonal migration of men that contributes to the abandonment of conservation measures in farms. Choudhury and Sundriyal (2003) recount, based on research in northeast India, that the absence of labor, due to migration, for crucial activities (such as weeding) reduces the capacity of families to cultivate and manage plots, which ultimately lowers productivity and reduces yields. Of course, some have countered by suggesting that where labor is abundant, migration need not necessarily cause shortages that would compromise productivity (Georges 1990). However, other evidence points out that agricultural productivity loss may be tolerated.

For example, in a study of households engaged in agriculture in Nigeria, Morse and others (2002) find that the constant immigration and emigration of males and females is necessary in the wider interest of ensuring family sustainability, even if agricultural sustainability is compromised. Other studies have revealed that remittance income can be used in unproductive ways, particularly through changes in consumption patterns that have no direct beneficial impact on productivity (Connell and Conway 2000).

4.1.3 Insurance

That households engaged in agriculture inherently need insurance mechanisms to cope with income risks has long been recognized. Moreddu (2000) outlines four types of risks faced by the agricultural sector, including *production risks* due to weather variation, crop disease and various other causalities; *ecological risks* from climate change, pollution, and natural resource management; *market risks*, which depend on input and output price variability; and *regulatory or institutional risks* due to state intervention in agriculture. Both formal and informal, as well as private and public, insurance programs have been discussed as effective measures to help reduce income losses as a result of climate-related impacts (IPCC 2001). Although strictly not an adaptation measure—in the sense that it does not involve a change of agricultural practice such as those outlined above, insurance is an important welfare-improving adaptation (that is, a means of reducing household vulnerability). Smit and Skinner (2002) maintain that institutional responses that provide opportunities for the costs of climate-related events to be distributed through such risk-spreading mechanisms as crop, flood, and other insurance schemes will have a significant

influence on shaping farm-level risk management strategies.

Both formal and informal, as well as private and public, insurance programs have been discussed as potential mechanisms by which to reduce income losses from climate related impacts (IPCC 2001). Examples from industrial countries include flood insurance programs such as the private insurance systems in the United Kingdom and Germany, or public initiatives where government bears some or all risks, as in France and Spain. In North America, federal- and provincial- (state-) level crop insurance programs⁵⁸ buffer incomes from climate-related risks (80 percent of which is allocated for flood relief), and taxpayer-subsidized flood insurance (Smit 1993; Chiotti and others 1997; de Loë and others 1999). Other types of financial instruments in spreading exposure to climate-related risks include investment in crop shares, and the use of futures or bank loans (see also Mahul and Vermersch 2000).

In contrast, despite the existence of formal government sponsored insurance programs, successful examples are rare in developing countries. In India, for example, a Comprehensive Crop Insurance Scheme (CCIS) has been in operation in the country since 1985. The scheme was introduced to provide an opportunity for risk management and relief to farmers whose crops suffer damaged from natural disasters. While the scheme has helped a number of farmers switch to the use of yield-increasing techniques, the program has generally suffered from low coverage rates and has become increasingly unviable due to claims far exceeding the premiums collected (Government of India (GOI), 1998). An Experimental Crop Insurance Scheme was introduced by the Government of India for one season during 1997/98 covering non-loanee small and

marginal farmers growing specified crops in selected districts. The scheme was implemented only in 14 districts of 5 states. A separate Livestock Insurance Policy⁵⁹ has been administrated by the General Insurance Corporation of India (GIC) since the early 1990s. In contrast, in Africa, millions of small-scale farmers are entirely at the mercy of weather patterns, with negligible availability and access to insurance programs. Crop insurance in South Africa, for instance, is primarily limited to hail insurance and associated property and casualty risk on major agricultural crops. According to Crane (2001) "universal availability of crop insurance in southern Africa is non-existent and crop coverage is limited to selected crops and regions where risk can only be effectively managed through the investment of private capital."

In developing countries with weaker financial institutions, particularly in rural areas, there has generally been more reliance on informal risk-coping strategies (Alderman and Paxson 1992). Bardhan and Udry (1999) outline numerous strategies including risk pooling (citing for example, Platteau and Abraham's (1987) discussion of a reciprocal credit system among fishermen in South India and Udry's (1990) investigation of households in northern Nigeria who simultaneously participate on both sides of the credit market). However, evidence also shows that such strategies are bound by numerous complications that compromise their effectiveness. For example, Bardhan and Udry (1999) assert that risk-pooling strategies function well provided that information asymmetries are minimized (for example, due to the limited size of the communities) and the existence of enforcement mechanisms.

Numerous studies highlight the range of problems that exist with providing insurance in

the agricultural sector. Siegel and others (1995) argue that while there are numerous risk-coping strategies for rural households, their real choice is limited. Households with extremely low incomes are inherently highly risk-averse, which in turn limits their financial ability and willingness to adopt new technologies that can maintain and enhance crop productivity. Also, while many risk-coping strategies will be successful where risk is shared within a small community, these strategies are not likely to be adequate for managing covariate risks. That is, as Skees and others (2002) state, traditional coping mechanisms are likely to fail where the entire community faces the same risks (that is, covariate risks) that create losses for all. In addition, Skees and others (1999) outline that many of the risks covered by multiple risk insurance are inherently uninsurable. Vaughan (1989), cited by Skees and others, declares that for risk to be insurable, various conditions that need to be satisfied in fact rarely are. These include “(a) quantification of the likelihood of an event; (b) damages must be attributable to that event and quantification of value; (c) not excessively high probability of occurrence; and (d) the occurrence of an event or the damages it causes should not be affected by the insured’s behavior (no moral hazard).” Skees and others (2000) underscore that factors such as prohibitively high monitoring costs,⁶⁰ and high opportunity costs of using public funds for agriculture (when a higher return can be obtained elsewhere) limit the viability of traditional crop insurance programs for medium and small farmers in developing countries.

In a study of India, Joshi (2001) emphasizes that the major problem that plagues the system of credit and insurance in India is the inadequacy of crop insurance premiums. The main problem, according to analysts, is that with risk shared

between the national and state governments and the General Insurance Corporation, the actuarial probability of the risk covered is not correctly estimated. Consequently, the system has encouraged false claims, resulting in its eventual failure. In another study based on experiences in Antigua and Barbuda, O’Brien (2000) highlights that although the insurance industry is the cornerstone of the islands’ development process, access to crop insurance is restricted. Constraints include weak capital structures, oversaturation of insurance providers, and a weak supervisory capability. The result is that the availability and affordability of catastrophe insurance is beyond vulnerable communities, including farmers, and fishermen and low-income households.

Another major difficulty in providing insurance in the agricultural sector is due to perverse incentives that arise from the availability of various schemes.⁶¹ That is, the speed at which farmers adapt can be adversely affected by the existence and extent of coverage of insurance programs. It has been noted, for example, that despite the availability of insurance, farmers are at times reluctant to purchase coverage because they can expect to receive alternative payments (such as emergency drought relief programs) in catastrophic years from government without incurring any costs (Skees and others 1999). IPCC (2001) highlights also that insurance programs that are inadequately targeted can foster complacency and, in the worst cases, maladaptation.

Much remains to be done in the case of using insurance to reduce vulnerability. Economic losses from extreme climatic events in the United States during the 1988–1999 period were substantial, with total damages/costs exceeding \$170 billion (Ross and Lott 2000). While in industrial countries much of this cost is due to

property damage, in developing countries the costs are often unaccounted but likely to also be substantial especially given the higher incidence of loss of human life. According to estimates, the ratio of global property/casualty insurance premiums to weather-related losses—an important indicator of adaptive capacity, decreased more than three-fold between 1985 and 1999. There is likely to be a need for both public and private insurance schemes. In the case of climate variability impacts, with relatively lower probability of occurrence and limited risks, private schemes should be sufficient. However, the increased incidence of climate-related economic losses is likely to reduce the profitability of insurance companies, translating to increases in consumer prices and premiums, withdrawal of coverage, and increase in publicly funded compensation and relief programs. This could not only impose severe budgetary burdens on government, but there is also the risk that government provision would result in similar perverse effects as an indirect subsidy on loss coverage.

In a recent article, however, Skees and others (2002) announce that developments in financial instruments could make climate-related insurance in developing countries more favorable than previous programs by making insurance more affordable and accessible.⁶² The introduction of tradable financial assets such as catastrophic bonds, insurance contracts, and other weather markets in Mexico are examples of recent innovations. The authors highlight also the recent effort commenced by the International Finance Corporation (IFC) in helping several countries, including Ethiopia, Morocco, Nicaragua, and Tunisia gain access to weather markets as an example of the growing interest in the private provision of weather insurance. At the same time, while insurance and disaster

assistance is important to address short-term vulnerability, it is also clear that incentives need to be introduced to ensure that any cycle of dependency on coverage of losses is gradually eliminated. Innovative schemes must be introduced to ensure that adaptations to minimize vulnerability are encouraged to ensure long-run sustainability.

4.2 Long-Term Adaptations

While farmers must withstand and minimize the adverse impacts of short term climate variability, a different set of measures will be necessary to reduce vulnerability to anticipated future impacts of climate change. A range of adaptation options at both the farm and policy level are seen as highly relevant in this regard (see discussion below).

Prior to examining these options, an important issue that has tended to lack clarity in the literature concerns the timing of long term adaptations. Some attribute the lack of initiatives in numerous countries to developing a long term approach to climate change to a variety of reasons, ranging from a general apathy (complacency) to difficulty of dealing with a insufficient information (e.g. Bryant and others 2001; Smit and others 2000). It is not that scientists and policy makers have ignored the importance of climate change but rather uncertainty of whether and where impacts will materialize and/or their magnitude (Barnett 2001). The latter in particular, it is argued, makes the design of an effective response strategy difficult. In addition, short term and non-climatic events such as agriculture price support schemes continue to drive local agriculture operations and policy (Lorenzoni and others 2001). The result is a tendency for various institutions responsible for planning adaptation strategies— often local Ministries and other

government agencies, to “muddle-through” (*ad hoc*) responses, a potentially more costly approach than designing and implementing a longer term strategy (World Bank 2000). For example, in the case of semi-arid Africa, which is prone to drought, the creation of food reserves and other costly relief efforts are continuously undertaken (often involuntarily) with limited, if any, long-term development plans to improve productivity and management in climate sensitive areas (FAO 2000).

