



## Agricultural adaptation to climate change in rich and poor countries: Current modeling practice and potential for empirical contributions<sup>☆</sup>



Thomas W. Hertel <sup>a,\*</sup>, David B. Lobell <sup>b,c</sup>

<sup>a</sup> Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University West Lafayette, IN 47907, United States

<sup>b</sup> Department of Earth System Science, Stanford University, United States

<sup>c</sup> Center on Food Security and the Environment, Stanford University, United States

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### 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 relatively well-endowed producers operating in market-integrated, developed countries. They likely underestimate 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.

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### 1. Introduction

The table has now been set for significant warming of the earth's surface in the coming decades. 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 as 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

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\* Corresponding author.

E-mail address: [hertel@purdue.edu](mailto:hertel@purdue.edu) (T.W. Hertel).

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.

## 2. Assessing the scope of the adaptation challenge: climate impacts on agriculture

Before discussing 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 toward dealing with longer-term trends (Cooper et al., 2008; Washington et al., 2006).

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 future climate trends will likely have some value in current climate, and conversely any effort to address current climate risks will have some value in the context of future climate. The key question is which risks are increasing fastest, and therefore which innovations are likely undervalued if considered solely 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 (Asseng et al., 2011; Ortiz et al., 2008).

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 et al., 2011; Tebaldi et al., 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 (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. Table 1 outlines five biophysical factors, their responses to changes in temperature and elevated CO<sub>2</sub>, and the relative impacts between temperate and tropical systems.

### 2.1. 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 (Hatfield et al., 2011). The main exceptions occur when faster development helps to avoid water stress at the end of season.

### 2.2. 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 are 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 varying according to plant type. C3 crops, which include rice, wheat, barley and rye, are found in a wide range of environments. Photorespiration in C3 plants increases with warming and therefore results in lower optimal temperatures, ranging between 15 and 30 °C. C4 crops, which include maize, sorghum and millet, evolved more recently, converting atmospheric carbon into a chemical compound with four (instead of three) carbon atoms. Having originated in sub-tropical areas, C4 plants exhibit a higher optimum temperature (30–40 °C) which has to do with their lack of photorespiration. As noted in Table 1, warming can either increase or decrease net carbon uptake, depending on crop type, 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 (Lobell et al., 2013). 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 leaf 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 aggregate agriculture in the tropical vs. temperate systems remains ambiguous.

### 2.3. 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

**Table 1**

Biophysical factors likely to be affected by climate change.

Biophysical factor	Response to heightened		Temperate vs. tropical impacts
	Temperature	CO <sub>2</sub> concentration	
1. Crop development	Faster development; shortened grain-filling stage leading to reduced yields; Can boost yields when water stress occurs at the end of the season		
2. Photosynthesis and respiration	Warming can either increase or decrease net carbon uptake depending on crop type, starting temperature and day/night time warming; higher temperatures increase vapor pressure deficit (VPD) which leads to water stress	Increased stomatal conductance leading to higher water use efficiency; photosynthesis rates and optimum temperature are raised for C3 plants	Tropical crops more likely already at or above optimal temperature so increases are deleterious; lack of adequate nutrients can constrain gains from heightened CO <sub>2</sub> ; Greater prevalence of tuber crops and dry conditions benefit tropical agriculture, but offset by lower share of C3 crops
3. Water stress	Heightened VPD leads to higher soil evaporation and plant transpiration & lower soil moisture	Improved water use efficiency	Lower soil moisture likely to be more constraining in tropics; length of growing period could decline by 20% in Africa due to soil moisture
4. Extreme temperature damage	Both cold and hot extremes can damage plant cells; extreme heat during flowering increases sterility	Sterility from exposure to high temperatures exacerbated by elevated CO <sub>2</sub> due to increased canopy warming	Higher temperatures benefit temperate crops by reducing frost constraints; tropical crops more likely hit by extreme heat effects
5. Pests and disease damage	Invasive weeds often more climate tolerant; also more responsive to changes in temperature due to short juvenile period, long-distance dispersal; reduced frost frequency will expand range of pests and diseases	Invasive weeds more responsive to changes in elevated CO <sub>2</sub> concentrations due to short juvenile period, long-distance dispersal; elevated CO <sub>2</sub> can make weed management more difficult	Increased extreme events reduce biotic resistance of native plants, thereby providing openings for invasive species

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 21st century (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> concentrations. A recent grassland study found that a CO<sub>2</sub> concentration of 600 ppm was enough to completely counteract the moisture decline associated with day/night warming of 1.5°/3.0 °C (Morgan et al., 2011).

