Chapter 8
Food Security and Adaptation to Climate Change: What Do We Know?

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Abstract The potential for agricultural systems to adapt to climate change is at once both promising and poorly understood. This chapter reviews possible producer and consumer responses to a changing climate, the ability of these responses to offset otherwise negative impacts on food security, and the role of public and private institutions in investing in adaptation where individual responses are insufficient. Accumulated evidence suggests that wealthier societies and households will be better able to adapt to a changing climate because of their greater availability of alternatives and their ability to take advantage of them. Accordingly, investments that improve options for the poor, such as improved agricultural production technologies, financial instruments, and off-farm income opportunities, will likely be critical for adapting food security to a changing climate.

8.1 Introduction

Climate change will not confront a static world. Humans respond to changes in their natural and economic environment and often make themselves better off by doing so, a responsiveness clearly evident in agriculture. As human populations grew and spread over past millennia, food production was expanded into far corners of the world, feeding growing populations in strikingly diverse environments and climates. This ability of humanity to adapt agriculture to new climates is evidence to many that climate change poses no fundamental threat to agriculture – that clever humans, as in centuries past, will simply adapt agriculture to its new growing conditions.

But the magnitude and speed of climate change that is expected over the next century raises serious questions about how much agriculture can be adapted to new climates, how quickly, and at what cost. Will simple farm-level measures such as switching crop varieties be enough to offset expected losses in much of the world? Or will larger investments in crop breeding or irrigation infrastructure be needed to meet

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the food needs of a growing global population? Or could even these efforts fall short? Such questions are central to both anticipating the full impacts of climate change on food security and human livelihoods, and in planning appropriate responses.

This chapter will explore potential adaptations to climate change that might improve food security, where “adaptation” is understood to mean any response that improves an outcome (Reilly and Schimmelpfennig 2000). Many possible adaptations involve direct changes to agricultural systems, such as changing when and where crops are grown. But because food security involves much more than just food production (Chapter 2), we also consider various broader responses to climate change that might improve food security, such as improving social safety nets that protect the poor in adverse years.

Of central interest is the potential of these measures to offset many of the anticipated negative effects of climate change on food security, and in particular the extent to which such adaptations will happen more or less on their own (so called ‘autonomous adaptation’) as opposed to requiring significant investment and foresight for them to occur (‘planned adaptation’). For instance, if we expect farmers to automatically recognize climate shifts and react in ways that offset expected losses, then the need for outside investment and policy intervention in adaptation is small. But if we expect farmers to have trouble responding on their own, and that this inability appears to threaten global or regional food security, then there would seem a pressing need to understand what broader investments in adaptation would be required.

Unfortunately, there is little existing quantitative evidence on the ability of adaptation to improve food security outcomes in the face of climate change, with large uncertainties surrounding both the potential gains from various adaptation measures and the extent to which they will be undertaken autonomously. Particularly difficult is disentangling the relationship between farmer responses to climate variability, which occur continually, and their likely longer run responses to changes in mean climate. Below we review the existing theory and evidence surrounding agricultural adaptation to climate change, and attempt to draw lessons both for investment priorities and for future research needs.

8.2 Farmer Adaptation to Climate: Dealing with Variability

The explicit focus of this book is on climate change – i.e. the potential shifts in the longer-run mean and extremes of temperature, precipitation, and other meteorological variables in a given area. And while longer-run climate exerts significant influence on agricultural decision-making, affecting what crops farmers grow and when and where they grow them, the actual amount of food produced in a given year depends on the specific realization of meteorological variables in that year. Year-to-year changes in these variables (or “climate variability”) play a central role in global and regional food systems and in food security outcomes.

As a result, climate variability can both illuminate and constrain possible longer-run adaptation to climate change. For instance, farmer and food system responses to past weather events are some of the only evidence we have to understand how farmers respond to climate shifts. At the same time, variability also makes production more risky, which might inhibit risk averse farmers from undertaking broader adaptation measures. Finally, the year-to-year noise of climate variability might make it harder to recognize that climate is actually changing.

Observed farmer adaptations to climate variability fall into two main camps: ex ante measures, for which action is taken in anticipation of a given climate realization, and ex post responses, which are undertaken after the event is realized. Ex ante adaptations to variability often center around strategies of diversification, which attempt to capitalize on the differential effects that a given climate event might have on different crops and activities in a given year (Pandey et al. 2007). For instance, farmers growing rainfed crops in a drought-prone environment might seek to diversify the location of their farm plots to take advantage of the high spatial variability of rainfall, grow a range of crops or crop varieties with different sensitivities to climate, or to diversify income sources into non-farm enterprises that are less sensitive to climate (Pandey et al. 2007). They could also choose to maintain flexibility with regard to input decisions until uncertainties about weather realizations are reduced, for instance by shifting when crops are planted. Where possible, farmers might also pay to insure their harvests against failure.

Farmers also undertake various ex post strategies to decrease crop or welfare losses once climate events have been realized. Such strategies include drawing down cash reserves or stores of grain, borrowing from formal or informal credit markets or family, selling assets such as livestock, or migrating elsewhere in search for work in non-affected regions. Ex post adaptations can also include changes to management after the growing season has started, such as replanting of faster-maturing varieties if early-season planting fails, or irrigating where possible if rainfall is meager.

Not all strategies are available to all farmers unfortunately, nor are the available strategies always successful in buffering food security against a variable climate. In wealthier countries, farmers rarely go hungry as a result of drought or other adverse climate events. The existence of social safety nets and functioning financial markets ensure that farmers are either insured against losses, can borrow around them, or can receive help from the government to maintain livelihoods during bad times. Similarly, consumers in rich countries spend only a small percentage of their income on food, and are thus not very sensitive to the food price increases that often accompany droughts or floods.