However, given that warming is largely a concern of the future, long term adaptation must also be in the future⁶³. The absence of long term adaptation plans has more to do with the fact that warming has been minimal to date than to a flaw of government. Adapting prematurely to climate change is not in the interests of countries and there are few examples of climate change that warrant a response today. In contrast, the same is not true with variation. It could be that short term variation will remain the same over time and it is in the interest of countries to respond to variation today. Addressing climate change—a long term phenomena, should entail a comprehensive long term response strategy at the national or local level (World Bank 2000) but will require a dynamic approach. The remainder of this section outlines numerous options that have emerged in the literature that can meet long term concerns about climate change.

4.2.1 *Changing Crop Type and Location*

As future climatic conditions unfold and farmers learn how to implement adaptive strategies (which in turn will depend on the form of tenure, incomes, etc.), farmers could make long term adjustments such as changing crop varieties that are grown as well as where they are grown (i.e. location). Potential options include switching to more robust varieties that are better suited to the

new environment. For instance, Matarira (1996) highlights that in Zimbabwe farmers have switched successfully to the use of more drought tolerant crop in areas where the frequent recurrence of droughts has made agriculture production difficult using the traditional crop varieties. In the extreme case, where agriculture is no longer viable, farmers have converted land use from crop production to game ranching. Agricultural analyses of future climates indicate also that crops will move poleward with warming (Mendelsohn and Neumann 1999; Mendelsohn 2001). The extent of this migration depends upon the severity of the warming.

Such types of long term adaptation however demand that a number of underlying prerequisites are in place. Clearly, the scope for shifting production to new lands, particularly in developing countries, is likely to be limited given population pressures and the availability of cultivable land. It is also likely to be constrained by other considerations such as farmers’ willingness and ability to move. Moreover, land-use regulations or regulations on agricultural production can hinder adaptation of this type. Under such circumstances, crop rotations that may not be optimal in a changed environment can be persisted with, resulting in severe losses in the long term (Lewandrowski and Brazee (1993). Appropriate land reform that establish or strengthen property rights as well as measures that enhance their financial ability to undertake the necessary adaptation (for example, by improving access to credit and banking facilities in rural areas) is necessary. In addition, investment in, and diffusion of access to irrigation, together with institutional support to promote the dissemination of knowledge through extension is important.

Shifting crop location, for example, depends on a number of factors such as the extent of resources

and mobility of the affected person(s) and on the availability of suitable conditions (for example, soil structure and other environmental characteristics). Changing crop types requires substantial investment in knowledge and skills. There is no guarantee that farmers will have the necessary information of possible options without an effective network of extension services that can filter knowledge gained through science to grass roots. In addition, it is necessary that farmers possess the necessary skills to implement an alternative production technique. There is thus a clear and distinct role for strengthening extension services in agriculture in vulnerable countries to enhance farmer awareness of potential adaptation response options.

There remain additional complications that need to be overcome. Institutional failures in agriculture can discourage farm management adaptation strategies such as changing the crop mix. Rigid agricultural and economic programs, with subsidies for certain crops in certain areas, can constrain change and reduce the flexibility of land-use changes. At the policy level, the support of certain crop prices can be disruptive when climate change can render such crops inappropriate in a changed environment. Similarly, food importation policies may discourage better national adaptation to the expected long-term climate changes. As stressed in Rosenzweig and Hillel (1995), adaptations of this type are not likely to be costless, and some may even cause disruptions to farmers as well as others in rural areas. For example, Alexandrov and Hoogenboom (2000), in a study on adaptations to climatic impacts in agriculture in Bulgaria, note that while changing sowing dates is relatively costless at the farm level, it is likely to interfere with the management of other crops grown at other periods in the year. There is also

concern that changing crop types will not automatically maintain previous levels of food production or nutritional quality levels.

Moreover, there can be conflicts between public and private objectives. While the national objective may be to grow crops that are less water-dependent, it does not necessarily imply that the new crops are equally (if not, more) profitable to the farmer. For example, You (2001) examines agricultural adaptations to climate change through a land-use change strategy (that is, switching crop types from rice to corn) to address the issue of water shortages in northern China. The author finds that there are insignificant disparities in expected yields from corn compared to rice to warrant concerns about switching. However, income from rice is more profitable than other crops (estimated to be nearly double the value). There is thus a conflict between a public or national objective of saving water and the private producer's objective. An incentive scheme, such as a government tax on incomes from rice cultivation (You 2001), could induce farmers to switch. However, the government will need to take care to make a range of concurrent changes (such as appropriate agricultural marketing policies and investments, pricing policies, review of agricultural credit schemes, and subsidization programs)—in short, an integrated and comprehensive plan that takes into account all key stakeholders. Without a complete adaptation strategy, the success of policies in addressing climate impacts is likely to be compromised.

Moreover, while more than one adaptation option remains possible, the best option may not be chosen given established preference for, or aversion to, certain options (Smit and Pilifosova 2001). In places where local subsistence farmers are conservative by nature, the acceptance of

change is likely to be gradual. Limited knowledge of the options in addition to other priorities, limited resources, or economic or institutional constraints (such as bureaucratic inefficiencies), are likely to make the requisite decisionmaking process challenging (Eele, 1996; Bryant and others 2000; de Loë and Kreuzwiser 2000).

4.2.2 Development of New Technologies and Modernization

Research and technological innovation in crop and animal productivity have enabled farmers to cope with various climatic conditions and have been fundamental to the growth and development of agriculture in both industrial and developing countries⁶⁴ (Hayami and Ruttan 1985; Houghton and others 1990; Rosenberg 1992; Reilly and Fuglie 1998; Evenson 1999; Gopo 2001). Smithers and Blay-Palmer (2001) identify two basic types of technological options, mechanical and biological, that are important for agriculture. Mechanical innovations include irrigation, conservation tillage, and integrated drainage systems— all of which have contributed significantly to the intensification of agricultural activity and permitted a wider range of agricultural activities than local resources would have otherwise permitted. On the other hand, biological options also have an important role in enabling cropping systems to adapt to a wide range of climatic conditions. Investment in crop breeding, the promotion of climate-resistant varieties that offer improved resistance to changing diseases and insects, breeding of heat- and drought-resistant crop varieties, the use of traditional varieties bred for storm and drought resistance, and investment in seed banks are necessary for success in overcoming vulnerability to climate impacts (Crosson, 1983).⁶⁵ Evenson (1999) and Smithers and Blay-Palmer (2001) cite numerous studies that illustrate that agricultural innovations have

been imperative to sustaining food production and adaptations to climate change.⁶⁶ A history of investments in technological innovations in agriculture is attributed to enabling the United States and other industrial countries to adapt much better to the expected climatic change relative to most countries (Crosson 1983). In South⁶⁷ and Southeast Asia the benefits of the green revolution are also well known⁶⁸, even when concerns regarding distributional inequities and health concerns that have been raised are taken into account (Evenson and Gollin 2000). At the same time, there is concern that there is yet an unfulfilled potential for technology in the agricultural sector in developing countries. For example, in places such as Africa, there is unease that poorer technologies and insufficient innovation strategies, compounded by other resource and institutional constraints, have contributed to worsening vulnerability to climate variability. In such places there is a need for the continuation and increased support of research on technological options for agricultural development in addition to the need for correcting institutional shortcomings.

Smithers and Blay-Palmer (2001), however, point out that climate change alone is unlikely to induce the relevant technological changes. The authors state that besides the challenges posed by knowledge for scientific discovery, innovations are also deeply rooted in legal, institutional, and economic circumstances that shape and direct their path of development, all of which vary from place to place. In this regard, government policy,⁶⁹ macroeconomic conditions, consumer demands and preferences, and science, each with its own set of driving forces, are important determinants of the rate at which technological innovations are made. Investment levels in public sector research, policies

governing the granting of and use of intellectual property rights, and the role of private-sector multinationals and contemporary research interests will constitute additional factors that need to be addressed with respect to *how, where, what type, and rate of*, technological innovations.

Finally, although advances in science and biotechnology offer powerful tools that hold much promise to overcome the many challenges posed by scarcity of resources and threats posed by pests and crop disease to the agricultural sector, there has been a debate over the advocacy of biotechnology—be it for climate or other reasons—in both industrial and developing countries. The role of multinationals and restrictive patenting practices; lack of diffusion of technologies in developing countries and the related issue of affordability of technology to poorer farmers; uncertainties about long-term implications of biotechnology on health due to use of pesticides and herbicides and resultant contamination of the ecosystem have been the focus in recent debates. McAfee (1999), for example, argues that there is evidence to doubt many of the perceived benefits of transgenic products. In particular, McAfee states (among other reasons) that the profitability criterion often dictates research goals which in turn can compromise the availability and diffusion of biotechnologies that the poor need most. While there is little doubt that concerns need to be addressed directly, the call for moratoriums on transgenic research is considered to hurt developing countries the most (Anderson 1999). Similarly, Pardey (2001) finds that claims that patents and intellectual property rights stifle research in developing countries are speculative. Instead, it is argued the more serious issue, based on current research, is that developing countries often lack the necessary funding and scientific and technical resources to access the benefits of biotechnology.

4.2.3 Improving Water Management

Improved water resource management will be vital to sustaining crop productivity levels in the face of both climate variability and longer-term change. In areas that are currently dependent primarily on rain-fed agriculture, the conjunctive use of surface and ground water resources will play an increasingly important role in enabling farmers to adapt to fast-changing climatic conditions. However, it is also clear that in the face of rising domestic and industrial demand, additional efforts are necessary to ensure efficient management of water resources. With climate change and variability increasing pressure on available water resources (and especially, net irrigation requirements), improved water management is one of the most important long-term adaptation options that countries must pursue.

According to recent estimates, irrigation efficiency in developing countries is extremely low. Rosegrant and others (2002) suggest that average irrigation efficiency⁷⁰ ranged from 25–40 percent for the Philippines, Thailand, India, Pakistan, and Mexico, to 40–45 percent in Malaysia and Morocco. In contrast, in Taiwan, Israel, and Japan, irrigation efficiencies average at 50–60 percent. At the same time, Döll (2002) finds that climate change impacts are likely to increase the net irrigation requirements in areas serviced by irrigation (as of 1995) by approximately 60 percent by the 2020s (and the 2070s). Simulations of irrigation requirements under two climate change scenarios in Döll's study suggest a likely shift in the optimal growing periods, by a month or more into the winter season, as well as a change in cropping patterns. In addition, results indicate that the negative impacts of climate change are likely to be more severe than those of climate variability. In particular, increased per hectare irrigation

requirements may be yet another factor limiting irrigation. Döll therefore recommends that it may be necessary to shift irrigated agriculture to regions where climate change will decrease per hectare irrigation requirements.

