Food and Agriculture Organization
of the United Nations

Climate change, agricultural trade and global food security

Background paper for
The State of Agricultural Commodity
Markets (SOCO) 2018

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Acronyms

AEZs	Agroecological Zones
AgMIP	Agricultural Modeling and Intercomparison Project
ARM	Armington models
CGE	Computable General Equilibrium
CDS	Constinot, Donaldson and Smith
GE	General equilibrium
GHG	Greenhouse gases
GTAP	Global Trade Analysis Project
HO	Homogenous product models
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
PE	Partial equilibrium
SS	Self-sufficiency
WTO	World Trade Organization

Abstract

Climate is an essential input to agricultural production. Changes in climate will inevitably have an impact on agricultural productivity, output, farm incomes and prices. Elevated temperatures will also affect human and animal health.

To date, most of the studies of climate impacts on agriculture have ignored the impacts on humans and livestock, focusing instead on the consequences for crop production. One of the foremost reasons is that research on crop impacts assessment is the field where the necessary modelling infrastructure was most fully developed.

The present paper provides an overview of the latest modelling research on the impact of climate change and agriculture. It specifically focuses on different modelling approaches that include the interlinkages between climate change and trade, and the potential role trade can play to support adaptation and mitigation to climate change.

I. Climate change impacts on agriculture

Background

Climate is an essential input to agricultural production and changes in climate will inevitably have an impact on agricultural productivity, output, farm incomes and prices. Historically, most studies of agricultural productivity ignored climate – implicitly assuming it is unchanging -- focusing instead on changes in productivity at a given location over time due to improved knowledge, new varieties of crops and livestock, as well as improved farming practices. However, as the Intergovernmental Panel on Climate Change (IPCC) has noted in its last assessment report, the impacts of a warming planet are now becoming detectable and these impacts are expected to accelerate in the coming decades (IPCC, 2013). Understanding these historical impacts as well as the potential future impacts of climate change on agriculture has become an entire field of science in its own right. The emergence of the Agricultural Modeling and Intercomparison Project (AgMIP) has lent structure and direction to this effort at assessing the impact of changes in climate on global agriculture.

There are many ways in which climate affects agriculture. Perhaps the most obvious is the impact of elevated temperatures on those people working outside and exposed to the sun. Kjellstrom *et al*. (2009) estimate that, under a high warming scenario, labour work capacity in agriculture will fall by 11-27 percent across Southeast Asia, Central America and the Caribbean. While many farmers in the wealthier regions can avoid heat stress by working inside air conditioned equipment, there remain many field tasks which are not yet mechanized. In short, this is likely to be a significant source of cost increases as well as threats to human health – particularly in those parts of the world where poverty and food insecurity predominate.

Just as humans suffer from high temperatures, so do livestock. While there is limited evidence of these effects at broad scale, experiments as well as observational data suggest that a warming planet will have negative effects on feed intake, rates of gain, dairy production disease and parasites as well as mortality rates. In addition, by altering the growth rate of pastures, climate change will have an indirect effect on ruminant and dairy productivity.

Climate change will also have important impacts on crop growth (see Table 1 in Hertel and Lobell (2014) for a summary). Higher temperatures tend to lead to faster crop development, a shortened grain-filling stage and reduced yields. Elevated temperatures also affect net carbon uptake and contribute to higher vapour pressure deficits leading to water stress. This is counteracted to some degree through increased stomatal conductance, owing to elevated carbon dioxide (CO_2) concentrations, which leads to improved water used efficiency and increased optimum temperatures for C3 plants. However high temperatures can damage plant cells, and extreme heat during the flowering stage increases sterility rates. On top of this, invasive weeds tend to be better adapted to a changing climate, with short juvenile periods, long distance seed dispersal and greater response to elevated CO_2 concentrations. In short, there are several different avenues through which climate change can affect crop productivity – many of them negatively – with the adverse impacts growing more dominant as temperatures rise (IPCC, 2014).

To date, most of the studies of climate impacts on agriculture have ignored the impacts on humans and livestock, focusing instead on the consequences for crop production. There are a variety of reasons for this. However, it seems one of the foremost reasons is simply that crop impacts assessment is where the necessary modelling infrastructure was most fully developed. Nonetheless, it should be noted that most of the crop modelling tools being used to assess climate impacts on agriculture were originally developed for different purposes and largely in the context of major field crops produced in the temperate (high income) regions of the world (White, Hoogenboom and Hunt, 2005). For this reason, there are (e.g.) many studies on maize production in the Midwestern of the United States of America, but relatively few of a crop like cassava in West Africa. This has further hampered our ability to assess the full effect of climate change on global agriculture. Even when a well-established model of maize crop growth is applied to the analysis of global warming impacts on African agriculture, it is likely to miss many important factors which are critical to climate impacts in the tropics, but which were not deemed significant when the model was developed for managerial purposes in the United States of America or Western Europe.

Methods for assessing climate impacts on crops

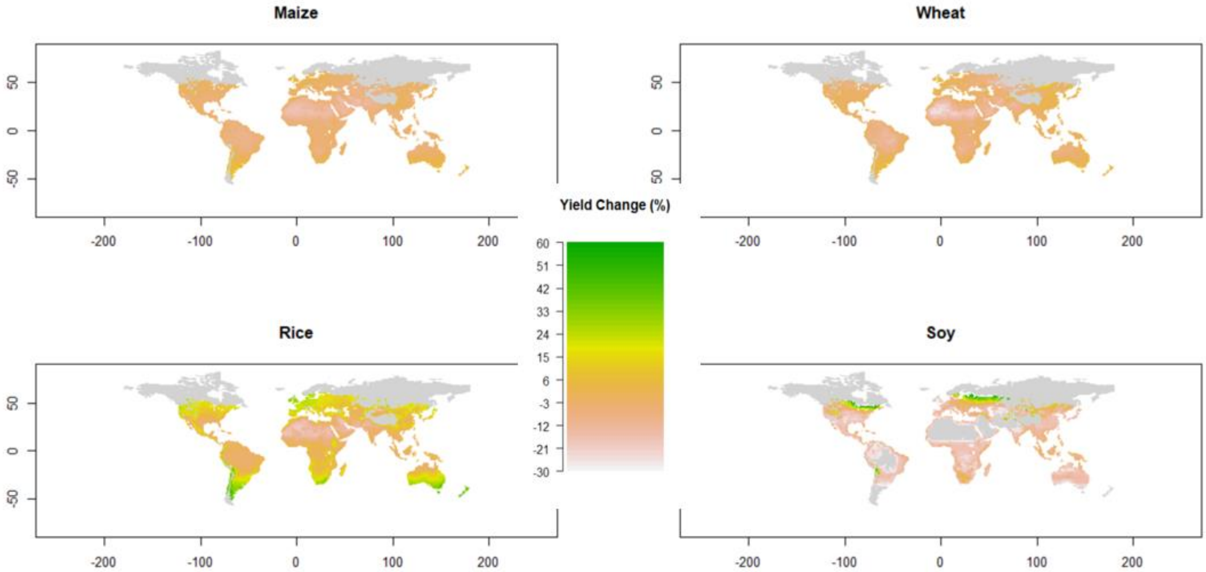
In their comprehensive (although now somewhat dated) review of crop models used for climate change analyses, White *et al*. (2011) find that, of the 221 studies using 70 different crop models to evaluate climate impacts, only six studies considered the effect of elevated CO_2 on canopy temperature and only a handful considered the direct effect of elevated temperatures on seed set or leaf senescence. Another key point is that any single crop model only includes a subset of the relevant processes. This may lead models to omit key interaction effects. In addition, the omitted processes are thought to become more damaging with climate change, so productivity may be upward biased as a result (Hertel and Lobell, 2014). Finally, and perhaps most important, is the fact that the types of climate impact pathways omitted by most crop growth models tend to be more important in the tropics. These include: pressures from pest and disease, the impact of heat stress on grain set and leaf senescence, and the impacts of high vapour pressure deficits on photosynthesis (Hertel and Lobell, 2014). So the estimates of crop productivity are likely to be upward biased in those regions of the world where food security is of greatest concern.