#### 2.4. 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 (Luo, 2011; Porter and Gavith, 1999). 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 et al., 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.

#### 2.5. 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 et al. (2011), 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 1990s, the first appearance of this blight was typically between 60 and 100 days after planting. However, by the early 2000s, 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. (2011) 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.

#### 2.6. Model evaluation

How well do biophysical crop models used in most climate impact assessments capture each of the factors outlined in Table 1? 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 (White et al., 2005, 2011). For example, a recent review of 221 studies using crop models for climate change impacts, covering more than 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 (White et al., 2011).

Nonetheless, existing crop models can provide an extremely valuable tool for understanding potential impacts and adaptation options. Three major caveats should be borne in mind, however. (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 (factors 1–2 in Table 1), but omit heat effects on grain set and pest damage (factors 4

and 5). 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.

### 3. Thinking about adaptation

[Fig. 1](#), reproduced from [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, 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 be changed to  $\tau_B$ , then this curve would likely shift and also change its shape. In [Fig. 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 from  $B'$  to  $B$ . Therefore, given  $\tau_A$ , the adverse climate impact is equal to  $AB'$  and the gain from adaptation is  $BB'$ . If technology did not change, as expected over the short run, this would be the end of the story according to [Antle and Capalbo \(2010\)](#).

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 [Fig. 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. Once both management and technology have adjusted, the loss due to climate change is reduced to the vertical distance between  $A$  and  $C$ .

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 [Fig. 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 (at least 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 will therefore require 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.

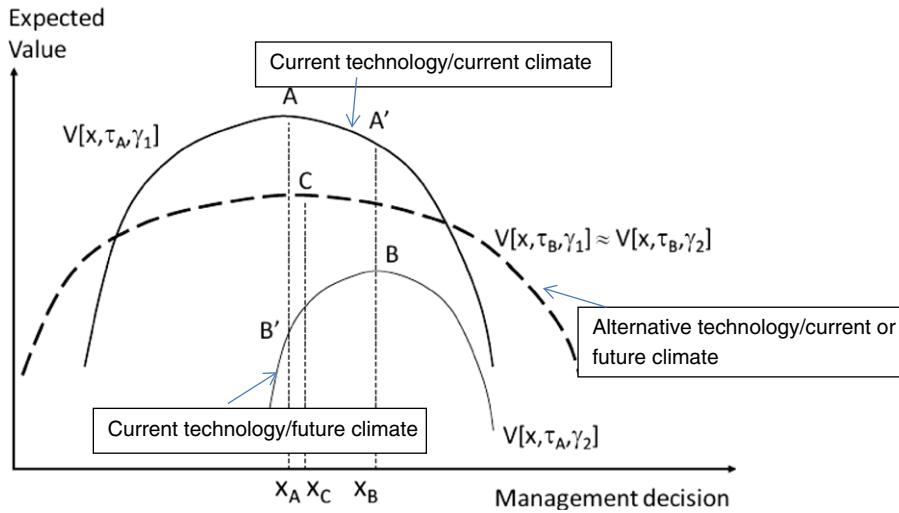
Before proceeding with our discussion of these three different types of adaptation, it is also useful to consider them through some of the other lenses which are used in the literature. One important distinction is that between processes that are expected to occur as a result of normal market forces – 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 are typically 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 remain largely 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* (or poorly planned, mal-adaptation), although some market instruments (e.g., insurance) could evolve autonomously in the context of climate change.