The same is not often true in poor countries. Although both ex-post and ex-ante strategies can reduce climate-associated losses to some degree, the poorest households in particular are often unable to fully shield consumption from the effects of climate variability. This inability can be dramatic and devastating, as in the case of the drought-related famines in the Sahel and Horn of Africa in the 1980s, but they can also be more subtle, such as in the longer run documented negative effects of climate variability on health and economic outcomes in agricultural households, particularly for women and children (Hoddinott and Kinsey 2001; Maccini and Yang 2008). Such effects are realized because ex ante measures are insufficient, or ex post measures such as insurance or savings are unavailable, or both.

Also important are the perverse longer run effects of some of these adaptive measures on the food security of poor households. For instance, while ex ante strategies can reduce the risk of catastrophic losses in bad years, they can also reduce the income earned in good years, because farmers might have planted a less-risky but lower-yielding (and typically lower-value) crop. The long-run costs in foregone income from this risk-mitigation can be high – as much as 15–30% of average income (Rosenzweig and Binswanger 1993; Dercon and R. World Institute for Development Economics, 2002). Similarly, ex-post strategies can also avoid devastating declines in consumption in ways that harm longer run earning potential. Distressed liquidation of productive assets such as livestock or land can prop up consumption in one year, but dampen the subsequent productivity and food access of households in later years, an effect again well documented in the developing world. These perverse temporal tradeoffs are a perennial and painful dilemma faced by farmers throughout much of the developing world.

Given the negative impacts of climate variability on economic livelihoods and food security in much of the developing world, helping farmers better adapt to this variability is a central concern of development. Many have also argued that a focus on adapting to climate variability is the best way to approach adapting to climate change. This is in part because most farmers and governments can more readily understand the threat of variability, and thus are more likely to engage in building knowledge and institutional capacity to cope with variability (Washington et al. 2006; Cooper et al. 2008). It is also because climate variability can have large effects on livelihoods, and thus that longer-run adaptations will only be undertaken if they do not compromise the ability to cope with variability.

But as climate change adds to the stress of variability, will existing coping mechanisms be enough to offset expected losses from climate change in the absence of adaptation? Are current strategies for adapting to variability appropriate strategies for adapting to longer-run climate change? If not, and novel adaptations are called for, should we expect farmers to adopt them on their own, or will significant investment and policy intervention be needed to adapt food production to new climates?

8.3 Adapting to Climate Change: Some Difficulties

8.3.1 Signal Detection

Adaptation at the farmer level requires three basic steps: detecting a shift in one's external environment, determining that it would favor a change in behavior, and undertaking that change (Hanemann 2000; Kandlikar and Risbey 2000). Thus the first step in adapting to climate change requires detecting the signal of climate change in the noise of climate variability. Given the amplitude of climate variability in many regions, this might be no small task.

Figure 8.1 illustrates this detection problem, showing historical and projected future trends in temperature and precipitation for millet areas in Niger based on the GFDL climate model, which happens to project much larger decreases in precipita-

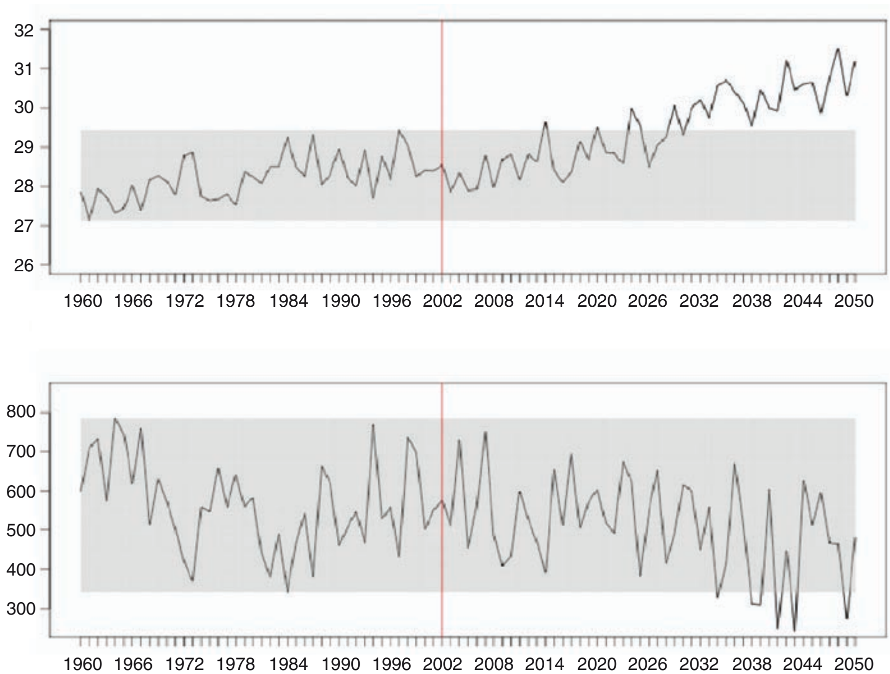

Fig. 8.1 Historical and projected future changes in temperature (*top panel*, in °C) and precipitation (*bottom panel*, in mm) for millet growing areas in Niger, 1960–2050. Data left of the vertical line are observed (CRU), and data to the right are based on projected changes from the GFDL climate model for the A1B scenario, assuming similar variability to the historical data. *Grey boxes* represent the range of historical variability between 1960 and 2002

tion in the Sahel (around 25% declines by 2050) than most other climate models. For temperature (top panel), the signal of climate change quickly emerges from the noise of past temperature variability, with every growing season hotter than the hottest year on record after around 2030 – a result we should expect for much of the tropics (Battisti and Naylor 2009). This is not the case with precipitation. Despite a very large projected decrease in average annual precipitation for millet-growing regions in Niger in this model, most years remain well within historical variability, potentially obscuring the underlying drying trend.