An alternative, lower cost means of assessing climate impacts is via statistical analysis. David Lobell and Wolfram Schlenker, among others, have been strong proponents of this approach. The work by Schlenker and Roberts (2009) identifying critical temperature thresholds for major field crops in the US stands as one of the most important findings to emerge from the statistical climate impacts literature. Until recently there was a common perception that the statistical models generated quite different – and possibly much more pessimistic – predictions in the context of climate change. However, a recent special issue of *Environmental Research Letters* has put this perception to rest. The lead article provides a good overview of the findings. It is authored by David Lobell and Senthold

Asseng (2017). Asseng is a leader in the crop modelling community and therefore a perfect complement to Lobell in this comparison of statistical and modelling approaches. They show that, when the studies refer to the same geographic location are equally carefully done, and control for the same variables, the results are remarkably similar across statistical and process models in terms of the yield impacts of moderately elevated temperatures on crop productivity (up to 2 degrees Celsius (^{0}C) global average warming). And the responses to precipitation also seem broadly consistent, although this is more difficult to evaluate. The main difference between the two approaches resides in the fact that most statistical models neglect the response of crop growth to elevated CO_2 concentrations. This stems from the fact that, unlike temperature and precipitation, there is little spatial variation in atmospheric CO_2 and the temporal variation is slow-moving and correlated with many other variables. This is why state-of-the-art work in the crop impacts area now has moved in the direction of blending insights from process models with the more cost effective statistical approaches (Lobell and Asseng, 2017).

In the second paper published in this special issue of ERL, Moore, Baldos and Hertel (2017), provide a formal, statistical meta-analysis of more than 1 000 impact estimates delivered to the IPCC under AR5. Their findings reinforce the intuition and case study comparisons offered by Lobell and Asseng (2017). In particular, they fail to reject the hypothesis that the meta-impact function is the same across statistical and process model estimates of temperature impacts. Figure 1 maps the yield impact results from Moore *et al*. (2017) for the four major field crops at 2 ^{0}C of global warming based on pattern-scaled temperature and including CO_2 effects which vary between C3 and C4 crops. Note that, while maize and wheat show losses in most regions, rice shows gains in high latitudes and at higher elevations. The gains in soy yields in the Northern latitudes should be discounted as these projections are solely based on temperature, precipitation and CO_2 – ignoring soils and other factors. Of far greater importance are the large losses in soy yields in the tropics –most importantly in Central Brazil (Mato Grosso). This meta-analysis also provides confidence intervals on the climate impacts, which can be used in characterizing uncertainty in climate impacts. This is important, since it is generally found that crop models are a greater source of uncertainty than the climate models feeding into them (Rosenzweig *et al*. 2014).

Figure 1: Global gridded yield shocks for maize, wheat, rice and soybeans at 2°C warming



Source: based on Moore *et al.* (2017).

Agricultural adaptation to climate change

In addition to comparing climate impacts from statistical and simulation models, Moore, Baldos and Hertel (2017) formally test the 'Adaptation Illusion Hypothesis' first posed by David Lobell several years earlier (Lobell, 2014). Based on his work as a Lead Author for the climate impacts section of the IPCC report (2014), he postulated that most of the so-called 'adaptation' identified by the process modellers was in fact not really climate adaptation at all, but rather simply beneficial farming practices which serve to boost yields equally under both current and future climate. Moore *et al.* (2014) are able to test this hypothesis by including an adaptation indicator variable in the meta-analysis. It appears in two places. The first is a pure shift effect (added to the intercept) thereby picking up adaptation 'illusions' which are independent of climate. The second interacts with temperature and picks up evidence of true climate adaptation under which (e.g.) adverse impacts of elevated temperature are moderated by adaptation. As predicted by Lobell, the pure shift effect is statistically significant, while the term capturing true climate adaptation is statistically insignificant. This does not mean that farm level adaptation is not important under a changing climate. It simply suggests that the types of adaptation included by crop modellers are not really climate *adaptation*. They are simply good practices which would be equally beneficial if implemented under current climate. Including these beneficial effects in a climate impact analysis is likely to be misleading, since adoption of these practices is likely constrained by other factors (e.g., access to credit). This is important when it comes to evaluating studies of climate impacts which rely on crop models and include adaptation components.

The foregoing confirmation of Lobell's adaptation illusion hypothesis in the context of agronomic models of crop growth notwithstanding, we do expect farmers to engage in very significant adaptation to climate change in the future. Antle and Capalbo (2010) identify three different types of adaptation to climate change. The first is adaptation based on current technology. For example, in the face of elevated CO_2 concentrations, farmers may choose to apply more fertilizer to relieve potential nutrient constraints. They may also employ more machinery and labour to deal with the increase in weed infestations. And they are very likely to increase irrigation rates in the face of higher temperatures. Indeed, in regions where irrigation is already being undertaken, those farms not employing irrigation are likely to consider investing in this technology. Across the literature, irrigation has been found to be one of the most effective tools for adaptation to a warming climate, as it both contributes to cooling the plants as well as overcoming water stress, which poses a major challenge to crop productivity at elevated temperatures. Schlenker and Roberts (2009) show that, for maize production in the United States of America, irrigation allows farmers to largely avoid the adverse impacts of temperature extremes. The desirability of irrigation as adaptation to a warming climate poses a significant sustainability challenge in a world of increasing water scarcity, and should be a part of all future studies of climate impacts on agriculture, as will be further discussed below.

The second broad avenue for adaptation in the face of climate change, identified by Antle and Capalbo (2010), is the development and dissemination of new technologies. This typically involves a mix of public and private investment and therefore requires a longer lead-time. It also likely entails irreversibilities such that investors may be reluctant to pursue these investments until some of the climate change uncertainties are resolved. Considerable work is already underway in both the public and private sectors to develop new crop varieties that are resilient in the face of drought and extreme heat. Less obvious is the need for greater cold tolerance in crops in order to facilitate a more rapid migration of crops to higher latitudes and cooler locations. Earlier sowing of seeds can also be beneficial to avoid extreme heat during the critical flowering stage. And improved pest resistance will be important under climate change. However, the time lag in development of new technologies can be quite long (Alston *et al*. 2010) and these typically require local adaptation. This is a major stumbling block in the poorest countries of the world, which are often the most vulnerable to climate change as well. Hertel and Lobell (2014) argue that this is one reason why many climate impact models likely overstate the potential for adaptation in the poorest parts of the world. In addition, farmers in the poorest countries often do not have access to credit – a critical determinant of adoption of new technologies. Models of climate impacts need to consider both the potential for the development of new technologies, as well as the barriers to their adoption throughout much of the developing world.

