



**AgEcon** SEARCH  
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

*The World's Largest Open Access Agricultural & Applied Economics Digital Library*

**This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.**

**Help ensure our sustainability.**

Give to AgEcon Search

AgEcon Search

<http://ageconsearch.umn.edu>

[aesearch@umn.edu](mailto:aesearch@umn.edu)

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*



## **Agricultural Adaptation to Climate Change in Rich and Poor Countries: Current Modeling Practice and Potential for Empirical Contributions<sup>1</sup>**

By

Thomas W. Hertel<sup>a</sup>  
David B. Lobell<sup>b</sup>

GTAP Working Paper No. 72

2012

---

<sup>1</sup> Paper prepared for the NBER workshop on “Climate Adaptation: Improving the connection between empirical research and integrated assessment models,” Cambridge, MA, May 17-18, 2012. Revised version under review with *Energy Economics*. Hertel acknowledges support under US DOE, Office of Science, Office of Biological and Environmental Research, Integrated Assessment Research Program, Grant No. DE-SC005171. The authors thank Robert Mendelsohn and other participants in the NBER workshop for valuable comments. In addition, valuable comments have been received from Stephanie Rosch, Petr Havlik and Delphine Deryng.

<sup>a</sup> Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University;

<sup>b</sup> Department of Earth System Science and Center on Food Security and the Environment, Stanford University

# **AGRICULTURAL ADAPTATION TO CLIMATE CHANGE IN RICH AND POOR COUNTRIES: CURRENT MODELING PRACTICE AND POTENTIAL FOR EMPIRICAL CONTRIBUTIONS**

## **Abstract**

In this paper we discuss the scope of the adaptation challenge facing world agriculture in the coming decades. Due to rising temperatures throughout the tropics, pressures for adaptation will be greatest in some of the poorest parts of the world where the adaptive capacity is least abundant. We discuss both autonomous (market driven) and planned adaptations, distinguishing: (a) those that can be undertaken with existing technology, (b) those that involve development of new technologies, and (c) those that involve institutional/market and policy reforms. The paper then proceeds to identify which of these adaptations are currently modeled in integrated assessment studies and related analyses at global scale. This, in turn, gives rise to recommendations about how these models should be modified in order to more effectively capture climate change adaptation in the farm and food sector. In general, we find that existing integrated assessment models are better suited to analyzing adaptation by relative well-endowed producers in the developed countries. They likely understate climate impacts on agriculture in developing countries, while overstating the potential adaptations. This is troubling, since the need for adaptation will be greatest amongst the lower income producers in the poorest tropical countries. This is also where policies and public investments are likely to have the highest payoff. We conclude with a discussion of opportunities for improving the empirical foundations of integrated assessment modeling with an emphasis on the poorest countries.

**Keywords:** Climate change, adaptation, integrated assessment models, investment, new technologies, developing countries.

**JEL codes:** Q54, Q55, Q56, Q58, Q15, Q16, Q17

## **I. Motivation**

The table has now been set for significant warming of the earth's surface in the coming decades. Those climate change mitigation policies currently being debated will do little to alter the expected rate of warming over the next 20-30 years due to the momentum already in the energy and climate systems. The long-lived, carbon-intensive energy systems currently in place in the rapidly growing developing economies of the world, along with continued reliance on expansion of commercial land uses into carbon-rich natural environments, both serve to ensure that GHG concentrations in the atmosphere will rise in the near term. Current estimates suggest that increased radiative forcings will result in temperature increases on the order of 0.3-0.4°C per decade in most agricultural regions to 2050. As we document here, such temperature increases are likely to threaten agricultural productivity growth – particularly in the tropics where the bulk of the world's poor currently reside and find their livelihoods.

The extent to which these climate impacts on agriculture translate into reductions in human welfare will depend critically on the ability of farmers, agri-businesses, regional and national economies to adapt to these climate-driven changes. Yet adaptation potential is critically dependent on access to markets, as well as the information and credit needed to develop and deploy new technologies. Unfortunately, such access is often missing in the poorest economies. Indeed, their poverty can often be traced back to missing markets, incomplete information and the inability to borrow the money needed for farming operations as elementary fertilizer applications. So we confront a situation in which climate impacts on agriculture are expected to be most severe precisely in those regions where households are least well-equipped to deal with them. Therefore, understanding the potential for agricultural adaptation to climate change is

critical in determining how such changes will affect global poverty, food security and the environmental well-being of the planet for decades to come.

## **II. Assessing the Scope of the Adaptation Challenge: Climate Impacts on Agriculture**

Before understanding the nature and scale of necessary adaptations to climate change, one must consider the various reasons that climate change poses a risk to agriculture. Climate risks, in the form of intra- and inter-season variability, have always presented a challenge to farmers. Droughts, frosts, floods, heat waves, hail storms, and other extremes are familiar worries. Indeed, natural climate variability causes so many losses, and is so high on the list of current concerns to farmers, that many scholars advocate focusing exclusively on coping with climate variability as a first step towards dealing with longer-term trends (Washington et al. 2006; Cooper et al. 2008).

Whether or not such a focus is wise, it is clear that (1) current climate risks are substantial and (2) climate trends will tend to amplify some risks and reduce others, but is unlikely to create entirely new risks or reduce existing risks to zero. It follows that any adaptation aimed at addressing climate trends will have some value in current climate, and conversely any effort to address current climate risks will have some value in future climate. The key question is which risks are increasing fastest, and therefore which innovations are likely undervalued if considered in the context of current climate variability. For example, heat stress is widely acknowledged as a current constraint to wheat production throughout the developing world (Kosina et al. 2007), but will become increasingly important as temperatures rise (Ortiz et al. 2008; Asseng, Foster, and Turner 2011).

Given that many working in the area of climate adaptation and integrated assessment modeling are unfamiliar with details of crop growth and production, we outline briefly the main

reasons that climate change affects crop productivity. We focus largely on the impacts of rising temperatures and CO<sub>2</sub> on crop yields because (1) trends in temperature are much larger relative to natural variability than for precipitation (Lobell, Schlenker, and Costa-Roberts 2011; Tebaldi, Arblaster, and Knutti 2011) and (2) crops provide the bulk of calories for human consumption, either directly or indirectly through animal feed. This brief discussion therefore ignores several elements of adaptation, including potential direct impacts of climate change on livestock (P. K. Thornton et al. 2009) and fisheries (Cheung et al. 2010) and impacts of elevated ozone levels (Avnery et al. 2011). However, the discussion of adaptation concepts and modeling approaches in following sections are more general.

All biological processes are influenced by temperature, and therefore the net effects of warming and elevated CO<sub>2</sub> on crops are the result of several separate yet interacting components. Below we describe five biophysical factors, their responses to changes in temperature and elevated CO<sub>2</sub>, and the relative impacts between temperate and tropical systems.

***Crop development.*** The speed with which crops proceed through different development stages, and the resulting duration of total growth, are strongly dependent on temperature (Parent and Tardieu 2012). Development rates increase linearly with temperature across a wide range, typically from 0 to 30°C, with the exact range depending on the crop. Because total accumulation of biomass and yield scales with the duration of the season (as well as key stages like grain filling), the yield effect of shortened duration from warming is frequently negative in both temperate and tropical systems. The main exceptions occur when faster development helps to avoid water stress at the end of season.

***Photosynthesis and respiration.*** Plants take up CO<sub>2</sub> through the process of photosynthesis, and release CO<sub>2</sub> during respiration, when the photosynthates are tapped for energy needed for plant growth and maintenance. Between one-quarter and one-half of the carbon uptake in photosynthesis is typically released as respiration (Amthor 1989). The difference between photosynthesis and respiration determines the net carbon uptake by a crop. Both processes depend on temperature, with an optimum temperature for net uptake in full sun between 15 to 30°C in C3 crops and a higher optimum of 30-40°C in C4 crops. (The higher optimum for C4 plants is related to the lack of photorespiration, which in C3 crops increases with warming.) At nighttime, when photosynthesis is absent, any warming increases respiration and reduces net uptake.

Warming can therefore increase or decrease net carbon uptake, depending on the crop type (C3 vs. C4), the starting temperature relative to optimum, and whether the warming occurs at day or night. In addition to the direct effects of temperature on photosynthesis and respiration, higher temperatures increase the saturation vapor pressure of air and, in the absence of added moisture, will increase the vapor pressure deficit (VPD) between the leaf and surrounding air. Plants respond to higher VPD by reducing stomatal conductance, leading to a decrease in CO<sub>2</sub> flux into the leaf and subsequent depression of photosynthesis rates. Thus, higher temperatures affect photosynthesis both directly, via effects of warming on enzymes, and indirectly via effects on CO<sub>2</sub> concentrations.

Elevated CO<sub>2</sub> generally leads to an increase in leaf CO<sub>2</sub> levels and a reduction in stomatal conductance. The former leads directly to higher photosynthesis rates in C3 plants, but typically not in C4 plants which are already saturated with CO<sub>2</sub>. Elevated CO<sub>2</sub> also increases the optimum temperature for C3 photosynthesis, because it inhibits photorespiration (Long 1991). The

stomatal effect reduces transpiration losses and leads to higher water use efficiencies in both C3 and C4 plants, which can result in greater overall yields in dry conditions because plants are able to reduce losses of soil moisture. However, the stomatal effect also increases canopy temperature because of lower transpiration rates.

The overall strength of yield response to CO<sub>2</sub> *can* be constrained by a lack of nutrients needed for grain biomass, so that regions with low fertilizer inputs – typically in the tropics – are expected to show reduced responses to CO<sub>2</sub> increase. At the same time, tuber crops with much lower nutrient content in harvested organs are able to respond more strongly to elevated CO<sub>2</sub>, with potatoes and cassava, for instance, showing responses well above grain crops. In general, tropical systems have a greater proportion of dry conditions and tuber crops, which will favor CO<sub>2</sub> responsiveness, but also have higher proportion of C4 crops, which diminishes CO<sub>2</sub> responsiveness (Leakey 2009). The net difference in CO<sub>2</sub> responses for tropics vs. temperate systems remains ambiguous.

**Water stress.** As mentioned, higher temperatures increase saturation pressure of water vapor in the atmosphere. Absolute humidity of the atmosphere is also expected to increase, mainly due to increased evaporation over oceans, but only enough to maintain constant relative humidity, with a corresponding increase in overall Vapor Pressure Deficit (VPD) (Held and Soden 2006). This higher VPD leads to higher rates of soil evaporation and plant transpiration, both of which lead to declines in soil moisture. Even in scenarios of increased rainfall, many regions still exhibit a decline in soil moisture due to the evaporative changes (Meehl et al. 2007). A decrease in moisture is significant for crop growth in both temperate and tropical systems, but is likely more problematic in tropical areas where the length of the viable growing period is determined by soil moisture. For example, projections in Africa show consistent reductions in



the growing period for most countries, with a reduction of more than 20% in Southern Africa and the Sahel by the end of the 21<sup>st</sup> century (Philip K. Thornton et al. 2011).