#### 3.1. Adaptation based on existing technology

The simplest form of adaptation to climate change is that represented by the movement from  $B'$  to  $B$  in [Fig. 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 [Fig. 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 [Fig. 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 [Fig. 1](#), for all the reasons highlighted in the first column of [Table 1](#), 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 autonomously altered by climate change is motivated by crops' response to elevated CO<sub>2</sub> levels. In order to translate higher CO<sub>2</sub> concentrations into faster plant growth, nutrient availability may need to be increased. This means a higher rate of fertilizer application is desirable. In contrast



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

**Fig. 1.** Adaptation to climate change based on existing and new technologies.  
Source: Antle and Capalbo (2010) (Fig. 3).

to the climate impacts shown in Fig. 1, heightened CO<sub>2</sub> 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. However, such adaptation will only be successful if producers have access to the necessary fertilizer. To the extent that their crops are already nutrient-constrained – as is the case in many developing countries – producers will not be in a position to benefit from such adaptation.

In some cases, the two production systems in Fig. 1 may be current choices facing producers. In this case, producers will likely have a relatively near term option to switch technology  $\tau_B$ . 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 currently 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 – perhaps responding to heterogeneous circumstances, or perhaps responding differently to the prospect of an exceptionally dry/hot year in which 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 Fig. 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 – following the lead of their exceptional neighbors who already have such a system in place.

The observation that production techniques can vary widely within a given region also forces us to consider the important point of producer heterogeneity. While most Integrated Assessment Models (IAMs) embody a single, 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 (Antle et al., 2004). Claessens et al. (2014) 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, highlighted in the final column of Table 1, is that many 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 climate 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 Fig. 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 °C rise in temperature on yields for maize, soybeans and spring wheat. The crop model is run twice, each time at the grid cell level over the entire globe. In the first run no adjustments in planting and harvesting dates, or in varieties of crops grown, are permitted. In the second simulation, both of these biophysical adaptations are permitted. Panel (a) in Fig. 2 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 across income levels. Panels (b) and (c) do so, using four income groupings of countries from World Bank: high income, middle-high, middle-low and low income countries.

From Fig. 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 temperature levels. 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 et al. \(2006\)](#) generate a similar finding in their global analysis of the direct impacts (they ignore 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 placed 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 on agriculture. 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 are small farms. This is driven by the heavy 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 which 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".

### 3.2. The role of new technologies in adaptation

In agriculture, introduction of new technologies has been the norm for at least the past two centuries, and these technologies have facilitated dramatic shifts in the location and environmental circumstances under which crops are grown ([Olmstead and Rhode, 2011](#)). More recently, 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 climate change impacts on agriculture summarized in [Table 1](#) naturally suggest the need for certain types of innovations. Amongst 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 they would allow faster transition of crops northward 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 the farmers' perspective) yield penalty in good years is extremely unlikely ([Sinclair et al., 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 ([Alston et al., 2010](#)).

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.

