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Featured Article

Adaptation of Agricultural and Food Systems to Climate Change: An Economic and Policy Perspective

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Abstract *Adaptation of agricultural and food systems to climate change involves private and public investment decisions in the face of climate and policy uncertainties. The authors present a framework for analysis of adaptation as an investment, based on elements of the economics, finance, and ecological economics literatures. They use this framework to assess critically impact and adaptation studies, and discuss how research could be designed to support public and private investment decisions. They then discuss how climate mitigation policies and other policies may affect adaptive capacity of agricultural and food systems. They conclude with an agenda for public research on climate adaptation.*

JEL Codes: Q10, Q50.

One of the most important sectors of the economy, U.S. agriculture is highly dependent on climate. Farms and ranches comprise the largest group of private owners and managers of land that impacts on ecosystems and the services they provide. In addition agriculture is playing an increasingly important role in the energy sector through biofuels and biomass production. Consequently the impacts of climate change on agriculture, and agriculture's ability to adapt to and mitigate the impacts of climate change, are critical issues for agricultural households as well as the general public and policymakers.

The importance of agriculture to the U.S. and global economies extends far beyond the farm and ranch to complex systems of storage, transportation, processing, and marketing. Whereas production agriculture accounts for less than 2 percent of U.S. gross domestic product (GDP), food systems beyond the farm gate represent more than 10 percent of GDP, and agricultural commodities and processed foods comprise about 10 percent of U.S. exports. Although most research to date on adaptation to climate change has focused on agricultural production, climate change and greenhouse gas (GHG) mitigation have implications for the food system that remain largely unexplored. Potential impacts include the effects of sea level rise on transportation infrastructure, changes in the design and location of storage facilities, changes in the geographic range and type of food pathogens, the effects of regulatory policies on adaptive capacity of the food system, and the implications of energy and GHG mitigation policies for the economics of our domestic food systems.

Despite these potential impacts of climate change on agricultural and food systems, and the resulting need to anticipate and adapt to climate change, climate policy remains highly contentious. Most people can agree that climate is highly uncertain—particularly at the spatial and temporal resolution relevant to agricultural systems—and likely to remain that way. Even if we cannot resolve the uncertainty about future climate, we can make investments to reduce the uncertainty about the value of alternative adaptive options and develop systems that are climate resilient. The prospect of an uncertain future climate raises many economic and policy questions about adaptation of agricultural and food systems. For example:

- Given probable climate scenarios, what technological, social, institutional, and policy adaptations are likely to be worthwhile private or public investments?
- What is the economic value of specific system adaptations, such as the development of systems that are more resilient to climate extremes?
- What are the environmental and social benefits and costs of systems that are more climate resilient? Are there synergies or trade-offs among these outcomes and economic outcomes?
- Can farmers, ranchers, and the food system beyond the farm gate learn about and adapt successfully to climate change with private investment, or is there a role for public investment in adaptation research and development, and in the provision of public information?
- How would the array of public policies related to agriculture and the food system, such as climate mitigation policies, food safety and environmental regulations, farm subsidies, and trade and energy policies, affect or be affected by adaptation to climate change? How can climate considerations be incorporated into other policies? Or how can other policy objectives be met with climate change policies?

Our reading of the literature indicates that despite decades of research on climate change, our ability to answer these kinds of questions with confidence is limited. This situation is due to the inherent uncertainties and complexities associated with climate change, and to the disproportionate attention paid to predicting impacts at the expense of addressing adaptation. Consequently in this article we attempt to provide a review of what is known about adaptation, but also an assessment of what we need to know. At the time of writing this article, the attention paid to adaptation by the scientific community is growing rapidly, as evidenced by the expanding published literature, and also governments are paying much more attention to adaptation. In 2010, the U.S. government announced major new research initiatives on climate change impact and adaptation, in part under the U.S. Department of Agriculture's newly reorganized research agency, the National Institute for Food and Agriculture, as well as other federal agencies. Similar initiatives are being undertaken in other countries, and also under the auspices of the Consultative Group for

International Agricultural Research. In addition, several non-governmental organizations have issued major reports on adaptation (National Research Council 2010; Smith et al. 2010), and the Obama administration is undertaking an interagency review of adaptation options for the federal government. Thus it appears to be an opportune time to evaluate adaptation to climate change and its policy implications, and to consider how to improve our ability to address these important questions as we move forward with the climate change research agenda.

We begin by presenting an analytical framework to highlight some of the key issues in assessing potential benefits and costs of adaptation of agricultural and food systems from an investment perspective. Next we review the economic literature on impact and adaptation, and use our analytical framework to highlight critical methodological limitations of the modeling studies used to assess impact and adaptation. We also identify some of the economic, environmental and social issues that have not been adequately addressed in the impact assessment literature. In the final section we consider policy implications, including the interplay between mitigation and adaptation policies, and how other policies may affect or be affected by climate change and adaptation. We conclude with an outline of an agenda for adaptation research.

Investing in Adaptation to Climate Change

The economics, finance, and ecological economics literatures provide useful concepts to help us think about making adaptation investments, both private and public. We begin with some concepts related to measuring climate impacts, and then use these concepts to evaluate climate adaptation as an investment.

Uncertainty, resilience, and the economic value of adaptation

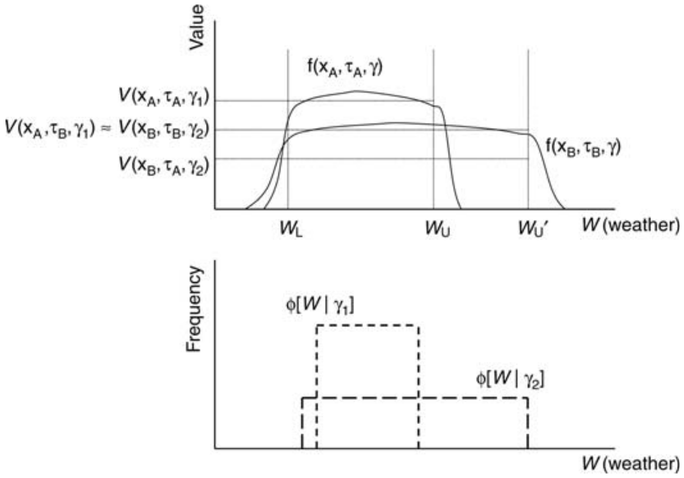
Economic analysis of adaptation begins with the premise that decisions by private entities about what production systems to use, and how to use them, are based substantially on economic considerations. To be viable in the long term, commercial activities must be profitable enough to stay in business. If environmental factors are “priced” in the marketplace or through policy mechanisms, they will be reflected in long term business plans. Whether or not they are explicitly incorporated into private decisions, environmental and social factors should play a role in assessing adaptation options for policy decision making, a point we will return to below.

Various processes are involved in generating economic, environmental, and social outcomes, including agricultural production systems, transportation and marketing of commodities, and transformation of commodities into food products. In a relatively certain world—e.g. greenhouse vegetable production for sale into a stable market—decisionmakers rationally choose systems based on maximum expected efficiency. However, faced with high levels of uncertainty about future environmental, economic, or policy conditions, it may be preferable to design and choose systems based on how well they perform over a range of probable conditions. Of course, from a decisionmaking perspective, this is the essence of risk management. To analyze and quantify the capacity of complex systems to withstand shocks and disturbances, and to adapt to change, we can also make use of the concepts of resilience and adaptability (e.g. Holling 1973; Perrings and Stern 2000; Walker et al. 2004; Antle, Stoorvogel and Valdivia 2006; Maler 2008). Resilience can be measured as the amount of disturbance a system can withstand before it moves to a substantially different state. Resilience can be defined in physical terms, as is commonly done in the ecology literature, but also in an economic dimension, such as economic outcomes of a farm or a sector. In the physical dimension, an agricultural system that is highly resilient is able to continue to produce valued outputs when it is subjected to large shocks, such as a period of extremely high temperatures, whereas a less-resilient system may experience significant productivity losses or even complete failure. A resilient economic entity such as a farm is one that can withstand either large physical or economic shocks (say, low output or high input prices). An example of a resilient system could be a diversified crop-livestock system, such as those typically used by small subsistence-oriented farms in developing countries; a less-resilient system might be a farm producing a single cash crop. Whether or not a farm is economically resilient will depend on the characteristics of its physical production system as reflected in its natural and physical capital, as well as its human and financial capital. As we discuss below, there can be important economic trade-offs between the maximum economic returns (value) that a system might provide under ideal conditions and its performance under adverse conditions.