Stakhiv (1998) asserts that the principles of traditional policies⁷¹ aimed at effective water management by various international agencies (including FAO, World Bank, United Nations Environment Programme) will promote “no regrets” adaptation to climate change. A wide range of adaptation measures have been highlighted in this regard, including improving water distribution strategies; changing crop and irrigation schedules to use rainfall more effectively; water recycling and the conjunctive use of groundwater; rehabilitation and modernization; and improving and strengthening farm-level managerial capacity. Kundzewicz (2002) proposes that non-structural measures including source control (watershed/ landscape structure management), laws and regulations (including zoning), economic instruments, an efficient flood forecast-warning system, a system of flood risk assessment, awareness raising, flood-related data bases, and so forth are vital. A site-specific mix of structural and non-structural measures is therefore in line with adapting to climate change and promoting sustainable development.

From among these options, irrigation is especially important to agricultural production in arid and semiarid regions where inadequate rainfall, high temperatures, and evapotranspiration rates limit crop growth. Impending pressures from climate change will only intensify the importance of improved irrigation efficiency as an adaptation tool (World Bank 2000). Even in other humid areas, irrigation has become the primary tool to increase and stabilize

agricultural production in the face of uncertainties associated with rainfall frequency and drought (Smith and others 1996, Brklacich and others 1997; Klassen and Gilpen, 1998). For example, Jolly and others (1995) find that agricultural production in Senegal must be better planned in order to avoid shortages in production below subsistence levels from climate change impacts. In particular, it is recommended that farmers need to adapt by shifting from a cash crop system to a more stable system (for example, maize), requiring long-term investments in irrigation. Chiotti and Johnston (1995) recommend altering the scheduling of existing irrigation options⁷² to avoid the incidence of salinization, and to foster an increase in moisture retention in the face of decreasing precipitation and increasing evaporation. An alternative strategy includes improved irrigation practices through better water management plans and usage of technological innovations. Current technological advances in irrigation, such as the use of center pivot irrigation, dormant season irrigation, drip irrigation, gravity irrigation, and pipe and sprinkler irrigation, make this possible (see also Lewandrowski and Brazee 1993; Reilly 1995; Benioff and others 1996; Reilly and others 1996; Downing and others 1997; Parry and others 2000). For example, Bullock and others (1996) state that when water is in short supply, improved irrigation practices (for example, drip irrigation, underground irrigation) can conserve 50 percent of water compared with conventional approaches.

Demand-side response strategies that have received considerable attention include the reform of water pricing for irrigation (see Dinar (2000) for a collection of case studies on water pricing reforms, and Guerra and others (1998), who review the literature on irrigation efficiency

and on the potential for increasing productivity of water in rice-based systems). Specific policy prescriptions are suggested for the elimination of subsidies in irrigation as well as incentives for increasing irrigation efficiency.

Pricing water at its social cost (through the introduction of a water surcharge) is another possibility, although these options then raise a plethora of political-economy issues concerning water property rights that need to be addressed. Alternative policy measures, including establishing well-defined, transferable property rights in water. Once current users have well established permits to use the water, allowing the permits to be traded, creates conditions for water banks and other institutions that would facilitate voluntary water transfers (Tobo 2000). In industrial countries, the removal of barriers to open water markets is seen as an important measure to facilitate improved adaptation. Economists argue that the development of water markets (for example, in North America) would promote the allocation of water from federal projects to those with the highest-valued use. At the heart of the argument is the notion of moving away from pricing water below its market value. In addition, the development of water markets, with accompanying reform of water laws, would encourage investment in (among other things) water-efficient irrigation systems. Thus, where irrigation is subsidized and water has alternative uses, social benefits of reducing the agricultural sector's use of water may justify government programs to help farmers acquire more water-efficient technologies.

O'Brien (2000) identifies other adaptation measures to promote the conservation of water through development of sustainable water projects. These include, for example, the construction of small dams for water storage and

flood control and measures to capture rainwater during the monsoon seasons (in some parts of the tropics). O'Brien also stresses the need for facilitating (through technology) improvement in water distribution systems in agriculture, with greater responsibilities for operations resting on the farmers themselves. Traditional practices, with stakeholder participation, can also be of immense value. An example is community management in rice farming in Sri Lanka. Under the Irrigation Ordinance of Sri Lanka, the Administrative Head of District Public Service (a government agent) is empowered to hold water management meetings prior to each season. During the meeting, farmers discuss the type of crop to be grown during the season and the timing of the first release of water and the final release of water. The final decisions reflect the extent of water in the main reservoir, and the probability of further rains as the season proceeds.

Traditional adaptation techniques will also be effective to deal with shortages in water. For example, evidence from agricultural areas in Sri Lanka suggests that during times of drought and when water supplies from reservoirs are limited, the farming community temporarily ignores the individual boundaries of the farms and jointly cultivates land close to the irrigation outlet in order to minimize losses from evaporation and movement of water. Each farmer cultivates an amount of the cultivable land that is in proportion to the amount owned. Similarly, when fragmentation of land makes it uneconomical to cultivate in small units, an alternative cooperative farming technique is adopted. A farmer with a very small unit of land can opt to forego the cultivation of his unit and give the opportunity to another to cultivate a larger unit including his own. This makes the operational unit more viable (U.N Economic and

Social Commission for Asia and the Pacific 2002).

It is clear, however, that there are challenges with regard to water use and availability that also need to be overcome. Increased demand for water by competing municipal and industrial sectors can limit the viability of irrigation to counter the adverse impacts of rainfall variation. Expanded irrigation can lead to groundwater depletion, soil salinization and water-logging. In some regions, these limits have already been realized, such as in China, where historical adaptations in agriculture such as relocating productions or employing irrigation are no longer options in some areas, as population pressures have increased on land and water resources (Fang and Liu 1992; Cai and Smit 1996). Numerous challenges need to be overcome in order to increase water supply. As emphasized by Dinar (2000), these challenges include financial crises; low-cost recovery of the investment in the water system; the role of political parties, electoral systems, and the role of political parties, electoral systems and interest groups.

Stakhiv argues knowledge exists of policies or management measures necessary to adapt water resource management to climate change. However, this knowledge is difficult to apply *a priori*, in advance of the climate change. Stakhiv argues that it is necessary to bring forward the timing of the implementation of the measures in anticipation of the projected climate impacts.⁷³ He argues for improved forecasting procedures, simulation models, and improved data monitoring systems. Other necessary preconditions include overcoming economic constraints (for example, irrigation and other high-efficiency water conservation technology require major, long-term, costly investments)

and undertaking requisite institutional reforms that hinder the pursuit of effective water resource management strategies. However, given the uncertainty surrounding forecasts of regional changes in precipitation, it has not yet been proven that making water adaptations in advance of climate changes is in fact prudent.

4.2.4 *Permanent Migration of Labor*

The second form of migration that Locke (2000) outlines is referred to as “frontier agriculture migration.” This encompasses permanent migration in the form of the movement of migrants into new economic areas, possibly due to government policies or permanent changes in their previous environment. For example, frontier agriculture migration can encapsulate the movement of migrants from poorer agricultural lowlands in one region to lowlands in other regions or even other resource highlands (that is, forced change). Westing (1992) finds approximately 3 percent of the African population have been permanently displaced due to (primarily) environmental degradation (where climate impacts are part of the range of causalities).

As Desanker (2002) stresses, long-lasting climate pressures, such as prolonged drought, which increase the vulnerability of migratory groups to climate change (by limiting the scope of areas to move to), can be disastrous. Short-term migrants can be forced into becoming more permanent migrants, resulting in dire consequences such as pressures on land and resources. Many of the adaptations outlined in the previous section to address concerns with short term climate variability will not be adequate in the face of new and long lasting climate conditions. For example, even insurance programs will not be sufficient if productivity of land becomes unviable and may in fact act as a deterrent to

change despite market signals that indicate otherwise (Reilly 2003)) Evidence suggests that, if unmanaged or uncontrolled, large-scale migration of this type can result in significant impacts on the environmental resource bases as well as indigenous societies.⁷⁴

In this context, a clearly defined system of property rights and enforcement become necessary to avert potential stress. For example, in the case of nomadic movements that can result in permanent migration if climate impacts persist, then “tragedy of commons” kinds of problems need to be avoided. The establishment of an appropriate system of property rights (at the individual or community level) is part of the likely solution (re-training and extension services are other solutions that would be needed). In practical terms, however, an appropriate policy response should be dynamic, evolving as the migration flow changes.

4.3 Adaptations Irrespective of the Temporal Dimension of Climate Impacts

Alternatively, policy makers have focused on the agriculture sector but on more immediate issues such as making agriculture production sustainable given a host of non-climatic impacts (including, for example, declining state support, rising cost of inputs, provision of infrastructure and irrigation, etc). Policies aimed at increasing the resiliency of the sector to other, including non-climatic, factors are necessary and will help in improving capacity to cope with both climate variability and climate change.

It is important that solving immediate concerns facing domestic agriculture sectors do not delay the formulation and implementation of efficient responses to promote long term sustainability issues (Smit and Pilifosova 2001). In particular, effective adaptation will also depend

considerably on underlying local environmental, institutional, and socio-economic conditions. Domestic, as well as regional cooperation in science, resource management, and development are extremely important. Some of the main economic and institutional issues are likely to be beneficial irrespective of the nature of the climate change.

4.3.1 Investment and Accumulation of Capital

One of the main impediments to adjustment to climate change is poverty itself. The absence of resources constrains the ability of farmers to make the necessary adaptations. In a study on Tanzania, O’Brien and others (2000) report that despite numerous adaptation options that farmers are aware of, and willing to apply, the lack of sufficient financial resources and shortage of farmland were among the significant constraints to adaptation.⁷⁵ In a similar study on the effect of climate forecasts in Namibia, O’Brien and others (2000) find that serious structural or economic constraints are among the primary reasons for lack of farmer response to the anticipated climate impacts. The report notes that subsistence farmers are heavily dependent on the availability of credit to meet the costs of agricultural activity⁷⁶. They are either not able to obtain the necessary credit to purchase the necessary inputs⁷⁷ or chose not to for various reasons.

Emphasis is therefore placed on providing additional resources to be allocated to increase the ability and flexibility of farmers to alter production strategies in response to the forecasted climate conditions. Brklacich and others (2000) suggest that capital (and labor) adjustments can help reduce risks from climate change in farm production. They argue that both a public and private injection of financial resources is necessary to facilitate the

transformation of marginalized farmers who lack sufficient access to credit. Additional measures (such as education) are required to overcome social practices that have traditionally been wary of, or constrained, borrowing. In addition, it will be necessary to design public policy to ensure that investment in the right type of capital is made to increase resiliency to climate change. However, there is a big difference between making capital available at world interest rates and subsidizing capital. Improving access to capital is surely going to increase overall efficiency but subsidies may only create new problems in the absence of climate change.