Farmers in developed countries have access to a wealth of climate and weather data, and so presumably could learn about trends in climate without having to sense them independently. The same is often not true for farmers in poorer countries, who rely on various traditional methods for climate forecasting, and who might be more or less on their own in discerning longer-run climate shifts.

Evidence is mixed on farmers' ability to correctly perceive such longer-run shifts. Meze-Hausken (2004) finds that farmers in northern Ethiopia report a decline in rainfall where rainfall gauges report no change. Maddison (2007) shows mixed results in farmers' ability to correctly perceive climate shifts across a range of African countries, with farmers in many countries correctly recognizing trends in mean temperature and rainfall, and others reporting trends in disagreement with observed climate data. Thomas et al. (2007) find qualitative evidence of South African farmers' abilities to detect subtle changes in mean state and variability of climate, but it is unclear whether this reveals actual recognition of trends, or the tendency to overestimate the frequency of negative events (Cooper et al. 2008).

8.3.2 Cognitive Biases

Once a farmer is convinced that the climate has changed, he or she must decide whether and how to respond. Most humans exhibit a considerable bias towards maintaining old ways, even in new environments, with the thought that what worked in the past should continue to work in the future. A clear example of this from the business world is that very few firms survive for long periods of time; the economy evolves largely by new firms replacing old ones rather than firms themselves adapting (Beinhocker 2006).

In agriculture, there may be a tendency to underestimate the need to change management in a new climate. For example, a survey recently conducted in the Yaqui Valley of Mexico asked wheat farmers whether they perceived a change in temperatures over the last decade, whether this change was positive or negative, and whether it had a positive, negative, or neutral effect on their yields (Ortiz-Monasterio and Lobell, 2005). Out of 88 farmers, 85 (or 97%) reported a significant shift in temperature, but only 33 (or 38%) felt the change had an effect on wheat yields, despite the fact that temperatures exert a strong control on yields in this region (Lobell et al. 2005).

Other surveys suggest an opposite problem: that farmers might be too quick to update their beliefs about changes in climate. In surveys of Canadian corn farmers, Smit et al. (1997) show that these farmers tend to heavily weight the previous year's weather in deciding what varieties to plant for the upcoming season. Though surveys are an imperfect means to gauging farmers' perceptions, these results illustrate that recognition of a climate trend is only one step towards successful adaptation.

8.4 Farmer Adaptations and Their Potential Gains

Supposing for now that a climate signal is detected, and that the need for a change in management is perceived, farmers must then decide how to respond. This response will depend on the choices they see themselves having and the perceived costs and benefits associated with each choice. Various potential adaptations are listed in Table 8.1, each of which we now explore in turn.

Table 8.1 Potential farmer adaptations to climate, and some reasons why they might or might not help

Adaptation	Why it might help	Why it might not help
Shift planting date	Take advantage of lengthened growing season	Less useful where current growing season length is not limited by cold temperatures
Switch varieties	Other existing varieties better suited to new climates	More suitable varieties not always available
Switch crops	Other crops more suitable to new climates	Hot countries have nothing to switch to
Expand area	Climate change could expand suitable area	Less true in the tropics; possible soil constraints; expansion may come with significant environmental costs
Expand irrigation	Helps alleviate moisture constraints	Can be expensive; often requires large government investment; many places have limited water resources
Diversify income	Non-farm income sources less climate sensitive	Rural non-farm economy linked to agricultural productivity
Migrate	Some areas might be hurt less than others by climate change	Urban areas already strained

8.4.1 Switching Planting Date

Perhaps the simplest farmer adaptations have to do with changes in on-farm management, which include decisions about what crops to grow and when and how to grow them. One of the more straightforward of these possible adaptations is the option to shift when in the year crops are planted. Current decisions about when to plant are made based on a number of factors, including available soil moisture, the expected timing of temperature extremes, and the demands of multi-cropped systems. Year-to-year shifts in planting dates are already a demonstrated farmer adaptation in the face of climate variability, particularly for farmers in rainfed environments who often must wait for the onset of the rainy season in order to plant. Farmers in parts of Africa and Asia, for instance, routinely shift planting dates by a month or more from year to year in response to variability in when monsoon rains arrive (Falcon et al. 2004; Tadross et al. 2005).

If climate change results in large shifts in the factors that determine optimal planting times, farmers could potentially gain by further changing the timing of their crop production. In a crop model simulation of US rainfed spring wheat under a warmer and wetter future climate, Tubiello et al. (2002) find that systematically shifting planting 2 weeks earlier transforms what would have been 20–25% yield losses by 2030 into modest gains. This is because cold temperatures limit early planting in current climate, subjecting the crop to heat and drought stress during critical stages of plant growth, and warmer climates appear to allow earlier planting and less stress during sensitive growth stages. Similarly, cropping systems where

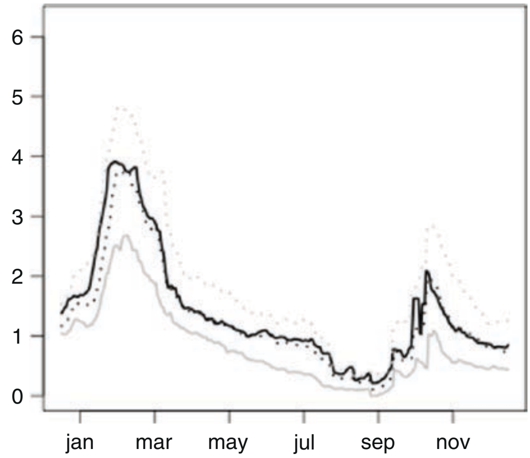

Fig. 8.2 Simulated maize yields (t/ha) in southeastern Kenya using CERES-maize. Planting is simulated independently on each day of the year, for current and hypothetical future climates. *Black solid line* = current climate; *black dotted*=+2°C; *grey solid*=+2°C, –20% precipitation; *grey dotted*=+2°C, +20% precipitation. Optimal planting for all scenarios peaks near the start of the long rains

irrigation is possible for much of the year might also benefit from shifting planting dates, particularly for crops likely to experience frequent temperature extremes in their current growing season as the climate warms.