We can represent agricultural and food systems in stylized form as a set of functional relationships, $v = \mathrm{f}[q, p, g, x, h, n, s, \tau, w]$, that show how inputs are transformed into outputs and create value, where v is economic value to society, q is planned outputs of the system that are valued in markets, p is prices of outputs and inputs, g is government policies and regulations, x is management decisions such as land use and variable input use, h is physical and human capital, n is natural capital, s is nongovernmental institutions and social capital, w is climate events (weather) governed by $\varphi[w|\ \gamma]$, $\varphi[w|\ \gamma]$ is a particular climate (i.e. a probability distribution for w with parameters γ which define the shape of the distribution), and τ is the type of production system and the associated technology (i.e. the parameters relating the above variables to q).

Many production processes involve critical environmental *thresholds* beyond which they experience large losses or even complete failure. An example of a value function with thresholds is illustrated in figure 1, which shows an outcome v as a function of a climate variable w, such as the temperature measured over a critical time interval during the process. There are lower (w_L) and upper (w_U) thresholds between which a high value of the outcome is attained, but beyond which the value falls rapidly to a low level or to zero. For example, w_L could represent the point at which a crop is damaged by frost and w_U could represent the temperature at which a crop is damaged by heat stress. Similarly we can define economic thresholds, such as the short-run shutdown point, where price falls below average variable cost during a single production period, or the financial threshold, such as bankruptcy forcing a farm business to be permanently shut down or sold. Clearly the physical and economic thresholds may be interrelated. For example, the serial correlation in farm returns, which is likely to be associated with serial correlation in weather, can have a large effect on financial viability (Just and Pope 2003); and

Figure 1 Value functions, climate distributions, and expected value

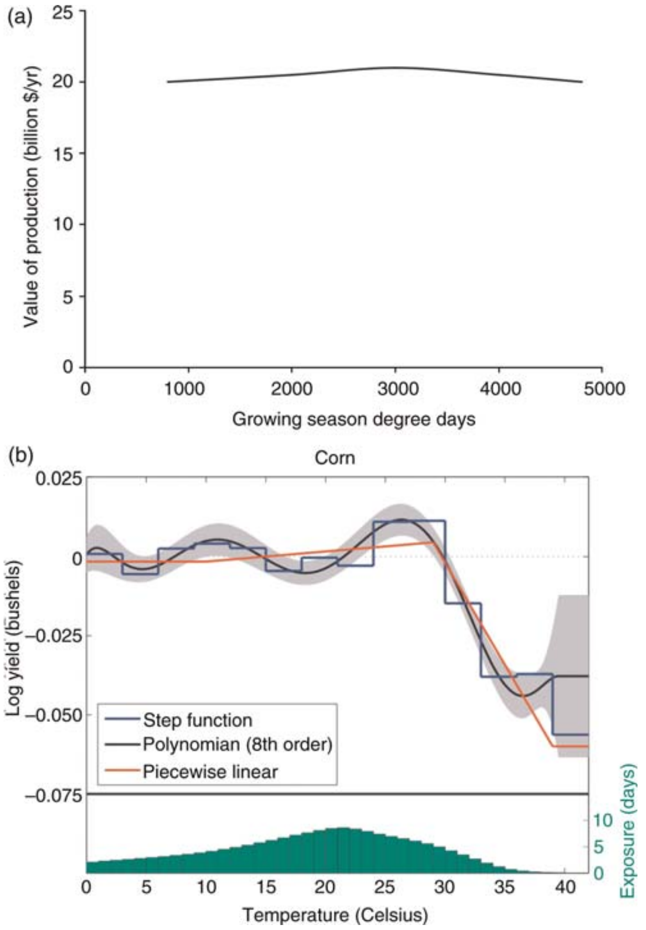


climate variability and extremes can affect the design and viability of agricultural insurance schemes (Linnerooth-Bayer and Mechler 2006; Odening, Berg, and Turvey 2008).

Most analysis of climate change impacts on agriculture have focused on physical thresholds. A well-established example of a physical process with critical thresholds is plant growth, which is governed by thresholds for temperature and water, and often soil depth and pest prevalence. These thresholds are incorporated into process-based crop simulation models. For example, the Food and Agriculture Organization of the United Nations (FAO) uses a simple plateau function like the one portrayed in figure 1 in its Ecocrop modeling system to estimate suitability for more than 2,500 plants based on monthly minimum and maximum temperature and rainfall data (FAO 2010). More detailed crop simulation models also exhibit such thresholds (Hansen and Jones 2000; Antle and Stoorvogel 2006; Challinor et al. 2009). Statistical data also reveal temperature thresholds in crop production when data are sufficiently detailed and appropriate nonlinear methods are used to estimate thresholds (e.g. Schlenker and Roberts, see figure 2[b]). Statistical methods also show threshold effects in crop production associated with environmental conditions such as soil fertility (Marenya and Barrett 2009). Researchers have also shown that livestock productivity is sensitive to temperature extremes (Nienaber and Hahn 2007; Thornton et al. 2009; 2010). Systems beyond the farm, such as transportation, storage, processing, and marketing, can also exhibit this type of threshold behavior. When coupled in a hierarchical series of essential stages, systems can be vulnerable to breakdowns if any stage of the system fails (Kremer 1993). These kinds of stages occur in crop growth within a growing season, as well as in a value chain linking farm production to the consumer. In addition to physical thresholds, economic systems involve thresholds with respect to economic variables, such as profitability and financial sustainability, which may be affected by climate-based physical variables.

The shape of the value function, and the location of climate thresholds, can determine how performance is affected by climate changes. We shall refer to this property as the system's "climate sensitivity" (often the term

Figure 2 U.S. corn yield modeled (a) as a quadratic function of seasonal degree days, and (b) as a nonlinear function of one-day temperature



"vulnerability" is used in the climate literature). Climate is represented in the lower half of figure 1 as distributions of weather events represented by w, with the distribution function written as $\phi[w|\gamma]$, where γ represents parameters defining the shape of the distribution. For simplicity, climates are shown as uniform distributions; in reality they would be more like bell-shaped distributions. Climate change means that there is a change in the distribution of weather events such as daily maximum temperature. For example, in figure 1 we see that the climate represented by the distribution $\phi[w|\gamma_1]$ is positioned so that there is little chance for w to fall below w_L or rise above w_U. In contrast, the climate represented by $\phi[w \mid \gamma_2]$ has a higher mean and also a higher variance, so that there is a substantial likelihood that w will exceed w_U but little chance that it will fall below w_L.

We can combine the upper and lower parts of figure 1 to evaluate the impact of climate change using the concept of "expected value." Expected value is the average value obtained by combining the value function in the upper part of figure 1 with the climate distribution in the lower part.[1]

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[1] *Mathematically, the expected value is* $V[q, p, g, x, h, n, s, \tau] = \int f[q, p, g, x, h, n, s, \tau, w]\phi[w|\gamma]dw$.