As mentioned, elevated CO<sub>2</sub> improves the water use efficiency of plants, which in turn leads to increases in soil moisture for the same level of biomass production. The net effect of elevated CO<sub>2</sub> and warming on soil moisture and water stress is not yet well known, and will likely depend on the particular combination of temperature, VPD, and CO<sub>2</sub> changes. A recent grassland study found that 600ppm was enough to completely counteract the moisture decline associated with day/night warming of 1.5°/3.0°C (Morgan et al. 2011).

***Extreme temperature damage.*** Both cold and hot extremes can directly damage plant cells, leading to severe injury or even death. Several reviews detail the specific thresholds relevant for various crops (Porter and Gawith 1999; Luo 2011). Hot extremes can be particularly damaging during the flowering period, where they can irreparably damage reproductive organs and young seed embryos. For example, rice spikelets exhibit dramatic increases in sterility when exposed to high air temperatures during flowering, with this effect exacerbated under elevated CO<sub>2</sub>, presumably because of decreased transpiration rates which contribute to further canopy warming (Matsui et al. 1997).

Warming is expected to reduce the incidence of cold extremes and increase the incidence of hot extremes, and indeed both trends are already clearly observed in many regions (Alexander et al. 2006; Zwiers, Zhang, and Feng 2011). Given that cold extremes cause much more crop damage in temperate than tropical systems, these trends are more damaging to tropical systems. Indeed, the reduction of frost constraints in temperate systems presents a lot of adaptation opportunities that do not exist in tropical areas, a topic to which we will return.

***Pest and disease damage.*** A final, but less understood, influence of warming and CO<sub>2</sub> is on major pests, weeds, and diseases. We refer interested readers to the recent review of Ziska and colleagues (Ziska et al. 2010), while noting simply that both warming and CO<sub>2</sub> are likely to affect these biotic stresses in various ways. For instance, invasive weeds tend to be more responsive than crops to changes in resource availability, such as elevated CO<sub>2</sub>. Reduction in frost frequency will also likely expand the ranges of many important pests and diseases. For example, Hannukkala, et al. (2007) report a steady march forward in the first observations of potato blight in Finland over the past decade. In the early 1990's, the first appearance of this blight was typically between 60 and 100 days after planting. However, by the early 2000's, observations as early as 20 days were common, thereby requiring considerably more effort on the part of producers to deal with this pathogen. Ziska et al. (2010) document the northward shift of the kudzu weed in the US Corn Belt from 1971 to 2006. Overall, there is little indication yet of whether changes will be more severe in temperate or tropical systems.

***Model Evaluation.*** How well do biophysical crop models used in most impact assessments capture each of these factors? With few exceptions, most models were initially developed with the explicit goal of aiding field management decisions, such as cultivar choice, irrigation timing and fertilizer application rates. Emphasis in crop modeling was therefore placed on factors like rates of crop development, soil water dynamics, and nutrient supply and demand. Developers of crop models have long cautioned against their use in climate change studies, given the lack of development and testing in extreme climate conditions (J. W. White, Hoogenboom, and Hunt 2005; Jeffrey W. White et al. 2011). For example, a recent review of 221 studies using crop models for climate change impacts, which spanned over 70 different models, found that only six studies considered the effects of elevated CO<sub>2</sub> on canopy temperature, and similarly few

studies considered direct heat effects on seed set or leaf senescence (Jeffrey W. White et al. 2011).

Overall, existing crop models provide an extremely valuable tool for understanding potential impacts and adaptation options, but with three major caveats. (1) Only a subset of relevant processes is included in any single model. For instance, most models include treatment of crop development and photosynthesis responses to temperature, but omit heat effects on grain set and pest damage. In general these omitted processes are thought to become more damaging with climate change, so models may provide estimates biased toward positive values. (2) The ability of models to correctly predict effects of adaptation is inherently limited to the types of impacts that are modeled in the first place. For example, effects of warming on crop duration may be fairly easily addressed by switching to existing longer maturing varieties, whereas effects on grain set could be more challenging and require development of new varieties. (3) The types of processes omitted by models tend to be more important in tropical than in temperate systems, including effects of high VPD on photosynthesis, heat stress on grain set and leaf senescence, and pest and disease pressures.

### **III. Thinking about Adaptation**

Figure 1, reproduced from (John M. Antle and Capalbo 2010), does a nice job of illustrating some of the key concepts associated with adaptation. This figure shows the expected value (given uncertainty associated with weather under a given climate) of a given production system, at a given location, as a function of management intensity,  $x$ , which serves as a proxy for the application of seeds, feed, nutrients, water, energy and labor within a given production system or technology, denoted by  $\tau_A$ , and conditional on current climate,  $\gamma_1$ . If the production

system were to change to  $\tau_B$ , then this curve would likely shift and also change its shape. In Figure 1, the new value function  $V(x, \tau_B, \gamma_1)$  is much flatter than the one for production system  $\tau_A$ . It also peaks at a lower value  $V$ , explaining why it is not observed at this particular location under the initial climate system,  $\gamma_1$ .

Now consider the impact of climate change at this particular location with its unique agro-ecological conditions, on these relationships. Given technology  $\tau_A$ , producers suffer a significant drop in the expected value of production under the new climate. Indeed, if they do not adjust their management intensity from  $x_A$ , the expected economic loss is equal to the distance  $AB'$ . By adapting management intensity to these new circumstances, within technology  $\tau_A$ , producers can mitigate these losses. Indeed, the new optimal management intensity for technology  $\tau_A$ , given by  $x_B$ , recoups expected economic value equal to the vertical distance  $B'B$ . Therefore, given  $\tau_A$ , the adverse climate impact is equal to  $AB'$  and the gain from adaptation is  $BB'$ . If technology did not change, this would be the end of the story. And indeed, in the short run, this is likely to be the end of the story.

However, in the longer run, we can expect producers to consider alternative technologies. For example, if the climate change results in more frequent and intense temperature extremes, producers may wish to consider adopting pre-existing technologies (e.g., cropping systems or crop varieties) which were previously rejected due to lower maximum profits. This point is illustrated by technology  $\tau_B$  in Figure 1. This alternative technology was deemed inferior to  $\tau_A$  under current climate, as it yielded a maximum value  $C$  which was less than  $A$ . However,  $\tau_B$  is much more resilient to higher temperatures, with the value function remaining essentially

unaltered under climate change. Therefore, it now becomes the preferred alternative for producers in this region, since  $C > B$  as measured on the expected value axis. Therefore, once both management and technology adjust, the loss due to climate change is just the vertical distance between A and C.

Antle and Capalbo (2010) suggest that producers can be expected to optimize over the managerial variables fairly readily, and they therefore term this ‘short run’ adaptation. However, the shift to a new production system may be much more costly and time-consuming, involving new techniques and associated learning, new infrastructure, and perhaps even the development of entirely new technologies. Accordingly, they categorize this as a ‘long-term’ decision, and this is where they focus the bulk of their discussion of the adaptation problem. They conceptualize the creation and adoption of new (different) technologies as a problem of investment under uncertainty. And they envision the role of adaptive policies as being that of reducing the uncertainties plaguing farmers and private investors seeking to make these decisions with incomplete information about future outcomes.

In our discussion of adaptation we draw inspiration from the Antle-Capalbo framework and distinguish between three levels/categories of adaptation. The first are those adaptations – typically involving managerial intensity decisions – based on current technology. These tend to be attainable in a shorter time period and do not involve major new investments or response uncertainties. In terms of Figure 1, they correspond to movements along a given value function, such as from B’ to B in the wake of climate change.

The second category of adaptation involves adoption of a new (to that site) technology. This may be a technology which was previously rejected due to lack of profitability under the old

climate, or it may be an entirely new technology. In those cases where the technology is entirely new, adoption will involve investments in information and infrastructure and therefore takes more time. To the extent that these investments are irreversible, they bear special risks in the presence of uncertainty about climate change and the performance of the new technology.

The third category of adaptation involves the institutional environment within which the producer is operating. This encompasses government policies, publicly available information as well as the functioning of input and product markets. Changes at this level result in shifts in the expected value functions as will be discussed below.

Before proceeding with our discussion of these three different types of adaptation, it is also useful to look at them through some of the other lenses which are used in the literature. One important distinction is that between processes that are expected to occur as a result of normal market forces – generally termed *autonomous adaptations* in the climate change literature, and those that are generally related to government investments, policies or institutional reforms – termed *planned adaptations*. Returning to the three categories of adaptation listed above, the first (optimization of managerial intensity) falls clearly into the *autonomous* category. The second type of adaptation -- that of technology development and adoption, is more likely to be the result of a mix of public and private actions. Shifts in the location of production systems and crops is likely to be the result of market-mediated effects, as is the development of stress-tolerant crop varieties in the industrialized world where private R&D is dominant. However, agricultural research and development in the developing world remains driven by public investments. Without planned adaptation, many of the new technologies would not emerge in these low income countries. By its very nature, the third and final category of adaptation – markets and

policy -- is much more likely to be the result of *planned adaptation*, although some market instruments (e.g., insurance) could evolve autonomously in the context of climate change.

***Adaptation based on existing technology.*** The simplest form of adaptation to climate change is that represented by the movement from B' to B in Figure 1. In this case, producers do not change their production system. However, they accommodate the change in their expected value function by adjusting variable input usage. Consider, for example, the challenges posed by increased weeds, pests and pathogens which may increase under climate change. Such an increase will likely require more intensive use of labor for weeding as well as labor, machinery and chemicals for the application of herbicides and pesticides. Such an autonomous adaptation under current production systems would suggest the likelihood of an increase in variable input use from  $x_A$  to  $x_B$  in Figure 1. However, note that, even at this higher level of variable input use, the expected value of the production system under future climate is considerably reduced from that attainable under current climate in Figure 1.

The intensity of irrigation is another important choice variable for farmers which may be affected by climate change and which may be viewed as a near term management decision on those farms already equipped with irrigation. At heightened temperatures, the rate of evapotranspiration rises and the plant requires more water to maintain normal development. Thus, it is natural to think of climate change as shifting down the expected value function, as shown in Figure 1, for all the reasons mentioned in the climate impacts discussion above, while simultaneously increasing the optimal rate of irrigation. In the end, the intensity of variable input use rises, but maximum expected value falls once again.