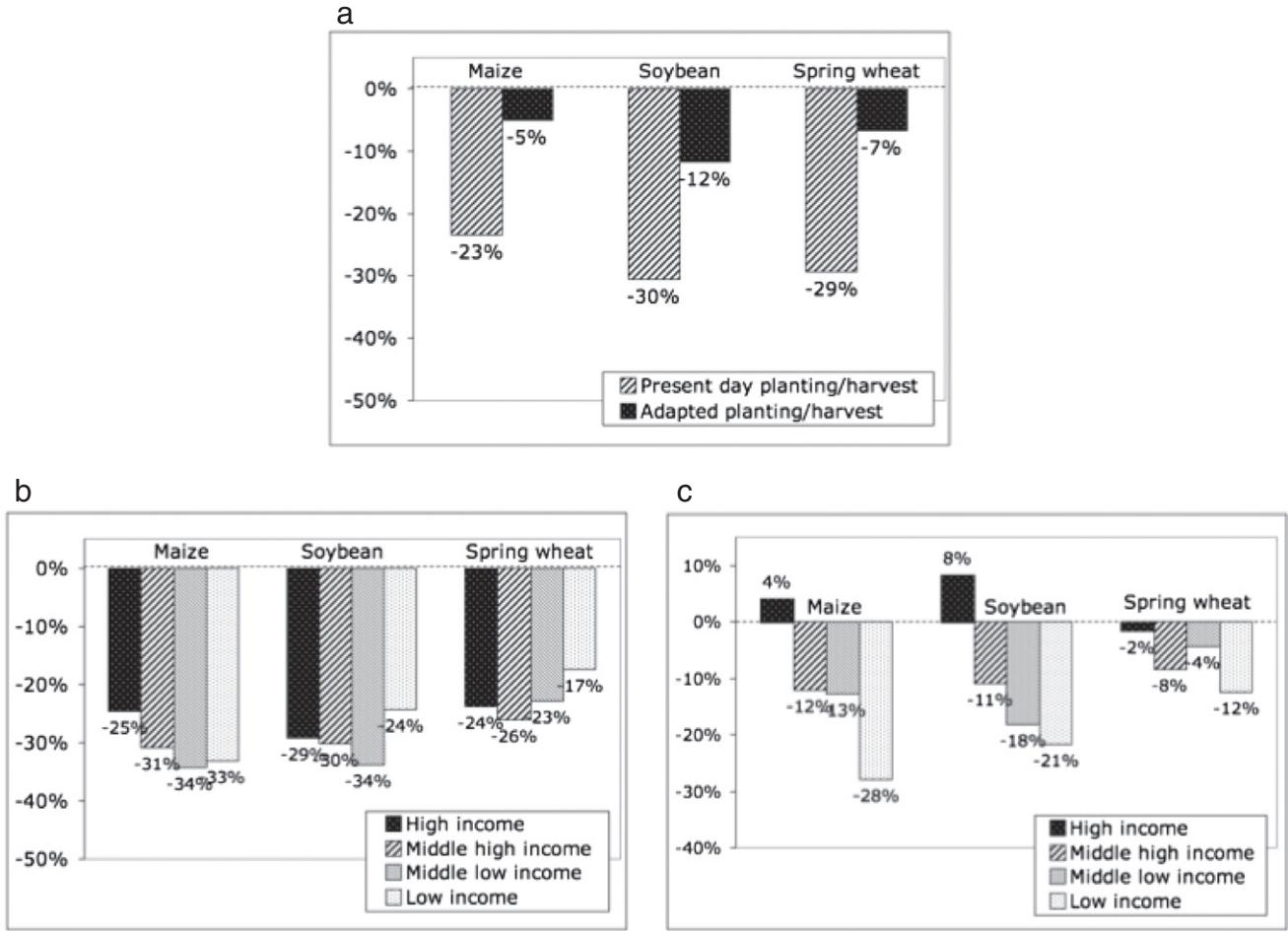
Once technologies are developed, there are additional lags in their adoption. This can be particularly true in the case of heat- or drought-tolerant seeds, which, unlike herbicide or pest resistance, typically only exhibit clear benefits in years of moderate stress. This feature can markedly slow adoption 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 that 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 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 large gap in research capacity of developed and middle-income countries, on the one hand, and the poorest countries on the other, 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](#)).

Half of the 22% jump in global agricultural R&D spending from 2000 to 2008 was fueled by India and China. In Latin America, 86% of the region's R&D spending growth is accounted for by just three countries: Argentina, Brazil and Mexico ([GFAR, 2011](#)). Some national research systems are simply too small and funding is too volatile to permit them to retain high quality staff and reach the critical mass needed to effectively address farmers' scientific and technological changes. In Sub-Saharan Africa, research funding is driven by large, donor-funded initiatives, which result in considerable year-to-year volatility. Indeed, R&D spending volatility in this region is twice as high as in Asia and Latin America, and Burkina Faso, Gabon, Mauritania and Tanzania recorded spending volatility nearly four times as high as these other regions ([GFAR, 2011](#)). All of these factors will result in considerable heterogeneity of planned adaptation responses to climate change, with the poorest countries likely experiencing the greatest challenges.

Perhaps the most important difference between rich and poor countries' capability to adapt to climate change lies 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 since the farmer cannot readily 'undo' their decision and recoup the costs expended. [Antle and Capalbo \(2010\)](#) discuss the impact of such uncertainty on producers' investment decisions, emphasizing the fact that, under these circumstances, it is often optimal to postpone making a decision



**Fig. 2.** Differential biophysical constraints to adaptation in high, middle and low income countries.  
Source: Deryng (2009).

until the uncertainty is further resolved. In developed countries, farmers have many forms of insurance that they can turn to if new technology fails. In developing countries, an investment that does not pay off in the first year could be disastrous to family income and assets. This is further exacerbated by a lack of access to credit. The inability to take such risks characterizes much of tropical cropping systems, and, for example, helps to explain the relatively low use of fertilizer inputs.