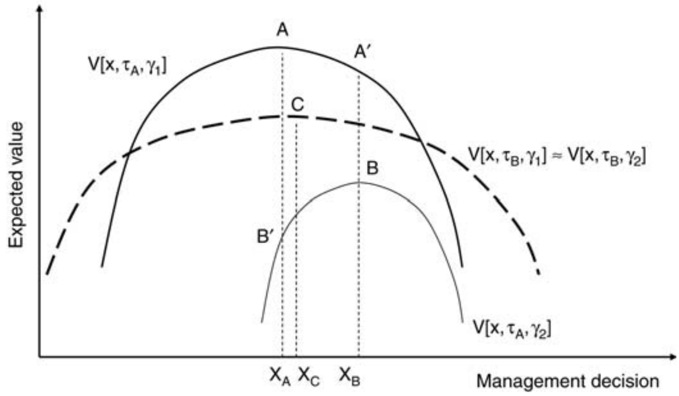
With production system A and climate γ_1, the expected value is $V[x_A, \tau_A, \gamma_1]$ and is roughly equal to the value obtained on the plateau section of the value function because the weather outcomes all fall between $w_L$and w_U. However, with climate γ_2, the expected value is much lower, at $V[x_A, \tau_A, \gamma_2]$, because with system A many of the weather outcomes fall above w_U where the value function is near zero. This example shows that the expected impact of climate change depends on how the distribution of weather events shifts in relation to the production system processes that determine economic outcomes. Clearly the wider is the plateau of the value function, the more resilient is the system and the less is the impact of any given climate change. As we discuss below, system τ_B in figure 1 is an example of a more resilient system.

Managers make two types of decisions. First, given an operating environment defined by p, g, h, n, s, and γ, managers must make long-term decisions about the type of production system to use. Second, given the choice of system, managers make the various shorter-run resource allocation decisions involved with managing the system, for example how to allocate land to crop and livestock production, and how to apply variable inputs such as seed, feed, nutrients, water, energy, and labor. Changes in the performance of the system have impacts which create an incentive for the manager to adapt by modifying both kinds of extensive and intensive decisions.

Figure 3 illustrates the economic analysis of impact and adaptation to climate change within this type of expected value framework (Antle et al. 2004). Two climates are considered, represented by γ_1 and γ_2. Associated with each climate is an expected value curve representing the relationship between the net expected economic value of agricultural activities and the short-term management decisions such as crop choice, planting time, fertilization, etc., associated with the agricultural system, taking as given the technology and associated capital stock and other fixed factors that influence the performance and outcomes of the system. Other types of decisions are involved in transportation, processing, and distribution systems, but the same principles can be applied.

There are two important features of the expected value relationships illustrated in figure 3. First is height, which shows the maximum value that can be obtained if the optimal management decision is made, referred

Figure 3 Analysis of adaptation and resilience using expected value functions



to as the system's "maximum efficiency." Second is curvature, which determines how rapidly value declines from its maximum if a suboptimal management decision is made. We will refer to this second property as the system's "management sensitivity." Returning to the concept of resilience, we can see that a highly climate-resilient system is one with low climate and management sensitivity. For example, τ_B portrayed in figures 1 and 3 would be highly resilient: its maximum efficiency (at point C, in figure 3) is little impacted on by the change from climate γ_1 to γ_2, and also deviations from the optimal management (x_C) have relatively small effects on system performance.

We can use figure 3 to assess the impacts of climate change on systems with different climate resilience. Suppose, for example, that γ_1 represents the current climate and γ_2 represents the future climate. Farmers who have adapted to the current climate will select system τ_A and will choose management decision x_A to maximize the value of production at point A. However, if the climate were to change to γ_2, the expected value function shifts and the economically efficient management x_A is not optimal and would result in a lower value B′. By appropriately adapting short-term management from x_A to x_B, the negative impact can be reduced to the vertical difference between A and B. Thus, given that system A is in use, there is an adverse impact of AB′ and an adaptive gain represented by the reduction in impact in the amount of BB′.

Consider now an alternative system, τ_B, that provides a lower maximum efficiency relative to system A, but a higher maximum value with climate γ_2, if short-term management is adapted appropriately. Thus, by changing to system τ_B and adapting short-term management, the decisionmaker could earn a value of C and reduce the impact of climate change accordingly. The value of this longer-term adaptation depends on whether the manager would make the appropriate short-term adaptations, and also would depend on what changes occur in other conditions affecting the value of the system, including changes in policy and institutions. Also note that policies, institutions, and the natural environment may change in response to climate change, and may affect the relative returns of both short-term management and available technologies.

The analysis in figure 3 illustrates several key elements in the analysis of impact and adaptation. First, the magnitude of the impact must be estimated, i.e. the shift in the functions showing the value of agricultural activities. Second, the relationship between management decisions and value must be estimated. Third, the magnitudes of impacts and the value of adaptation depend on what is assumed about short-term management, longer-term management, and the rest of the system influencing the performance of the system. A key implication of this analysis is that the value of adaptation cannot be inferred from the net effect of climate change, i.e. from the change in value from point A to point B. To know the value of adaptation, we must be able to estimate points such as A′, B′, and C as well.

Adaptation as an investment under uncertainty

As the discussion of figure 3 indicates, adaptation involves both short-run decisions about management of systems currently in use, as well as longer-run decisions about system changes that typically involve investments in technology and physical capital, as well as investments in the managerial and other human capital skills needed to use the new systems. We can often assume that farm managers have the ability to adapt short-term management decisions to changes in observed conditions, so what is critical for adaptation are the longer-term investment decisions related to the choice of production system. Moreover, in order to develop new systems, investments in research and development are typically needed by either public or private organizations. Thus, both on and off the farm, adaptation decisions generally take the form of an investment decision. The conventional economic assessment of an investment involves calculating its net present value, defined as the discounted future expected gain from the adaptation minus the costs of making the adaptive investment.

There are many uncertainties involved in assessing the impacts of climate change on agricultural and food systems, which can be classified broadly as climate uncertainties and valuation uncertainties (Yohe and Tirpak 2008). First, the future climate is uncertain because of the various limitations in understanding the global climate system and how it interacts with human activities such as changes in land use and emissions of GHGs (Solomon et al. 2007). This uncertainty is particularly high for assessment of impacts on agricultural systems because they depend on highly site- and time-specific weather events such as temperature, precipitation, wind, and solar radiation. Global climate models typically operate at coarse spatial and temporal scales, such as 500 square kilometer grids and annual or seasonal averages, which are not very meaningful for assessing impacts on biological processes such as crop growth. Attempts to link data at a low spatial or temporal resolution to a higher resolution—referred to as downscaling—cannot provide information about critical changes in climate such as changes in variability and extreme outcomes that are likely to have important threshold effects (Baron et al. 2005; Schneider et al. 2007). Moreover global climate models are not very good at predicting the rate of change of climate, another key feature in assessing the potential for adaptation. One promising area of research, that is beginning to reduce the uncertainties in climate model simulations, is the use of regional climate models that operate at higher spatial and temporal resolution. As yet regional models are not available for all regions of the world and continue to present scientific and computational challenges, particularly for the simulation of dynamic paths of adjustment and feedbacks from human activity to climate.

In addition to climate uncertainty, there are the uncertainties associated with the various other factors affecting agricultural and food systems identified above. These include: future prices of products—particularly agricultural commodity prices and energy prices; population and income growth; investments in physical and human capital associated with technological change; institutions and policies; and other changes in the physical environment that may be associated with climate change or with other ongoing processes.

All of these uncertainties mean that actions taken based on what is known now may not be the best actions once the true state of the world is realized in the future. Research on this kind of decision problem has shown that conventional investment decision rules—i.e. invest when present discounted value of an adaptation is positive—are likely to be incorrect in the face of uncertainty, because there are irreversible costs of taking action in the present if uncertainty is reduced by waiting. Put differently, in the face of uncertainty, there is a value of information equal to the irreversible costs of taking actions with uncertain outcomes. In the literature on investment under uncertainty, this value of information is referred to as "option value" (Dixit and Pindyck 1994; Lombardi 2009).

The option value associated with uncertainty is related to the benefits and costs of adaptation illustrated in figures 1 and 3. As is shown in figure 1, if climate is uncertain, then the potential impacts of climate change are uncertain. In figure 3, as uncertainty about climate change and technologies increases, the vertical and horizontal distances between expected value functions increases. As a result, the likelihood and magnitude of a wrong system choice or management decision increase and the magnitude of the likely decision error and its cost increase. Thus the more uncertain are future outcomes, the greater is the value of information that resolves uncertainty and the greater is the value of adaptations that reduce the effects of uncertainty.