Another example of how variable input use is likely to be affected by climate change is motivated by crops' response to elevated CO2 levels. In order to translate higher CO2 into faster plant growth, nutrient availability may need to be increased to facilitate the faster growth. This means a higher rate of fertilizer application is desirable. In contrast to the climate impacts shown in Figure 1, heightened CO2 levels – in the absence of changes in temperature or precipitation – shift the expected value function *upward and to the right*, such that the optimal intensity of variable inputs also rises.

In some cases, we may wish to think of the two production systems in Figure 1 as current choices facing producers – as opposed to technology  $\tau_B$  representing an entirely new system requiring development and adoption over a longer time horizon. In this case, producers have the near term option to switch technology  $\tau_A$ . For example, consider  $\tau_A$  to represent rainfed corn production in the US Corn Belt, and  $\tau_B$  to represent a production system with supplemental irrigation. Most farmers in this region do not invest in supplemental irrigation, suggesting that the maximum expected value of the rainfed system is higher than for supplemental irrigation, which has a higher variable input requirements,  $x_C$ , as well as significant fixed costs, leading to the lower value function. However, in some places in the Corn Belt, producers do invest in irrigation, recognizing that, while it is not required in every year, in the exceptional dry/hot year, this system will pay off. Under a future climate in which the temperature distribution shifts rightward and there are more frequent, extremely hot days during critical periods of the growing season, such supplemental irrigation may permit producers to avoid weather-induced losses. This is anticipated in Figure 1 which shows little change in the expected value function for technology  $\tau_B$  under the two climate regimes. Under such circumstances we would expect producers to



switch production systems, as well as varying their intensity of production, in the relatively near term – following the lead of their exceptional neighbors who already have such a system in place.

This discussion raises the important point of producer heterogeneity. While most IAMs model a representative producer in each region, the Antle-Capalbo framework allows for heterogeneous producers who are differentiated by biophysical and socio-economic endowments. This endowment heterogeneity leads to incomplete adoption of new technologies and heterogeneous effects from climate change. For example, in their study of the impacts of climate change on a representative sample of producers from the Northern Plains of the United States, they find that poorly endowed farmers are hardest hit (J. M Antle et al. 2004). Claessens et al. (2012) apply this framework to two regions in Kenya and find that climate change is expected to have an adverse impact on 76% of producers in Vihiga and 62% in the Machakos region.

This type of heterogeneity also exists at global scale, with the most important difference being the potential impacts of warming on tropical versus temperate agriculture where the options for adaptation may be quite different. One glaring distinction mentioned in section II is that temperate systems will likely see increases in growing season length (defined as time between last and first frost), whereas many tropical systems will likely see reductions in growing seasons (defined as the period with sufficient soil moisture). Temperate farmers will have the option of an earlier sowing date to escape hot conditions during critical periods such as flowering, as well as adopting longer maturing varieties in order to compensate for faster rates of crop development. Both of these can be effective at reducing simulated impacts in crop modeling studies, but such options are generally not as attractive under tropical systems.

A nice illustration of this differential adaptation potential in temperate and tropical regions is shown in Figure 2, taken from the MS thesis written by Deryng (2009) (See also Deryng et al., (2011).) In this study, the author uses the Pegasus global crop model to estimate the impact of a 2 degree Celsius rise in temperature on yields for maize, soybeans and spring wheat. The crop model is run at the grid cell level, globally, twice: first without any adjustment in planting and harvesting dates, or in varieties of crops grown, and secondly with full adaptation of these factors. Panel (a) shows the importance of such biophysical adaptation at global scale – it sharply reduces the global average yield losses from warming for all three crops. However, these aggregate results hide a great deal of regional variation. And one way to highlight this regional variation is by aggregating by income level. Panels (b) and (c) do so, with using four groupings of countries from the World Bank’s classification scheme: high income, middle-high, middle-low and low income countries.

From Figure 2, panel (b) we see that the adverse yield impacts are quite uniform across regions, regardless of crop, when no biophysical adaptation is permitted. However, when planting dates and varieties are allowed to adjust, there emerges a sharp difference in impacts by income level. In particular, the high income countries – disproportionately represented in the temperate zone, experience yield increases for maize and soybeans, and only a marginal average loss in spring wheat yields. By extending the frost-free period in these regions, productivity can benefit from such global warming when planting dates and varieties are adjusted. However, this is not true of the low income region, comprising countries located predominately in the tropics. Here, producers are constrained by soil moisture, and the varieties of crop grown are already tuned to high levels of GDD. Therefore, even after allowing for adjustment of planting dates and varieties grown, the yield losses are substantial for all three of these major staple crops.

Mendelsohn, Dinar and Williams (2006) generate a similar finding in their global analysis of the direct impacts (ignoring market impacts) of climate change on the agriculture, water, energy sectors, as well as damages due to sea level rise. They find that poor countries (defined by per capita income in 2100) suffer much more from climate change than do rich countries. Indeed, rich countries lose from climate change in only one of their eight ‘scenarios’. Further analysis reveals that these adverse impacts stem from two factors. First and foremost is the fact that the low income countries are disproportionately represented in the tropics, where temperatures are already above the optimum for many crops. Thus further temperature increases bring large crop losses, whereas they bring gains in the higher latitudes. Secondly, since agriculture is the most severely affected sector in their analysis, the relatively heavier reliance of these poor countries on farming results in larger losses as a proportion of GDP.

Mendelsohn and Dinar (2009) emphasize the heterogeneity of impacts by farm size in the tropics in their synthesis of “Ricardian” analyses of climate change impacts. They point out that the emphasis on staple crops in much of this literature misses economically important impacts on other crops and livestock. In the case of livestock impacts in Africa, they find that large farms are likely more economically sensitive to climate change than small farms. This is driven by the reliance on heat intolerant beef cattle in the large livestock farms, as compared to the more diversified herds of small farms. In general, they find that economic returns to small ruminants (e.g., goats) are less sensitive to climate change. In Latin America, the studies they summarize focus on returns to land as a summary statistic of farm well-being. Here, they conclude that large farms are also slightly more vulnerable to climate change than are small farms. They suggest (p. 214) that this is “likely due to large farms specializing in high-value crops and livestock that are both heat-intolerant”.

*The Role of New Technologies in Adaptation.* In agriculture, introduction of new technologies has been the norm ever since the invention of the Haber-Bosch process for producing synthetic fertilizer in the early 20<sup>th</sup> century. Indeed, technology improvements have come to be taken for granted, and models of future agricultural production typically account for new technology by including some exogenous rate of growth in yields. Of interest here, however, are those particular technologies that would reduce the sensitivity of agriculture to weather, thereby helping to adapt to climate change. While new crop seeds are the simplest example of an innovation that could foster adaptation, we also include in this category agronomic innovations, such as new methods of water harvesting or conservation agriculture.

The nature of climate change impacts on agriculture (section II) suggests the need for various innovations. Among the obvious candidates are innovations that improve production under extreme heat and drought conditions. However, technologies that help improve cold tolerance could also be beneficial, as it would allow faster transition of crops into cooler locations. Technologies that facilitate earlier sowing, such as those witnessed in the United States over the past few decades (Kucharik 2006), could also help to avoid harmful weather. Seeds with improved pest and disease resistance could become more valuable if climate change exacerbates biotic stresses. And cropping systems that are more capable of surviving inundations, such as the new submergent tolerant rice varieties, will have added value as frequency of heavy rainfall increases.

It is extremely difficult to predict the potential rate of improvement incurred from any of these innovations. Some, for instance, argue that achieving drought tolerance without incurring a significant (and potentially unacceptable, from farmers' perspective) yield penalty in good years is extremely unlikely (Sinclair, Purcell, and Sneller 2004). Others are more optimistic, but there

is widespread agreement that traits such as heat or drought tolerance are unlikely to be improved very quickly. Even for relatively straightforward improvements, the historical record underscores the substantial time lags associated with returns on agricultural investments, with benefits peaking an average of 20 years after the initiation of research.

Major innovations often take longer. Hybrid corn research started 59 years before release of the first variety, and Bt corn research started 96 years before its release in 1997 (Alston et al. 2010). New genetic techniques are almost certain to speed things up, yet at the same time many of the traits desirable for climate adaptation are complex and even modest gains are difficult. The recent efforts toward releasing drought tolerant maize in the United States, for example, have been characterized by companies trying hard to manage expectations.

Once technologies are developed, there are additional lags in their adoption. This can be particularly true in the case of heat or drought tolerant seeds, which, unlike herbicide or pest resistance, typically only exhibit clear benefits in years of moderate stress. This feature can markedly slow adoption as farmers are not easily convinced that the benefits outweigh the costs (Lybbert and Bell 2010).

For modeling purposes, the substantial time lags involved with development and dissemination of adaptation technologies is therefore an important consideration. Whether these lags are likely to be longer in developing countries is not clear, but there are reasons to believe both biophysical and institutional constraints are more severe in these low income, predominately tropical, countries. Biophysically, temperate systems do not have many of the severe moisture and disease constraints of many tropical areas, and as mentioned previously, they will benefit from a reduction in frost occurrence. Institutionally, the capacity for research is

clearly higher in developed countries. Indeed, the gap in research capacity of developed and developing countries is large and growing, with the United States alone spending roughly five times the total for all of Sub-Saharan Africa on public and private agricultural research and development (\$10B vs. \$2B in 2006 USD) per year (Pardey 2006). Extension and marketing services are also typically of far lower capacity in developing countries.

Perhaps the most important difference, however, is in the ability of farmers to take on the risk associated with new technologies. Adaptation will be an investment decision, with uncertainty associated with the costs and benefits of this investment. Many farm level investments are irreversible, and bring with them a stiff penalty for being wrong – the farmer cannot readily ‘undo’ their decision and recoup the costs expended. Antle and Capalbo (2010) discuss the impact on producers’ investment decisions, emphasizing the fact that, under these circumstances, it is often optimal to wait until the uncertainty is further resolved. In developed countries, farmers have many forms of insurance that they can turn to if an investment turns out bad. In developing countries, an investment that does not pay off in the first year could be disastrous to family income and assets. The inability to take risks characterizes much of tropical cropping systems, and, for example, helps to explain the relatively low use of fertilizer inputs.