4.3.2 Reform of Pricing Schemes, Development of Open Markets, and other Reforms

The reform of agricultural policy may also be necessary not only to address climatic impacts, but also to encourage efficient resource use and promote growth of the sector—which in turn will themselves foster greater adaptability and resiliency to climate change. Examples of such reforms include the encouragement of flexible land use—which could necessitate the removal of subsidies that otherwise slow land-use change—as well as long-term price stabilization measures. Other options include the design of financial programs that promote greater access to credit/loans (through insurance or micro credit schemes), developing agricultural marketing systems and training, and assisting farms with gaining access to irrigation.

The reform of agricultural markets has been promoted to induce greater efficiency. Smit and Skinner (2002) suggest that the review of agricultural subsidy and support schemes, private insurance, and resource management practices can help reduce the risk of climate-related losses and spread exposure to climate-

related risks. In a recent study, Mizina and others (1999) evaluate the appropriateness of various adaptation measures for agriculture in Kazakhstan. The paper discusses the decision theory behind a choice of a core adaptation strategy and problems that are likely to be encountered in such an exercise. The results of their decision analysis suggest that the following steps (in order of importance) need to be taken: the promotion of free market reform, the establishment of regional consultation centers that would impart knowledge on adaptation alternatives to farms, the enforcement of measures to control soil erosion, and the improvement of forecasting mechanisms.

In another recent publication, Kherallah and others (2002) review agricultural reforms implemented across Africa. While the findings do not directly or specifically relate to adaptations to climate change, the impact of the reforms on agricultural production and prices, and the net effect on the well-being of African households does have an important influence on the potential to adapt to climate change.⁷⁸ As Carter (1996), and Frederick (1997), and others such as Stakhiv (1998) comment, some measures should be implemented because they not only help to remove constraints to growth but may also be beneficial to encourage adaptation to climate change.

According to the findings of Kherallah and others (2002), while food markets have been dramatically transformed⁷⁹ in some countries in Africa (such as Ethiopia, Madagascar, and Tanzania), in others the transformation of food markets has been limited (such as Malawi, Zambia, and Zimbabwe). The authors note that in places where domestic markets have been liberalized, the outcome has been greater competition and reduced marketing margins.

However, Kherallah and others maintain that scale of operations by traders is limited due to the nominal investments that are made. While poor transport infrastructure increases marketing costs and uncertainty, the authors note that export marketing has generally become more efficient, allowing farmers to keep a larger share of the export price. The authors also contend that liberalized export markets may be vulnerable to collusion by the small number of exporters, particularly given the significant role that political connections play in gaining access to markets. Another problem highlighted is the reluctance of agricultural traders to offer farmers inputs on credit because the farmers can sell to a competitor and avoid repayment.

There are several dangers these reforms can introduce (Kherallah and others 2002). The removal of price controls (through the curtailment of public support) can hurt some clusters of rural farmers (as experience in Tanzania and Zambia have shown). A similar finding is noted in O'Brien et al (2002). These farmers are not necessarily the poor. Benefits from lower marketing margins and lower food prices, particularly in eastern and southern Africa are cited as examples. Exchange rate adjustments have been beneficial to export crop producers and crops that compete with imports (such as rice). The costs associated with eliminating fertilizer subsidies have been proportional to the quantities of fertilizer used, so larger, commercial farmers were more adversely affected than marginal farmers.

4.3.3 Adoption of New Technologies

The improvement of total factor productivity through the adoption of new and improved technologies has been an important means of increasing agricultural yields. Gabre-Madhin and others (2002) state that technological change

can bring about improvement in total factor productivity in two ways: reducing average *fixed costs* by increasing yields per fixed factor or reducing *variable costs* by reducing the cost of the technology itself. Most technological advances have elements of both types of change. In this respect, public and private investment in agricultural research, and, in particular, research and extension and innovations, are important sources of productivity growth.

Reilly and Hohmann (1993) highlight that the effectiveness of technological and institutional agricultural adaptations are bound by socioeconomic capacity. The issue of who adopts new technologies, how quickly, and at what cost is addressed in a recent paper by Gabre-Madhin and others (2002). The authors highlight that one of the limitations on the adoption of new technologies (especially in Africa) has been the removal of government support for agricultural inputs. (see also Kherallah and others 2002). The other has been increasing production (such as in eastern Africa), which has led to lower producer prices and and creation of disincentives to adopt new and costly technologies by producers

Constraints to the adoption of new technologies in the context of climate change can be extremely damaging. Such constraints can be natural, as Meertens and others (1995) warn that the adoption of new technologies may be limited in areas where there is abundant land and market access is poor. Adoption of technologies can also be constrained due to farmers' lacking the necessary financial strength. For example, De la Court and Verolme (1995) state that the non-affordability of organic relative to chemical inputs is one of the main reasons for nutrient depletion in soils on farms in dryland savannahs in India. In contrast, others have also argued that higher production in industrial countries could

lead to increased worldwide production, thereby lowering world food prices, making things even worse for developing countries (Mendelsohn and Dinar 1999).

4.3.4 *Promotion of Trade*

That trade plays an important role during periods of variable climatic conditions is already established in the literature. For example, Rosenzweig and others (1993) stress shortfalls in crop production due to insufficient rains in the late 1980s in South Asia as one of the main reasons for the import of wheat into the region during that period. Similarly, research has shown that trade will play an important role in enabling countries moderate the impacts of climate change on crop. Reilly and others (1994) suggest that agricultural trade will moderate impacts by enabling farmers in regions less adversely affected to sell their produce in areas more severely affected by climate change. Rosenzweig and Hillel (1995) suggest that trade adjustments should shift commodity production to regions where comparative advantage improves. Darwin and others (1995) argue that the competitiveness of U.S. grain producers in global markets depends on world agriculture's ability to expand into areas where temperatures now limit crop production.

Trade policy is expected to have important repercussions on the prospects for adaptation. The general consensus to emerge is that both regional and international trade can lead to improvements in access to international markets, which in turn can help a country diversify and reduce of risk of food shortages from climate change.⁸⁰ That is, the trading system is a risk-spreading mechanism through the geographic relocation of world food supplies according to changing comparative advantage and spatial diversification of climatic risks (Randir and Hertel 1999).

High tariffs on imported goods, and trade-restrictive policies reduce the effectiveness of trade. The IPCC (2001) also stresses that restrictive policies can impede the entry of efficient technologies into new markets.⁸¹ Continuation of restrictive policies will result in diminished global welfare. Results of Randir and Hertel (1999) has shown that liberalization facilitates economic adjustment to climate change. They propose the need for reductions in agricultural tariffs and subsidies under future trade deliberations. Their results suggest that the removal of distortions in global agricultural activities is likely to improve allocative efficiency in agriculture and improve aggregate welfare provided that it is accompanied by the removal of farm support mechanisms.

While numerous studies show that trade has the potential to mitigate the effects of adverse climatic impacts, one area of research remains conspicuously absent. As highlighted by Horowitz,⁸² there is little research on the impact of trade if climate change risks are positively correlated in major agricultural areas (such as, for example, the United States and Europe). Although countries at similar latitudes are expected to experience similar outcomes from warming, countries at different latitudes are expected to have very different impacts (Mendelsohn et al 2000). It is widely expected that warming will benefit agriculture in high latitude countries and damage farming in low latitude countries. Further, there is every reason to believe that the changes in precipitation will vary across regions (IPCC 2001).

4.3.5 *Extension Services*

Extension services have played a key role in promoting agricultural productivity in developing countries, and their role in promoting various adaptations to climate change is no less

important. For example, Mizina and others (1999) state that given regional differences in climatic impacts, local experiments, as well as ensuring information flows, need to be encouraged. Traditionally, extension services have generally been in the purview of services provided by government, given that agricultural research is typically a public good.⁸³ However, private and non-governmental agencies (or the formation of research cooperatives) do play a significant role in some countries. According to Evenson (1997), numerous studies, for example, in India, Kenya, and Burkino Faso have shown that there is strong evidence to link extension services with awareness and knowledge of agricultural practices. Other studies have established a link between extension and adoption of farm practices, although farm size and levels of education also have a significant influence. Evenson also states that there is a strong link between the extent of extension services (in terms of number of extension agents per region) and membership in extension organizations to be a significant contributing factor to productivity.

Crucially, as Evenson (1997) notes, the economic contribution of extension services is governed by location-specific factors. In this regard, numerous programs have been found to be ineffective given the underperformance of agents, design limitations, and management failures. Collier and Gunning (1999) find similar problems through their study of Africa. The authors maintain that extension services in general in Africa have traditionally been weak. The authors state that extension services in East Africa have tended to discount traditional practices such as inter-cropping, which research has proved to be an effective buffer against climatic impacts. Poor incentives for extension workers and organizational failures are cited as

likely reasons for poor productivity. Evenson (1997), in fact, stresses that where extension programs have been well designed, researchers have been effective, and farmers have adequate schooling, the rewards can be very encouraging.

4.3.6 Diversification of Income-Earning and Employment Opportunities

Seasonal effects and climatic uncertainty that characterize the agricultural sector effectively mean that diversification of income and employment opportunities is an important adaptation strategy for households in the sector. In dryland areas, traditional practices to help cope with drought include the accrual of a surplus in a superior year, in the form of cash or assets (for example, cattle) for use in poorer years (Burton 2001). While measures such as crop storage, sales, and household savings⁸⁴ can and do offer relief from temporary (or seasonality) effects, risk and market imperfections that abound in rural settings render diversification into off-farm opportunities necessary to reduce income instability (Alderman and Paxson 1992).

Consequently, policies that provide the opportunities to pursue alternative livelihood options need to be encouraged. Ellis (1998) indicates that diversification into non-farm income ensures low-risk correlations between livelihood components. It can be both a transient phenomenon (Saith 1992) as well as a means of ensuring long-term livelihood security.⁸⁵ For example, in Kenya, effective smallholder response to drought has been to shift from traditional planting strategies to employment diversification (Downing and others 1997).