The role of induced innovation

Several economic concepts can help us understand the process of public sector investment in information and technologies that support investment in adaptation. On the one hand, the political economy literature suggests that public investment is likely to be increased when agricultural interests see value in adaptation. On the other hand, the theory of induced innovation indicates that the demand for investments in information and research are motivated by opportunities to generate higher returns by taking advantage of resource endowments (Hayami and Ruttan 1985). It follows that if climate change occurs, agricultural interests would demand adaptation research. However, the Hayami–Ruttan theory does not address uncertainty about resource endowments. The preceding discussion suggests that if uncertainty about climate change is high, or if agricultural interests are not well informed about climate change, the perceived benefits from adaptation research may be low and the induced innovation process may not operate effectively (Antle 1996). This logic may explain why, thus far, investment by the public sector in adaptation research has been low. In addition the magnitude of climate change impacts, and the ability of both private and public research to adapt to impacts, may depend on the rate of climate change and the length of the innovation cycle, as we discuss further below.

Adaptation in the agricultural R&D paradigm

The preceding discussion indicates that public investments in research on resilient systems, and provision of this kind of information to the public, can reduce uncertainties and encourage adoption of resilient systems. However, as the discussion below will demonstrate, there is a need for more research on specific adaptations to existing systems, and also on the design of alternative systems, to evaluate which ones appear to be good targets for public investments.

Viewed as an investment decision, agricultural adaptation to climate change is similar to the investments in agricultural research that have been studied by economists for the past half-century. There are well-established methods for assessment of research investments (e.g. see Alston, Norton and Pardey 1995; International Food Policy Research

Institute 2009a), although there remain a number of important methodological challenges in conducting ex ante assessments, and these challenges would be even greater for analysis of investments in adaptation to uncertain future climate change. A major component of agricultural research investment is adaptation of technologies that have been successful in one environment to work better at locations with different environments (Evenson and Gollin 2003). In this sense, agricultural research on climate adaptation is similar to other types of system adaptation research, with the important difference that there is uncertainty about the future climate. Recent agronomic and crop breeding research has begun to address climate adaptation (Wassman et al. 2009; Reidsma et al. 2009).

Designing ex ante assessments of climate-adapted systems will involve addressing future uncertainties in the technological aspects of the future systems, the costs of adopting and using these systems, as well as external conditions including climate, markets, and policies. The goal of the analysis should not be to evaluate the value of the system under one set of conditions, but rather the range of conditions under which the system may be profitable or have other desirable outcomes. Walker et al. (forthcoming) provides an example of the use of both ex ante and ex post economic technology assessment methods. An example of how those kinds of methods could be extended to assess prospective technologies under climate scenarios is provided by Claessens et al. (2010).

As we discuss further below, there has been little research aimed at assessing the adaptation of transportation, processing, and distribution systems. The recent study by Winkler et al. (2009) provides a conceptual framework for analysis of marketing system adaptation, but there have not been empirical studies thus far.

Assessing environmental and social impacts of adapted systems

There is a growing demand by governmental and non-governmental organizations that fund agricultural research for assessment of the economic, environmental, and social impacts of agricultural technologies (e.g. see International Food Policy Research Institute 2009b; Gates Foundation 2009; Integrated Pest Management Collaborative Research Support Program 2009; National Institute for Food and Agriculture 2010). In addition to conventional ex post economic assessments of returns to aggregate investment in agricultural research, increasingly there is a demand for broader economic, environmental, and social assessments of technologies that are proposed or under development. Due to the time required for technologies to be disseminated and adopted, assessments need to be completed long before most adoption occurs and most impacts can be observed. An important motivation for prospective assessments is to avoid unintended consequences of new technologies, particularly when they may be adopted by environmentally, economically, or socially vulnerable populations, such as poor farm households in developing countries.

Assessment of economic, environmental, and social impacts of agricultural systems under climate change will necessarily involve modeling. A number of models have been developed to study how various aspects of technology and policy affect farm decision making, environmental outcomes associated with those decisions, and certain environmental and social aspects of agricultural systems. Many studies have been designed for a particular system or region and typically use highly detailed data and complex production system or household models (e.g. see Crissman, Antle and Capalbo 1998; Berger; Stoorvogel et al. 2001; Wu et al. 2004; Holden 2005; Lee and Barrett 2001; Lubowski, Plantinga and Stavins 2006; Moyo et al. 2007; Adato and Meinzen-Dick 2007; van Ittersum et al. 2008; International Food Policy Research Institute 2009a).

The use of these kinds of detailed, site-specific models holds the promise of overcoming many of the shortcomings of the large scale integrated assessment models and statistical models that we discuss below, such as the ability to incorporate important system details such as threshold effects and costs of adopting alternative systems. Nevertheless to use these models to assess climate change impacts and adaptations, a number of methodological challenges will have to be addressed. First, these models tend to be data intensive and location specific, so it is difficult to use them for broader regional assessments. Second, these models will have to be linked to climate data to estimate the impacts of climate on productivity. In the context of existing large-scale integrated assessment models, there are many important limitations of process-based crop and livestock models for simulating system performance under climate change. Third, most of these models can only address those environmental impacts for which there are process-based environmental models. Another important question is how to quantify other outcomes, such as impacts on biodiversity and genetic resources, and social impacts, for which process-based models do not exist. Finally, most of these models are not designed to simulate technology adoption and therefore have limitations for analyzing technological adaptation.

Impact and Adaptation: What Do We Know?

We have outlined a framework for evaluating adaptation options. In this section we consider what has been learned from the literature on impact and adaptation. Here we do not attempt a comprehensive review of the vast literature (for this see the Intergovernmental Panel on Climate Change (IPCC) assessment reports), but rather select certain studies to illustrate key points and focus our discussion mostly on U.S. agriculture.

Economic studies of impact and adaptation

Since the first assessment of climate change was published by the IPCC (1990), substantial efforts have been directed toward understanding climate change impacts on agricultural systems. The resulting advances in our understanding of climate impacts have come from the collection of better data, the development of new methods and models, and the observation of actual changes in climate and its impacts. Early impact studies largely ignored adaptation, but it was soon recognized that this is a critical factor in determining impacts, and more recent studies have attempted to incorporate adaptation using either integrated assessment models or statistical models.[2]

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[2] *Here we use the term "integrated assessment models" to refer to systems models that link together several subsystems, e.g. climate, crop growth, economic, and environmental. Such models may operate on spatial scales ranging from farm to regional and global.*

Integrated assessment modeling studies typically link climate data from climate models with crop growth models to simulate impacts of climate change on crop productivity and then input these productivity changes into economic models that determine economic impacts. Most such models operate at regional or national scales, and some integrate national analysis to global equilibrium models. These modeling studies typically account for possible autonomous farm-level adaptations by adjusting planting dates and genetic characteristics of crop varieties in crop growth models, and by using economic models that reallocate land to crops according to changes in profitability.

To illustrate the use of integrated assessment models, we consider the latest U.S. assessment study (Reilly et al. 2003), updated by McCarl (2008). Simulations from four climate models were used, together with assumptions about carbon dioxide (CO_2) concentrations, as inputs into a number of crop simulation models to evaluate impacts on rain-fed and irrigated systems. The simulations were carried out for existing management practices and for adaptation scenarios that included changes in planting dates and the use of cultivars adapted to warmer climates. An important issue in modeling studies is how they account for CO_2 fertilization, the effect of atmospheric CO_2 concentrations on crop yield.

Table 1 presents a summary of the crop yield simulation results, by climate model and adaptation scenario. These results show that crop yields are expected to increase in the range of 3 to 25 percent by 2030, to as much as 50 percent by 2090, and that the increases are larger under the adaptation scenarios. Disaggregated by crop and region, the data show that the national averages obscure important differences in yields among crops, e.g. cotton, soybeans, and barley increase much more than corn, wheat, and some vegetable crops. Northern regions generally have larger, positive yield changes, whereas southern regions increase less and decline in some cases. The use of the Hadley model results in the largest yield gains; the Canadian and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) models give positive, but smaller, gains; and the Regional Climate Model (RegCM) results in the smallest gains. The RegCM is a downscaled version of the CSIRO model, suggesting that disaggregation may lead to predicted impacts that are less positive than the predictions of aggregated models.