*Changes in the Market and Institutional Environment.* Changes in the institutional/market environment affect producer decisions (and the expected value functions in Figure 1) by altering prices received for outputs, prices paid for inputs, the information set upon which investment decisions are made, and how farmers perceive the riskiness of adopting different crops and technologies. As such they can be an extremely important form of adaptation. These are reflected by shifts in the value functions depicted in Figure 1. For example, a drop in the price of an input used to grow the crop produced under the current technology,  $\tau_A$ , would

shift the associated expected value function upwards, making it even more attractive. Assuming the two production systems in Figure 1 correspond to two different crops, then a rise in the relative price of output  $B$  would result in an upward shift of that value function relative to that currently in use, and this might result in a shift to  $\tau_B$  under current climate.

Of course climate change is itself likely to be accompanied by relative price changes, with those products which are more severely affected at the regional or global scale experiencing relative price rises. Thus, from the farm level perspective, the expected value functions in Figure 1 are not static, rather they may be expected to shift in the wake of climate change. Government policies, too, can alter these expected value functions. For example, a government subsidized insurance scheme which effectively truncates the lower tail of the underlying distribution of weather-driven returns will shift these functions upwards.

Improving information on the distribution of possible weather outcomes underlying the expected value function in Figure 1 is likely to influence adaptation decisions. Jarvis et al. (2011) suggest that the potential benefits of seasonal climate predictions can be enormous, citing the case of Mali, where farmers receive forecasts at seasonal, 10-day and 3-day scales. Moorehead (2009) finds that farmers participating in this program have significantly higher yields and incomes than non-participants. Extending such forecasts to include predictions of the spread of pests could yield additional benefits (Farrow et al. 2011).

Climate change is also likely to be accompanied by relative price changes, with those products which are more severely affected at the regional or global scales experiencing relative price increases (Hertel, Burke, and Lobell 2010). Thus, from the farm level perspective, the

expected value functions in Figure 1 are not static, rather they may be expected to shift in the wake of climate change.

Farming is a risky business in much of the world, and, even with improved weather forecasting, there will be the potential for significant losses, which may prove devastating for asset-poor households. Dercon (2005) finds that it took households in Ethiopia an average of ten years to rebuild livestock holdings in the wake of drought. Asset-poor households often rely on traditional risk sharing mechanisms such as local credit, transfers from local households and informal networks to insure against idiosyncratic shocks, such as accidental death. However, adverse weather events affect the entire community, and therefore eliminate the benefits of diversification within the local economy. This has led to the implementation of government subsidized insurance schemes in some areas. Where they are available, these schemes effectively truncate the lower tail of the underlying distribution of weather-driven returns, which would shift the expected value functions upwards. Unfortunately, low income households rarely purchase commercial insurance, even where such instruments are readily available (Kiviat 2009).

One method of increasing insurance coverage for the poor, which is receiving considerable attention, is weather index insurance designed to pay out when pre-specified trigger events occur such as when rainfall levels fail to meet a pre-specified threshold. Few studies exist yet of the adoption of index insurance by poor farmers, but there is some evidence that wealthier farmers, as well as those growing more drought-sensitive crops are more likely to purchase this rainfall insurance in the Andhra Pradesh region (Gine, Townsend, and Vickery 2008). Based on experience to date, Gine, Townsend, and Vickery (2008) offer criteria for a well-designed index insurance mechanism. Firstly, it should be transparent and verifiable to policyholders. It should be based on a measure which can be determined cheaply and quickly, whose calculation is not



vulnerable to tampering or manipulation, and whose ex-post measures are highly correlated with household incomes and consumption risks. Index insurance also requires estimation of an underlying probability for the pre-specified weather-related parameter. Such distributions, however, are likely to be highly sensitive to climate change. Finally, they note the importance of offering credit for the poorest households seeking such insurance, as the timing of the premium payments can present a real obstacle to the purchase of insurance by the poor.

Market integration can be an effective tool for asset-poor households to adapt to climate-driven shocks to agriculture. In an interesting historical study of the rainfall and famine in colonial India, Burgess and Donaldson (2010) find that the arrival of railroads – and hence ready access to national markets -- in Indian districts “dramatically constrained the ability of rainfall shocks to cause famines in colonial India” (p. 450). To the extent that adverse climate shocks are not uniformly distributed, there can be significant gains from trade between grain surplus and grain deficit regions of the country/world (Ahmed et al. 2012). However, poor households face many barriers to participating in commercial markets.

Poorly functioning product markets, and the absence of credit markets are just two of many market failures faced by low income, climate-vulnerable agricultural producers in the poorest regions of the world. Off-farm work would be an excellent income diversification option for many such households, but access to the towns where such jobs are available is often costly and may require temporary migration of the household member employed, thereby removing their contribution to the farm. Government policies, too, can frustrate access to markets. In the wake of the 2007-08 commodity crisis, many countries imposed export bans on staple grains, thereby exacerbating the world price rise during this period and likely throwing additional households around the world into poverty (Anderson and Nelgen 2011; Ivanic and Martin 2008).

In short, policy and the market environment have significant potential to impact the extent to which farmers, particularly asset-poor and vulnerable populations, adapt to climate change. The challenge for climate change researchers is then to bring this understanding of markets, household behavior, and institutions together with biophysical models to produce integrated assessment models which accurately reflect these barriers to adaptation.

#### **IV. Overview of the Modeling Landscape**

Integrated Assessment Models (henceforth IAMs) were initially developed to focus on emissions and mitigation pathways associated with different global economic growth scenarios. Some of these economics-oriented IAMs seek to find the ‘optimal’ carbon tax or mitigation pathway – trading off the economic impacts of climate change against the costs of mitigation (Nordhaus 2008). Within this framework, mitigation policy is something that is dictated in a ‘top-down’ fashion, with GHG emissions quotas or carbon taxes set by government policy, and individual sectors or consumers responding to this induced scarcity. However, as pointed out by Patt et al. (2010), most adaptation activities are fundamentally ‘bottom-up’ in nature. This makes them much more difficult to capture in a sector- and region-aggregated IAM. As noted above, agricultural adaptive capacity varies greatly by location, by resource endowments, and by institutional context of the farmer. Furthermore, one cannot estimate adaptation until the impacts of climate change are known. And estimation of these heterogeneous impacts is also problematic. In short, it is hardly surprising that most IAMs have, to date, done relatively little on the adaptation front.

We begin the discussion of adaptation in IAMs with the two, economics-oriented, perfect foresight models listed at the top of Table 1 which have their roots in the seminal work of Nordhaus (2008). These two models are necessarily simple in terms of sector complexity, but

they are rather rich in terms of the range of adaptation concepts included in them. Furthermore, they are fully documented (Agrawala et al. 2011), making it easy to discuss exactly how they work. The sparsest IAM – in terms of its agricultural treatment – is AD-DICE, in which there is a single global agricultural sector. Damages are an exponential function of temperature, with the damage function calibrated to crop modeling results obtained from Tan and Shibasaki (2003). Adaptation reduces these gross losses by some proportion between 0 and 1, with the cost of these reductions rising to infinity as this proportion approaches 1. In this modified DICE model, there are both flow and stock adaptation expenditures, with both playing an important role in reducing losses. Stock expenditures are based on irrigation and water supply costs, whereas other types of on-farm adaptations are assumed to result in benefits which are contemporaneous with the costs. Since the two types of expenditures are imperfect substitutes, it is never optimal to engage in just one type of adaptation. Adaptation is determined as part of an overall globally optimal path, which also includes mitigation activities. Along the socially optimal path, stock investments tend to dominate early and represent the majority of expenditures throughout the 21<sup>st</sup> century.

In the AD-WITCH model (Bosello, Carraro, and De Cian 2010), as modified by Agrawalla et al. (2011), activities are disaggregated by 12 regions. This allows for differential impacts and adaptation rates in the “North” (OECD) and “South” (non-OECD) regions. Damages are specified in the same manner as in AD-DICE, albeit varying by region. While both stock and flow adaptations are permitted, only the former is accounted for in agriculture. Water related investments are applied in a different sector and therefore do not reduce agricultural damages. In addition to stock and flow adaptations, which substitute imperfectly here as well, AD-WITCH allows for investments in adaptive capacity, which in turn lowers the cost of adapting to climate change. Adaptive capacity consists of both generic and specific capacities,

wherein the former is simply a function of the overall level of development. In this way, the authors capture the idea that adaptation is more costly in the South. This, combined with higher damages, leads to higher optimal investments in adaptation in the non-OECD regions, reaching about 0.75% of GDP by the end of the 21<sup>st</sup> century (vs. just two-thirds of that GDP share in the OECD regions). At the outset, the optimal path of adaptation includes equal parts of specific adaptation capacity expenditures and adaptation actions. However, the former levels off at 0.1% of GDP by mid-century while the latter continues to grow linearly through to 2100.

We now move on to a set of IAMs which are not as tightly integrated, drawing instead on a suite of models, but which have much richer representations of agriculture. One such suite of models is that developed by PIK. Of particular importance are the modules related to crop growth, LPJmL, and global land use, MAgPIE (Popp et al. 2011). LPJmL is based on biophysical, biogeochemical and hydrological processes on the world's land surface, simulated across 0.5 degree grid cells. It simulates crop growth at daily time steps, accounting for differential phenology, as well as water requirements and consumption on both rainfed and irrigation lands. Adaptation in this model involves dynamic computation of the most suitable crop variety and growing period in each grid cell. MAgPIE computes changes in crop area/location based on a global cost minimization objective function, which is constrained by resource availability at the grid cell, as well as national self-sufficiency goals. This model also determines the rate of technological progress in agriculture endogenously, either by imposing another constraint (e.g., no deforestation) or as a function of the cost of innovation. GLOBIOM ((Havlik et al. 2012) has a similar design, allowing for autonomous intensification, irrigation, changes in crop mix and location, along with adjustments to consumption and trade, all optimized in the context of a global linear programming model.

Another illustration of the potential complexity of IAMs is offered by the IGSM-TEM-EPPA suite of models run by the MIT group. We do not have space here to describe the entire suite, but the key features for agricultural adaptation arise in the Terrestrial Ecosystem Model and the Economic Prediction and Policy Analysis model. The TEM model allows for changes in planting dates, multiple cropping, and variety changes – albeit in a rather stylized way (not crop-specific). Nutrient intensification is also provided, as needed to take advantage of heightened CO<sub>2</sub> levels. Furthermore, once the effects of climate change on land productivity are felt, the EPPA model permits the substitution of other inputs for land, thereby gaining further at the intensive margin of production. Finally, since it is a CGE model, EPPA allows for a host of market-mediated changes, including area expansion, cropland migration, trade and consumption adjustment. Through a combination of area down-scaling of EPPA results and the running of TEM at the grid cell level, the MIT group is able to offer a very high spatial resolution to their agricultural adaptation. Indeed, it seems that their adaptation of agriculture to climate change may be “too good” – particularly in the South, where poor information, credit constraints and low input levels are likely to severely limit adaptation potential.

