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# Structural approaches to modeling the impact of climate change and adaptation technologies on crop yields and food security

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ABSTRACT

Achieving and maintaining global food security is challenged by changes in population, income, and climate, among other drivers. Assessing these threats and weighing possible solutions requires a robust multidisciplinary approach. One such approach integrates biophysical modeling with economic modeling to explore the combined effects of climate stresses and future socioeconomic trends, thus providing a more accurate picture of how agriculture and the food system may be affected in the coming decades. We review and analyze the literature on this structural approach and present a case study that follows this methodology, explicitly modeling drought and heat tolerant crop varieties. We show that yield gains from adoption of these varieties differ by technology and region, but are generally comparable in scale to (and thus able to offset) adverse effects of climate change. However, yield increases over the projection period are dominated by the effects of growth in population, income, and general productivity, highlighting the importance of joint assessment of biophysical and socioeconomic drivers to better understand climate impacts and responses.



## 1. Introduction

Achieving food security is challenged by changes in population, income, and climate, among other factors. Challenges in the agricultural sector include increasing demand and competition for natural resources as well as biotic and abiotic stresses. Geographic and temporal variability add complexity. These issues are being increasingly studied using a combination of tools and methodologies, some relying on purely biophysical approaches through process-based, agro-ecosystem, or statistical models, and others estimating the economic effects resulting from changes in productivity. The so-called "structural approach" (Fernández and Blanco, 2015) relies on the combination of biophysical and economic models and has been increasingly used and developed in recent years.

A combined, structural approach provides a flexible, scenario-based framework which can offer a more complete understanding of the complex and diverse impacts of climate change on agriculture and food security. In the face of potential future changes, such an approach can inform better investment decisions by estimating gains from adoption measures. Studies based on this approach have showed that, from a purely biophysical standpoint, climate change effects by 2050 could reduce global maize, rice and wheat yields by as much as 25% compared to a no-climate-change (no CC) baseline before economic adjustments are considered (Rosegrant et al. 2014). Market effects moderate the impacts of climate change through price mechanisms. When changes in prices and global trade are included, yields of major crops (coarse grains, rice, wheat, oilseeds, and sugar) in 2050 are instead projected to be 11% lower compared to a scenario of perfect mitigation in the same year (Nelson et al., 2014b). These studies also showed that—in response to drivers such as population, income, and climate—commodity prices are expected to increase significantly over time, even accounting for the development of new technologies. The flexibility of the structural approach in linking climate and crop models together with socioeconomic analysis also has the potential to open up new research areas and avenues for collaboration. Use of the structural approach can contribute to

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better targeting and prioritization of plant breeding, which represents a large share of the investments by national and international agricultural research institutions.

In this paper, we provide a brief overview of the principal components of the structural approach, how they are represented in the literature, and what they offer to research on climate change impacts on crop yields and food production. We then show how recent work by the CGIAR adds to the body of research, answers some of the questions raised in previous studies, and fills some of the gaps highlighted by other authors.

## 2. Synthesis of previous work

The issue of how climate change may affect agricultural productivity and food security has been addressed using a range of tools. Although the general research question may be the same, each tool takes a specific angle and therefore generates an answer that is informed, and limited, by the scope and power of the chosen methodology. Many of the tools and methods can also be combined in a structural approach (Fig. 1) using both soft and hard links between models and data (Reilly and Willenbockel, 2010). There are three major components of this approach: 1) physiological studies, 2) crop models, and 3) economic models. Each component can stand on its own and represents an important body of research, but the components can also be linked together to present a more complete picture. Physiological research addresses how changes in weather (e.g. temperature and precipitation) and other factors affect crops. Crop modeling work simulates how yields change under different conditions, whether using historical data or future projections. Economic studies examine how yields change when market interactions are considered and how this affects prices, production, consumption, and trade. Each component of the research is influenced by other factors such as climate stress (precipitation, temperature, availability of water, among others) based on General Circulation Model (GCM) results. They may include information on specific technologies, such as drought and heat tolerance, as we do here.

Much research focuses on the physiological traits that influence how climate stresses affect plants. Water shortages and increased temperatures are key constraints to agricultural productivity. Therefore, development of drought and heat tolerant cultivars is of utmost importance to maintain yields (Barnabás et al., 2008), and we focus on the literature that addresses these traits. This research mainly covers how planting dates, fertilizer regimes, water limitations, and changes in temperature affect particular plants (Araus et al., 2008, Barnabás et al., 2008). These studies generally find that under plausible future climate change scenarios and holding other factors such as crop varieties and management practices

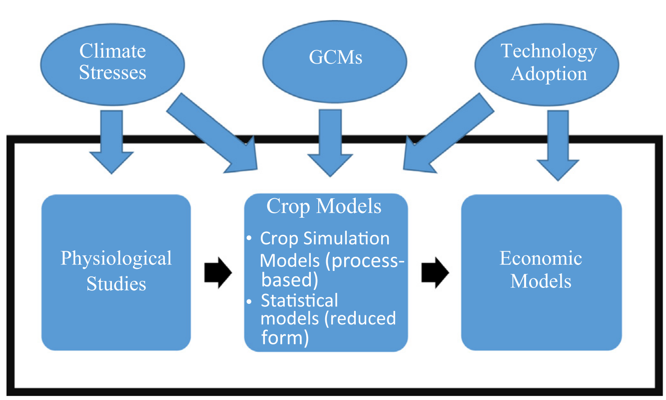


**Fig. 1.** Primary components of the structural approach used in research on climate impacts in agriculture and food systems.

constant, we are likely to see decreased yields for many crops (Campos et al., 2004). Yield maintenance is therefore of paramount importance in developing drought and heat resistant cultivars (Barnabás et al., 2008). Stresses during different developmental stages of the plant influence the level of yield decline. For example, heat stress during germination can slow or in some cases totally inhibit the process and lead to crop failure (Wahid et al., 2007). Crop physiology improves our understanding of the interlinked determinants of crop yield and the combined plant response can consequently improve crop simulation models (Araus, 2008).