Livestock and poultry are sensitive to temperature, and the U.S. assessment estimated that livestock productivity would decline 5–7 percent, on

Table 1 Impact of climate change on U.S. crop yields in 2030 and 2090, without and with adaptation % change

	Hadley			*Canadian*			*CSIRO*			*RegCM*		
	All	*Dry*	*Irr*	*All*	*Dry*	*Irr*	*All*	*Dry*	*Irr*	*All*	*Dry*	*Irr*
2030 without adaptation	16	17	11	8	8	4	4	3	9	4	4	88
2030 with adaptation	21	22	16	14	15	10	5	5	11	6	5	10
2090 without adaptation	35	37	20	14	14	12	19	20	16	7	5	16
2090 with adaptation	43	46	25	27	28	19	28	29	22	16	16	22

Notes: Dry = dryland crops, Irr = irrigated crops.
Source: McCarl (2008).

average, by midcentury. Some studies suggest that productivity losses in the southern United States could be on the order of 10 percent or more (Reilly et al. 2003). However, there remain large gaps in our understanding of climate impacts on livestock systems and estimates are highly uncertain (Thornton et al. 2009).

Economic effects of climate change estimated by the U.S. assessment study are summarized in tables 2 and 3. Broadly the analysis suggests that in highly productive regions, such as the U.S. corn belt, the most profitable production system may not change much; however, in transitional areas, such as the ecotone between the corn belt and the wheat belt, substantial shifts may occur in crop and livestock mix, in productivity, and in profitability. Impacts may be positive if, for example, higher temperatures in the northern Great Plains were accompanied by increased precipitation, so that corn and soybeans could replace the wheat and pasture that presently predominate. Impacts also could be negative if, for example, already marginal crop and pastureland in the southern Great Plains and southeast became warmer and drier.

Table 3 shows that the aggregate economic impacts of climate change on U.S. agriculture are estimated to be very small, on the order of a few billion dollars (compared to a total U.S. consumer and producer surplus of $1.2 trillion). This positive outcome is due to positive benefits to consumers that outweigh negative impacts on producers. Impacts on producers differ regionally (table 4), and the regional distribution of producer losses tends to mirror the productivity impacts, with the corn belt, Northeast, South, and Southwest having the largest losses and the northern areas gaining. The overall producer impacts are estimated to range from −4 to −13 percent of producer returns, depending on which climate model is used.

Table 2 Annual changes in U.S. and global agricultural economic surplus due to climate change in 2030 and 2050, without and with adaptation $ millions

	Climate model			
	Canadian	*Hadley*	*RegCM*	*CSIRO*
2030 without adaptation				
United States	424	2,953	−1,531	−1,603
Rest of the world	1,697	1,949	410	313
Total globally	2,121	4,902	−1,121	−1,290
2030 with adaptation				
United States	1,870	4,466	−224	−429
Rest of the world	2,720	2,959	621	634
Total globally	4,590	7,425	397	205
2090 without adaptation				
United States	457	5,432	−2,015	406
Rest of the world	1,981	3,614	−37	1,381
Total globally	2,439	9,047	−2,052	1,788
2090 with adaptation				
United States	2,948	8,048	1,760	3,749
Rest of the world	3,422	4,077	2,192	2,747
Total globally	6,370	12,125	3,952	6,496

Note: U.S. baseline is $1,200,000.
Source: McCarl (2008).

Table 3 Regional U.S. producer welfare changes for 2030, with adaptation $ millions

	Canadian	*Hadley*	*RegCM*	*CSIRO*
Corn belt	−1,745	−1,962	−1,218	−1,209
Great Plains	−370	−968	−72	−200
Lake States	1,357	352	−50	−94
Northeast	−91	−236	−21	−63
Rocky Mountains	721	307	878	885
Pacific Southwest	325	−97	134	132
Pacific Northwest, east side	112	9	274	264
South Central	−868	−448	−505	−518
Southeast	−419	−365	−223	−219
Southwest	−250	−483	−293	−297
Total	−1,228	−3,891	−1,096	−1,391
% of baseline	−5.1%	−13.0%	−3.7%	−4.4%

Source: McCarl (2008).

Table 4 Montana agro-ecozone yield and net returns changes for 2050, using the Canadian climate model %

	Climate only	*CO_2*	*Climate + CO_2*
MT winter wheat	−27 to −19	+19 to +56	+6 to +25
MT spring wheat	−47 to −44	+48 to +57	−17 to +8
Net returns without adaptation	−60 to −49	+37 to +46	−28 to 0
Net returns with adaptation	−45 to −25	+56 to +69	−8 to +18

Notes: Yields are for wheat grown in a fallow rotation. Climate = climate change, CO_2 = CO_2 fertilization.
Source: Antle et al.

Statistical modeling studies

One of the limitations of integrated assessment modeling studies emphasized by some economists is their limited ability to simulate all of the adaptations that could occur in response to climate change. Mendelsohn, Nordhaus, and Shaw (1994) proposed an alternative statistical modeling approach, referred to by some researchers as a "hedonic" method. The basic idea is to use historical data to estimate a statistical relationship between economic values, such as land values or profits, and climate variables. These statistical relationships are combined with climate data to estimate the economic impacts of climate change. The major motivation for this approach, according to Mendelsohn, Nordhaus, and Shaw (1994), was the argument that integrated assessment models are not capable of representing all of the kinds of adaptations that economic agents can actually make. By using historical statistical relationships, they argued that a model would embody all of the actual adaptations in the reduced-form statistical model. However, as we noted above, in order to assess the value of adaptation, researchers need to distinguish between the impacts of climate change and the ability of adaptation to offset negative impacts or take advantage of positive impacts. This fact means that the hedonic model is of limited value in providing decisionmakers with the kind of information they need to evaluate adaptation options.

A more recent hedonic study of U.S. agriculture used county-level data from the agricultural census, together with soils and climate data, for the six agricultural census years from 1978 to 2002, to estimate a quadratic statistical relationship between annual precipitation, degree days, and aggregate profits of production agriculture (Deschenes and Greenstone 2007). As figure 2 shows, this study produced a slightly concave relationship between aggregate profits and seasonal average temperature and precipitation variables. Combining their model with climate projections for 2070–99, the authors concluded that climate change impacts were likely to be in the range of 3 to 6 percent of the value of agricultural land, and could not reject the hypothesis of a zero effect.

Limitations of economic modeling studies for analysis of adaptation

As simplifications of reality, all models have limitations, and our purpose here is not to argue that the studies described above could have been done better, given the available data and modeling methods. Recent reviews of limitations of integrated assessments and statistical economic modeling studies are provided by Yohe and Tirpak (2008), Winkler et al. (2009), Schlenker and Roberts (2009), and Patt et al. (2010). Rather our goal here is to summarize some of the relevant limitations of these studies as a basis for answering the kinds of questions about adaptation to climate change identified at the outset.

The use of average climate data. Figure 1 shows that the use of averages is likely to result in underestimates of impact, in both integrated assessment and statistical approaches, because the effect of thresholds and extreme events are not taken into account. The use of spatial gradients to infer temporal changes is not without precedent in ecology and other fields, but the approach has significant limitations (e.g. Fukami and Wardle 2005). Figure 2 shows graphically the contrast between the statistical relationships obtained with historical seasonal average data based on quadratic models (as in Deschenes and Greenstone 2007) and the use of daily data with nonlinear models (as in Schlenker and Roberts 2009). The Schlenker and Roberts analysis confirms the importance of accounting for thresholds in quantifying climate impacts.