The final avenue for adaptation involves changes in governance and institutions. This is an area in which there is ample evidence of both positive and negative adaptation (sometimes termed maladaptation) (Hertel and Lobell, 2014). Free trade is one oft-touted avenue for adaptation, and this will be discussed at length later in this report. Subsidies for agriculture are another important governance variable affecting the farm sector. In the United States of America, the shifting of most government payments to crop insurance subsidies is having an adverse effect on climate adaptation as it is discouraging investment in irrigation as well as encouraging production of more weather sensitive crops in risky locations (Müller, Johnson, and Kreuer, 2017). These types of adaptation and maladaptation will be important to take into account in modelling exercises – particularly as they affect the degree of market integration. As will be shown below, market integration can have a significant impact on the expected consequences of climate change for food security.

II. Consequences of climate change for commodity markets, trade, food security and aggregate welfare – an overview of the models

Incorporating climate impacts into a trade model

There is now a robust and growing literature seeking to estimate the impacts of climate change on commodity markets, trade and food security. The first question which must be addressed in any such study is how to translate the productivity shocks emerging from the statistical and/or biophysical models discussed above into a form which can be entered into the global economic models. There are basically three approaches which have been used in the literature (Hertel, Baldos and van der Mensbrugghe, 2016). The first is an *ad hoc* approach favoured by reduced-form, partial equilibrium commodity models such as International Food Policy Research Institute's (IFPRI) IMPACT model. It treats the climate-induced productivity shock as a parallel shift in the supply function, which we denote here as shock to yields, or, in terms more familiar to modellers using Computable General Equilibrium (CGE) models, an exogenous shift in the derived demand for land by the crops sector: Δ_L^D . When this shift is positive, there is an improvement in productivity, yields rise, and the derived demand for land at current output levels falls. The first column of Table 1 reports analytical expressions for the resulting change in crop output and price in the case where nonland inputs are available in perfectly elastic supply (Hertel, Baldos and van der Mensbrugghe, 2016). These equilibrium output and price changes logically depend on the supply and demand elasticities in the model – a point to which we will return momentarily. For the time being, note the important role played by the total elasticity in the commodity market in question: $\varepsilon^{S,I} + \varepsilon^{S,E} + \varepsilon^{D}$, where $\varepsilon^{S,I}$ is the intensive margin of supply response, $\varepsilon^{S,E}$ is the extensive margin of supply response, and ε^{D} is the absolute value of the farm-gate price elasticity of demand for the commodity in question. The total elasticity appears in the denominators throughout the expressions listed in Table 1. The less responsive is the model to price changes – both on the supply and demand sides, the larger the price adjustment required to restore equilibrium after a given climate change shock.

Table 1. Impacts of climate change shocks on equilibrium output and price changes

Variable	Supply shift	Land-augmenting technical change	Hicks-neutral technical change
Output	$\dfrac{\varepsilon^{D}\Delta_{L}^{D}}{\varepsilon^{S,I}+\varepsilon^{S,E}+\varepsilon^{D}}$	$\dfrac{\varepsilon^{D}(\theta_{L}\varepsilon^{S,E}+1)a_{L}}{\varepsilon^{S,I}+\varepsilon^{S,E}+\varepsilon^{D}}$	$\dfrac{\varepsilon^{D}(\varepsilon^{S,E}+\varepsilon^{S,I}+1)a_{O}}{\varepsilon^{S,I}+\varepsilon^{S,E}+\varepsilon^{D}}$
Price	$\dfrac{-\Delta_{L}^{D}}{\varepsilon^{S,I}+\varepsilon^{S,E}+\varepsilon^{D}}$	$\dfrac{-(\theta_{L}\varepsilon^{S,E}+1)a_{L}}{\varepsilon^{S,I}+\varepsilon^{S,E}+\varepsilon^{D}}$	$\dfrac{-(\varepsilon^{S,E}+\varepsilon^{S,I}+1)a_{O}}{\varepsilon^{S,I}+\varepsilon^{S,E}+\varepsilon^{D}}$

Source: Hertel, Baldos and van der Mensbrugghe (2016).

The second column of Table 1 reports the changes in output and price which arise when climate change is introduced as a type of land-augmenting (or, more likely, dis-augmenting) technical change in the agricultural production function. This approach is preferred by many of the CGE modellers in their analyses of climate change impacts on agriculture (Robinson *et al*., 2014). In this case, climate change is treated as a form of biased technical change in the context of an explicit production function, with the shock reported in Table 1 as $a_L > 0$ for a positive (land-augmenting) technical change and negative for adverse climate impacts. *This approach assumes that the climate change does not have an impact on the productivity of nonland inputs.* Based on a comparison with the supply shift model in the prior column of the table, it is clear that this approach will give rise to larger changes in output, and hence larger price changes, for a given yield shock. The difference between these two arises from the fact that, in the explicit production function approach, technical change not only affects the derived demand for land, but also the profitability of farming. This is why there is an additional term, related to the extensive margin of commodity supply, in the numerator. Assuming the price elasticities are the same between two models, we expect to see a larger output and price response in the CGE model. Of course these elasticities are not the same across models, as we will see below (Table 3), further complicating such inter-model comparisons.

The third methodology for translating climate driven productivity changes into an equilibrium model is shown in the final column of Table 1. It is also an explicit shock to the production function for crop output. However, in this case, the climate shock is viewed as a Hicks-neutral technical change. Here, the idea is that, if the farmer does everything the way they did under the historical climate (no adaptation at this point – so all input levels are the same as before the shock), but climate change reduces yield by ten percent, then a_O = -10% and ten percent more of all inputs – including land -- are required to restore the original output level in the absence of adaptation. This is the approach taken by Hertel, Burke and Lobell (2010), Diffenbaugh *et al*. (2012), Costinot, Donaldson and Smith (2016) and Moore *et al*. (2017). As can be seen from a comparison of the entries in the second and third columns of Table 1, this makes a big difference in the model outcomes. Since all factors are impacted, there is a much larger change in profitability and a larger output response in the case of the Hicks-neutral treatment, *provided the model elasticities are the same across the two approaches*.

Which of these approaches to administering a climate shocks is preferred? To my knowledge this issue has not been formally explored. A natural test would be to see which approach gives the best fit to historical output and price variability, given observed yield shocks. Of course, the answer will be conditional on the supply and demand elasticities in the model. On this point, Diffenbaugh *et al*. (2012) found the Hicks-neutral approach, which they incorporated into a short run CGE model of year-on-year corn yield shocks in the United States of America, to give a level of annual corn price variability which was broadly consistent with that observed in the United States of America over the period from 1980-2000. The question of which approach to implementing climate shocks is most appropriate remains a topic worthy of deeper exploration as work in this area proceeds.

Evaluating global economic models of agriculture and climate

As noted previously, AgMIP has provided an institutional framework for comparing models of climate impacts on agriculture. While the bulk of that project's efforts have been focused on crop models, they have also assembled a diverse team of global economic modellers for purposes of assessing the impacts of climate change on regional and global production, trade and welfare. In the process of undertaking this model comparison, they have generated some useful results which permit a deeper comparison of the models – in particular their supply and demand elasticities. In addition, we consider other global economic models which have been used to assess global climate impacts. The models considered here are listed in Table 2 which divides them into partial equilibrium (PE), at the top panel of Table 2, and general equilibrium (GE), at the bottom panel of Table 2.