Income diversification in agriculture is not restricted to poor developing economies. Skinner and others (2001) stress that household income

diversification strategies were an important adaptation option among farmers in Canada (see also Brklacich and others (1997); Smithers and Smit (1997); de Loe and others 1999). Frequently, income diversification among farmers involved livestock ownership, but also off-farm activities, such as trading home-produced goods or providing services (Bryant, 1989). Diversification of household incomes is likely to be undertaken in response to a number of factors (such as availability of alternative employment opportunities and prospects for seeking and obtaining new opportunities) as opposed to climatic perturbations alone (IPCC 2001).

In order to ensure that diversification of income-earning and employment opportunities is a realistic alternative for rural farmers, certain prerequisites need to be fulfilled. In some instances, private initiatives and expectations will suffice, but other cases will require public support. In particular, training, information dissemination, and support services will require some public organization, resources, and institutional support.

4.3.7 Dissemination of Climate Data

A reason frequently cited for not adapting in time to climatic impacts is the lack of reliable climate monitoring and forecasting data. In a paper that investigates the effect of scientific uncertainty on planning for climate change, Barnett (2001) argues that an increase in the availability of information to understand the biophysical and social environment is necessary. The timely dissemination of climate forecasting information and early warning to farmers (including information on risks) can strengthen the ability of farmers to cope and optimize the management of hydrological variability and change.⁸⁶ Monitoring data and indicators of change are also necessary across all sectors in

society, not just policy makers. A key role for state, society, and media is envisioned through both horizontal and vertical exchanges of information through regular meetings with key stakeholders.

While some countries do have resource constraints on collecting and disseminating reliable data, evidence suggests that lack of data may not be the only problem. With both science and technology making vast contributions to improving water use efficiency and drought-tolerant cultivars, the real problem, it is argued, is the lack of application of existing knowledge (Burton 2001). This is due to poor distribution of knowledge or, when it is available, the information is not in a form that is usable. Burton identifies the failure to apply knowledge that conflicts with traditional practices, social and legal conventions, and the existing power structures within communities and nations. Skepticism toward seasonal forecast information has, in some instances, led to inaction on the information provided.

4.3.8 Institutional Planning and Implementation

Insufficient institutional and decisionmaking structures to support long-term planning in central governments in developing countries has long been recognized to be a problem in pursuing general development objectives (see for example Hernes and others 1995; O’Riordan and Jordan 1999). A recent World Bank report underscored the finding that in some countries, such as Bangladesh, planning for climate change is not even mandatory, an outcome of planning agencies’ being “formed not by law but by administrative resolution” (World Bank 2000). Under such extreme circumstances, not uncommon in many other developing country settings, it makes little sense to discuss

adaptation options to reduce long-term vulnerability until the necessary underlying conditions, such as institutional support, are first met. Further, Rosenzweig and Hillel (1995) draw attention to the fact that some agricultural institutions and policies can discourage farm management adaptation strategies, such as changing crop mix. Weak and underdeveloped land-use control and physical planning functions increase vulnerability, and bureaucratic inefficiencies can restrict the effectiveness of institutional systems that do exist, rendering even the most basic attempts to plan and implement a major problem.

Institutional reforms, with the participation of key stakeholders, is therefore essential to enhance adaptations to both short- and long-term climate impacts. The relative success in adapting to possible changes will depend on the type of institutional changes that occur, where they occur, and on timely and appropriate investments in adequate adaptation strategies. For example, Stakhiv (1998) asserts, with reference to the management of water, that not only are well-functioning institutions in sectors such as hydrology and meteorology essential, but they need to be supported by equally well-functioning institutions in other sectors that provide information on the changing socioeconomic structure, demographics, technology, and public preferences.

Previous studies (Smith 1997; World Bank 2000) have highlighted that in some cases, it is necessary to first assess whether current growth policies and programs can facilitate adaptation. It may be necessary to formulate a new institutional framework to deal with climate change. For example, improvements in institutional capacity to administer and regulate environmental issues, including more resources

to support existing policies, would reap substantial benefits. Other factors that will assist adaptation, and which may not require new frameworks, include improving organizational capacity, responsibility, and operational effectiveness of current institutions; integrating national, regional, and local actions; and technology and infrastructure development and adoption.

IPCC (2001) underline that strengthening adaptive capacity requires integrated management practices to be in places where management institutions are weak, and they need to fit specific institutional settings. Adaptation must also be addressed on a country-by-country basis, taking into account local environmental, political, economic, and social conditions. Coordination failures between central and local governments need to be rectified, and sectoral management plans need to be overhauled by multisectoral management plans so that linkages with other major sectors in the economy affected by or enabling adaptation are taken into account.⁸⁷ The preparation of such comprehensive development plans, as well as the review and upgrading of current physical planning laws and regulations,⁸⁸ will be an important step toward catalyzing the requisite institutional change to facilitate adaptations. In short, climate change management plans need to incorporate the participation of all tiers of government, as well as private and civil society.

Additional considerations need to be taken into account. Smith and Lenhart (1996) declare that adaptation must be resilient to meet stated objectives given a range of future climate scenarios with potential to produce benefits that outweigh costs (including financial, physical, human terms or otherwise). Similarly, O'Brien (2000) argues that adaptation needs to satisfy

multiple criteria, including flexibility to suit a range of likely impacts; feasibility given political and socioeconomic and institutional realities; and economic affordability. Mizina and others (1999) stress that adaptation measures should be assessed in terms of their cost-effectiveness rather than cost-benefit ratios.⁸⁹ According to Mizina and others, this would enable an evaluation of the various measures for their (a) effectiveness in reducing risks of damage from climate change; and (b) social, technical, and institutional feasibility. Finally, adaptation measures to climate change cannot be considered in isolation, but relative to the impacts of other exogenous sectoral changes. In short, the key lesson to emerge is that the prioritization of appropriate adaptation measures needs to be contextual and fit the capacity of local institutional and legal frameworks.⁹⁰

For example, in the case of water, agriculture, and adaptations to climate change, Benioff (1996) in Smith and others (1996) outlines several measures, including the development of comprehensive river basin, lake, or reservoir management plans, as well as the implementation of water conservation plans. The latter include demand-side management measures such as pricing incentives (for example, adjusting water prices to reflect the full cost of recovery), and improving regulations and technology standards. Other options include developing new water supplies, encouraging the combined use of ground and surface water in addition to rainwater, recycling, increasing capacity to transfer water between and within river basins, improving flood protection schemes, developing storage capacity, enhancing and executing drought response planning programs,⁹¹ and, in general, public education programs focusing on adapting to climate change in agriculture.

O'Brien and others (2000) outline, with respect to adaptation to climate change in Antigua and Barbuda, that a comprehensive coastal area management plan is required. The plan, the authors contend, should cover items that range from improving the employing technology options to reduce vulnerability to weather extremes, to the development of technical capabilities in agriculture and fisheries management,⁹² to concurrent public health programs on controlling dengue and other vector-borne diseases.

In many countries resolving socioeconomic and environmental issues is an important means of addressing climate change impacts.⁹³ A stable macroeconomic environment, progress in taming corruption, and stronger legal infrastructure for stimulating domestic and international investment, including that in the agricultural sector, have been highlighted as necessary (Kherallah and others 2002). In addition, changes in international and domestic competition laws need to be implemented to ensure viable competitive technology markets, improvements in the flow of technological information, and technical capacity building.

Moreover, the necessary institutional reforms need to be supported by appropriate social policies. For example, many countries have experienced difficulty in adjusting water prices, or subsidies that support various agricultural inputs that are aimed at improving allocative or use efficiency. While many reasons have contributed (including the pursuit of short-term objectives, persistence with the continuation of traditional practices) the existence of such perverse incentives has continued long enough that they are now institutionalized. Citizens often view free water and affordable agricultural inputs as an inalienable right. Although

arguments can be made both ways, it is also clear that the current economic realities of many developing countries rarely allow such support schemes without aggravating other economic problems such as inefficiency (due to the continual dependency on state support, often worsening national deficits). There is no doubt that some difficult choices need to be made to help countries overcome past social norms and expectations. Adjustments need to reflect lessons that have emerged from previous structural adjustment policies. Changes need to be dynamic and complementary; social programs need to be

devised to provide a credible safety net for households adversely affected by the reforms. As Kherallah and others (2002) argue, governments need to reverse declining investments in other areas, such as agricultural research and extension; improve transport infrastructure; promote the sustainable use of natural resources; and develop public services such as market information, plant protection, and disease control. Such programs are justifiable on their own terms as well as for the political sustainability of the necessary reforms.

5 Matrix of Adaptations

<i>Adaptations Options in Agriculture to Climate Change and Variability</i>				
<i>Adaptation option:</i>	<i>Purpose</i>	<i>Necessary supporting policies</i>	<i>Other prerequisites</i>	<i>Limitations</i>
Short term				
Crop Insurance				
Private/public programs	Enabling improved risk coverage	Improving access	Synergies between govt. and private sector in bearing risks	Risk averse communities/ insufficient collateral
Formal/informal schemes		Risk management through risk reduction and risk sharing Improving supervisory capacity Revising pricing incentives Improving affordability/ availability of coverage for catastrophes	Minimizing information asymmetries Establishing enforcement mechanisms Introducing measures for the correct estimation of premiums Innovative schemes should be pursued (e.g. tradable financial assets; catastrophic bonds; weather markets)	High opportunity costs of public funds High monitoring costs (institutional limitations) Adverse selection/moral hazard Need to establish well-functioning producer organizations
Portfolio (Crop/Livestock) Diversification				
Replacement of plant types, cultivars, hybrids and animal breeds with new varieties	Risk-spreading/ promoting farm-level risk management	Availability of extension services	Tenure reform to ensure property rights are established	Traditions, lack of awareness, and other limitations (high opportunity costs) may dampen willingness to diversify
Alternative production techniques (adjustment of capital and labor inputs)	Increasing productivity	Financial support/ alternatives should be provided by private and public sector	Land-use regulations need to be reviewed to enable diversification	Over-dependence on government support mechanisms needs to be reduced
Multi-cropping	Defending against disease, pest	Enable mobility of activities	Education/training/ extension services need to be provided	Need alternatives that maintain quantity and income from production
Mixed farming systems of crops and livestock		Remove subsidies on certain crops/livestock production not conducive to changed climatic and resource conditions		
Adjusting Timing of Farm Operations				
Adjusting cropping sequence	Reducing risks of crop damage/ maximizing output in light of new conditions	Extension services/training is necessary	Mechanisms for the dissemination of agronomic and climate information	Investment in collection of climate data and disseminating information required
Adjusting timing of irrigation		Pricing policies have to be reviewed	Institutional support must be strengthened	Limitations of existing infrastructure