To illustrate further some of the possible effects of aggregation and model limitations, it is also instructive to compare the results of the U.S. assessment to the field-scale study by Antle et al. (2006). This latter study used the Canadian Climate Model to estimate the effects of climate change on winter and spring wheat and barley yields for major land resource areas in Montana; specifically, the study considered (a) the effects of climate change without CO_2 fertilization, (b) the effects of CO_2 fertilization only, and (c) the combined effects of climate change and CO_2. Likely adaptations in wheat systems include changes in intraseasonal management such as planting date, fertilization, and cultivation, and interseasonal changes such as use of fallow and substitution between winter and spring wheat. As shown in table 4, without the effects of CO_2 fertilization, yields are estimated to change by −47 to −9 percent, whereas with CO_2 fertilization and climate change, yields are expected to change in the range of −17 to +25 percent. In contrast, the U.S. assessment's averages for winter wheat and spring wheat are −11 and 14 percent. Economic returns in the Montana study were generally negative without the CO_2 fertilization effect, in the range of −60 to −50 percent without adaptation, and −50 to −30 percent with adaptation. When CO_2 fertilization was included, changes in returns were −25 to 0 percent without adaptation, and −10 to +20 percent with adaptation, implying substantial uncertainty in the impacts. In contrast, the impacts on producer surplus shown in table 3 are small and negative for the Great Plains region. Thus the disaggregated results imply a larger range of possible outcomes, with much more adverse outcomes possible if the effects of adaptation and CO_2 fertilization are not fully realized.

The use of biophysical simulation models to represent productivity effects. Crop models are capable of simulating the effects of temperature and water stresses for single crops and some crop rotations, but there are many challenges and limitations in their use for climate impact estimation (Challinor et al. 2009). In addition to issues such as making linkages with simulated climate data, models do not exist for some economically important crops, and most models do not include the effects of insect pests, diseases, and weeds, and how they may be affected by climate. Climate-sensitive livestock and poultry simulation models are also largely lacking.

The use of historical statistical models. Antle (1996); Schneider (1997); and Schneider, Easterling, and Mearns (2000) argue that use of historical data requires the assumption that future climate has the same statistical properties as past climate. In terms of the framework presented above, the statistical studies can only represent the range of variation observed in historical climate and economic data. In addition, as reduced-form statistical relationships, these models embed the effects of all the other historical and spatial factors that affect economic outcomes described above, including prices, policies, institutions, natural capital, and technology. It is important to observe that the Deschenes and Greenstone (2007) analysis (see figure 2[a]) concluded that impacts of climate change would likely be near zero, based on statistical analysis that uses seasonal average data and also using a reduced-form model that does not allow impacts of climate change to be distinguished from the effects of adaptation. Therefore it is not possible to determine whether the results of the Deschenes and Greenstone analysis are attributable to the aggregated historical data and the type of functional form, or whether it is due to the use of the reduced-form analysis that implicitly assumes that adaptation will occur. The Schlenker and Roberts (2009) analysis implies that, without adaptation, impacts would be negative and larger than those implied by the Deschenes and Greenstone analysis, but the Schlender and Roberts' analysis does not attempt to model adaptation.

Climate data, comparative static analysis, and costs of adjustment. Antle, and Quiggin and Horowitz (1999; 2003) have noted that integrated assessment studies and statistical studies mostly use a comparative static approach, i.e. they compare outcomes under the current climate to outcomes under a future climate, but do not attempt to simulate the transition path from current to future climate. In part this is explained by the limited capability of climate models to simulate the dynamics of the climate over time. In addition neither integrated assessment models nor statistical models incorporate investments that would be needed for adjustments in capital stocks in response to climate change. Therefore the ability of systems to adapt to different rates of change over time through long-term investments has not been evaluated. Quiggin and Horowitz (2003) and Patt et al. (2010) argue that many of the costs associated with climate change are likely to be adjustment costs, and therefore comparative static impact assessments incorporate benefits of adaptation but largely ignore the costs. McCarl (2007) did attempt to estimate adaptation costs as changes in physical capital, research, and extension at the sector level as of 2030, although the analysis was based on arbitrary assumptions about the effect of climate change on these investments.

CO_2 fertilization and other physical changes. Some of the integrated modeling studies, such as the one carried out for the U.S. assessment, have attempted to incorporate the impacts of CO_2 fertilization and impacts of climate change on water resources, a key constraint in the arid U.S. West and parts of the South. Other potentially important changes include vegetative cover and soils (Hatfield et al. 2008). The statistical studies, however, are incapable of accounting for any of these future changes in the physical environment and how they may feedback to agricultural systems, including the effects of CO_2. Estimates of CO_2 fertilization based on crop models have been questioned as well (Easterling et al. 2007; Challinor et al. 2009).

Financial and distributional impacts. Climate change is likely to have important distributional impacts, not only across regions, as suggested by the data in table 3, but also across different types and sizes of farms. Commercial agriculture in the United States is becoming increasingly concentrated in a relatively small number of large farms, and the process of consolidation continues. Another important fact is that off-farm sources of income (including employment earnings, other business activities, other investments, and transfer payments) provide more than 85 percent of household income. Very large commercial farms (sales greater than $500,000) have average household income about four times the U.S. household average, and this is the only size class that earns a large share of its income (80 percent) from farm sales.

These facts about farm structure and income have important implications for the climate resilience of farm households. Smaller farms often produce a more diverse mix of crops and livestock, and also depend to a large degree on nonfarm income less that impacted on by climate change. Larger farms tend to be more specialized and thus more vulnerable to climate changes, but are stronger financially, have greater wealth, and receive a larger share of their income from government subsidies. Larger, more specialized farms are also more likely to use market-based risk management tools and to sell into national and international markets that are less vulnerable to local climate variation.

Most of the research on climate change impacts reviewed above has not addressed the vulnerability of U.S. agriculture in the sense of assessing the likelihood of production or incomes falling below critical thresholds. This can be explained in part by the fact that most studies use data aggregated to a regional level and thus are only able to assess impacts on total production and income, not on the likelihood that production or income falls below a threshold for some individuals in the population. The Antle et al. (2004) study developed methods to assess the climate vulnerability of dry-land grain producers in Montana, a semi-arid region where the risk of low soil moisture is a key vulnerability. Several measures of vulnerability were used, including the likelihood of crop income falling below a threshold, as well as the percentage change in income for all farms. One of the goals of the study was to test the hypothesis, put forth in the IPCC (2001) assessment report, that vulnerability is inversely related to resource endowments. The results supported the hypothesis that the most adverse changes occur in the areas with the poorest resource endowments and when mitigating effects of CO_2 fertilization or adaptation are absent. The study also found that the vulnerability of agriculture to climate change depends on how it is measured (in relative versus absolute terms, and with respect to a threshold), and it also depends on complex interactions between climate change, CO_2 level, adaptation, and economic conditions. The results showed that relative vulnerability did not increase as resource endowments become poorer and that without adaptation there may be either a positive or negative association between endowments and relative vulnerability. However, vulnerability measured in relation to an absolute threshold did vary inversely with resource endowments, and a positive relationship was found between absolute gains from adaptation and the resource endowment of a region.

Financial vulnerability of farm businesses is another relevant consideration that has largely been ignored by the literature on climate change impacts and adaptation. To effectively quantify financial vulnerability, a model of the farm firm would be required that includes financial condition as a function of production income, debt structure, nonfarm income, and use of financial risk management tools such as futures markets, crop insurance, and agricultural subsidies, as with models that have been used to assess weather risk and related insurance instruments (e.g. Berg and Schmitz 2008). In the past, farms faced periodic financial crises when adverse climatic or economic conditions occurred, because of high debt to asset ratios and imperfect capital markets, but this is much less true today for commercial farms. Farm households owning commercial farm operations have higher incomes and wealth than most U.S. households, and most are financially sound. State average debt to equity ratios range from 5 to 20 percent, and farm failure rates are far lower than nonfarm rates. However, family farms tend to have a large share of their total wealth invested in their farm business, potentially increasing their vulnerability.

Impacts on ecosystem services and the environment. Changes in climate are expected to have significant impacts on ecosystem function, and thus on the ecosystem services valued by humans (Antle 1996; Backlund et al. 2008). The changes in land use and management associated with agriculture are also likely to affect the ecosystem services associated with agricultural lands—such as the regulation of water quantity and quality and the global carbon cycle—and to affect conservation of biodiversity. In many cases there are common-property aspects of managed ecosystems that need to be taken into account. Due to both data and model limitations, ecosystem services have not been incorporated into integrated assessment studies and cannot be linked to reduced-form statistical studies that do not model land use changes and other aspects of management decisions.