The spatial dimensionality of these models is summarized in the third column of Table 2 and is categorized across both the demand and the supply sides of the model. All of the GE models (excepting CDS – which is effectively a PE model) rely on some aggregation of the Global Trade Analysis Project (GTAP) database (see Aguiar *et al*., 2016) that may include large countries individually, but typically collapse global activity to between 20 and 30 regions. Using GTAP's supplemental Agro-Ecological Zones database (see Monfreda *et al*., 2009), production within a region can be distinguished across up to 18 Agroecological Zones (AEZs) and this is the case in a number of the GE models. The PE models specify demand at either an aggregate regional or country level. Supply, on the other hand, varies from the grid-cell level (MAgPIE, GLOBIOM, CDS, GL), to sub-regional (that may be defined by AEZ or water basin), to national. For example, IFPRI's IMPACT model has a country resolution for demand (and trade), but sub-regional Food Production Units (which tend to follow major river basins) for production.

Table 2: Overview of the models

Models	Source	Spatial Resolution		Global Drivers				Price Responsiveness					Productivity Growth	International Trade
		Demand	Agricultural Production	Population	GDP	Income	Biofuels	Demand	Intermediate	Intensive S	Extensive S	Nonland S		
Partial Equilibrium Models														
GCAM	PNNL	Regional	Regional/AEZ	X	X	-	✓	X	-	-	✓	-	YS	HO
GLOBIOM	IIASA	Regional	Gridded	X	X	-	✓	✓	✓	✓	✓	-	YS	HO
IMPACT	IFPRI	Country	Sub-regional	X	X	✓	X	✓	-	-	✓	-	YS	HO
MAgPIE	PIK	Regional	Gridded	X	X	-	✓	-	-	✓	✓	-	YS	SS/HO
GAPS	FAO	Country	Country	X	X	✓	X	✓	-	-	✓	-	YS	HO
General Equilibrium Models														
CDS	MIT	Regional	Gridded					✓	✓	✓	✓	-		ARM
GL	IFPRI	Country	Gridded					✓	✓	✓	✓	-		ARM
AIM	NIES	Regional	Regional	X	✓	✓	✓	✓	✓	✓	✓	✓	PF	ARM
ENVISAGE	FAO/WB	Regional	Regional	X	✓	✓	-	✓	✓	✓	✓	✓	PF	ARM
EPPA	MIT	Regional	Regional	X	✓	✓	✓	✓	✓	✓	✓	✓	PF	ARM
FARM	ERS/USDA	Regional	Regional/AEZ	X	✓	✓	✓	✓	✓	✓	✓	✓	PF	ARM
GTEM	ABARES	Regional	Regional	X	✓	✓	✓	✓	✓	✓	✓	✓	PF	ARM
MAGNET	LEI/WUR	Regional	Regional	X	✓	✓	✓	✓	✓	✓	✓	✓	PF	ARM

Model References: GCAM: Wise and Calvin (2011); GLOBIOM: Valin *et al*. (2013); IMPACT: Robinson *et al*. (2015); MAgPIE: Lotze-Campen *et al*. (2008); GAPS: Kavallari *et al*. (2016); CDS: Costinot, Donaldson and Smith (2016); GL: Gouel and Laborde (2017); AIM: Fujimori *et al*. (2012); ENVISAGE: van der Mensbrugghe (2008); EPPA: Chen *et al*. (2015); FARM: Sands *et al*. (2014); GTEM: Pant (2007); MAGNET: Woltjer and Kuiper (2014).

The global drivers of these models are reported in the next column of Table 2. These are not the focal point of this review, but are relevant in driving the underlying economy forward in the context of climate change. Suffice it to note that: (a) population is exogenous in all of these economic models, and (b) GDP is exogenous in the PE models. In some notable cases (GCAM), food consumption is specified exogenously, based on the idea of eventual convergence of caloric consumption. This means that food demand is unresponsive to the economic forces which may vary across scenarios. Empirical evidence suggests that both the price- and income-responsiveness of consumers' demand for food becomes smaller in absolute value as households become wealthier (Muhammad *et al*. 2011) Some of the models in Table 2 seek to take this into account through a series of *ad hoc* parameter adjustments over the course of their simulation.

Of course it is not just final demand that is potentially responsive to prices. Intermediate demands by the livestock and food processing sectors are also potentially quite important. All of the GTAP-based GE models have both of these channels for determining aggregate agricultural demand (but not CDS and GL). None of the PE models have food manufacturing sectors; a few incorporate the livestock sector and price sensitive feed demand (e.g., GLOBIOM, GAPS, IMPACT). Biofuel demand is included in most of the models as a long run driver. In the case of the partial equilibrium models, this source of demand is typically exogenously specified, whereas in the general equilibrium models this may be related to the price of oil, as well as to government mandates which may, or may not be binding, depending on the oil price scenario (e.g., MAGNET). When these other sources of demand are also price responsive, we expect a larger farm level price elasticity of demand and a more muted market price responses to supply side shocks – particularly when the biofuel mandates are not binding.

The next set of columns of model characteristics identified in Table 2 are those associated with the price responsiveness of crop supply. This depends critically on the scope for endogenous intensification in response to scarcity (or the reverse in the case of crop surplus). In most cases, this intensification is viewed simply as increased application of variable inputs per hectare. However, in the case of the MAgPIE model, land scarcity engenders increased investment in agricultural R&D which, in the longer run, can generate higher yields (Dietrich *et al*. 2014). As shown in Table 2, several of the models do not allow for endogenous intensification (GCAM, IMPACT, GAPS, CDS and the baseline version of GL) – although some models allow for the choice between alternative fixed-proportion technologies thus exhibiting some substitution in the aggregate factor proportions (e.g., GCAM). These fixed proportions models tend to favour land conversion as an avenue for responding to scarcity, such as that induced by adverse climate change, in global food markets.

Virtually all of the models in Table 2 rely on endogenous land supplies as a key factor in equilibrating long run supply with growing demands. However, as we will see below, the magnitude of this component – the extensive margin of supply response -- varies greatly across models. There is also a column in Table 2 relating to the role of non-land factor supply response to the crops sector. This is a largely overlooked constraint on long run crop output. Yet the supply of labour, capital, fertilizer and other non-land inputs to the farm sector can play an important role in constraining crop output expansion in response to food scarcity (Hertel, Baldos and van der Mensbrugghe, 2016). Nearly all of the PE models ignore this element, thereby overstating the importance of land (and possibly water) as the sole constraining factors on the supply side. The fact that they explicitly incorporate non-land factor supplies is a strength of the GE models – although the empirical basis for these non-land input supply elasticities is quite limited.

As noted in our discussion of alternative methodologies for applying climate shocks to PE and GE models, *even when two models use the same approach to incorporating the very same climate shocks, unless they employ the same supply and demand elasticities the results will be different*. This raises the question: what are the values of these elasticities in the models currently being used for global economic analysis of climate change? And how might these influence the outcomes predicted by these models? Hertel, Baldos and van der Mensbrugghe (2016) took advantage of outputs generated by one of the AgMIP economic model intercomparison exercises undertaken recently and used a set of expressions like those in Table 1 in order to 'back out' the global elasticities from nine of the global economic models most widely used to analyse climate impacts in agriculture (these were the participants in the AgMIP economic model comparison exercise). Table 3 reports these elasticities for a variety of models. In the case of the AgMIP models, these elasticities pertain to a composite of the five major field crops (which they term CR5), at global scale (see footnote in Table 3). For purposes of comparison, the final row reports the global elasticities from the more aggregated (all crops combined) SIMPLE model which has been validated against historical data for the aggregate crops sector over the period 1961-2006 (Hertel and Baldos 2016; Baldos and Hertel, 2013). This long run validation makes it an appropriate point of comparison for the more disaggregated models which have not been compared against a multi-decadal historical record comparable in length to the projections period.