While the goal of the papers in this special issue of *Energy Economics* is to better inform the empirical specification of IAMs, as we have seen, these models are themselves built on other models of agricultural impact and adaptation. Indeed, even the damage functions and adaptation costs in the highly aggregated AD-DICE model are based on more detailed crop models. For this reason, it is instructive to turn to the broader suite of models which seek to quantify the impact of climate change on agriculture.

The FASOM model (Adams et al.; Schneider, McCarl, and Schmid 2007) focuses on the US agriculture and forestry sectors and takes a linear activity analysis approach to agricultural

production, with producers choosing the optimal activities for production of commodities over the course of the next century. As with AD-DICE, it is a perfect foresight, optimization model, although it just covers one country (with subnational production regions disaggregated) and therefore is not optimizing globally. As a consequence, when costs rise, the US can benefit from selling their products at a higher price to the rest of the world. Endogenous adaptation activities in this model include irrigation decisions, as well economically motivated changes in production activities, land use (allocated amongst crops and between cropping, livestock and forests), consumption and trade. Adaptation via adjustment in planting and harvest dates, as well as crop varieties is imposed based on external estimates.

Close in its structure to FASOM is the GLOBIOM model (Havlik, Schneider, Schmid, et al.). GLOBIOM shares with FASOM the sectorial coverage (agriculture and forestry), bottom-up production technology representation, spatial equilibrium approach to international trade modeling, and the objective function specification as a linearization of the consumer and producer surplus maximization problem. Major differences between the two models consist in their regional focus – US *versus* global in GLOBIOM –, and representation of dynamics – intertemporal optimization *versus* recursive dynamics in GLOBIOM. Similarly to MAGPIE, GLOBIOM is based on detailed spatially explicit data infrastructure. Production functions are calibrated at the pixel level for discrete management systems by means of biophysical process based models - the crop growth model EPIC (Izaurre et al. 2006), livestock model RUMINANT (Herrero et al. 2008), and the forest growth model G4M (Kindermann et al. 2008). Climate change impacts on crop yields are simulated through EPIC which automatically adjusts timing of planting, harvesting, and tillage operations, and timing and level of fertilization and irrigation. GLOBIOM allows for adaptation through switches between different crop

management practices, changes in crop mixes and their location, including land use change. It also considers different livestock production systems and switches between them (Havlik et al. 2013). Partial equilibrium adjustments through demand and trade across regions complement the representation of autonomous adaptation.

One of the most widely publicized, global agricultural models is the IMPACT model, developed and utilized by the International Food Policy Research Institute (IFPRI). It is run in conjunction with a global suite of DSSAT-based crop models in order to assess climate change scenarios (Nelson et al. 2010). Agricultural adaptation in this framework allows for autonomous adjustment in sowing dates, variety choice, intensification of production and area responses to commodity prices. It is a competitive partial equilibrium model and so consumption and international trade adjustment in response to scarcity as well. Irrigation is a planned adaptation. Apart from the AD-WITCH model which allows for aggregate R&D to be optimally chosen, this is the only model to acknowledge the importance of R&D in agricultural adaptation – albeit planned adaptation. Investments in agricultural R&D boost yields based on a ‘expert estimated’ elasticity of 0.30. The IMPACT model also allows for investment in roads to influence agricultural productivity – a consideration that is especially important in Africa, but also in many other developing regions where market access is difficult.

The next model listed in Table 1 is Pegasus – a global scale, process-based crop model for individual crops which allows for just two types of adaptation – changes in planting dates and changes in varietal choice. Models do not have to be comprehensive in order to prove useful in enhancing our understanding of adaptation. Pegasus is listed here because of the useful insights about relative potential for biophysical adaptation in the North and South as previously discussed.

The so-called “Ricardian” approach to analysis of climate impacts and adaptation in agriculture (R. Mendelsohn, Nordhaus, and Shaw 1994; R. Mendelsohn 2009) has garnered a great deal of attention in the literature, and it contrasts sharply with the biophysical models discussed above. There are two core ideas behind this work. The first is that we can learn something about climate impacts and adaptation by looking at cross-section data and observing the long run equilibrium returns to agriculture in the context of differing climatic circumstances, while controlling for other factors. The second key idea is that these long run effects should be capitalized in the value of land, so that the dependent variable is not yields, but instead is land rents. Adaptation is implicit in this approach, and includes changes in the mix of agricultural activities, as well as changes in variable inputs and investments. It ignores the time path of adjustment to climate change, focusing solely on the new long run equilibrium. Some of the insights into the distributional impacts of climate change offered by this Ricardian approach have been discussed above.

The final approach to modeling climate impacts and agricultural adaptation listed in Table 1 is nick-named TOA-MD (Claessens et al. 2012; J. M Antle et al. 2004) and offers an interesting blend of the biophysical modeling approach and a statistically based version of the Ricardian idea of different activities competing for a common land resource. The climate-induced impacts are obtained from a biophysical model, but the choice of activities, as well as the intensity of input use, are based on economic considerations as determined by the econometrically estimated supply equations (recall Figure 1).

Having discussed a range of models, some allowing for primarily biophysical adaptation, and others focusing on economic adaptation, it is useful to consider a recent study (Aisabokhae, McCarl, and Zhang 2012) in which the authors seek to compare the relative economic



importance of these different types of adaptation. Specifically, they consider: (a) on-farm adaptation, (b) re-location of production, and (c) market adaptation. Here, the first two are defined based on exogenous changes to yield impacts and crop choices, whereas market adaptation is defined as all of the *endogenous adjustments* in the model in response to the exogenous productivity shocks. The authors utilize the FASOM model of the US agriculture and forestry sectors and turn various adaptation measures off, then on, to determine their contribution to total gains from each type of adaptation. The (now quite dated) US National Assessment data on climate change effects (McCarl 1999; J. Reilly et al. 2003) were used – including climate change effects on crop yield, irrigated crop water use, irrigation water supply, livestock productivity, grazing/pasture supply, grazing land usage, international trade and pesticide usage. Adaptations in the cropping system are considered using data of adaptation-adjusted performances simulated by crop models (Francesco N. Tubiello et al. 2000; F. N. Tubiello et al. 2002; J. M. Reilly et al. 2002; Mearns et al. 2003). In scenarios without adaptation, water availability, yield rates, and livestock performance change, while in scenarios with adaptation, irrigation and fertilizer use, livestock and crop mixes, as well as planting time, harvest time and variety adaptation also adjust, with the latter three components being imposed based on the crop model simulations.

Four climate scenarios, each from a different model, were used: Canadian, Hadley, CSIRO and REGCM. Overall, the national welfare impacts of climate change are positive for the US – although the regional effects are mixed, with productivity losses in the South and gains in the North. However, this does not eliminate the potential for gains from adaptation to the new environment. They break adaptation into three parts: markets, on-farm practices, and an exogenous northward shift in production. In the modest climate impacts scenarios (CSIRO and

RegCM), the benefits from all three sources of adaptation are quite similar. The two sets of results which show by far the largest benefits from adaptation in the US are the Canadian and Hadley scenarios, with benefits reaching \$12 and \$16 billion, respectively. In these two models, the value of market adaptation is pre-dominant – accounting for two-thirds and three-quarters of the total adaptation benefits, respectively.

The predominance of market-based adaptation is perhaps to be expected in a model that emphasizes markets – particularly one such as FASOM – which is fully intertemporal and therefore includes market tradeoffs over time as well as across space and activities. In addition, the list of biophysical adaptations permitted in the model is likely to be somewhat limited, therefore biasing the results further in the direction of the market effects. Nonetheless, it is interesting to see the important role for market-based adaptations. This suggests that those IAMs which treat some types of economic behavior (e.g., consumption) as being exogenously determined should think seriously about endogenizing the relevant adaptation responses.

While this discussion of existing models is far from exhaustive, it does cover those modeling approaches most widely cited in the current literature and, as such, gives a very good feel for range of adaptations considered. We turn now to a critical assessment of these models as well as to opportunities for empirical contributions aimed at enhancing their performance.

## **V. Critical Assessment and Opportunities for Empirical Contributions**

Overall, our view of the literature in agriculture agrees well with the conclusions of Patt et al. (2010) on the broader question of adaptation in IAMs, namely that models are prone to overstating the benefits of adaptation. From our perspective, the risk of overstating adaptation

potential is especially large in poor countries. These model biases exist partly because the costs of adapting are often ignored, and also because models tend to ignore the biophysical, institutional, economic, informational, and social constraints that prevent adaptation from happening. One could argue that many of these constraints mainly affect the time lag associated with adaptation, not necessarily the equilibrium levels of adaptation that models seek to capture. However, if the time lags are sufficiently long (as with the lag between development and full deployment of some of the major agricultural innovations of the 20<sup>th</sup> century – see above), then one might question the practicality of model-based projections which ignore these lags.

How might IAMs' and other models' treatment of adaptation be improved with empirical approaches? Two main avenues seem appropriate. The first involves accepting the maintained hypotheses associated with current models (e.g., adaptation of growing seasons or varieties) and focusing on estimation of the underlying parameters governing such behavior. For example, the DSSAT crop models used to simulate impacts in the IMPACT model include cardinal temperatures that define the response to warming. As noted in section II, the parameterization of these models with respect to the impact of high temperatures on yields remains limited, yet will likely play a critical role in defining the scope for adaptation. Providing improved estimates of these cardinal temperatures should be a high priority.

The second avenue for empirical work aimed at improving these IAMs involves testing the maintained hypotheses themselves. This suggests that econometricians consider evaluating the predictions from IAM's about how adaptation should be occurring in areas of the world where significant climate changes have already been observed. For example: Are farmers facing higher temperatures switching varieties in the manner that the PEGASUS or DSSAT-IMPACT models predict? Are they switching crops as quickly as the TOA-MD models predicts? What

about the adjustment in nutrient levels assumed by the TEM model? Is this borne out in the observed responses of producers? Does irrigation investment adjust to changing climate in the manner maintained by the FASOM model?

In addition, many of the empirically estimated models, including the cross-sectional Ricardian studies mentioned above, deserve further empirical scrutiny. Since the Ricardian studies are not explicit about the path toward adaptation, empirical work aimed at testing whether changes over time in land values or cropping revenues match predicted changes would be quite useful.