<i>Adaptation option:</i>	<i>Purpose</i>	<i>Necessary supporting policies</i>	<i>Other prerequisites</i>	<i>Limitations</i>
<p>Changing Cropping Intensity</p> <ul style="list-style-type: none"> Adjusting fertilizer and other inputs Changing land use practices Changing location of crop/livestock production Rotating or shifting production between crops and livestock Abandonment of land Changing the timing of activities (of sowing, planting, spraying and harvesting) Changing the timing of irrigation 	<ul style="list-style-type: none"> Improving moisture and nutrient retention Reducing soil erosion Adjusting to changing length of growing season Increasing plant protection 	<ul style="list-style-type: none"> Extension services must be improved Pricing policy adjustments for incentives to making adjustments 	<ul style="list-style-type: none"> Location-specific solutions should be sought 	<ul style="list-style-type: none"> Availability of cultivable land; availability of alternative lands Socioeconomic (financial) Conflicts with other farm operations at other times of the year Traditions, lack of awareness, and other limitations (high opportunity costs) may dampen willingness to diversify Concerns regarding maintaining similar production levels
<p>Livestock Management</p> <ul style="list-style-type: none"> Change in biological diversity, species Altering the breeding management program (i.e., changing composition, or species distribution) Change in grazing management (timing, duration, and location) Changing the location of watering points Changes in rangeland management practices Modifying operation production strategies Changing market strategies Implementing feed conservation techniques/ varying supplemental feeding 	<ul style="list-style-type: none"> Spreading risks; increasing productivity Adjusting to new climate conditions 	<ul style="list-style-type: none"> Provision of extension services 	<ul style="list-style-type: none"> Promoting investment in livestock management Institutional support 	<ul style="list-style-type: none"> Traditions, lack of awareness and other limitations (high opportunity costs) may dampen willingness to diversify

<i>Adaptation option:</i>	<i>Purpose</i>	<i>Necessary supporting policies</i>	<i>Other prerequisites</i>	<i>Limitations</i>
Changes in Tillage Practices (Conservation Tillage) Land contouring and terracing Maintaining crop residues Fallow and tillage practices Planting of hedges Alternative drainage methods Construction of diversions and reservoirs and water storage Irrigation Reducing water use in land preparation	Conserving soil moisture and organic carbon contents and increased soil erosion maintain soil fertility and prevent erosion (nutrient management) Maintaining soil quality/provide protection against wind erosion Increasing production per unit of evapotranspiration Reducing water runoff/improving water uptake Recharging water supply Reducing runoff and erosion Nutrient restocking Conserving water	x Extension services need to support activities Pricing incentives to promote conservation	Investment Land tenure reform Indigenous knowledge	
Temporary Migration	Risk diversification strategy to withstand climate shocks and seasonal effects	Employment training/opportunities	Institutional support	Availability of employment opportunities in urban areas; growth elsewhere in economy Skills and earnings potential High population density in cities
Short-Term Forecasts	Improve preparation for medium-term climatic impacts	Institutional support for collection and dissemination, information dissemination	Infrastructure for monitoring	Financial resources constraints
Food Reserves and Storage	Temporary relief		Delivery mechanisms	Expensive/complacency

<i>Adaptation option:</i>	<i>Purpose</i>	<i>Necessary supporting policies</i>	<i>Other prerequisites</i>	<i>Limitations</i>
Changing Crop Mix				
Adopting new crops	Spreading risk of damage	Revising pricing; food importation policy	Promoting investment	Institutional failures
Planting in different part of farm	Move away from unstable cash crop systems	Tenure; extension; pricing incentives	Institutional support to administer	Acceptance of change gradual
Converting land use		Improving access and affordability Need viable alternatives (incomes)	Agricultural marketing policies Review of agricultural credit schemes	Economic failures (maintaining incomes) Knowledge
Irrigation	Increase productivity; withstand rainwater shortages	Investment by public and private sectors	Clear water management policy	Institutional support and enforcement mechanisms
Modernization of Farm Operations	Increase productivity	Promoting the adoption of technological innovations	Establishment of intellectual property rights Role of private multinationals	Conflicts between national/private objectives Maintaining similar production levels Subsidization programs may create perverse incentives
Research and development (biological and mechanical options) Adoption of technology (e.g., use of sprinklers)	Withstanding climate effects			
Permanent Migration	Diversify income-earning opportunities To overcome long lasting climate impacts	Education and training for alternative opportunities Retraining	Institutional support (property rights)	Impacts on resource base Land pressure
Defining Landuse and Tenure Rights	Incentives to make necessary investments in agricultural land to withstand climatic impacts	Legal reform and enforcement		

<i>Adaptation option:</i>	<i>Purpose</i>	<i>Necessary supporting policies</i>	<i>Other prerequisites</i>	<i>Limitations</i>
Efficient Water Use				
Improving water distribution	Water conservation	Pricing reforms for water	Sustainable water projects	Cost Competing demands Financial crises Low-cost recovery of the investment in the water system Political economy issues
Promoting irrigation efficiency	Avoid salinization; increase in moisture retention	Clearly defined property rights	Diffusion of technological advances in water management	
Changing crop and irrigation schedules	Water storage and flood control	Develop open markets	Institutional reforms	
Water recycling and the conjunctive use of groundwater Rehabilitation and modernization		Strengthening farm level managerial capacity		
<i>Both short and long term</i>				
Investment Promotion	Overcome financial limitations to adapt	Property rights; designing innovating financial tools Injection of initial capital		Social constraints against capital accumulation Reluctance of agricultural traders to offer inputs on credit
Develop Market Efficiency				
Pricing reform	Promote more efficient use of resources	Remove barriers	Institutional support	Poor transport infrastructure
Develop open markets		Property rights; pricing policy	The establishment of regional consultation centers Impart knowledge on adaptation alternatives	
Reform of agricultural markets		Adjustment of agriculture input subsidies that constrain adaptation Land use regulations	Legislative reform	
Adoption of Technological and Other Adaptation Measures	Increasing agricultural yields	Pricing incentives/ tax reform	Community management and cooperation programs	Natural constraints- if land is available Socioeconomic capacity to adapt Complete removal of government support Lower producer prices Lower world food prices Attitudes towards risk Level of uncertainty of the future Availability of funds for investment Access to assets, capital, and credit High tariffs in export markets
	Reducing average fixed costs	Extension services for training		
	Reducing variable costs	Finance schemes		

<i>Adaptation option:</i>	<i>Purpose</i>	<i>Necessary supporting policies</i>	<i>Other prerequisites</i>	<i>Limitations</i>
Promoting Trade	Promoting economic growth Strengthening long-term food supply and production limitations Reducing risks of food shortages	Pricing and exchange rate reform and stabilization Adjustment of agricultural subsidies and tariffs	Social policy	Subsidies in developed markets
Developing Extension Services	Improve agricultural productivity Improve awareness and knowledge of measures	Role of private, non-governmental and cooperative agencies Ensuring sufficient agents per farmer/region	Ensure agents are productive through adequate incentives Limit/remove management failures Public organization, resources, and institutional support Utilize indigenous knowledge	
Improving Forecasting Mechanisms	Assist planning Strengthen ability of to cope	Extension Institutional support (e.g. establishment of farmer cooperatives to spread knowledge)	Information needs to be distributed across all sectors Horizontal and vertical exchanges of information Ensure information is in a usable form	Financial Conflicts with traditional practices/ social conventions Skepticism
Institutional Strengthening and Decision-making Structures	To support long term planning Reduce vulnerability Provide information on the changing socioeconomic structure, demographics, technology, and public preferences Improving organization capacity, responsibility and operational effectiveness	Reform existing institutions that support agricultural sector Pricing incentives; improving regulations and technology standards Legal infrastructure (reform) for stimulating domestic and international investment Changes in international and domestic competition Social policies	Participation of key stakeholders Requires integrated management practices; need to fit specific institutional settings Comprehensive multi-sectoral management plans Resilience; flexibility; public education program Remove bureaucratic inefficiencies	Planning agencies formed by administrative resolution as opposed to being mandatory

<i>Adaptation option:</i>	<i>Purpose</i>	<i>Necessary supporting policies</i>	<i>Other prerequisites</i>	<i>Limitations</i>
		Upgrading of current physical planning laws and regulations	Equally well functioning institutions in other sectors	
			Improve coordination between central and local government	

6 Conclusions and the Way Forward

A growing literature suggests that while climate mitigation strategies are necessary, that alone is unlikely to be sufficient as a climate policy. Because global mitigation measures are unlikely to keep climate constant, every country must also examine how they will adapt to the changes that will occur. Each country must examine how they can reduce their vulnerability to climate change and increase desirable outcomes. Some degree of climate change will have to be confronted by the agriculture sectors across developing countries thereby rendering adaptation imperative.

Diverse and location-specific impacts on agricultural production are anticipated. While the global agricultural supply is likely to be robust in the face of moderate climate change, severe regional variation is expected. While temperate and polar regions stand to gain relatively in terms of agricultural productivity, developing countries in tropical regions are expected to be the worst-affected from climate change, suffering significant agricultural production losses. Many of these countries are also currently under severe economic and ecological stress. Climate change is expected to push the agricultural sectors in these countries into further hardship. In particular, the stress is likely to be over and beyond that caused by the traditional economic, political, social, and institutional imperfections that currently affect the agricultural sector. Moreover, it will increase the incidence of poverty in rural areas given the high dependency on the agricultural sector for rural livelihood opportunities.

It is thus essential that there is increased recognition by governments in developing countries of the impending threats of climate change on their agricultural sector. Results from scientific and economic studies of likely impacts on agriculture in developing countries must be disseminated with increased urgency, and political awareness must be raised to confront the main issues. It is essential that steps be taken to support farmers and households engaged in the agricultural sector to cope with both the threat of climate variability as well as the challenges that climate change will pose on future livelihood opportunities. Consequently, simultaneous to international efforts to mitigate emissions of greenhouse gases, pursuing a complementary strategy at the national and local levels of enabling the agriculture sector to adapt to climate variability and change and negate many of the expected adverse impacts is equally, if not more, urgent.

A host of recent impact studies show that reducing vulnerability to climate change by strengthening the adaptive capacity of the agricultural sector can reap substantial benefits. Several key themes emerge from the review.

- Given the range of current vulnerability and diversity of expected impacts, there is no single recommended formula for adaptation. Instead, increasing adaptive capacity of the agricultural sector will require a host of complementary measures. Suitable strategies

will have to be specific to local conditions, including economic, political, and social realities, and reflect institutional and legal capacity and national development goals.