Table 3. Demand and supply elasticities for global economic models [a]

Model	Total	Demand	Extensive	Intensive
Partial equilibrium models				
IMPACT	0.58	0.24	0.37	-0.03
GCAM	2.80	0.63	2.52	-0.36
GLOBIOM	0.49	0.28	0.08	0.13
MAgPIE	0.36	0	0.18	0.18
General equilibrium models				
CDS	2.46	1.00	1.45	0.01
GL	0.53	0.20	0.33	0.00
AIM	0.85	0.10	0.92	-0.17
ENVISAGE	3.22	0.47	1.57	1.18
FARM[b]	1.33	0.07	1.30	-0.04
GTEM[b]	0.96	0.07	0.52	0.36
MAGNET	0.93	-0.04	1.23	-0.26
SIMPLE	1.16	0.29	0.36	0.51

[a] Elasticities for IMPACT, GCAM, GLOBIOM, MAgPIE, AIM, ENVISAGE, FARM, GTEM and MAGNET are based on five major crops. See Hertel, Baldos, and van der Mensbrugghe 2016 for the method by which these arc elasticities are calculated, using a set of simultaneous equations. Elasticities for CDS apply to all crops combined and these marginal elasticities were obtained via simulation by Christope Gouel (personal communication). The demand elasticity for GL applies to all crops while the supply elasticity applies to maize and was obtained from Christophe Gouel (personal communication). Elasticities for SIMPLE are obtained via model simulations and apply to marginal changes.

Examination of the elasticities in Table 3 leads to a number of important conclusions. Firstly, the aggregate response of these models to crop prices varies greatly. With the exception of GCAM, which is a hybrid model designed as part of an Integrated Assessment modelling system, the partial equilibrium models tend to have a much smaller total elasticity than the general equilibrium ones. This point has been made previously by Hertel (2011) who hypothesizes that these settings may reflect the evolution of these agricultural commodity models from near term forecasting to long term projections frameworks. The only way to obtain the kind of crop price volatility observed on an inter-annual basis is to have a relatively low total price elasticity. This is obtained in the commodity models by having small supply elasticities at the intensive margin – a point consistent with short run analysis. By contrast, the CGE models are not used for year-on-year forecasting, and price volatility is a lesser point of emphasis. Furthermore, the supply elasticities are functions of deeper parameters (Robinson *et al*. 2014) which are consistent with longer run, equilibrium assumptions. Thus we see in the CGE models larger aggregate responses to scarcity, with the supply side of the market dominating the overall price responsiveness.

Combining this information about the total elasticities (generally smaller in the PE models), with the analytical expressions in Table 1 which show that, for equivalent elasticities, the output and price responses will be smaller in the PE models due to their methodology for introducing the climate impacts on yields, we find that we cannot reach a definitive conclusion based on theory about which model will generate larger impacts. However, with just a little additional information (the cost shares of land), we can make some rough calculation to speculate about which models will tend to show more price responsiveness to climate change.

In addition to determining the aggregate effects on price and output, the relative size of the demand and supply elasticities in each model will play a key role in determining the relative incidence of an adverse climate change shock. The smaller the share of the total elasticity contributed by the farm-gate demand elasticity, the greater the share of the burden which will be borne by consumers. Indeed, producers in many regions stand to gain from the higher prices under such circumstances. The MAgPIE model is a case in point. By design, demand is exogenously specified. This inelasticity of demand, coupled with a small aggregate supply elasticity, yields very large price changes (recall the second row of Table 1). This is evidenced in the MAgPIE paper authored by Stevanović *et al*. (2016) which reports significant producer gains from climate change over the 21st century, while consumers lose a great deal of consumer surplus. Introducing a larger role for consumer response to higher prices, as in the IMPACT model (Table 3), will shift some of the burden of climate change towards producers, as households reduce their food consumption or shift away from the most heavily affected commodities. In this dimension, along with MAgPIE, the CGE models reported in Table 3 appear to be particularly oriented towards consumer-incidence of climate change shocks due to their relatively small role for farm-level price elasticities in the overall demand elasticity, and hence the relatively large supply elasticity. A major reason for these small farm gate demand elasticities in the CGE models is the fact that very little of the crop commodity is sold directly to consumers – a fact faithfully reflected in the underlying input-output tables. Rather, crops must first pass through multiple processing activities, which tend to mute the farm-level price responsiveness of final demand. Finally, note the extremely large price elasticity of demand for food implied by the demand system used in CDS. This results in some peculiar conclusions about the role of trade in climate adaptation which will be discussed below.

There are also a number of counter-intuitive signs in Table 3 (i.e., negative entries in this table – since the demand elasticities in Table 1 are defined as being positive as are the supply elasticities). This is presumably due to compositional effects. For example, the MAGNET model has very large land supply elasticities and relatively small intensification elasticities, suggesting that the main response to adverse technological change (i.e., a negative climate change impact) will be to bring in more cropland area. At this point, given the focus on compositional effects, we need to bring in the final column of Table 3 which identifies the trade structure of the model. Given the trade specification in MAGNET (segmented markets via the Armington assumption), if the adverse climate shocks are largest in regions with relatively low yields, this is where the price rises will be largest. If, in addition, these regions also have large land supply elasticities (e.g., Africa), then we expect strong expansion in low-yielding land areas. This would result in a decline in global average yields for grains and oilseeds in MAGNET. This outcome is observationally equivalent to a negative intensive margin when viewed at global scale through our conceptual lens, which is why we see the negative entries in the final column of Table 3. The AIM and FARM (also Armington models) also show negative intensive margins at global scale. In the case of the two PE models which show a negative intensive margin, IMPACT and GCAM – neither of which incorporate product differentiation, this appears to be due to the absence altogether of intensification possibilities, combined with a more muted compositional effect.

The question of how international trade is modelled is central to the impact of climate change on food security – particularly when climate shocks vary widely across countries/geographic regions. The final column of Table 2 reports on the trade structure of the models reviewed here. HO denotes homogenous product models. SS refers to a self-sufficiency specification where countries/regions are assumed to strive for a given level of self-sufficiency which may evolve slowly over time. ARM denotes Armington and refers to those models in which products are differentiated by country of origin, therefore allowing for market segmentation and the divergence of prices for the same product (e.g., wheat) across markets (homogenous product models can have price divergences in the presence of transport costs – e.g., GLOBIOM).