In the initial pursuit of some of these questions, we come across some familiar challenges. One is that the historical signal of change to date may not be large enough or fast enough to cause predicted changes to deviate beyond the level of noise in the data. Here, we note that the signal of climate change is increasingly clear in many major agricultural regions (Lobell et al. 2011), and is likely to continue to grow over the next decade. A second complication stems from the fact that there are many other contemporaneous changes affecting farmer decisions and outcomes, not least of which are changes in global prices and domestic policies. How can one properly control for these when comparing models to data, to ensure that any differences reflect model errors and not input errors? A third, more fundamental question, is whether it is fair to compare observed responses to transient changes, with predictions from equilibrium models. If not, then how long must one wait before declaring that an equilibrium model has failed the test? All of these point to the challenges faced by those seeking to improve the empirical foundations of IAMs and related models of agricultural adaptation.

## **VI. Summary and Conclusions**

In their survey of adaptation in IAMs, Patt et al. (2010) make the case that such models are very likely to overstate producers' adaptation response to climate change. Firstly, they suggest that most adaptation occurs in response to extreme events, as opposed to gradual climate change, which is much harder to detect. In this context, they also cite the psychology/behavioral economics literature which suggests that individuals have a difficult time dealing with decisions involving low probability/high damage events. When adaptation involves significant investments, either in infrastructure protection against extreme events, or in new technologies, high discount rates and credit constraints can make these investments difficult and, in the presence of significant uncertainties, there is a strong tendency to postpone the investments until some of the uncertainty is resolved. While these latter three factors are consistent with rational, inter-temporal optimization, they reflect considerations (high private discount rates, credit rationing and option values) that are generally not present in IAMs. Therefore the models will likely overstate the actual adaptation undertaken.

The problem of uncertainty associated with climate change is exacerbated by the associated information deficit – particularly in developing countries. Quiggin and Horowitz (2003) describe climate change as something which destroys information: “This information may in some cases be represented by formal probability distributions over temperature and rainfall derived from historical records. More frequently, it is the informal knowledge of particular local climates that is acquired by attentive individuals over a long period (Quiggin and Horowitz 2003, 444).” This loss of privately acquired information is particularly problematic in Africa, where public institutions have a poor track record of investing in the production and dissemination of new information about changing climate conditions (A. G. Patt, Ogallo, and Hellmuth 2007).

When information is provided it is seldom used in an optimal fashion (Stern, Easterling, and Variability 1999; A. Patt 2007).

In addition to arguing that IAMs likely overstate the true adaptation response of highly-constrained farmers, Patt et al. (2010) argue that the same IAMs likely understate the impacts of climate change. This point is certainly underscored by the review of agricultural adaptation offered in this paper. As we have noted, most of the biophysical crop models currently used to assess climate impacts were not developed with this use in mind and, as such, they likely understate the impacts of extreme temperatures. And the IAMs surveyed here often draw on older crop modeling results, which are even less satisfactory. Furthermore, the types of processes omitted by most crop models are precisely those which tend to be more important in tropical than in temperate systems, including effects of heat stress on grain set and leaf senescence, and pest and disease pressures. This suggests that the understatement of climate impacts will be considerably larger in the tropical regions.

In sum, we conclude that the effects of climate change on farming will be most severe in low income, agriculture-dependent, tropical countries, with minimal adaptive capacity – the very countries least well equipped to cope with these changes. Meanwhile, many of the Integrated Assessment Models being used to evaluate the global impacts of climate change and formulate global climate policy, are built on assumptions which are more appropriate for the high income, industrialized economies exhibiting high adaptive capacity. Since many of these economies also enjoy temperate climates, they are also less biophysically constrained when it comes to agricultural adaptation. As a result, decision makers relying on these models are likely underestimating the challenge posed by climate change to the world's poorest populations – particularly in Sub-Saharan Africa.

## References

- Adams, R. M, Ralph J. Alig, B. McCarl, Brian C. Murray, L. Bair, B. Depro, Greg Latta, et al. "FASOMGHG Conceptual Structure, and Specification: Documentation." [http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG\\_doc.pdf](http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf).
- Agrawala, Shardul, Francesco Bosello, Carlo Carraro, Kelly De Bruin, Enrica De Cian, Rob Dellink, and Elisa Lanzi. 2011. "PLAN OR REACT? ANALYSIS OF ADAPTATION COSTS AND BENEFITS USING INTEGRATED ASSESSMENT MODELS." *Climate Change Economics* 02 (03): 175. doi:10.1142/S2010007811000267.
- Ahmed, Syud Amer, Noah S. Diffenbaugh, Thomas W. Hertel, and William J. Martin. 2012. "Agriculture and Trade Opportunities for Tanzania: Past Volatility and Future Climate Change." *Review of Development Economics* 16 (3): 429–447. doi:10.1111/j.1467-9361.2012.00672.x.
- Aisabokhae, Ruth, B. A. McCarl, and Y.W. Zhang. 2012. "Agricultural Adaptation: Needs, Findings and Effects." In .
- Alexander, L. V., X. Zhang, T. C. Peterson, J. Caesar, B. Gleason, A. Klein Tank, M. Haylock, D. Collins, B. Trewin, and F. Rahimzadeh. 2006. "Global Observed Changes in Daily Climate Extremes of Temperature and Precipitation." *J. Geophys. Res* 111: D05109, doi:10.1029/2005JD006290.
- Alston, J.M., J.S. James, M.A. Andersen, and P.G. Pardey. 2010. "Research Lags and Spillovers." *Persistence Pays*: 239–269.
- Amthor, J.S. 1989. *Respiration and Crop Productivity*. Springer-Verlag.
- Anderson, Kym, and Signe Nelgen. 2011. "Impact on World Prices of Many Countries Using Trade Policy to Stabilize Domestic Food Prices." In St. Petersburg, Florida.
- Antle, J. M, S. M Capalbo, E. T Elliott, and K. H Paustian. 2004. "Adaptation, Spatial Heterogeneity, and the Vulnerability of Agricultural Systems to Climate Change and CO 2 Fertilization: An Integrated Assessment Approach." *Climatic Change* 64 (3): 289–315.
- Antle, John M., and Susan M. Capalbo. 2010. "Adaptation of Agricultural and Food Systems to Climate Change: An Economic and Policy Perspective." *Applied Economic Perspectives and Policy* 32 (3): 386–416. doi:http://aepp.oxfordjournals.org.
- Asseng, S., I. Foster, and N.C. Turner. 2011. "The Impact of Temperature Variability on Wheat Yields." *Global Change Biology* 17: 997–1012.
- Avnery, S., D.L. Mauzerall, J. Liu, and L.W. Horowitz. 2011. "Global Crop Yield Reductions Due to Surface Ozone Exposure: 2. Year 2030 Potential Crop Production Losses and Economic Damage Under Two Scenarios of O3 Pollution." *Atmospheric Environment*.
- Bosello, Francesco, Carlo Carraro, and Enrica De Cian. 2010. "CLIMATE POLICY AND THE OPTIMAL BALANCE BETWEEN MITIGATION, ADAPTATION AND UNAVOIDED DAMAGE." *Climate Change Economics* 01 (02) (August): 71–92. doi:10.1142/S201000781000008X.
- Burgess, Robin, and Dave Donaldson. 2010. "Can Openness Mitigate the Effects of Weather Shocks? Evidence from India's Famine Era." *American Economic Review* 100 (2) (May): 449–453. doi:10.1257/aer.100.2.449.
- Cheung, William W. L, Vicky W. Y Lam, Jorge L. Sarmiento, Kelly Kearney, Reg Watson, Dirk Zeller, and Daniel Pauly. 2010. "Large-scale Redistribution of Maximum Fisheries Catch Potential in the Global Ocean Under Climate Change." *Global Change Biology* 16 (1): 24–35.
- Claessens, L., J.M. Antle, J. Stoorvogel, Validvia, R.O., Thornton, P.K., and Herrero, M. 2012. "A Method for Evaluating Climate Change Adaptation Strategies for Small-scale Farmers Using Survey, Experimental and Modeled Data." *Agricultural Systems* Forthcoming.
- Cooper, P. J. M., J. Dimes, K. P. C. Rao, B. Shapiro, B. Shiferaw, and S. Twomlow. 2008. "Coping Better with Current Climatic Variability in the Rain-fed Farming Systems of sub-Saharan Africa:

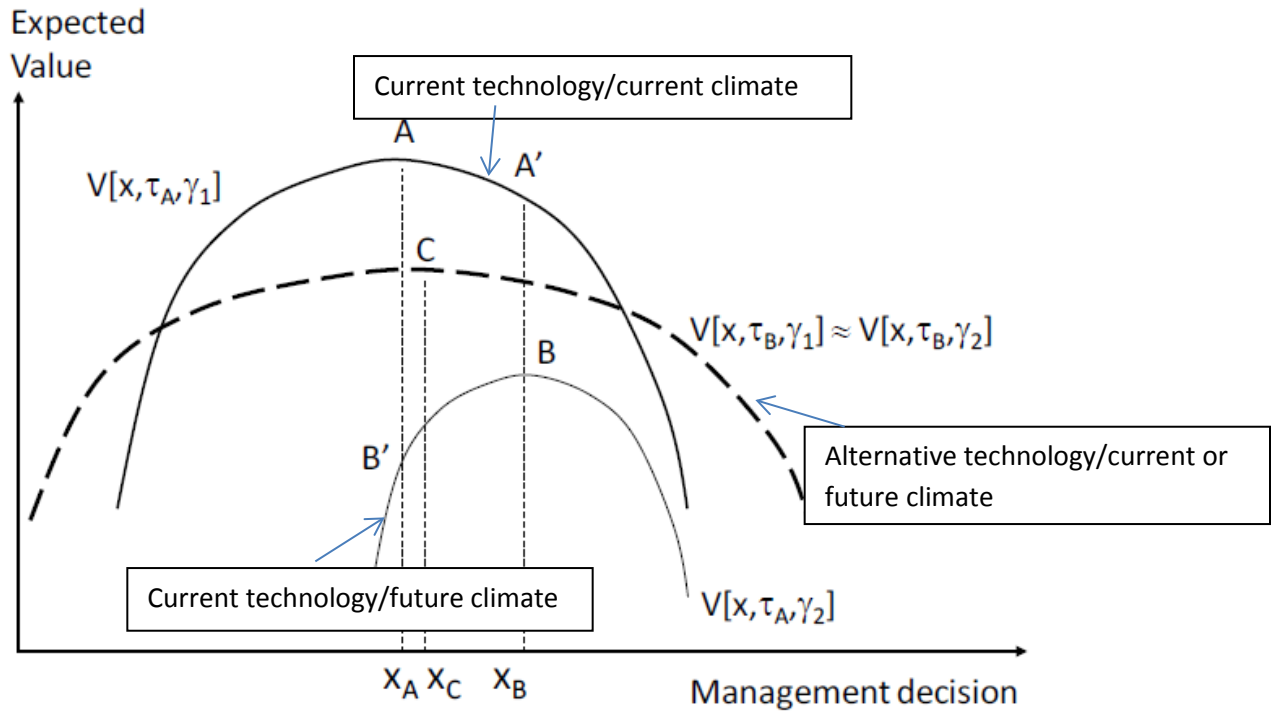
- An Essential First Step in Adapting to Future Climate Change?" *Agriculture, Ecosystems & Environment* 126 (1-2): 24–35.
- Dercon, S. 2005. "Vulnerability: a Micro Perspective." In *Annual Bank Conference on Development Economics (ABCDE) Conference*. Amsterdam.
- Deryng, D. 2009. "Simulating the Effects of Climate and Land Management Practices on Global Crop Yield". Unpublished MS thesis, Department of Geography, McGill University.
- Deryng, D., W. J. Sacks, C. C. Barford, and N. Ramankutty. 2011. "Simulating the Effects of Climate and Agricultural Management Practices on Global Crop Yield." *Global Biogeochemical Cycles* 25 (May 20): 18 PP. doi:201110.1029/2009GB003765.
- Farrow, Andrew, Didace Musoni, Simon Cook, and Robin Buruchara. 2011. "Assessing the Risk of Root Rots in Common Beans in East Africa Using Simulated, Estimated and Observed Daily Rainfall Data." *Experimental Agriculture* 47 (Special Issue 02): 357–373. doi:10.1017/S0014479710000980.
- Gine, X., R. Townsend, and J. Vickery. 2008. "Patterns of Rainfall Insurance Participation in Rural India." *The World Bank Economic Review* 22 (3): 539.
- Havlik, Petr, Michael Obersteiner, Aline Mosnier, Tatiana Ermolieva, and Mykola Gusti. 2012. "Spatial Land Use in the GLOBIOM Model." In Snowmass, CO.
- Havlik, Petr, Uwe A. Schneider, Erwin Schmid, Hannes Bottcher, Steffen Fritz, Rastislav Skalsky, Kentaro Aoki, et al. "Global Land-use Implications of First and Second Generation Biofuel Targets." *Energy Policy* In Press, Corrected Proof. doi:doi: DOI: 10.1016/j.enpol.2010.03.030. <http://www.sciencedirect.com/science/article/B6V2W-4YT09G0-2/2/ab18bd767baa3d23174bcff38edb42f8>.
- Havlik, Petr, Hugo Valin, Aline Mosnier, M. Obersteiner, J. Baker, Mario Herrero, M. rufino, and Erwin Schmid. 2013. "Crop Productivity and the Global Livestock Sector: Implications for Land Use Change and Greenhouse Gas Emissions." *American Journal of Agricultural Economics* in press.
- Held, I.M., and B.J. Soden. 2006. "Robust Responses of the Hydrological Cycle to Global Warming." *Journal of Climate* 19 (21): 5686–5699.
- Herrero, M., P.K. Thornton, R. Kruska, and R.S. Reid. 2008. "Systems Dynamics and the Spatial Distribution of Methane Emissions from African Domestic Ruminants to 2030." *Agriculture, Ecosystems & Environment* 126 (1–2) (June): 122–137. doi:10.1016/j.agee.2008.01.017.
- Hertel, Thomas, Marshall Burke, and David Lobell. 2010. *The Poverty Implications of Climate-Induced Crop Yield Changes by 2030*. Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University.
- Ivanic, Maros, and Will Martin. 2008. "Implications of Higher Global Food Prices for Poverty in Low-Income Countries." *Agricultural Economics* 39 (November): 405–416. doi:<http://www.blackwellpublishing.com/journal.asp?ref=0169-5150&site=1>.
- Izaurrealde, R.C., J.R. Williams, W.B. McGill, N.J. Rosenberg, and M.C. Quiroga Jakas. 2006. "Simulating Soil C Dynamics with EPIC: Model Description and Testing Against Long-term Data." *Ecological Modelling* 192 (3–4) (February 25): 362–384. doi:10.1016/j.ecolmodel.2005.07.010.
- Jarvis, Andy, Charlotte Lau, Simon Cook, Eva Wollenberg, James Hansen, OSANA BONILLA, Andy Challinor, et al. 2011. "An Integrated Adaptation and Mitigation Framework for Developing Agricultural Research: Synergies and Trade-Offs." *Experimental Agriculture* 47 (2): 185–203. doi:10.1017/S0014479711000123.
- Kindermann, Georg, Michael Obersteiner, Brent Sohngen, Jayant Sathaye, Kenneth Andrasko, Ewald Rametsteiner, Bernhard Schlamadinger, Sven Wunder, and Robert Beach. 2008. "Global Cost Estimates of Reducing Carbon Emissions Through Avoided Deforestation." *Proceedings of the National Academy of Sciences* 105 (30) (July 29): 10302–10307. doi:10.1073/pnas.0710616105.
- Kiviat, B. 2009. "Why The World's Poor Refuse Insurance." *Time*, September 21.



- Kosina, P., M. Reynolds, J. Dixon, and A. Joshi. 2007. "Stakeholder Perception of Wheat Production Constraints, Capacity Building Needs, and Research Partnerships in Developing Countries." *Euphytica* 157 (3): 475–483.
- Kucharik, Christopher J. 2006. "A Multidecadal Trend of Earlier Corn Planting in the Central USA." *Agron J* 98 (6): 1544–1550. doi:10.2134/agronj2006.0156.
- Leakey, A. D. B. 2009. "Rising Atmospheric Carbon Dioxide Concentration and the Future of C4 Crops for Food and Fuel." *Proceedings of the Royal Society B: Biological Sciences*: doi: 10.1098/rspb.2008.1517.
- Lobell, D. B., W.S. Schlenker, and J Costa-Roberts. 2011. "Climate Trends and Global Crop Production Since 1980." *Science* 333 (6042): 616–620.
- Long, SP. 1991. "Modification of the Response of Photosynthetic Productivity to Rising Temperature by Atmospheric CO<sub>2</sub> Concentrations: Has Its Importance Been Underestimated?" *Plant, Cell & Environment* 14 (8): 729–739.
- Luo, Q. 2011. "Temperature Thresholds and Crop Production: a Review." *Climatic Change* 109 (3): 583–598.
- Lybbert, T.J., and A. Bell. 2010. "Stochastic Benefit Streams, Learning, and Technology Diffusion: Why Drought Tolerance Is Not the New Bt."
- Matsui, T., O.S. Namuco, L.H. Ziska, and T. Horie. 1997. "Effects of High Temperature and CO<sub>2</sub> Concentration on Spikelet Sterility in Indica Rice." *Field Crops Research* 51 (3): 213–219.
- McCarl, Bruce A. 1999. *Results from the National and NCAR Agricultural Climate Change Effects Assessments, Report on USGCRP National Assessment*. <http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/778.pdf>.
- Mearns, L. O., F. Giorgi, L. McDaniel, and C. Shields. 2003. "Climate Scenarios for the Southeastern U.S. Based on GCM and Regional Model Simulations." *Climatic Change* 60 (1): 7–35. doi:10.1023/a:1026033732707.
- Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, et al. 2007. "Global Climate Projections." In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
- Mendelsohn, R. 2009. "The Impact of Climate Change on Agriculture in Developing Countries." *Journal of Natural Resources Policy Research* 1 (1) (January): 5–19. doi:10.1080/19390450802495882.
- Mendelsohn, R., W. D. Nordhaus, and D. Shaw. 1994. "The Impact of Global Warming on Agriculture: A Ricardian Analysis." *The American Economic Review* 84 (4) (September): 753–771.
- Mendelsohn, Robert, Ariel Dinar, and Larry Williams. 2006. "The Distributional Impact of Climate Change on Rich and Poor Countries." *Environment and Development Economics* 11 (02): 159–178. doi:10.1017/S1355770X05002755.
- Mendelsohn, Robert O., and Ariel Dinar. 2009. *Climate Change and Agriculture: An Economic Analysis of Global Impacts, Adaptation and Distributional Effects*. Edward Elgar Pub.
- Moorhead, A. 2009. *Climate, Agriculture and Food Security: A Strategy for Change*. Alliance of the CGIAR Centers.
- Morgan, J.A., D.R. LeCain, E. Pendall, D.M. Blumenthal, B.A. Kimball, Y. Carrillo, D.G. Williams, J. Heisler-White, F.A. Dijkstra, and M. West. 2011. "C4 Grasses Prosper as Carbon Dioxide Eliminates Desiccation in Warmed Semi-arid Grassland." *Nature* 476 (7359): 202–205.
- Nelson, Gerald C., Mark W. Rosegrant, Amanda Palazzo, Ian Gray, Christina Ingersoll, Richard Robertson, Simla Tokgoz, et al. 2010. *Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options*. Research reports. International Food Policy Research Institute (IFPRI). <http://ideas.repec.org/p/fpr/resrep/geraldnelson.html>.
- Nordhaus, W. 2008. *A Question of Balance: Weighing the Options on Global Warming Policies*. New Haven, CT: Yale University Press.