### 3.3. Changes in the market and institutional environment

Changes in the institutional/market environment affect producer decisions (and the expected value functions in Fig. 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 Fig. 1. For example, a fertilizer subsidy which lowers the price of an important cropping input would shift the associated expected value function under current technology,  $\tau_A$ , upwards, making it even more attractive. Assuming the two production systems in Fig. 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 (Hertel et al., 2010b). Thus, from the farm level perspective, the expected

value functions in Fig. 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, subsidized crop insurance, such as that available in the United States, will alter both the shape and the height of the value functions in Fig. 1. Indeed, it has been estimated (Babcock, 2014) that the pay-out from federal crop insurance following the US drought of 2012 was twice as much as would have been paid under a conventional form of disaster protection. This type of program can significantly alter behavior in favor of riskier activities, and is also likely to influence farmers' response to climate change. For example, this could lead producers to refrain from investing in supplemental irrigation as discussed above. In terms of Fig. 1, this could lead them to remain with technology,  $\tau_A$ , instead of  $\tau_B$ , even in the face of a change in climate from  $\gamma_1$  to  $\gamma_2$ . Improving information on the distribution of possible weather outcomes underlying the expected value function in Fig. 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. Moorhead (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).

However, even with improved weather forecasting, there will be the potential for significant losses, which may prove devastating for asset-poor households, who often rely on traditional risk sharing mechanisms such as local credit, transfers from local households and informal networks to insure against idiosyncratic shocks. Yet adverse weather

events affect the entire community, and therefore limit the benefits of diversification within the local economy. [Dercon \(2005\)](#) finds that it took households in Ethiopia an average of ten years to rebuild livestock holdings in the wake of drought. The correlated nature of weather-related risks often leads to the implementation of government subsidized insurance. There is currently a strong interest in weather-index insurance which is 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 et al., 2008](#)). Based on experience to date, [Gine et al. \(2008\)](#) 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. However, poor households face many barriers to participating in the very commercial markets which might facilitate adaptation to weather-induced variability. Poor infrastructure, coupled with remote location, leaves many farmers – as well as rural consumers – only weakly connected to product markets. And the absence of credit markets can make the investment in new technologies for climate adaptation prohibitive. Similarly, while off-farm work would be an excellent income diversification option for many climate vulnerable, rural households, 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.

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 – “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](#)). 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, the policy and market environments have significant potential to impact the extent to which farmers, particularly asset-poor and vulnerable populations, adapt to climate change. The research challenge is 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.

#### 4. Overview of the modeling landscape

Integrated Assessment Models (henceforth IAMs) seek to combine, into a unified framework, representations of the climate and earth systems together with models of social and economic behavior in order to capture both the societal impacts of climate change and the costs of mitigating the greenhouse gas emissions contributing to such change. The economics-oriented IAMs utilize this interplay between natural and human systems to characterize the ‘optimal’ carbon tax or

mitigation pathway – trading off the economic costs 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. 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 in the area of agricultural adaptation.

We begin the discussion of adaptation in IAMs with the two, economics-oriented, forward-looking models listed at the top of [Table 2](#) which have their roots in the seminal work of [Nordhaus \(2008\)](#). Given their ambition to derive an intertemporally optimal global carbon price path, these two models are necessarily quite aggregate, but they are rather rich in terms of the range of adaptation concepts represented. Furthermore, they are fully documented ([Agrawala et al., 2011](#)), making it easy to discuss exactly how they work. The sparest 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. Flow expenditures facilitate adaptation in the current period, while stock expenditures accumulate (and depreciate) over time and therefore facilitate adaptation over multiple periods. Stock expenditures for agricultural adaptation 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 (flow adaptations). 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 they represent the majority of expenditures throughout the 21st century.