- Policies to promote adaptation to climate variability need to be undertaken today. If society is to deal with climate change effectively, the necessary policies to adapt to climate change should be implemented in a dynamic way as climate change unfolds.
- Distinction must also be made between adapting to extreme events to prevent disaster versus adapting to persistent changes. That is, a different set of solutions will be necessary to address climate variability and climate change concerns respectively. While in some cases, measures will reinforce each other, more often they will not. Many policies aimed at reducing vulnerability to short-term climate variation will not reduce vulnerability to long-term climate change. At the same time, adaptations that help reduce long-term susceptibility to climate change impacts will not alleviate short-term vulnerabilities.
- Responsibility for adaptations will be in the hands of private individuals as well as government. Private agents motivated by self-interest and underlying welfare-maximizing objectives will undertake some types of adaptations. That is, adaptation measures will be undertaken for private gain and these will be undertaken by the market without new public policy. Some adaptations will require coordinated responses across many agents. In light of high information requirements, equity considerations, and other externalities associated with adaptation, government-sponsored adaptive measures will be necessary.

- Policymakers need to acknowledge that limiting non-climate-change stress on the agricultural sector will also increase the resilience of key stakeholders to climate variability and change. Successful adaptation is unlikely without also addressing wide-ranging problems that make the agricultural sectors vulnerable in the first place.
- While the poor can adapt, it will not be costless given that as a group, more effort and a considerable proportion of per capita income will be required to adapt. There is therefore a need to simultaneously address underlying causes of poverty, vulnerability, development, and to tackle displacement, division, and degradation issues (Kates 2000).

This paper has revealed that there is a wealth of knowledge of a range of measures that can help the agricultural sector in developing countries become more resilient to climate vulnerabilities. Some measures, implemented at the farm level, are aimed at reducing vulnerabilities to climate variability. These include, essentially, risk diversification strategies such as crop diversification, changes in intensity of production, nutrient and pest management programs, insurance schemes, food storage, forecasting and disseminating climate information, and temporary migration in search of off-farm employment opportunities. However, while effective in the short term, they are likely to be insufficient for coping with the threats of climate change in the longer term. Accordingly, there is also a need to pursue a different set of strategies aimed at reducing long-term vulnerability. The range of options in this regard includes changing the crop mix, improving water management, adopting and utilizing new technologies (that is, modernization of the

agricultural sector), and migrating permanently away from unviable agricultural areas.

The literature also suggests that it is necessary to overcome factors that contribute to vulnerability regardless of the temporal dimension of climate change. In particular, low per capita income, high dependency on subsistence agriculture and natural resources, weak governmental and institutional capacity, prevalence of preventable and non-preventable diseases, high incidence of armed conflict, and dependence on aid have been identified as issues that make economic development and growth challenging (Desanker, 2002). These, as well as other reasons, such as insufficient investment in infrastructure and social capital (relative to growth potential), lack of openness to trade, deficient public services, and inconsistent government policies (Collier and Gunning 1999), are also likely to increase the agricultural sector's vulnerability to climate change. This paper highlighted that, in response, a suite of strategies, preferably through government intervention, should be adopted regardless of the temporal dimension of climate change. In this regard, research has shown that economic, institutional, political, and social factors are likely to play an important role in enabling the agricultural sector to adapt to climate change. In particular, institutional strengthening through improved organization, managerial capacity, and development of adequate legal frameworks are imperative. Macro level measures will be necessary not only to promote the accumulation of capital but also to direct investment in areas that reduce vulnerability to climate impacts. In addition, agricultural price reform (such as the removal of distortionary subsidies in industrial countries as well as elsewhere) and the development of open markets, promotion of increased trade, and improvement in institutional planning and

structures are imperative. Other measures will necessitate micro level approaches to encourage the adoption of new technologies, develop extension services, and improve access to credit in agriculture in rural areas; to increase opportunities to diversify income-earning and employment opportunities; and the effective dissemination of climate data and development of early warning systems. In some cases these policies will reinforce each other. In other cases, there will be competition, and the success of policy will depend on their design and the existence of institutions to support their implementation.

The adoption of many of these measures is of importance for reasons other than climate. That is, they are necessary for the pursuit of sustainable development. The pursuit of such "no-regrets" options through an interdisciplinary approach is fundamental to strengthening the capacity of the agricultural sector to adapt to climate change.

While the menu of adaptation options presented in this review is extensive, it need not necessarily be overwhelming to policymakers. In the short run, adaptation options need to reflect what is known currently about climate conditions. In contrast, in the long term, national and sectoral policy and assistance provided by international agencies to developing countries should reflect expected impacts from climate change. The attention of policymakers should then be on prioritizing, formulating, and implementing policies that promote adaptation based on site-specific conditions. In this respect, three key lessons emerge. First, incentives need to be formulated and incorporated into project designs. Second, it is also clear that dynamic adaptation needs to be promoted, as it is unlikely that there will be one solution to address climate concerns. Finally, it is not necessary that an

entirely new and alternative suite of policies be designed to address climate concerns. Evidence is abundant of the numerous measures that can address various climate concerns. It is important, however, that incentives that promote

adaptation policies are appropriately incorporated into poverty reduction and other sustainable development policies in order to enhance the resiliency of the poor.

Notes

1. P. Kurukulasuriya and S. Rosenthal are doctoral students at the Yale University's School of Forestry and Environmental Studies.
2. Downing (1993); Mendelsohn, Dinar and Sanghi (1998); Mendelsohn and Neumann (1998); Mendelsohn and Schlesinger (1999); Mendelsohn and others (1999); Cline and Rosegrant (2002).
3. Darwin and others (1995) links agricultural productivity of land to a CGE model of the world economy to arrive at this estimate.
4. Comment made by Sachs at a invitational lecture on "Mobilizing Science for Sustainable Energy Systems" at the School of Forestry and Environmental Studies, Yale University, on January 29, 2003.
5. GSM Models (GFDL, GISS, UKMO) tested three climate change scenarios, including increments of 4, 4.3, and 5.2 degree Celsius respectively, and change in global precipitation of 8, 11, and 15 percent respectively.
6. According to WRI (1998) estimates cited in IPCC (2001), countries in the Organization for Economic Cooperation and Development (OECD) depend on agriculture for about 2-3 percent of annual GDP while African countries generate 5-58 percent (similar evidence is cited in World Bank 1994).
7. Different adaptation strategies can lead to different levels of greenhouse gas emissions and therefore mitigation options will also be affected.
8. Burton (1996) outlines six reasons including (i) climate change cannot be entirely avoided; (ii) anticipatory adaptation is less costly than forced adaptations after impacts are realized; (iii) unexpected events are possible given that climate change can be more rapid than expected; (iv) immediate benefits from adapting to extreme events and variability of climate; (v) there can be substantial gains from removing maladaptive policies and other ad hoc practices that otherwise increase vulnerability; and (vi) must grasp the opportunities that climate change will bring.
9. It has been estimated that a doubling of CO₂ (relative to 1880 levels) will force an increase in global average surface temperature of 1.5-4.5 degrees C by 2060 (IPCC, 1990). More recently, estimates have ranged from 1.0-3.5 degrees C by 2100 (IPCC, 1996).
10. In addition to the usual operational decisions that have to be made regarding inputs, outputs, and technologies, farmers also need to also consider when they will make changes, contingent on uncertain climate effects.
11. See Rosenzweig and Liverman (1992) who discuss the biophysical response of agriculture crops in light of interactions with thermal regimes, changes in hydrological regimes, physiological effects (CO₂), soils, and pests. See also, Rosenzweig and Hillel (1995).
12. This includes primarily changes in the length of time that soil temperature and moisture conditions are most appropriate for crop growth (Darwin 2001).
13. Warmer temperatures are likely to adversely affect soil nutrients and organic matter through microbial decomposition.
14. Plants are classified as C₃, C₄, or CAM according to the products formed in the initial phases of photosynthesis. C₃ species respond more to increased CO₂; C₄ species respond better than C₃ plants to higher temperature, and their water-use efficiency increases more than for C₃ plants. C₃ plants: cotton, rice, wheat, barley, soybeans, sunflower, potatoes, most leguminous and woody plants, most horticultural crops and many weeds. C₄ plants: maize, sorghum, sugarcane, millets, halophytes (that is, salt-tolerant plants) and many tall tropical grasses, pasture, forage, and weed species. CAM plants

- (Crassulacean Acid Metabolism, an optional C₃ or C₄ pathway of photosynthesis, depending on conditions): cassava, pineapple, onions, castor (from Sombroek and Gommès, 1996).
15. Moreover, other fossil fuel emissions such as sulfur dioxide and ozone are likely to negate some of the beneficial impacts of carbon dioxide effects.
 16. Personal communication during review of paper.
 17. Oceanic-atmospheric interactions in the Indian Ocean and southern Atlantic are also seen as important influences on rainfall patterns in southern Africa.
 18. The models effectively held farmer behavior constant despite the different simulated environment that they operated in.
 19. That is, estimates have been based on results from carefully controlled agronomic experiments that assumed hypothetical responses Adams and others (1989; 1990; 1993; 1999); Easterling and others (1993); Kaiser and others (1993a; 1993b); Rosenzweig and Parry (1994); Kumar and Parikh (1998).
 20. The argument is that rising temperatures, and changes in the frequency and extent of precipitation are likely to make agricultural areas in these marginal areas in developing countries unsurprisingly even less productive.
 21. That is, in terms of total costs and total revenue of agriculture production.
 22. The case studies cited are adapted from <http://www.ccasia.teri.res.in/country/india/impacts>.
 23. Government of Zimbabwe (1998) *Initial Communication on Climate Change*, prepared in accordance with the UN Framework Convention on Climate Change.
 24. Results for Zimbabwe are based on an analysis of the suitability of various agro-ecological zones for maize production, using the same CERES-Maize model that is widely used among African counties (referred to in publications by Makadho (1996) and Muchena (1994)).
 25. The report, however, notes that the research does not take account of the effects of CO₂ enrichment.
 26. The research builds on work reported in Strzepek and others (1996) using a mathematical model of Egypt's agricultural sector together with an earlier study of the country's macro-economy, agronomy, water resources and land resources.
 27. Not only is the Nile a source for most water, but a large proportion of the arable land (predominantly in the deltaic region) is vulnerable to sea level rise.
 28. Holdridge (1947) formulated a life zone classification to capture the complexities of tropical vegetation. Zones are defined according to "biotemperature"—that is, all temperatures above freezing, with all temperatures below freezing adjusted to 0° C. The assumption, based on plant physiology, is that there is no real difference between 0° C and temperatures less than zero, as within this range, plants are dormant. The life zones are thus defined based on a climatic variable—degrees mean annual biotemperature and not according to degrees latitude or meters of elevation (Woodward, 1996).
 29. Based on two different GCMs (the Hadley Centre (HadCM2) and the Canadian Climate Center) models.
 30. The prediction of precipitation changes are inherently more difficult than predictions of future temperature.
 31. In their model, Mendelsohn and others, (1994) include the economic effects of farm-level adaptation without having to enumerate specific adjustments.
 32. See Lewandrowski and Schimmelpfenning (1999) for an excellent summary of the findings of climate change impacts on U.S. agriculture.
 33. Etterson and Shaw (2001) discuss constraints to adaptive evolution in response to global warming with respect to plant migration and adaptation.
 34. In line with IPCC (1996; 2001), as well as Carter and others (1994), UNEP (1998), Smit and others (2000) and Smit and Pilifosova (2001) adaptations in this paper also refers to adjustments that are intentionally made in agriculture systems in response to expected climatic conditions and impacts.
 35. See Hay (2002) for study on Pacific Islands and Deeb (2002), who focuses on the Caribbean, and Huq, (2002) who looks at Bangladesh for case studies on adaptations to climate change.
 36. Based on new research using the Ricardian approach. The analysis is undertaken at the county level in the United States, district level in India, and municipal level in Brazil.