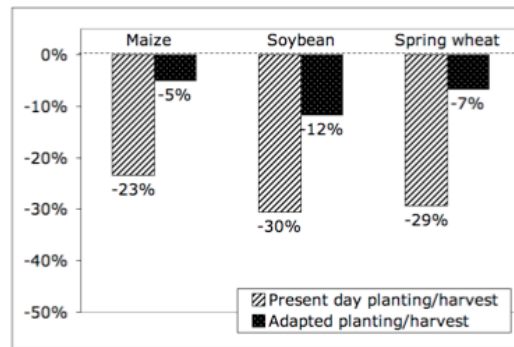
- Ortiz, Rodomiro, Kenneth D. Sayre, Bram Govaerts, Raj Gupta, G. V. Subbarao, Tomohiro Ban, David Hodson, John M. Dixon, J. Iván Ortiz-Monasterio, and Matthew Reynolds. 2008. "Climate Change: Can Wheat Beat the Heat?" *Agriculture, Ecosystems & Environment* 126 (1-2): 46–58.
- Pardey, P.G. 2006. *Agricultural Research: A Growing Global Divide?* Intl Food Policy Research Inst.
- Parent, B., and F. Tardieu. 2012. "Temperature Responses of Developmental Processes Have Not Been Affected by Breeding in Different Ecological Areas for 17 Crop Species." *New Phytologist*.
- Patt, Anthony. 2007. "Assessing Model-based and Conflict-based Uncertainty." *Global Environmental Change* 17 (1) (February): 37–46. doi:10.1016/j.gloenvcha.2006.10.002.
- Patt, Anthony G., Laban Ogallo, and Molly Hellmuth. 2007. "Learning from 10 Years of Climate Outlook Forums in Africa." *Science* 318 (5847) (October 5): 49–50. doi:10.1126/science.1147909.
- Patt, Anthony G., Detlef P. van Vuuren, Frans Berkhout, Asbjoern Aaheim, Andries F. Hof, Morna Isaac, Reinhard Mechler, and patt@iiasa.ac.at. 2010. "Adaptation in integrated assessment modeling: where do we stand?" *Climatic Change* 99 (3-4): 383–402. doi:10.1007/s10584-009-9687-y.
- Popp, Alexander, Jan Philipp Dietrich, Hermann Lotze-Campen, David Klein, Nico Bauer, Michael Krause, Tim Beringer, Dieter Gerten, and Ottmar Edenhofer. 2011. "The Economic Potential of Bioenergy for Climate Change Mitigation with Special Attention Given to Implications for the Land System." *Environmental Research Letters* 6 (3) (July 1): 034017. doi:10.1088/1748-9326/6/3/034017.
- Porter, John R., and Megan Gawith. 1999. "Temperatures and the Growth and Development of Wheat: a Review." *European Journal of Agronomy* 10 (1): 23–36.
- Quiggin, J., and J. Horowitz. 2003. "Costs of Adjustment to Climate Change." *The Australian Journal of Agricultural and Resource Economics* 47 (4): 429–446.
- Reilly, J. M., J. Hrubovcak, J. Graham, D. G. Abler, R. Darwin, S. E. Hollinger, R. C. Izaurralde, et al. 2002. *Changing Climate and Changing Agriculture*. New York, NY: Cambridge University Press.
- Reilly, J., F. Tubiello, B. McCarl, D. Abler, R. Darwin, K. Fuglie, S. Hollinger, et al. 2003. "U.S. Agriculture and Climate Change: New Results." *Climatic Change* 57 (1): 43–67. doi:10.1023/a:1022103315424.
- Schneider, Uwe A., Bruce A. McCarl, and Erwin Schmid. 2007. "Agricultural Sector Analysis on Greenhouse Gas Mitigation in US Agriculture and Forestry." *Agricultural Systems* 94 (2) (May): 128–140. doi:10.1016/j.agsy.2006.08.001.
- Sinclair, T. R., L. C. Purcell, and C. H. Sneller. 2004. "Crop Transformation and the Challenge to Increase Yield Potential." *Trends in Plant Science* 9 (2): 70–75.
- Stern, Paul C., William E. Easterling, and National Research Council (U S. ) Panel on the Human Dimensions of Seasonal-to-Interannual Climate Variability. 1999. *Making Climate Forecasts Matter*. National Academies Press.
- Tan, Guoxin, and Ryosuke Shibasaki. 2003. "Global Estimation of Crop Productivity and the Impacts of Global Warming by GIS and EPIC Integration." *Ecological Modelling* 168 (3) (October 15): 357–370. doi:10.1016/S0304-3800(03)00146-7.
- Tebaldi, Claudia, Julie M. Arblaster, and Reto Knutti. 2011. "Mapping Model Agreement on Future Climate Projections." *Geophysical Research Letters* 38 (23): L23701. doi:10.1029/2011gl049863.
- Thornton, P. K., J. van de Steeg, A. Notenbaert, and M. Herrero. 2009. "The Impacts of Climate Change on Livestock and Livestock Systems in Developing Countries: A Review of What We Know and What We Need to Know." *Agricultural Systems* 101 (3): 113–127.
- Thornton, Philip K., Peter G. Jones, Polly J. Ericksen, and Andrew J. Challinor. 2011. "Agriculture and Food Systems in sub-Saharan Africa in a 4°C+ World." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369 (1934): 117–136. doi:10.1098/rsta.2010.0246.
- Tubiello, F. N., C. Rosenzweig, R. A. Goldberg, S. Jagtap, and J. W. Jones. 2002. "Effects of Climate Change on U.S. Crop Production: Simulation Results Using Two Different GCM Scenarios. Part I: Wheat, Potato, Maize, and Citrus." *Climate Research* 20: 259–270.

- Tubiello, Francesco N., Marcello Donatelli, C. Rosenzweig, and Claudio O. Stockle. 2000. "Effects of Climate Change and Elevated CO<sub>2</sub> on Cropping Systems: Model Predictions at Two Italian Locations." *European Journal of Agronomy* 13 (2-3): 179–189.
- Washington, R., M. Harrison, D. Conway, E. Black, A. Challinor, D. Grimes, R. Jones, A. Morse, G. Kay, and M. Todd. 2006. "African Climate Change: Taking the Shorter Route." *Bulletin of the American Meteorological Society* 87 (10): 1355–1366.
- White, J. W., G. Hoogenboom, and L. A. Hunt. 2005. "A Structured Procedure for Assessing How Crop Models Respond to Temperature." *Agron J* 97 (2): 426–439.
- White, Jeffrey W., Gerrit Hoogenboom, Bruce A. Kimball, and Gerard W. Wall. 2011. "Methodologies for Simulating Impacts of Climate Change on Crop Production." *Field Crops Research* 124 (3): 357–368. doi:10.1016/j.fcr.2011.07.001.
- Ziska, L. H., D.M. Blumenthal, G.B. Runion, E. R. Hunt, and H. Diaz-Soltero. 2010. "Invasive Species and Climate Change: An Agronomic Perspective." *Climatic Change* in press.
- Zwiers, Francis W., Xuebin Zhang, and Yang Feng. 2011. "Anthropogenic Influence on Long Return Period Daily Temperature Extremes at Regional Scales." *Journal of Climate* 24 (3): 881–892. doi:10.1175/2010JCLI3908.1.

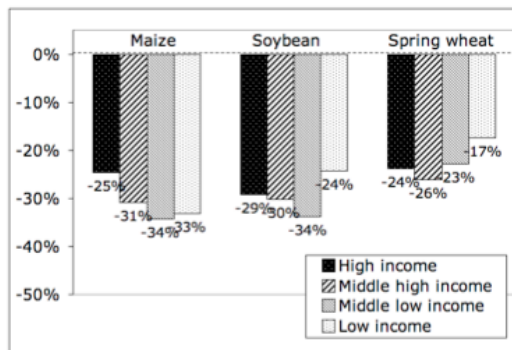


Source: Antle and Capalbo, 2010 (Fig. 3)

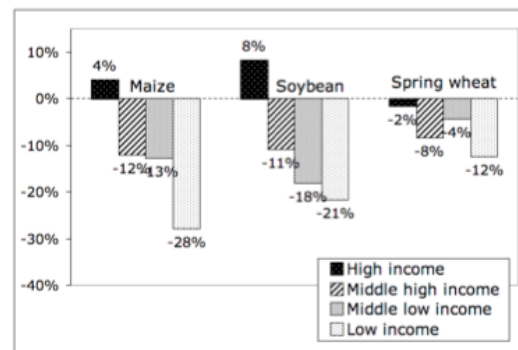
Figure 1. Adaptation to climate change based on existing and new technologies



(a)



(b)



(c)

Figure 2–13: Estimated change in global average crop yield with a global warming of 2 °C for the two scenarios of planting and harvesting decisions (a), by national income categories for present-day planting and harvest dates (b) and for adapted planting and harvest dates (c). We consider four income economy categories: high-income economy, higher-middle-income economy, lower-middle-income economy, and low-income economy.

Source: Deryng, 2009.

Figure 2. Differential biophysical constraints to adaptation in High, Middle and Low Income countries.

Table 1. Agricultural Adaptation in Global Models of Climate Change and Agriculture (n.a. denotes information not available)

Model	Contact: Reference, if available	Adaptations considered: Autonomous vs. planned
<i>Integrated Assessment Models (IAMs)</i>		
AD-DICE	Rob Dellink; Agrawalla et al. (2011); Norhaus (2007); de Briun et al. (2009)	Global intertemporal model; cooperative solution to global climate problem; aggregated damages an exponential function of temperature; both flow adaptation and stock adaptation in agriculture, the latter includes water supply and irrigation. Stock and flow adaptations treated as imperfect substitutes
AD-WITCH	Rob Dellink; Agrawalla et al. (2011); Bosello et al. (2010)	12 region, intertemporal model determines optimal policy as a non-cooperative solution to individual region optimization; damages also an exponential function of temperature and based on similar data as DICE; however, R&D investments explicit; Agricultural adaptation is only a flow activity and does not include irrigation. Investments in are adaptive capacity also permitted. These are specific and generic (based on level of development). Adaptation is cheaper in the North.
PIK-LPJmL-MAGPIE	Hermann Lotze-Kampen; Muller et al. (2010)	Autonomous changes in crop mix, location, irrigation and varieties to minimize global production costs, subject to geospatial resource constraints and self-sufficiency constraints. Technological change is endogenous and may be determined either by the other constraints (e.g., no deforestation) or as a function of the cost of innovation.
MIT-IGSM-TEM-EPPA	John Reilly	TEM allows for changes in planting dates, multiple cropping, and variety changes; nutrient intensification as needed to take advantage of CO <sub>2</sub> ; substitution of inputs under existing technology, area changes, cropland migration, trade and consumption adjustment
IIASA: EPIC & GLOBIOM	Petr Havlik; Michael Obersteiner	GLOBIOM allows for autonomous intensification, irrigation, crop mix and relocation, trade and consumption adjustments
GCAM-PNNL	Marshall Wise: Wise and Calvin (2011)	Exogenous yield changes lead to autonomous crop and cropland relocation; future versions will permit autonomous intensification
IMAGE	Detlef van Vuuren	n.a.
<i>Other models which include climate impacts and adaptation in agriculture</i>		
FASOM	Bruce McCarl	Autonomous adjustment in planting time, harvest time, varieties and irrigation. Consumption, area and trade adjust based on economic scarcity.
IMPACT w/ DSSAT	Nelson et al. (2010). Jerry Nelson	Autonomous adjustment in sowing dates, variety choice, intensification and area responses to price. Consumption and trade adjustments. Irrigation is planned adaptation; yields depend on planned R&D investments.
GAEZ-IIASA	Guenther Fischer	n.a.
FARM-ERS	Ron Sands	n.a.

Pegasus	Dernyg et al. (2011); Navin Ramankutty	Autonomous sowing date, variety choice, irrigation
Ricardian Approach	Robert Mendelsohn	Autonomous technology and crop choice implicit; choice based on most profitable of observed alternatives
TOA-MD	John Antle: Claessens et al. (2012)	Autonomous changes in management practices for existing production system; crop choice and rotation autonomous. Planned adaptation through introduction of new varieties