But for rainfed systems throughout much of the tropics, where planting is typically limited by moisture rather than temperature, it is less clear that shifts in planting date will offset much of the expected damages from climate change – largely because climate change is expected to reduce growing season length throughout much of the tropics (Chapter 3). Figure 8.2 shows representative results for maize at a somewhat arid site in southeastern Kenya, with yields simulated using CERES-Maize for every possible planting date in the year under current and hypothetical future climates. The planting dates resulting in maximum yield occur near the beginning of the long rains, as expected, with a second smaller peak during the short rains (when a second crop is often planted). With planting moisture-limited, future climates suggest gains or losses in yield but no shifts in optimal planting date.

8.4.2 *Switching Varieties or Crops*

A second possible farmer adaptation to climate change is to switch varieties or crops to something better suited to the new climates they face. A farmer currently growing maize might switch to a faster-maturing maize variety if drought becomes more common, or might choose to grow a potentially more drought-tolerant crop like sorghum. But such decisions will not be made on the basis of climate alone. Different varieties and crops have different input requirements and costs associated with their production, different responsiveness to local stressors and can face very different output prices in ways that affect their profitability. To the extent that climate change affects the relative profitability of different crops and varieties in ways apparent to farmers – and in ways they can respond easily to – crop or variety switching could constitute a fruitful adaptation strategy.

In the case of switching varieties, climate change suggests two primary adaptation alternatives, the choice of which depends on whether moisture or heat is expected to be limiting. In low-rainfall areas where moisture stress is expected to remain a primary constraint on plant growth, a promising adaptation might be to plant faster-maturing varieties that avoid drought or heat stress during sensitive stages of plant growth, such as flowering or grain filling. Developing faster-maturing varieties for areas with short and variably rainy seasons (i.e. much of Africa) is a common goal of many breeding programs, and such a strategy would seem promising anywhere climate change is expected to shorten growing seasons.

In areas where moisture regimes exhibit little change, however, a move in the opposite direction toward longer maturing varieties might be preferred, because warmer temperatures tend to speed development and lower yields (Chapter 4). Longer maturing varieties would thus be required to maintain the length of time for total crop development as temperatures warm. Simulation studies indicate some benefits for this strategy. For instance, Tubiello et al. (2002) find that switching to longer-maturing winter wheat varieties at a site with plentiful moisture fully offsets the 15% projected yield losses under climate change, but find somewhat smaller gains for more arid areas.

Beyond shifting among varieties, farmers could also switch what crops they grow as the climate changes. As with choice of variety, farmers' choices about what crops to grow depend only partly on climate, and year-to-year crop choice decisions are likely dictated much more by expected prices at harvest than by climate concerns. For instance, farmers in the Midwestern US readily shift area between maize and soybeans depending on market signals. Nevertheless, over the long run climate exerts clear influence on crop choice. Climate clearly explains much of why rice is grown in the warm wet climates of Southeast Asia and wheat in the cooler, drier northern temperate latitudes of North America and Europe, and not the reverse. Similarly, the highly variable climates of much of Africa induce poor risk-averse farmers to grow lower-value but drought-tolerant crops such as cassava.

If climate matters to crop choice, then farmers could plausibly gain by switching crops if new climates favor a different crop over the one currently grown. This is the basic thrust of the so-called "Ricardian" estimates of climate change impacts on agriculture (Chapter 6). Instead of determining the potential impacts of climate change on the yield of a specific crop, as many studies do, these studies seek to isolate the effect of mean climate on land values in a given region, while controlling for other factors beyond climate that might affect land value (slope, soil type, etc.). The argument is that with well functioning markets, the value of land should reflect the current and (discounted) future stream of profits that can be made from using the land – whether it be used to grow corn or wheat or golf courses. The estimated effect of climate on land values should then in theory reflect all of the crop-switching adaptations farmers could make over the long run (Mendelsohn et al. 1994).

Consistent with the argument that the land values approach offers more thorough picture of farmer adaptation, estimated impacts of climate change are often more positive/less negative in these studies than in other studies that focus on single crops (e.g., Cline 2007, Chapter 5). But this method of modeling adaptation is not without its significant critics, who point out among other things that such methods might overstate the choice set that each individual farmer might have (Hanemann 2000), and thus overstate potential gains from adaptation.

More broadly, there are various factors that might constrain a farmer's ability or willingness to switch varieties or crops, such as the limited availability of alternatives, or the costs or perceived risks associated with adopting a new crop or variety. For instance, seed systems throughout much of Africa are poorly developed, such that locally adapted varieties of different maturity lengths or resistance to various abiotic stresses are not always available – and where they are developed, poor, risk averse farmers are often slow to adopt new technologies. Further, farming systems and local consumer taste preferences are often strongly intertwined, likely inhibiting rapid switching among crops. Finally, in countries with recurrent droughts but where temperatures will warm significantly under climate change (i.e. most of Africa), the optimal variety choice might be far from apparent: choose a shorter-maturing variety that avoids big losses in very dry years, or a longer-maturing variety that might maintain average yields as the climate warms?