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37. Based on personal communication from Horowitz regarding recent (unpublished) research by Horowitz and Quiggin (2003).
38. Climate variability could also be the forerunner of longer term changes in climate means (Qunying and Lin 1999).
39. For example, although major infrastructure works are expected to last a substantial period, not including the possibility of climate impacts in the design stages could undermine their overall performance and cast doubt on the effectiveness of long-term investment decisions (Klein and Tol (1997).
40. For example, changing the adaptive capacity of an agriculture system or facilitating particular adaptations to climate change.
41. Public adaptation has the characteristics of a "public good" as defined by Samuelson (1954).
42. For example, poor and landless households are often constrained in their ability to adapt, which in turn can be costly (in terms of increasingly their vulnerability to displacement, morbidity, mortality, and deprivation). Moreover, in contrast to commercial farmers, subsistence farmers do not have as wide a portfolio of adaptation options, which can be due to a variety of reasons; perhaps the most important is access to financing.
43. For example, multiple users of water will necessitate any water supply adaptations to involve landowners, private traders, local authorities, water dependent businesses, national governments, and international organizations.
44. For instance, if there are high information costs to undertake forecasting and identifying patterns on impacts across diverse regions, or inequitable distribution of wealth and access to credit, private adaptation may not only be inefficient but may not be just (Esty and Mendelsohn,1998).
45. However, given political influences on government policy, it is not obvious that even efficient levels of public adaptation will be undertaken.
46. There have been numerous attempts to present a typology of adaptation measures to climate change in agriculture, but few have focused on developing countries. For example, Skinner and others. (2001) and Dolan and others (2001) present reviews of adaptation options in Canadian agriculture. Abildtrup and Gylling (2001) provide the results of a survey of the literature on the experiences of agriculture in the European Union. Schimmelpfenning and others (1996) similarly review the implications of adaptations in the United States. Clearly, the inventory presented here is meant as an overview of the spectrum of primary response strategies that have been highlighted.
47. Dolan and others (2001) indicate that adaptation options can be categorized by their timing (reactive, concurrent, or anticipatory), or temporal scope (short- versus long-term).
48. See also Reilly (1995); Erda (1996); Iglesias and others (1996); Reilly and others (1996); Downing and others (1997); Parry and others (2000).
49. That is, by ensuring that that irregular damages to one crop/livestock can be buffered by the production of other crops/livestock not affected by the same problems.
50. Morgan (1995) provides a review of the use of conservation techniques to mitigate soil erosion.
51. Rosenberg (1981); Dumanski and others (1986); Lewandowski and Brazee (1993); Reilly (1995); Rosenzweig and Hillel (1995); Benioff and others (1996); Downing and others (1997); Erda (1996); Easterling, (1996); Reilly and others (1996); Parry and others (1998); Adams and others (1999); Metz and others (2000); Parry and others (2000).
52. See section 4.2.4.
53. For example, excessive population growth, education and training, employment opportunities, income differentials, political and other freedoms, communication and transportation, urbanization, and climate conditions.
54. In economics research, the classic migration model is that introduced by Todaro (1969) and Harris and Todaro (1970); see Bardhan and Udry (1999).
55. The climate relationship between equatorial Africa and subtropical southern Africa is found to be inverse.
56. For example, Meze-Hausken (2000) suggests that the treatment of the environment-migration relationship has often been based on Malthusian arguments.
57. Goria (1999) discusses direct effects, such as the availability and access to natural resources,

- and indirect effects, where climate factors have a significant influence on income, as factors which can induce migration.
58. Examples from Canada include the Dairy Subsidization Program, the Agricultural Income Disaster Assistance Program, and the Net Income Stabilization Account.
 59. Insurance cover is provided for the sum insured or the market value of the animal at the time of death, whichever is less (GOI 1997).
 60. Studies by Skees and others (1999), Skees (1999); and Skees (2001) are cited in support of the finding that there are few crop insurance programs without government subsidization.
 61. Issues concerning adverse selection and moral hazard are well recognized in the case of insurance.
 62. Studies by Gautum and others (1994); Sakurai and Reardon (1997); Skees, Hazell and Miranda (1999); and Skees (2000).
 63. In contrast, existing climate variation and severe events warrant a response today.
 64. A concurrent crucial measure is the development of seed banks (Benioff and others (1996); Easterling (1996); Mizina and others (1999) and promotion of extension services to diffuse new knowledge among local farmers.
 65. See also Kaiser and others (1993); Reilly (1995); Iglesias and others (1996); Benioff and others (1996); El-Shaer and others (1996); Erda, (1996); Easterling (1996); Reilly and others (1996); Schimmelpfening and others (1996); Downing and others (1997); Parry and others (2000); Mortimore and Williams (2000).
 66. The literature makes a distinction between technological innovations available currently and those that are necessary but should be made available in the future to address climate change.
 67. In a recent article in *Science*, it was highlighted that field experiments in India found that genetically modified cotton crops designed to resist insects have produced dramatically increased yields (Quaim and Zilberman (2003).
 68. Especially with reference to enabling countries to achieve self-sufficiency in cereal grains in the face of rapid population growth.
 69. Given the *public good* nature of research of this type and the need to disseminate results widely, government intervention is also likely to be necessary. In addition, private research initiatives are unlikely to be attractive given that the timeframe for realizing benefits is often too long.
 70. Based on irrigation system efficiency and field application efficiency.
 71. See World Bank (1993) Policy Paper, *Water Resources Management*.
 72. Including deciding which fields to irrigate and when and how much irrigation is necessary given that over-irrigation can have negative effects on quantitative and qualitative yield.
 73. Based on the review of publications, including integrated regional and national economic impacts studies of climate change (Rosenberg (1993), Frederick and Rosenberg (1994) and Yates and Strzepek (1996)) and river basin and urban areas studies (Kaczmarek and Napiorkowski (1996), Stakhiv (1996), Boland (1997), Hobbs and others (1997), Georgakakos and others (1998), Lettenmaier and others (1999)).
 74. For example, compromising indigenous management practices in those areas with an influx of migrants.
 75. Other factors, such as gender bias in the ability to make a decision to change a farming practice can also be a limitation.
 76. For example, purchasing seeds, transportation, draft power (animals), hiring temporary workers, and expanding land under cultivation.
 77. The underdeveloped state of formal rural credit markets in Africa has been highlighted in numerous studies such as Collier and Gunning (1999).
 78. Since the 1980s, reform programs across a number of African countries have aimed to eliminate price controls on agricultural commodities, privatize state farms and state-owned enterprises, reduce taxation of agricultural exports, phase out subsidies on fertilizer and other inputs, and allow greater competition in agricultural markets. Results overall have been mixed. The authors suggest that evidence exists of improvements in market efficiency, reduction in budget deficits, increments in exports, and higher farmgate prices. At the same time, there is also evidence of agriculture price instability, widening of the income distribution gap, and impediments that plague access to inputs.

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79. Albeit the pace and extent of market reforms have varied across countries in the continent.
 80. There are additional benefits. As You (2001) states with reference to China, imports can help meet shortages in local supply of food, but also implicitly will help overcome shortages in the local supply of water.
 81. The report draws attention to the example of government regulation through high import duties imposed on Compact Fluorescent Lamps (CFLs) in Pakistan. According to the authors, the reduction of the duty from 125 percent to 25 percent in 1990 led to the reduction in price and increase in sales of CFLs, which would have contributed to improved energy efficiency (IPCC 2001).
 82. Communication during review of this paper.
 83. Given also the issue of "free riding," research and development and dissemination of results may be necessary by a public authority.
 84. Paxson (1993) found in a study that Thai households engaged in agriculture activities used savings to buffer consumption from income fluctuations, caused by, among other factors, changes in climate.
 85. Ellis (1998) reviews the recent literature on diversification as a livelihood strategy for households in developing countries.
 86. See, for example, Molua (2002) who suggests many of these policies as crucial to assisting farm households in Southwestern Cameroon to cope with climate variability.
 87. In the case of water, all sectors and agencies dependent on fresh water hydrology (agriculture, forestry, urban, energy, ecosystems, and so forth).
 88. While admittedly these recommendations are made with reference to adaptation in Antigua and Barbuda, it is easy to see that they are equally applicable in places with similar institutional frameworks to address climate change.
 89. Thereby avoiding the well known problems of discounting damages that occur in the future.
 90. Smith and others (1996) advocate that the primary tools for determining the appropriateness of response policies include benefit-cost and cost-effectiveness analysis, and adaptation decision matrix and index of changes in vulnerability.
 91. Such as encouraging efficient water use or developing efficient irrigation systems.
 92. Potential adaptations include modifying farming practices through the use of drip irrigation technologies, improved field drainage, selection of drought tolerant species, improved shelter or housing for livestock. For fisheries, modernization and upgrading of on-shore moorings and storage facilities as well as measures to promote greater sea-worthiness and safety of fishing vessels.
 93. Burton (2001) argues that poverty in dryland areas is intensifying due to a combination of factors. These include a reduction in the value of agriculture commodities, an intensification of competition, an increase in the cost of inputs, limited access to markets and a large burden of debt.

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