Nevertheless there have been some attempts to relate existing impact assessment studies to environmental outcomes. The national climate models used in the U.S. assessment showed that pesticide use could increase, although the authors did not attempt to evaluate the potential environmental or health effects of such an increase (Reilly et al. 2003). Considering that the crop models used in the U.S. assessment do not effectively represent possible impacts of pests and diseases on crops, it would be reasonable to assume that a warmer climate with elevated CO_2 levels would increase pest and disease pressure and thus result in greater use of pesticides than these models predict (Hatfield et al. 2008). Increased use of pesticides would be expected to have adverse effects on ecosystem services such as water quality, pollination, and biodiversity.

Another likely major impact of climate change is on water availability and water resources. Reilly et al. (2003) presented results from case studies of groundwater quantity in the Edwards aquifer in Texas and the impact of agriculture on water quality in the Chesapeake Bay. The study indicated that a drier, warmer climate would result in greater depletion of the aquifer due to both agricultural and urban demands for water. It indicated that increased corn production in the region would substantially increase nutrient loadings into the bay.

Land-use change is estimated to be an important source of GHG emissions through the loss of carbon stored both in soils and in above-ground biomass. Antle, Capalbo, and Paustian (2006) found that the stock of soil carbon in the central United States could be reduced by an order of 20 percent if the effects of CO_2 fertilization are negligible, but would be much less if CO_2 fertilization effects on crop productivity are large. In addition the study showed that the impacts on soil carbon were much more positive with management adaptation than without. This study also found substantial regional variation in these effects, an indication that generalizations about the effects of land-use change on GHG emissions from a small number of sites, as is typically done in large-scale integrated assessments, may be misleading.

Food quality and safety. The assessments of climate change impacts discussed above suggest that food availability is not threatened by climate change, but there are reasons to believe that food quality and safety may be impacted. Increased CO_2 may increase plant growth but result in lower protein content of grains, for example. In addition, vegetable and fruit quality are highly vulnerable to temperature and water stresses (Hatfield et al. 2008).

Food safety is also likely to be impacted on by climate change through several mechanisms (FAO 2008). Food-borne pathogens, such as cholera and mycotoxins, are likely to expand their geographic range, and outbreaks are often associated with extreme weather events. Increased stress on water resources is also likely to increase pathogen growth and human infection. Climate change is also likely to increase the occurrence of harmful algal blooms and the contamination of fish and seafood by pathogens and toxins, including through the increased pesticide contamination that is likely to be associated with climate change. Increased disease incidence in livestock is likely to increase the use of veterinary drugs and thus increase the risk of food contamination, antibiotic resistance, and related health issues. Addressing these increased risks will require the adaptation of existing public information, disease surveillance, and intervention practices.

Market infrastructure. Another potentially important impact of climate change on agriculture is its impacts on the location and functioning of transportation infrastructure. As noted above, climate change is likely to result in the spatial reorganization of agricultural production such that, for example, maize and soybean production move westward and northward in the United States. These geographic shifts may mean that storage and shipping facilities and rail infrastructure may need to be relocated. The increasing globalization of agriculture and the food system also has increased the amount of traded agricultural commodities, as well as processed products, through rivers and by sea. In the United States, a large share of agricultural commodities in the corn and wheat belts is shipped by barge on the Mississippi River. Competition between upstream and downstream uses of water in the Mississippi watershed is already intense and is likely to be impacted on by climate change. Changes in sea level also could have important implications for the location and operation of storage and shipping facilities at major ports. As yet these issues have not been investigated systematically to assess the possible costs of changing transportation infrastructure that supports agriculture and the food system. The rate of climate change and sea level risk can be expected to be critical factors in determining these costs.

The food processing and distribution system. Very little research has addressed the potential vulnerabilities of the food processing and distribution system. Here a few observations are offered that may be suggestive of possible vulnerabilities.

The meat slaughter industry is one area in which important issues may arise. Regarding food safety in particular, higher temperatures would increase the costs of refrigeration, packaging, handling, and storage of perishable meats that are vulnerable to dangerous pathogens such as E. coli. Changes in the location of livestock production could also necessitate changes in the location of livestock transport, feedlots, and slaughter plants. Similar issues could be expected to be associated with the storage, transport, and marketing of perishable fruits and vegetables.

Most components of the food processing and distribution system are dependent on fossil fuels for transportation and packaging and on electricity to power processing operations and refrigeration. Thus policies to reduce GHG emissions that raise fossil fuel costs are likely to have significant impacts across many dimensions of this sector as well as production agriculture. Researchers studying climate change impacts and adaptation have devoted little attention to this issue.

Adaptation and Policy

The potential impacts of climate change on agriculture and the food sector suggest that there is a need for a comprehensive assessment of existing and likely future policies on adaptation in the agriculture and food sectors. The main focus of climate change policy thus far has been on policies to reduce GHG emissions (mitigation); adaptation has been largely ignored in the policy domain, although as we noted at the outset there are signs that U.S. government agencies are beginning to focus more attention on adaptation research. But adaptation and mitigation are linked: the need for and extent of mitigation policies is in part dependent upon the costs of adaptation. Conversely, how mitigation policies may affect agriculture and agricultural adaptation provides a useful case study of the kinds of information that adaptation research could provide to support more informed agricultural management and policy decisionmaking. In addition to possible future mitigation policies, many other existing policies affect agriculture and the food sector, and many of these are likely to affect adaptation. Climate change is not likely to be the focus of many of these policies, but it does make sense for policy design to take adaptation into consideration. Finally, there is a role for publicly funded agricultural research to play in producing information about climate change impacts and adaptation options.

Climate change mitigation and adaptation policy interactions

Climate change is likely to be one of the most challenging political and policy problems that the world has ever had to deal with. “The problem is not a technological one . . . Climate change is the hardest political problem the world has ever had to deal with. It is a prisoner’s dilemma, a free-rider problem and the tragedy of the commons all rolled into one” (Duncan 2009). A key challenge in climate policy is suggested by the analysis of investment under uncertainty discussed above: a high degree of uncertainty makes it individually rational to delay action, even though collectively this may risk irreversible, possibly catastrophic damage. The global nature of the problem transcends national political jurisdictions, and costs of action are local (e.g. higher taxes or higher energy costs), whereas the benefits are global and in the future. Similar challenges are faced in implementing public policies for adaptation to future climate change. However, adaptation in reaction to perceived current climate changes seems much more likely, because both costs and benefits of adaptation investments are local and in the present. Another strategy being considered by both federal and state governments in the United States is the requirement that climate adaptation be explicitly incorporated into new policies, particularly ones that directly relate to sea-level rise and other situations where climate impacts are likely to be substantial.

Several types of mitigation policies are under consideration in the United States. A 2007 Supreme Court ruling granted the U.S. Environmental Protection Agency the authority to regulate CO_2 as a pollutant. This outcome has increased the likelihood that Congress will take legislative action. The two policy options that have been widely discussed are a cap and trade policy to restrict GHG emissions and a tax on carbon emissions. These policy instruments differ in terms of cost effectiveness, equity, and feasibility.

The importance of policy detail to policy impacts is evident in testimony on the Waxman-Markey climate bill passed by the U.S. House of Representatives in 2010 (U.S. House of Representatives). The bill proposes a cap and trade regime for CO_2 and allows agricultural offsets; agricultural emissions are not capped. The net economic impact on different types of farms would depend on the tradeoff between gains from participation in the offset market and losses from higher energy costs induced by the legislation. U.S. Department of Agriculture research indicates that farmers with energy-intensive crops may see energy costs of production go up 10 percent over the next 50 years due to higher fuel and feed costs, but the impact would depend on how agricultural systems could adapt to higher fuel costs, how they would be affected by climate changes, and which systems could effectively participate in an offset market for carbon emissions. Much of the needed information—how farmers and ranchers will respond to the proposed climate legislation, how production costs and land use will change, and how the prices of carbon may stimulate a market for carbon offsets—have yet to be analyzed with sufficient detail to guide decisions by farmers, despite the substantial amount of research on agricultural potential to sequester carbon in soils and trees (Paustian et al. 2006). Many of the critical details would depend on policy parameters, such as: eligibility requirements for participation in carbon offset contract (e.g. land-use history and previous adoption of conservation practices); duration of contracts and terms for termination of contracts; design of payment mechanisms (e.g. payments for actual or estimated changes in soil carbon versus adoption of practices eligible for credits); and costs of required monitoring and verification.