These constraints are typically not captured in simulation studies of farmer adaptation, such as those using crop models, but can be picked up in some statistical approaches (Chapter 6). The limited evidence available from these approaches suggests that even in rich countries the potential for farmer adaptation within crops could be limited. For instance, using county-level data on US rainfed corn yields, Fisher et al. (2007) show that the estimated effect of temperature on yields is nearly equivalent whether you look at short run yield responses to variability (where little adaptation would be possible) or responses of yield to longer-run climate averages (under which farmers would have had time to adapt). This suggests that, at least under the range of existing technology and management, switching corn varieties would do little to stem the harmful effects of rising temperatures (see Chapter 6).

8.4.3 Expanding Irrigated and Total Cropped Area

In addition to changing their crop mix, farmers could also change how much land they farm or the way in which they farm what they have. Introducing irrigation into currently rainfed systems is an often cited adaptation option, and will indeed likely be critical for some regions. As mentioned, irrigation not only alleviates water stress but could expand the opportunities for switching planting dates and varieties, as well as increasing returns on investments in fertilizer and other inputs. Large scale expansions of irrigation infrastructure are typically financed and regulated by the public sector, and therefore farmers often cannot decide on their own to implement irrigation.

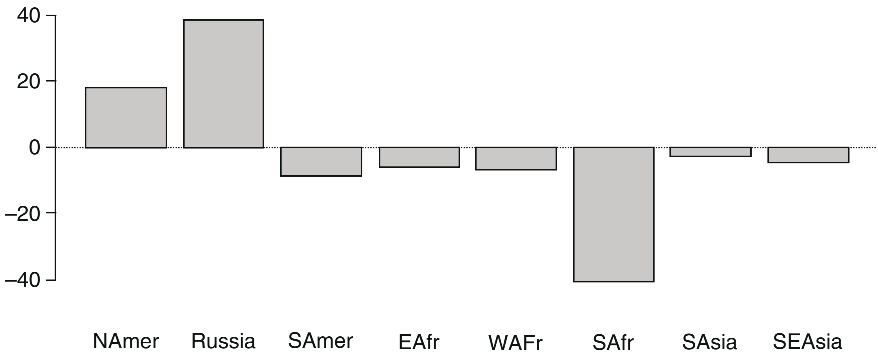

Fig. 8.3 Percent change in land suitability for rainfed cereal production, for selected regions by 2080 (Hadley model, A2 scenario) (from Fischer et al. 2002)

But in some systems irrigation may represent a truly autonomous adaptation, for instance if a treadle pump is installed to irrigate a small number of fields.

There is also considerable scope for implementing technologies that improve soil moisture without irrigation, such as conservation tillage and rainwater harvesting (Ngigi et al. 2005; Hobbs et al. 2008). The latter includes techniques such as farm ponds and zai pits, and may be increasingly relevant if rainfall becomes more episodic and intense, as suggested by many climate models (Chapter 3).

In areas currently too cold or dry to support rainfed agriculture, climate change might enable the expansion of cropped area into new regions. If such expansion is deemed socially and environmentally acceptable, then gains from production in these new areas could offset potential regional or global losses elsewhere (see Section 8.5).

Figure 8.3 shows one estimate of regional changes in the amount of land suitable for rainfed production, based on the agro-ecological zoning (AEZ) model and output from one climate model (Fischer et al. 2002). High latitude temperate regions generally gain and tropical areas generally lose suitable land in these projections, with changes exceeding 40% in either direction by the end of the century for some climate scenarios. Critical uncertainties in these projections are assumptions about soil constraints in these new regions, which are usually incorporated into assessments but on the basis of scant data. Improving the accuracy and use of soil information in these regions is a major need for determining future potential of expansion in places like Canada and Russia.

8.4.4 *Diversify Income*

On-farm adaptations are not the only possibility for bolstering food security in the face of a changing climate. Recall from Chapter 2 that while many rural poor lean heavily on agricultural activities for income generation, off-farm income can also play an important role in economic livelihoods. To the extent that non-agricultural income sources are less climate-sensitive than farm activities, further diversification of incomes out of agriculture might seem a promising adaptation strategy in the face of a changing climate. Indeed, some commentators have suggested that such a strategy is the only plausible way that Africa can adapt to climate change (Collier et al. 2008).

The ability of an income diversification strategy to buffer food security in the face of a short-run climate shock or longer-run climate shift depends on the off-farm income-generating activities available, and the extent to which households can take advantage of them. As Davis et al. (2007) show, almost all rural households earn at least some off-farm income, but the nature and motivation of this earning can differ significantly. For some households, off-farm work in manufacturing or in the service sector can offer much higher returns than farming, and households that can take advantage of these opportunities often benefit greatly.

But for many of the poorest households, participation in these potentially more lucrative non-farm activities is often limited by liquidity or human capital constraints (the cash to invest in a sewing machine, for instance, or the skills to run it). For these households, off-farm income generation often entails lower-return activities such as seasonal wage labor, which are used more as a coping strategy to deal with seasonal credit constraints in agriculture or with farm productivity shocks due to climate or other factors.

Using off-farm income as a climate coping strategy is likely more successful when climate shocks are idiosyncratic rather than covariate – i.e. when in a given year they affect some households in a region but not others. This is because in many developing countries, particularly the poorest ones, returns to off-farm activities can be highly correlated with agricultural productivity (Jayachandran 2006; World Bank 2008b). If most people in a village are farmers, and all experience a yield (and thus income) decline simultaneously, then demand for both agricultural wage labor and off-farm goods and services will likely also fall.

Overall, if there are specialization options available, and households can take advantage of them, then diversification looks like a very appealing adaptation to climate change. But where diversification is used as a necessary but low-return coping strategy and households face significant barriers to entry into higher-return activities, or where the non-farm rural economy is tightly linked to an agricultural sector deeply harmed by climate change, then income diversification looks less promising. Again, as with new technology adoption, diversification will likely be more challenging in poorer countries with less developed infrastructure, and for poorer households within those countries.