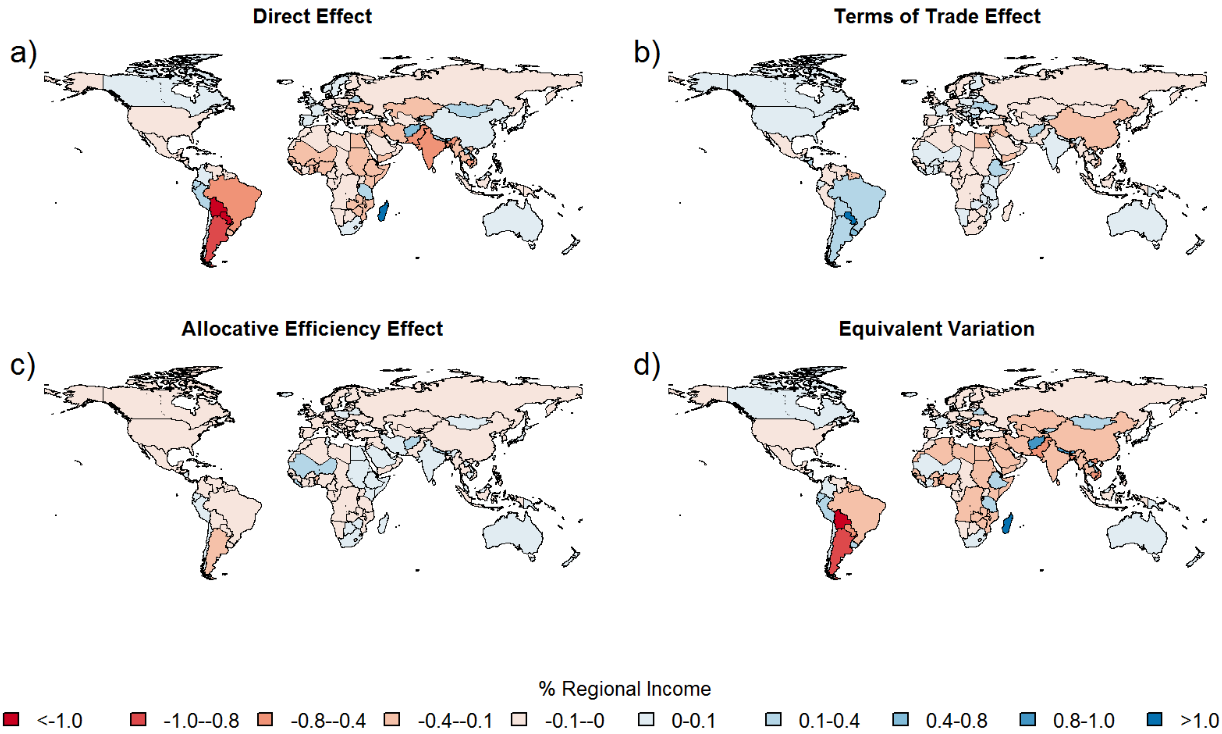
In their paper on globalization of the food system, Hertel and Baldos (2016) emphasize the critical importance of the distinction between the HO and ARM specifications by contrasting the impacts of a variety of different shocks on food and environmental outcomes under the two types of models. In the case of the adverse (most extreme) climate change scenario which they consider, nonfarm undernutrition rises by 45 percent, relative to the baseline year 2050 under segmented markets, but just 27 percent under fully integrated markets. When trade is frictionless and there is a unified global market, it is much easier for consumers in severely affected regions with the highest undernourished headcount (South Asia and Africa) to access lower cost food from abroad. Of course agricultural trade is not frictionless. Rather it is hampered by transport costs – but more importantly by government interventions – both at the border and at the consumer and producer levels. Given the need to constrain the HO models to avoid specialization and overly dramatic changes in trade patterns -- which would fly in the face of historical evidence -- many of the HO models find other ways to constrain trade. As noted above, MAgPIE introduces a self-sufficiency criterion. GLOBIOM introduces trade costs as well as increasing costs of adjustment for changing trade flows.

Which model more accurately reflects the evolving geography of world trade? Villoria and Hertel (2009) formally test the integrated markets hypothesis using a model of global cropland change and reject it in favour of the Armington specification. I believe that, in the near term, the answer to this question is quite clear – the Armington model of product differentiation fits the data much better, which is why virtually all of the empirical trade models now employ product differentiation by country of origin (or by firm/country of origin pairs, which is empirically isomorphic). However, over the very long run (decades – or even a century) there is a legitimate concern about how persistent will be the historical geography of trade in agricultural products. I believe it is fair to say that the jury is still out on how best to model the evolution of agricultural trade patterns over the very long run.

Given the tendency for the bilateral geography of agricultural trade to persist over time, it is interesting to draw out the implications for the incidence of climate impacts. Moore *et al*. (2017), begin to explore this issue, employing the meta-analysis of Moore *et al*. (2017) underpinning Figure 1 to characterize the biophysical impacts of climate change and insert these into the GTAP model of global trade to elicit the national welfare impacts. Using the welfare decomposition tool of developed by Huff and Hertel (2001), the resulting national impacts can be decomposed into three components: (a) the direct (biophysical impact) contribution to welfare, (b) the terms of trade effect, (c) the allocative efficiency effect and (d) the total national welfare effect (see Fig. 2). From Figure 2a it is clear that South America is hard hit by the direct effects of climate change. This derives from its heavy reliance on soybeans which are adversely affected by higher temperatures – particularly in the tropics, where current growing season temperatures are already high (recall Figure 1). However, exporters in this region (e.g., Brazil) are able to shift some of this burden of climate change to other regions through higher export prices. As a consequence, there is a substantial improvement in the terms of trade for Brazil, Argentina and Paraguay (Figure 2b). On the other hand, China – a large importer of soybeans from South America, experiences a strong terms of trade loss (Fig. 2b). In addition to international adjustments to climate change, there is potentially significant scope for intra-national adjustments. Constinot, Donaldson and Smith (2016) (CDS) explore the latter in detail, using their globally gridded CGE model. Their model, which does not include an opportunity cost for land expansion, and which represents food demand as being price-elastic (recall Table 3), leads them to conclude that most of the adjustment to climate change occurs within countries, by shifting production from land less-well suited to a crop under the new climate to more suitable land. Constraining land use change within a country results in significantly higher welfare losses from climate change. On the other hand, freezing trade patterns does not have a large impact on the resulting welfare losses, leading them to conclude that international trade does not play a large role in adaptation to climate change.

Taking the CDS model as a starting point, Gouel and Laborde (2017) develop a new model of global gridded production and trade in which there are explicit opportunity costs for cropland expansion. This feature, coupled with an inelastic demand for agricultural products – the authors argue this is more consistent with empirical evidence – leads to a very different conclusion from CDS. In their model, international trade plays a crucial role in the adjustment to climate change shocks in agriculture, with trade patterns changing rather dramatically under their climate change scenario. These authors also show how, as they increase the price elasticity of demand for food, the role for changing trade patterns is diminished, since, in the face of more expensive food household reduce consumption instead of importing more food. This underscores the important role for the price elasticities of supply and demand – as was emphasized earlier in this survey – albeit now in the context of trade.

Figure 2: Decomposition of national welfare changes at 2°C warming



Source: Moore *et al*.. 2017.

One final dimension of the climate change/trade modelling literature which is crucially important, but which has not received sufficient attention, is the role of irrigated agriculture and potential impacts on water scarcity (Rosegrant *et al*. 2013). As noted above, we expect that irrigation will be an important adaptation response to a warming climate. Yet many parts of the world where irrigation is prevalent are already water scarce (Wada *et al*. 2010). And in many of these water scarce regions, fossil groundwater is being mined. And, with agriculture accounting for 70 percent of water withdrawals, worldwide, there will be little choice but to respond by restricting irrigation withdrawals (in addition to investing in more efficient irrigation systems).

What will this mean for international trade and for climate change adaptation? Liu *et al*. (2014) use a CGE model with rainfed and irrigated cropping disaggregated and both land (AEZs) and water (river basins) broken out, in order to explore the implications of projected water scarcity in 2030, in the absence of climate change, for food security and land use. They find that international trade offers an important vehicle for adaptation to a water scarce future. While significant local scarcity is projected in some regions – particularly in South Asia and the Middle East – the impact on prices is relatively modest. This is in large part due to the fact that water becomes less scarce in some regions, which, in turn, boost net exports. If we add climate change to this picture, it is likely that the mediating role for international trade will become even more pronounced, as many of the regions projected to show scarcity in the absence of climate change (e.g., South Asia) are also expected to be hard hit by climate change.