In the AD-WITCH model ([Bosello et al., 2010a](#)), as modified by [Agrawala et al. \(2011\)](#), activities are disaggregated into 12 geographic 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 latter 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 relatively 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 21st century (vs. just two-thirds of that GDP share in the OECD regions). At the outset, the optimal path of adaptation includes equal parts specific adaptation capacity expenditures and adaptation actions. However, the former levels off at 0.1% of GDP by mid-century while the expenditures on adaptation actions continue 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. These are labeled “Linked

Integrated Assessment Modeling Frameworks" in **Table 2** and they offer much richer representations of agricultural activity — albeit within a recursive dynamic framework. 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° 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. Biophysical 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, as a function of the cost of innovation, which gives rise to another form of autonomous adaptation. In light of the earlier discussion about the importance of such R&D for climate adaptation, as well as the heterogeneous nature of national agricultural R&D investments, this is an aspect of IAM modeling which would appear to deserve greater attention.

GLOBIOM (Havlik et al., 2013) shares a similar design with the PIK-MAgPIE model. Once again production and consumption decisions are all optimized in the context of a global linear programming model — now taking livestock and forestry production activities (including short rotation tree plantations) into account as well. The objective function involves the maximization of producer and consumer surplus at a given point in time, with dynamics playing out in a recursive fashion. The model allows for autonomous adaptation through intensification of production, irrigation, changes in crop mix and location. Production functions are calibrated at the pixel level for discrete management systems by means of biophysical process based models — the crop growth model EPIC (Izaurrealde 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.

Another illustration of the potential complexity of linked 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 (TEM) and the Economic Prediction and Policy Analysis (EPPA) model. TEM allows for changes in planting dates, multiple cropping, and variety changes — albeit in a rather stylized way for a generic plant type (so this is 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 capital, labor and other inputs for land, thereby allowing for autonomous adaptation at the intensive margin of production. Finally, EPPA, which is a competitive general equilibrium model, allows for a host of market-mediated changes, including area expansion, trade and consumption adjustments. 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 in their analysis of agricultural impacts and adaptation. Overall, the assumption that nutrients are not constraining, varieties adjust to accommodate the new climate, and capital is forthcoming for new investments and intensification of production, are all characteristic of most of the IAMs and suggest that these models may well overstate

the potential for adaptation to climate change in the world's poorest economies.

The Global Change Assessment Model (GCAM) Agriculture and Land Use Model (Calvin et al., 2012), developed at the Joint Global Change Research Institute at the University of Maryland, is now used in concert with a variety of biophysical earth system models, including the GCAM IAM (Edmonds et al., 1997) and the Community Earth System Model (<http://www2.cesm.ucar.edu/>). The agricultural component of GCAM is a recursive-dynamic system which tracks a dozen types of land cover, with cropland broken into about 20 individual crop categories. Competition for land occurs at the level of 151 sub-regions which represent the intersection of regional economies and 18 potential Agro-Ecological Zones. Land use within any sub-region is shared out based on relative profitability of activities. In the version referenced here, there are fewer opportunities for market-mediated adjustments than in the EPPA model. For example, there is no scope for autonomous intensification of production in response to increased scarcity, and the price responsiveness of consumer demand is limited. The strength of GCAM lies in its linkage of land cover changes and the terrestrial ecosystem.

As with the other models in this category of **Table 2**, the IMAGE IAM framework (Bouwman et al., 2006), maintained by the Netherlands Environmental Assessment Agency, comprises a system of linked components. It simulates climate, carbon and nitrogen cycles as well as global economic activity. The latter is handled via the MAGNET model (formerly LEITAP) (Van Meijl et al., 2006). IMAGE allocates agricultural land use at the grid cell, while MAGNET determines total agricultural land use at national scale using a land-supply function built up from the grid cell productivity data. Climate-induced yield changes originate in the biophysical IMAGE model and are passed over to MAGNET as exogenous productivity shocks. Results from the two models are iterated until there is close agreement on total land use in agriculture. Most of the adaptation occurs in the economic component of the model, which allows for autonomous area expansion, intensification of production, changes in the mix of crop and livestock activity, price-sensitive food consumption behavior and international trade.

The goal of the papers in this special issue of *Energy Economics* is to better inform the empirical specification of IAMs. However, as we have seen above, these IAMs are themselves built upon 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, as well as the potential for adaptation.