8.5 Broader Economic Adjustments to Climate Change

Even if individual farmers do not successfully perceive and adapt to climate change, market forces will tend to favor those farmers and regions that are more successful in the new climate. These market-mediated responses can range from individual farmers taking over their neighbor's land, to entire regions shifting into and out of production of different crops.

Most studies of market effects to date have focused on the latter mechanism, namely markets adjusting through international trade. All countries participate to some degree in international trade in agricultural commodities, and few households anywhere are fully isolated from markets. Under current climate variability, in which climate shocks typically correlate poorly across regions in a given year, global and regional agricultural markets can move food from areas of surplus to areas of deficit and dampen what might have otherwise been large price effects in regions experiencing shortfall.

Studies that attempt to directly capture these trade effects in understanding the potential impacts of climate typically embed regional production effects in a global trade model, which add up supply and demand across regions for a given period and calculate a market-clearing world price. Farmers and consumers then react to this price in the next period by adjusting what they produce and consume, new production effects are included, and a new world price calculated.

Such studies typically find that allowing countries to trade with one another tends to reduce the estimated negative impacts on global production, as production shifts into areas where the climate becomes more favorable (Rosenzweig et al. 1993; Darwin et al. 1995; Fischer et al. 2002). Figure 8.4 shows production impacts with and without economic adjustment estimated as reported by two major studies (also plotting estimates of gains from all farmer adaptations added together), which suggest that including these adjustments reduces estimated climate losses by anywhere between 25% and 75% of the unadjusted losses. These gains in turn dampen what would otherwise have been large increases in food prices, and reduce negative impacts on food security relative to a non-adjusting world.

But there are many important caveats to these conclusions that relate to the often poorly tested assumptions of the trade models. Most notably, growth in national GDP in these studies is often assumed to be independent of agricultural productivity

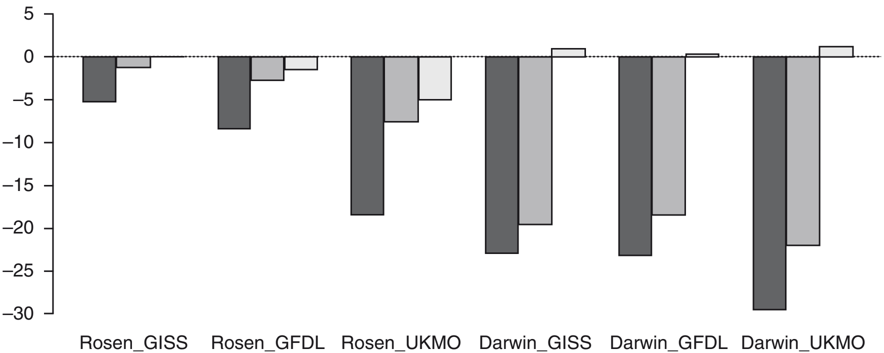

Fig. 8.4 Estimated effects of climate change on global cereal production to 2060 for two global studies, each running three climate models. *Dark grey* = no adjustment, no farmer adaptation; *medium grey* = economic adjustment, no farmer adaptation; *light grey* = with adjustment and farm-level adaptation (from Darwin et al. 1995 and Rosenzweig et al. 1993)

changes, and is projected into the future at rates often much higher than recent historical experience. As a result, declines in agricultural productivity do not translate into income declines, and so agriculturally dependent countries that are hit hard by climate change still have the income to purchase imports and cover production shortfalls, thus perhaps underestimating the income-related impacts on food security.

Whether or not agriculturally dependent countries (or households) will in fact be able to maintain food consumption in the face of declines in a primary income source is a crucial question, and underscores the importance of climate interactions with broader economic trends. On the whole, wealthier societies and households appear more adaptable to climate change: they are more willing to adopt higher-risk higher-return technologies because they can smooth consumption through savings or credit markets, they are less sensitive as consumers to food price rises, and they have the infrastructure and resources to import in the face of shortfalls.

Recall from Chapter 2 that climate is only one of many possible factors that shape a given country's longer-run economic trajectory. If households or societies are able to enrich themselves despite the potential adverse effects of climate change, then food security could overall become less sensitive to climate. But in countries where agriculture is a primary engine of growth, climate change could slow overall growth trajectories and limit the expansion of choice that typically accompanies economic development.

8.6 Planned Adaptations

Although autonomous adaptations of farmers and markets will certainly help, many studies indicate that they will be limited in their capacity to reduce the costs and impacts of climate change (Rosenzweig et al. 1993). Planned interventions by governments and other institutions may therefore be needed beyond what can be expected automatically. Here we provide a brief discussion of several potentially important planned adaptations.

8.6.1 Investments in Crop Development

As climate change pushes regional climates outside of historical experience, development of crop varieties better suited to these new climates will be an important component of adaptation. Chapter 9 reviews the breeding challenges associated with developing crops for new climates. Throughout much of the world, these challenges will mostly be met by the private sector. In high-income countries, the private sector accounts for 55% of total agricultural R&D expenditures, and many companies are actively publicizing their efforts to develop varieties well suited to changing climates (see, for instance, Monsanto's efforts with drought-tolerant maize).

But private sector investment will likely not be enough in many developing countries, where input markets are more poorly functioning and poor farmers represent limited economic demand for new varieties. Public-sector expenditures currently account for 94% of agricultural R&D in the developing world (Pardey et al. 2006), and historically these investments have yielded extremely high social returns (Alston 2000). Unfortunately, inflation-adjusted public sector spending on agricultural R&D in developing countries has been roughly stagnant since the 1980s, and key sources of external aid to developing country agriculture have fallen dramatically over the same period (Pardey and Beintema 2002). At the same time, however, large recent investment in agricultural development by foundations such as the Gates and Rockefeller are beginning to fill some of the public-sector void, particularly in Africa.