We can gain further insight into the potential interplay between water scarcity, irrigation and adverse climate shocks from the paper by Taheripour *et al*. (2013). While their object of investigation is the United States of America biofuels boom, the international market effects of an increase in the excess demand for food production is not dissimilar from the role of an adverse climate shock – albeit now a shock to the supply side of the market. Those authors examined the land use and terrestrial carbon impacts of an increase in biofuel demand – both in the absence and presence of constraints on irrigation expansion in the most physically water scarce regions of the world. They find that the presence of an irrigation constraint boosts overall land expansion – since irrigated yields are, on average, higher than rainfed yields. In addition, the irrigation constraint has a dramatic impact on terrestrial carbon emissions, since the rainfed areas also have higher levels of above-ground carbon. By forcing more land expansion into more carbon-rich regions, the irrigation constraint in the presence of a shock to global excess demand was shown to be very significant. We might expect a similar result in the context of an adverse climate scenario.

A word of caution is in order for those considering incorporation of irrigation and water scarcity into models of climate impact on agriculture. Water scarcity is a highly localized phenomenon and gridded projections of water scarcity at mid-century show considerable variation across sub-basins within countries and even within river basins (Liu *et al*. 2017). On average, there may be plenty of water, but the water may not be where it is needed for climate adaptation, in a timely fashion. So addressing the irrigated agriculture challenge is likely only appropriate in those models with considerable spatial detail.

III. Climate mitigation, international trade and food security

In addition to facilitating adaptation to climate change impacts, international trade also plays a key role in determining the impacts of policies aimed at climate change mitigation. Indeed, Havlik *et al*. (2015) find that the near term impacts of land-based mitigation efforts on food prices are likely to be significant. Thus any discussion of climate change and global food security cannot ignore the mitigation side of the story. This section discusses the potential impacts of land based mitigation on food security and poverty and the role which international trade might play in distributing the associated costs of mitigation actions.

First of all, it is important to highlight the disproportionate role which land-based mitigation – largely in agriculture and forestry – can play in economically efficient, near-term abatement of greenhouse gases (GHG) emissions. In a paper for the Copenhagen Consensus, Brent Sohngen (2010) calculated, using the DICE model, how much the optimal carbon tax would be reduced by incorporating forest sequestration as a mitigation option in that framework which had hitherto largely focused on fossil fuel abatement. The downward shift of the DICE model's optimal tax path is dramatic and amounts to roughly a 50 percent reduction in carbon tax in any given time period. This finding is further underscored in a paper by Golub *et al*. (2009) who use a global CGE model with both fossil fuel abatement, carbon sequestration and non-CO_2 GHG abatement possibilities to show that roughly half of the economically efficient near term abatement should come from agriculture and forestry. Clearly including these land-based sectors in the overall mitigation strategy will be beneficial from the point of view of global welfare.

However, such massive interventions into the land-based activities can be expected to have significant consequences for food prices. This lead Hertel and Rosch (2010) to conjecture that the near term impacts of climate mitigation on food prices and poverty could be larger than the near term impacts of climate change itself. This conjecture is borne out in the work of Havlik *et al*. (2015) who use the GLOBIOM model to examine the impacts of a global carbon tax aimed at reducing Agriculture, Forestry and other Land Use (AFOLU) emissions as part of a climate stabilization scenario (2 ^{0}C). Results depend heavily on the range of mitigation options available. In GLOBIOM these are dealt with as discrete technologies. They find that this policy would result in lower agricultural production in 2030, relative to baseline: a 4 percent decline for crops, a 5 percent decline for meat and a 9 percent decline for milk. This, in turn results in higher world prices: a 4 percent increase for crops and a 7percent increase for livestock, but these could be much higher in some regions, reaching a 22 percent increase in Sub-Saharan Africa. These higher prices, in turn result in reduced consumption. Indeed, these impacts rival, and in some cases exceed, the impacts of climate change over the same time horizon.

The potential adverse impacts of land-based mitigation on the poor is further elaborated by Hussein *et al*. (2013) who use the GTAP-POV model in order to assess the poverty impacts of a global carbon tax. They find that land-based mitigation policies can have significant impacts on poverty, with the consequences depending on the earnings source of the poor – they consider seven different types of poor households, distinguished by agriculture/non-agriculture, land, labour, capital and transfer payments, earnings sources. To the extent that the climate mitigation policy raises food prices, all types of poor households suffer. However, the policy also boosts land returns and, in some cases, can boost rural wages. This can benefit rural households. Unfortunately, most poor rural households control relatively little land, and so the adverse effect of higher food prices dominated. Overall, the authors find that a land based mitigation policy tends to boost national poverty across the sample of countries which they studied. For this reason, these authors, as well as Havlik *et al*. (2015) suggest some form of revenue recycling of the carbon tax receipts to offset these adverse effects on the poor.

Of course, the impacts of mitigation policies on food prices depend very much on how the policies are implemented. The simplest form of implementation from the economic modelling point of view – and also the most economically efficient – is that of a global carbon tax. However, the distributional consequences of such a tax – both across countries and within them – are dramatic. Avetisyan *et al*. (2011) focus on the ruminant livestock sectors in their analysis of a global carbon tax and find that this hits the poorest countries in the world hardest – resulting in significant increases in food prices and reductions in livestock output and earnings. This suggests that such a policy would be politically untenable.

Henderson *et al*. (2017) also focus on the ruminant livestock sector – the most emissions intensive agricultural sector – and explore a variety of policies aimed at reducing emissions. They incorporate differences in emissions factors by livestock type and region, and also include abatement cost curves that represent a summary of many different mitigation alternatives as estimated by Henderson *et al*. (2017). They find that a global carbon tax of USD 20/ton CO_2^e emissions could mitigate 626 metric megatons of CO_2/year through the adoption of new production practices and a restructuring of cattle production, increasing the share of meat coming from the dairy sector, compared to the more emissions intensive beef sector. However, they, too, deem such a policy politically unlikely due to the adverse impacts on livestock output, incomes and prices in developing countries. Therefore, they explore a revenue recycling policy which provides a subsidy to producers aimed at helping them maintain profitability in the face of the carbon tax on emissions. While this policy does maintain production levels, it greatly dilutes the original objective of reducing emissions, with the abatement falling to just 185 metric megatons of CO_2/year. There is an unavoidable conflict between abatement and consumption. This points to the importance of boosting income growth so households can afford the higher food prices which result from a carbon tax.

These adverse impacts on developing country food security, from any global carbon policy which includes land-based mitigation, suggest that it is unlikely that such a policy will be adopted worldwide. Therefore, it makes sense to evaluate a policy which exempts developing countries, or at least allows them to set their own, nationally determined plans. This was indeed the spirit of the Paris Accord on climate mitigation. However, once some regions are either exempted, or impose less restrictive standards, the issue of 'leakage' immediately arises. Will livestock production simply shift from the more restrictive to the less restrictive regions? If this occurs, and if the less restrictive regions also have much higher emissions intensities, then the mitigation effects of such a policy could be greatly diluted. In short, the response of international trade to this policy regime becomes much more important in this context.

Golub *et al*. (2012) find that such leakage due to international trade is indeed significant when developing countries are omitted from the land-based mitigation policy. However, they also find that much of this leakage can be eliminated if a global forest carbon sequestration policy is put in place. This is due to the fact that restricting deforestation in the tropics, and encouraging afforestation in some places, raises the cost of ruminant livestock production throughout much of the tropics, thereby acting as a brake on expansion of this industry when the industrialized economies apply a carbon tax to agriculture.