The FASOM model (Adams et al., 2005; Schneider et al., 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. Rather, interactions with the rest of the world are characterized by upward sloping-import supply schedules and downward-sloping export demand schedules. The presence of the latter means that any perturbation to US agricultural supplies will have an impact on 'world prices' for exports. In particular, with climate change reducing supplies, export prices rise, and the US experiences a 'terms of trade' gain — i.e., export prices will rise relative to import prices. Endogenous adaptation activities in this model include irrigation decisions, as well as 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.

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

**Table 2**

Agricultural adaptation in models of climate change and global agriculture.

Model	Reference	Adaptations considered: autonomous vs. planned
<i>Aggregate economics-oriented integrated assessment models</i>		
AD-DICE	Agrawala et al. (2011), Nordhaus (2008)	Global intertemporal model; cooperative solution to global climate problem; aggregated agricultural 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 so that they co-exist along the optimal path.
AD-WITCH	Agrawala et al. (2011), Bosello et al. (2010a,b)	12 regions, intertemporal model determines optimal policy as a non-cooperative solution to individual region optimization; agric damages are an exponential function of temperature and based on similar data as DICE. Explicit R&D investments; agricultural adaptation is only a flow activity and does not include irrigation. Investments in adaptive capacity are permitted. These are specific and generic (based on level of development). Adaptation is cheaper in the North.
<i>Linked integrated assessment modeling frameworks</i>		
PIK-LPjml-MAGPIE	Bondeau et al. (2007)	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	Paltsev et al. (2005), Prinn et al. (1999)	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 GCAM-PNNL	Havlik et al. (2013) Calvin et al. (2012)	GLOBIOM allows for autonomous intensification, irrigation, crop mix and relocation, trade and consumption adjustments Exogenous yield changes lead to autonomous crop and cropland relocation; future versions will permit autonomous intensification
IMAGE-MAGNET	Bouwman et al. (2006), Eickhout (2008), Van Meijl et al. (2006)	Yield changes from the IMAGE model are transferred as exogenous shocks to the MAGNET model that calculates production, trade and consumption adaptations based on market signals.
<i>Other global models which include climate impacts and adaptation in agriculture</i>		
FASOM	Adams et al. 2005	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)	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.
Pegasus	Deryng et al. (2011)	Autonomous sowing date, variety choice, irrigation
<i>Other analytical frameworks addressing climate impacts and adaptation in agriculture</i>		
Ricardian Approach	Mendelsohn et al. (1994)	Autonomous technology and crop choice implicit; choice based on most profitable of observed alternatives
TOA-MD	Claessens et al. (2014)	Regional modeling framework featuring autonomous changes in management practices for existing production system; crop choice and rotation autonomous. Planned adaptation through introduction of new varieties

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, market model and so consumption and international trade adjust in response to scarcity. Irrigation is a planned (exogenously specified) adaptation. Apart from the AD-WITCH and MAGPIE models, which both allow for aggregate R&D to be optimally chosen, this is the only other model to acknowledge the importance of R&D in agricultural adaptation – albeit planned adaptation, as opposed to an optimal response to market conditions. Investments in agricultural R&D boost yields based on an ‘expert-estimated’ elasticity. 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 a major barrier facing agricultural producers.

The next model listed in Table 2 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 its relative ease of use and transparency and the useful insights about relative potential for biophysical adaptation in the North and South as previously discussed.

Another useful approach to climate change adaptation in agriculture is the so-called “Ricardian” approach to analysis of climate impacts and adaptation in agriculture (Mendelsohn, 2009; Mendelsohn et al., 1994) which has garnered a great deal of attention in the literature. This approach contrasts sharply with the biophysical models discussed above and therefore warrants discussion. 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 differences in long run equilibrium returns to agriculture in the context

of differing climatic circumstances (while attempting to control 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 in the Ricardian regressions is not yields, but instead is land rents. Adaptation is implicit in this approach, and encompasses 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 which is listed in Table 2 is nick-named TOA-MD (Antle et al., 2004; Claessens et al., 2014) and emphasizes ‘Trade Off Analysis’. This approach – typically implemented at the sub-national level – 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 (recall Fig. 1) with supply relations based on econometric estimates.