More broadly, given the decade or more it typically takes to develop and release new varieties, breeding programs face the difficult task of identifying regional and global priorities in the context of rapidly warming temperatures and continued uncertainty about the relative impacts of climate change on yields of different crops (Lobell et al. 2008). Supplying breeders with better information on the conditions and constraints that climate change will pose for future agricultural systems is therefore a major research priority.

8.6.2 *Making Markets Work for the Poor*

Developing improved agricultural technology will almost certainly be necessary for adapting agriculture to climate change, but it is unlikely to be sufficient. Current adoption of improved cereal varieties differs widely across Africa, with estimates ranging from 0% adoption of improved millet varieties across much of the continent, to 80% adoption of improved maize varieties in parts of East and Southern Africa (Maredia et al. 2000; World Bank 2008). To adapt to climate change, farmers need access to these improved technologies and the knowledge and incentives to use them. While information provision to farmers will likely continue to require direct public-sector action (see Section 8.6.3), farmer access to new technologies is likely better served by the private sector in the long run, given the high fiscal and administrative costs often associated with government input distribution programs (World Bank 2008). Governments are often better positioned to provide investments in the physical and financial infrastructure that underpin functioning agricultural markets. These could include investments in transportation infrastructure to better link farmers to input and output markets, investments in the functioning of these markets themselves, and investments in improving poor farmer access to financial infrastructure such as credit and insurance.

For instance, input markets in many poor regions – notably Africa – are often poorly functioning and hamper farmer response to changes in climate. Expanding private-sector provision of inputs like seeds and fertilizer faces numerous difficulties, including high transport costs and weak demand from credit constrained and risk averse farmers. Government investment in roads and ports could help reduce transport costs, and recent foundation investments in agrodealer networks in East Africa has shown promise in linking smallholders to input markets (World Bank 2008).

Similarly, improvements in financial infrastructure could boost both ex-post and ex-ante adaptation capabilities of farmers. Expanding the availability of credit and insurance in poor countries, for instance, could help farmers finance the purchase of inputs, smooth incomes in the face of production shortfalls, and thus encourage diversification out of low-risk, low-return crops and into higher-reward activities.

In particular, there is widespread interest in the development of crop insurance schemes that would reimburse farmers in the event of a climate-related production shortfall. If risk avoidance explains much of why poor farmers are reluctant to adopt higher-return technologies, then the availability of insurance could speed the adoption of new, better-adapted varieties, in addition to helping maintain incomes in bad years.

Providing climate insurance products to poor producers faces a number of hurdles, including the transaction costs of dealing with high numbers of dispersed smallholders, moral hazard problems (were observed production shortfalls a result of bad weather or farmer laziness?) and issues related to the covariate nature of climate risk. This latter concern, in which climate shocks cause simultaneous losses across farmers in a region and thus exceed the reserves of the insurer, is a primary explanation for why insurance is unavailable in many poor regions (Barnett et al. 2008). If climate change greatly increases the incidence of "bad" years, the stability of existing insurance schemes could be further compromised.

Various solutions have been proposed to overcome these problems, including the development of index-based insurance products where payouts are linked to a publicly observable index such as rainfall. In these products, payments would be triggered if rainfall (or some other variable) fell below a pre-determined threshold. Such "weather-indexed" crop insurance schemes would overcome moral hazard problems, and could be helped to remain solvent in the face of covariate shocks if further guaranteed by governments or larger financial institutions. Various products are being piloted throughout the developing world, with some apparent successes (World Bank 2005; Gine et al. 2008).

8.6.3 Building Local Knowledge

Public-sector involvement in information provision to farmers has long been a cornerstone of agricultural development strategies, with large proven benefits to agricultural output in both rich and poor countries (Birkhaeuser et al. 1991; Alston 2000). These strategies can involve educating farmers about the availability of new technology and how to use it, providing information on improved farm management techniques such as optimal input use, or providing forecast information about likely short- or longer-run shifts in climate. Including farmers in research design and implementation can also be an important means toward successful technology adoption. For example, adoption of new wheat varieties and no-till management in South Asia has been greatly accelerated through participatory research trials conducted in farmers' fields, where farmers' can see first-hand the benefits of new seeds or techniques (Ortiz-Ferrara et al. 2007).

8.6.4 Expansion of Irrigation Infrastructure

Irrigation was discussed above (Section 8.4.3) as a possible autonomous adaptation, but in many cases major public investments will be needed to provide farmers access to water. Some of these investments would undoubtedly happen even without climate change. For example, as part of its recent outlook assessment, the FAO projected changes in irrigated area for 93 developing countries notwithstanding climate change (Faurès et al. 2002). Overall an additional 40 Mha in irrigated area was anticipated by 2030, an increase of 20% over 1997–1999 levels. An increase in the cropping intensity (number of crops per year) on these lands is also anticipated, which results in a 33% increase in the effective area of crops harvested from irrigated land. A regional breakdown of these projections (Table 8.2) shows that most of the expansion in absolute terms is expected in Asia, with Africa anticipated to remain with only roughly 2% of cropland area under irrigation.

The additional irrigated areas will reduce impacts of climate change relative to no expansion, and in that sense will represent an adaptation. But as with most other planned adaptations, these investments also accrue benefits in the current climate, and some level of investment would therefore occur even without concern for climate change. Partitioning out the additional investments needed or benefits occurring because of climate change can therefore be difficult. This is similar to the questions of additionality that plague funding of mitigation projects, and will certainly be a challenge for evaluating pledges of adaptation funding in the future.