IV. Policy implications related to trade as a tool for adaptation

International trade can play an important role in facilitating adaptation to climate extremes and climate change. One of the most compelling examples of this potential role comes from 19th Century India and is documented by Burgess and Donaldson (2010) who studied the impact of variation in the annual monsoons on mortality in the Subcontinent – either failure of the monsoon to arrive early enough for planting or excessive rainfall and flooding. In the absence of infrastructure to transport large amounts of food to the stricken regions, monsoonal variations resulted in considerable price and income volatility as well as high levels of mortality. After the introduction of a railroad system, the local impacts of such climate extremes were greatly moderated, illustrating the great potential of market integration to facilitate adaption to the vagaries of climate and extreme weather events.

Climate models currently predict an increasing likelihood of extreme events – both temperature and precipitation – and these are expected to result in more frequent and more severe supply-side shocks which can only be accommodated by reductions in consumption, increases in costly stockholding, or increases in imports into, or reductions in net exports from, the affected regions. In the context of such climate change, increased market integration could have greater value to society. This point is illustrated in a paper by Verma *et al*. (2014) who focus on the potential for market integration to lessen the commodity market volatility resulting from increased year-on-year variability in maize supplies in the United States of America under a mid-century climate. They characterize supply-side volatility using high resolution climate model outputs in conjunction with a non-linear climate impact function estimated by Schlenker and Roberts (2009). After validating this approach on historical data, they use it to project supply side shocks under mid-century climatology, considering two different types of market integration as adaptation alternatives. The first involves international market integration, through which global trade barriers in maize trade are removed. This results in a modest (8 percent) reduction in domestic maize price volatility in the United States of America, relative to what would have existed under future climate in the presence of current tariffs.

Of course current trade policies are in fact endogenous, and can respond to market conditions – particularly natural disasters and extreme climate events. This is the case, even though World Trade Organization (WTO) disciplines impose some rules and binding constraints on import barriers. The fact is that current tariffs are often well-below bound WTO rates, leaving significant room for endogenous tariff adjustments – both upwards and downwards -- in the face of changing market conditions. In addition, an agreement to discipline export restrictions under the WTO remains elusive, thereby leaving room for countries to respond to food crises by banning exports. This can generate panic and knock-on effects as was seen in food crisis a decade ago. The problem of endogenous policy responses in the face of changing market conditions has been highlighted by Kym Anderson and Will Martin in the context of the 2006-2008 food price spikes (Martin and Anderson 2012; Anderson and Nelgen 2012). They find that endogenous policy responses (export taxes and downward adjustments in import tariffs) contributed significantly to the rise in world commodity prices over this period. The estimated contribution was largest for rice, where two-fifths of the world price rise is attributed solely to policy responses – as opposed to changes in supply or demand conditions. For wheat, the figure is one-fifth, while for maize it was just one-tenth.

These findings are particularly disturbing since, when fewer countries participate in the adjustment to periodic regional or global production shortfalls, the remaining countries are forced to absorb more of the adjustment. And typically it is the poorest countries that are least able to insulate their domestic markets. Add to this, the fact that the price elasticity of demand for crops is highest amongst the poorest elements of the population, and we have a recipe for nutritional disaster, as the poorest households in the poorest countries are forced to bear a disproportionate share of the burden of extreme climate events and output volatility.

In their study of market integration as a vehicle for adaptation to climate change, Verma *et al*. (2014) also examine the effect of closer inter-sectoral integration. Here, as opposed to integration of maize markets across borders, the authors explore the effects of integration between the agriculture and energy sectors. This has, in fact, been an important feature of the agricultural economy in the United States of America over the past decade. Higher energy prices, accompanied by biofuel mandates under the United States of America Renewable Fuel Standard, have resulted in as much as 40 percent of maize production in the United States of America going to ethanol – and ultimately being consumed as a liquid fuel. The authors explore two different kinds of inter-sectoral integration – one driven by higher energy prices (market-driven integration) and one driven by ethanol mandates in the face of low energy prices (mandate-driven integration). In their projections of the market-driven integration scenario, the mandate is not binding under future climate, whereas under low energy prices it is binding. They find a very large difference between commodity market price volatility under these two different types of integration. Specifically, market-driven integration reduces maize price volatility under future climate by about one-quarter. This stems from the fact that the demand for ethanol is far more price-elastic than the demand for food. With ethanol comprising just a small share of total liquid fuel demand, variation in crop supplies are readily accommodated with modest price changes. This stands in marked contrast to the situation under mandate-driven agriculture-energy integration wherein demand is completely inelastic. In this case, maize price volatility under future climate by more than half due to the presence of the ethanol mandate. In short, inter-sectoral integration can serve as an important avenue for adaptation to greater supply-side volatility under future climate, but only if this integration is market-driven.

In the long term, by fundamentally changing the pattern of comparative advantage in global agriculture, climate change calls for a significant reconfiguration of international trade and production patterns to reflect this new comparative advantage (Reilly *et al*. 2002; Tobey, Reilly and Kane, 1992). Regions which once tended to be self-sufficient or net exporters may well become net importers of crops in the face of adverse climate change, while some regions – particularly in the northern latitudes – may become more competitive in a wider range of agricultural products. The more readily these shifts can occur, the higher and more robust will be global welfare. These findings are evident in recent research which seeks to explore the interplay between climate change and international trade over the course of the 21st century. Stevanović *et al*. (2016) run the MAgPIE model under a wide range of climate scenarios using a variety of biophysical crop models, while considering two *hypothetical* trade regimes: FIX and LIB. The FIX regime fixes the pattern of trade at 1995 levels, while the LIB regime allows for free and unfettered trade in agriculture, worldwide. The authors find that introduction of the LIB regime reduces global welfare losses (relative to impacts under the hypothetical FIX regime) by about two-thirds. Expected aggregate agricultural welfare (factoring in both consumer and producer surplus) is also benefited in most regions of the world. However, the free trade scenario results in a significant redistribution of global agricultural welfare between consumer and producer groups. Free trade benefits consumers in the most adversely affected regions (tropical South) while hurting consumers in the temperate and boreal North who must now compete in world markets for access to food. Producer impacts are logically reversed, as farmers in the climate change-benefited North gain greater access to markets in the South, while producers in the South face more intense competition from climate-benefitted farmers in the North. Overall, the authors find that world food prices are far lower under the LIB scenario.

The role of international trade as a vehicle for adaptation to climate change in the long run is also explored in depth by Baldos and Hertel (2015) who focus specifically on the impact on undernourishment at mid-century. They use the SIMPLE model of global crop supply and demand and contrast the impacts under optimistic and pessimistic climate impact scenarios and two trade regimes (currently segmented markets vs. fully integrated world markets – where the latter is analogous to the LIB scenario discussed above, but the former allows for currently observed responsiveness of trade flows). They focus on their worst-case climate scenario which involves climate predictions from the HADGEM global circulation model, crop impacts from the LPJmL crop growth model, and which ignores potential crop growth gains from elevated CO_2 concentrations. Under this extreme scenario, they estimate that global undernutrition in 2050 (largely in South Asia and Sub-Saharan Africa) could rise by nearly 55 percent, relative to their 2050 baseline. However, this increase would be considerably moderated (by about one-third) under integrated markets. Overall, the authors find that deeper integration in international trade offers an excellent vehicle for shielding against worst case climate scenarios by giving consumers improved access to world markets. The global trading system is a public good which will only become more valuable in the future. Free and unfettered access to global food supplies must be ensured in the face of the great uncertainty around future climate change and its impacts on agricultural production.

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