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 et al., 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; 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 (Mearns et al., 2003; Reilly et al., 2002; Tubiello et al., 2000, 2002). In scenarios without adaptation, water availability, yields 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 different GCM projections were used. The Canadian and Hadley projections are those that were used in the US Global Climatic Change Research Program, (Reilly et al., 2003). In addition, projections using the CSIRO GCM and REGCM were also used (Mearns et al., 2003). Overall, the national welfare impacts of climate change are positive for the US (recall the preceding discussion of terms of trade effects in this model). However, the regional effects are mixed, with productivity losses in the South and gains in the North. Nonetheless, these gains do not eliminate the potential for gains from adaptation to the new environment which the authors proceed to investigate. They break adaptation into three parts: market adaptations, changes in on-farm practices, and an exogenous northward shift in production. In the modest climate impact projections (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 note the potential significance of 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 these market-based effects.

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

## 5. Critical assessment and opportunities for empirical contributions

Overall, our view of the literature in agriculture suggests that there is substantial risk of overstating adaptation potential — especially in poor countries. These model biases exist partly because the costs of adaptation 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 20th 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 2, 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.

In the same spirit, improved estimation of the economic parameters governing adaptation in the IAMs will also be valuable. In addition to the customary price elasticities of demand and supply which govern market-based adaptation, high priority should be accorded to the linkage between R&D expenditures and agricultural productivity. As we have seen, only two of the IAMs explicitly acknowledge this linkage, yet it is a key element of the adaptation puzzle. Since the stock of R&D capital and growth in current expenditure varies dramatically by country and region, understanding this linkage, and the potential for spillover benefits between the innovating region and other regions, is critical.

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?

Another set of key maintained hypotheses which are imbedded in all of the IAMs in Table 2 is that of market integration. Yet, as noted in Section 3, many rural markets are not fully integrated into the global economy. In those cases where the models treat agricultural production as occurring at national scale, there may be little scope for capturing such deviations from received wisdom. However, increasingly IAMs are modeling agricultural production at the subnational level. Indeed, three of the IAMs listed in Table 2 model crop production at the grid cell. This high degree of geographic resolution has thus far only been used to introduce biophysical heterogeneity. And yet, economic heterogeneity within countries can be equally — or even more important. In a study of the impacts of US–Mexico trade liberalization on rural household in Mexico, Nicita (2004) finds that the effects of tariff cuts were incompletely passed through to consumers in Mexico, with the extent of pass-through smaller for agriculture than manufactured goods. Ultimately, agricultural tariff cuts were found to have little or no impact on the more remote regions of Mexico. In the context of climate change, this incomplete linkage between rural agricultural producers and world markets has important implications. When climate change hits a remote rural area particularly hard, the lack of connection to international markets means that prices will rise more sharply and nutrition outcomes will suffer more than under integrated markets (recall the reduction in famine when India introduced a railroad network (Burgess and Donaldson, 2010)). Conversely, when climate change hits other parts of the world hard, rural producers in the relatively favored regions will only contribute to reducing the global deficit if they are connected to world markets, thereby receiving the appropriate price signal. In short, testing for market integration and incorporating incomplete integration into spatially explicit IAMs would allow for much improved representation of the potential for market-based adaptation.

In the initial pursuit of these questions, we come across some familiar challenges. One is that the historical signal of climate 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.

A final area for collaboration – both across and within the IAM and empirical communities is that of global geospatial data for analysis of agriculture and climate change. Despite the large sums of money being spent in this area, the data sets being generated are still fundamentally incompatible in their spatial representation of agricultural production (Hertel et al., 2010a,b). Problems as fundamental as differences in country boundaries, definition of cropping intensity and irrigation area result in discrepancies which must be resolved ‘at the end of the pipeline’ (You and Wood, 2006). Furthermore, to address the empirical questions raised here, there is a need for the data to be maintained over time – thereby building a time series which can be used for panel estimation. There are some promising efforts currently underway at the regional level (e.g., <http://harvestchoice.org>), and there is a pilot effort underway at global scale (<http://geoshareproject.org/>). However, these efforts will require much wider involvement in order to be truly successful.

## 6. 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 (Patt et al., 2007). When information

is provided it is seldom used in an optimal fashion (Stern et al., 1999; 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 underestimate 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 underestimate 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 underestimation 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.

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