Nonetheless, it is clear that only irrigation beyond this baseline amount can truly be considered an explicit response to the added pressures of climate change. What will such investments cost? A recent review of project costs by the African

Table 8.2 One study's projection of increases in irrigated area for developing countries, without adaptation to climate change (Faurès et al. 2002)

	Irrigated area in 1997–1999		Irrigated area in 2030		Increase 1999–2030	
Region	Mha	As % of total crop area	Mha	As % of total crop area	Mha	%
All developing countries	202	21	242	22	40	20
Sub-Saharan Africa	5.3	2	6.8	2	1.5	28
Near-East/North Africa	26	30	33	35	7	27
Latin America and Carribbean	18	9	22	9	4	22
South Asia	81	39	95	44	14	17
East and Southeast Asia	71	31	85	36	14	20

Development Bank and the International Water Management Institute (Inocencio et al. 2007) puts the average cost of new irrigation projects at roughly $8,200/ha in developing countries, with higher costs in Sub-Saharan Africa ($14,500) relative to other regions (ranging from $3,400 in South Asia to $8,800 in the Middle East and North Africa). Much of this difference can be attributed to the smaller size of most irrigation projects in Africa, which increases per area costs.

Applying these costs to the expected rates of expansion in Table 8.2 yields a total cost of roughly $300 billion over the 30-year period. If doubling the anticipated rate is considered as a target for adaptation, then the cost would be roughly $10 billion per year. Doubling rates in Sub-Saharan Africa would cost roughly $650 million per year assuming past costs, although several strategies for cost reduction have been identified (Inocencio et al. 2007). These are of course extremely crude estimates, but they raise important questions about the opportunity costs of such investments, particularly given the dismal past performance of most large-scale irrigation projects in Africa (World Bank 2008). Potentially more cost-effective solutions include the rehabilitation of existing systems, investments in rainwater harvesting approaches (discussed in Section 8.4.3), and investments in smaller-scale irrigation systems for high-value crops.

8.6.5 When Adaptation in Agriculture Is Not Enough

Even if all of the above adaptation measures are taken (perhaps a big if), food systems may still not be fully shielded from the negative effects of a changing climate. As a result, a final set of planned adaptations might involve strengthening social safety nets to deal with climate-related shocks to food systems when they inevitably occur.

The expansion of insurance products to farmers (explored above) would be a primary means for smoothing producer income in the face of climate induced productivity shortfalls. But what about agricultural wage laborers whose incomes typically fall in bad climate years (Jayachandran 2006), and rural and urban net-consumers who are hurt by rising food prices? Typical social safety nets in this context include public works programs that employ individuals who would otherwise lose significant income in the face of a climate shock; conditional cash transfer schemes, in which payments are made to households in the face of a shock, conditional on some behavior (e.g. sending their children to school); or food aid, where donors contribute either food or cash, which is then distributed to households (in the case of direct food aid) or used by various organizations to purchase food locally which is then distributed.

Operation of these safety nets is typically improved when programs are in place before a shock arrives, and when governments hold reserve funds for their operation (given that government revenues, and thus funding, can also decline in a bad year) (World Bank 2008). In the specific case of food aid, most research suggests cash-based food aid is a more efficient means of aid delivery in the face of shortfalls, although there are caveats (Barrett and Maxwell 2005).

8.7 Measuring Progress in Adaptation

Given the importance of climate adaptation to the future of agriculture, it is imperative that we improve our understanding of how and how fast management and technologies adaptations will proceed. In particular, understanding the pace and impact of autonomous adaptation will be necessary for identifying the scope and type of needed planned adaptations. The recent and ongoing changes in climate may offer some insight into what farmers are actually doing in response. However, how will we recognize adaptation if and when it is happening? Among the many changes sure to occur in agricultural management and technology, will we be able to distinguish those that qualify as adaptation? Put more simply, what will an "adapted" food production system look like?

Broadly speaking, an adapted world in 2050 will have some key characteristics to look for: widespread planting of new crop varieties; area expansion of crops and shifts in planting dates, particularly in temperate regions; expansion of irrigation and water harvesting; and effective institutions for anticipating and responding to droughts and local food production shortfalls. Realizing this adapted world, however, will require difficult decisions on the part of public and private sector agencies around the world with regard to how, where and when to invest. Further scientific research will be critical in informing this process, both to further reduce uncertainties surrounding likely impacts in the absence of adaptation, and to identify regions where producers and consumers will be unable to respond on their own and where investment could be most needed.

8.8 Summary

The rapid pace of climate change and its anticipated large negative effects on many agricultural systems suggest a broad and pressing need for adaptation. For farming households, the nature of these responses will depend on their recognition that climate is changing and their ability to adjust their behavior in response, perhaps through altering farm management practices or diversifying into off-farm income-generating activities. Such responses must happen in the context of climate variability, which can obscure longer-run climate trends and make more risky the adoption of various adaptation measures. Further contributing to the difficulties is the limited choice set already faced by many food insecure households, which is often a result of high productivity risk, lack of access to insurance and credit, and/or limited connection to functioning input and output markets.

As a result, broader public and private investments will almost certainly be needed to help poor households adapt to climate change. These could include direct investments in the productivity of agriculture, such as in the development of improved crop varieties better suited to new climates; investments aimed at improving the physical and market infrastructure that typically underpin functioning economies; or investments that bolster the social safety nets that help poor households maintain their welfare in the face of a livelihood shock. While the optimal composition of investments will likely vary by country, scientific research can contribute important information concerning where climate change will hit hardest, how agricultural systems are likely to respond, and what particular investments in adaptation could yield high returns.

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