Other policy-adaptation interactions

Agricultural subsidy and trade policies. Agricultural subsidy programs for commodity crops such as wheat, corn, rice, and cotton, as well as trade policies such as the import quota on sugar, were established in the 1930s and continue today. The structure of these programs has changed over time, but a common feature is that they reduce flexibility by encouraging farmers to grow subsidized crops rather than adapting to changing conditions, including climate. Over time, conservation and environmental aspects of agricultural land management have been increased, and the case can be made for converting subsidies based on production of a commodity to subsidies based on the provision of public goods such as climate mitigation and other ecosystem services, along the lines of the climate mitigation policies discussed above.

Production and income insurance policies and disaster assistance. There is a long history of both private and public crop insurance schemes for agriculture and disaster relief programs. The most recent farm policy legislation, enacted in 2008, continued existing crop insurance subsidies, introduced a new revenue insurance program, and established a permanent disaster assistance program. Publicly subsidized crop and income insurance could be one way to address increasing climate variability and extremes associate with climate change. Whether this is an appropriate policy response to climate change is an open question that deserves further study. In any case, public subsidies for crop or revenue insurance and disaster assistance, like other types of agricultural subsidies, are likely to reduce the incentive for farmers and ranchers to adapt to climate change.

Soil and water conservation policies and ecosystem services. Over time U.S. agricultural policies have shifted from commodity subsidies alone toward a variety of policies that provide subsidies to protection of soil and water resources and the provision of ecosystem services. For example, the Conservation Reserve Program (CRP) has resulted in more than 30 million acres of land being taken out of crop production and put into permanent grass and tree cover, through cost sharing of conservation investments and long-term contracts providing payments to maintain conserving practices. While these policies protect surface water quality from soil erosion and chemical runoff, and enhance ecosystem services such as wildlife habitat, they also reduce flexibility to respond to changes in climate over time by reducing the ability to adapt land use and also reducing the ability to respond to extreme events. For example, according to CRP rules, farmers are not allowed to use CRP lands for grazing or to harvest grasses as animal feed. As a result, when severe droughts reduce availability of livestock feed in pasture and rangeland, CRP lands cannot be used for grazing livestock, even though in many places this could be done on a temporary basis without substantially impacting on the environmental benefits of the CRP. In some cases the Secretary of Agriculture can waive these rules to allow grazing. Changes in program design, such as more flexibility in administrative rules, and better targeting of the policies toward lands with high environmental value, could facilitate adaptation to extreme climate events.

Environmental policies and agricultural land use. Many environmental policies affect agricultural land use and management. Policies governing the management and disposal of animal waste from confined animal feeding operations are an important example that has clear implications for adaptation (Nene, Azzam, and Schoengold 2009). Both state and federal laws regulate the location and management of these facilities. As noted above, changes in average climate and climate extremes are likely to impact significantly on the viability of these operations in some locations, for example where waste ponds become vulnerable to extreme rainfall events and floods. Environmental regulations raise the cost of relocating facilities and thus have the unintended consequence of discouraging adaptation. Including benefits of climate adaptation in regulatory design could lead to policies that achieve the dual goals of environmental protection in the current climate and the need for adaptation to the future climate.

Tax policies. Many tax policies affect agriculture, including the taxation of income and the depreciation of assets. Tax rules could be utilized to facilitate adaptation in a variety of ways, for example by accelerating the depreciation of assets. However, effectively targeting incentives for climate adaptation may prove difficult to implement, since many other types of economic and technological changes may also lead to capital obsolescence.

Energy policies. The increasing public interest in developing domestic sources of nonfossil based energy, including biofuels, has already resulted in significant policy developments, such as subsidies for corn ethanol, and is likely to have important implications for both food and fuels prices and for adaptation. Further developments in biofuels could further change the way land is used for food and fuel production, have implications for adaptation, and be impacted on by related energy policies, such as requirements for use of renewable energy. Development of other types of energy technologies, such as the use of animal waste for energy production, may have important impacts on the adaptability of these systems and the way they are regulated.

Conclusions: Toward an Adaptation Research Agenda

We have presented a framework for analysis of adaptation as an investment and discussed the literature on agricultural impacts of climate change and its limitations for analysis of adaptation. Our main conclusion is that there is a need for the kinds of information that can support both private and public decisions about adaptation investments. Private decisionmakers need information that can reduce uncertainty about climate change and its impacts on the systems they are managing now and maybe managing in the future. Public decisionmakers need information that can show the economic and other public benefits of investments that reduce uncertainty about climate change and adaptation options. These public investments will have to compete for scarce public resources and will have to be justified in terms of economic, environmental, and social net benefits they produce, taking into account likely tradeoffs among the various relevant outcomes. We conclude with the following outline of some elements of an agenda for public research on climate adaptation.

Reassessment of impacts and estimation of adaptation costs

As noted above, adaptation is an investment decision and appropriate information is needed to support more informed decisions about adaptation investments. The impact assessments carried out thus far have not accounted for critical climate thresholds, and the statistical modeling methods used by some economists do not allow the impacts of climate change without adaptation to be distinguished from the benefits of on-farm or off-farm adaptations. Moreover the costs of adaptation for the agricultural production sector and for the broader food industry have been largely ignored, yet they are needed to inform both private and public investment decisions. Costs should be evaluated under alternative scenarios for the rate of climate change, climate variability, and the occurrence of extreme events. Thus far, most of the research effort has been devoted to the impact on grain crops. More research on impacts and costs of adaptation in other agricultural systems is needed, particularly for livestock, poultry, and other high-value, climate-sensitive products such as vegetables and fruits.

Identifying adaptation strategies and supporting basic research needed for development of adaptation technologies

Our analysis suggests that research is needed to identify climate resilient technologies. Some examples would be:

- Basic crop and animal research on vulnerability to extremes and strategies to reduce impacts of extreme events.
- Research on resilient systems and their management, particularly in climate-vulnerable regions. This should include economic analysis of tradeoffs in production systems between maximum efficiency and resilience.

- Research on effects of climate change on pests and diseases and their management.
- Evaluation of climate mitigation technologies (e.g. afforestation, use of no-till cropping systems, crop rotations with legumes, biofuels production strategies) in the context of climate change adaptation.
- Development of more resilient livestock waste management technologies, and incorporation of waste into biofuels production.

Methods for ex ante analysis of adoption of climate-resilient technologies, and assessment of their economic, environmental, and social impacts

Existing methods for ex ante research impact assessment need to be improved, including the capability to predict adoption rates of proposed technologies under heterogeneous conditions associated with differences in soils, climate, and farm characteristics. Impact assessment methods also need to account for economic, environmental, and social impacts, including impacts on the distribution of income among different types of farms and impacts on ecosystem services. Although many detailed models of agriculture–environment interactions exist, the data requirements and complexity of these models reduce their usefulness for impact assessment and adaptation research. Methods are needed that can be implemented in a timely manner with the kinds of data that are typically available in both industrialized and developing countries.

Provision of public information about long-term climate trends and their economic implications

There is a great deal of public information available on short-term weather forecasts, but there appears to be a need for more public awareness of long-term climate trends and forecasts. This information is a public good that needs to be supported, at least in part, with public funds, to reduce uncertainties about climate change and its likely impacts.

Implications of climate change and mitigation policies for agriculture and the food sector

As discussed above, potential climate change impacts and adaptation strategies for the food sector have not been studied adequately. The costs of adapting the food distribution system to a changing climate should be included in this research, as well as the potential impacts on the prevalence and control of food-borne pathogens. The dependence of this sector on fossil-fuel-based energy also suggests that GHG mitigation policies could have substantial impacts on the national and global food system as it presently operates.

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