Crop models are the second component of the structural methodology. They can be divided into two types: crop simulation models that are process-based and statistical models that are reduced form. Process-based models specify agents and their behavior in dynamic systems to estimate the effects of counterfactual changes (Chetty, 2009; Sims, 1986) and can take non-linearities into account (Olmstead, 2009). On the other hand, reduced form models describe relationships among selected variables while holding others constant and estimate statistical relationships. Process-based models require a large amount of data to calibrate and validate, and as such, reduced form models are useful alternatives in data-sparse environments (Chetty, 2009).

A handful of models make up the majority of crop simulation work to date, including process-based models such as the Decision Support System for Agrotechnology Transfer (DSSAT) model (Hoogenboom et al., 2012; Jones et al., 2003), the Agricultural Production Systems Simulator Model (APSIM) (Keating et al., 2003), and the Global Agro-Ecological Zone (AEZ) modeling framework (Fischer et al., 2002, 2005). The Lund-Potsdam-Jena managed Land (LPJmL) model (Bondeau et al., 2007) has also been used in more recent work (Blanco et al., 2014; Frank et al., 2014) along with DSSAT, EPIC, pDSSAT, PEGASUS (Nelson et al., 2014a, 2014b; von Lampe et al., 2014; Wiebe et al., 2015), and the General Large Area Model (GLAM) for annual crops (Challinor et al., 2010). Crop modeling focuses on the biophysical dimensions of climate change effects on future crop yields and how adaptation strategies may be used to minimize negative outcomes. These studies tend to focus on yield effects for maize because data for maize has the most extensive and detailed coverage. It is also an important food and feed crop globally. Other crops studies include beans in East Africa (Thornton et al., 2010), sorghum in Tanzania, India, and Mali (Msongaleli, 2015), wheat in China (Challinor et al., 2010), groundnuts in India and West Africa (Singh et al., 2014b), and chickpea in South Asia and East Africa (Singh et al., 2014a).

Reduced form statistical analyses use historical and field trial data to estimate relationships between yield and climate variables which are then used to project yields into the future under various GCMs. For example, Lobell et al. (2008) modeled 94 crops worldwide using historical harvest data, while Schlenker and Lobell (2010) modeled maize, sorghum, millet, groundnuts, and cassava in Sub-Saharan Africa. The International Maize and Wheat Improvement Center (CIMMYT) and its partners conduct yearly field trials to assess the performance of improved maize varieties in eastern and southern Africa (Bänziger et al., 2006, Lobell et al., 2011). The data from these trials have been used in a regression-based approach to estimate the effects of changes in rainfall and temperature (Lobell et al., 2011).

Process-based and statistical approaches often rely on a large set of projected climate change effects from various GCMs that take into account temperature, precipitation, water stresses, and other variables. The studies range from using a single, representative GCM (Jones and Thornton, 2003) to 21 GCMs (Cooper et al., 2008). The Special Report on Emissions Scenarios (SRES) from the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (AR4) is the common source for GCM climate change projections for many of the studies that were done prior to the release of AR5. Many studies use two SRES emissions pathways which cover a broad spectrum of effects from different temperature and rainfall patterns (Ciscar et al., 2009; Thornton et al., 2010; Nelson et al., 2010; Ciscar et al., 2011; Calzadilla et al., 2013). In more recent work using the IPCC AR5 report, Msongaleli et al. (2015) modeled maize and sorghum in Tanzania under two representative concentration pathways (RCPs), 8.5 and 4.5, and Wiebe et al. (2015) used RCP 4.5, 6.0, and 8.5. A greater number of combinations of GCMs and RCPs/SRES scenarios enables a wider range of plausible futures for analysis, however, it is not always possible to run every combination due to computing power and data requirements of the crop models. The spectrum of positive and negative effects is sometimes modeled using a no climate change baseline along with an extreme climate change scenario such as RCP 8.5.

The final component of the structural methodology pictured in Fig. 1 is economic modeling. Partial equilibrium (PE) models of the agricultural sector and computable general equilibrium (CGE) models have been used to estimate the impacts of climate change on crop productivity. These models help in understanding the market effects of crop production and its response to climate change. This can be done in a stylized manner where climate change is incorporated into the crop yield response in economic models (Lobell et al., 2013). Hertel et al. (2010) and Calzadilla et al. (2013) measure the effects of climate change in the GTAP and GTAP-W economic models, respectively, with exogenous yield shocks by region obtained from the crop modeling literature. These models use historical data for calibration and validation, but the focus is on future responses to climate change.

Linking biophysical models (along with climate models) and socioeconomic analysis allows for a potentially deeper and broader understanding of future climate change impacts and how to plan for them (Challinor et al., 2010). Adding the socioeconomic component to crop modeling allows accounting for the response of global markets to climate shocks, providing a more complete representation of the response of the larger food system. Macroeconomic scenarios of population and income growth for many structural modeling approaches often rely on the Shared Socioeconomic Pathways (SSPs) developed for the IPCC AR5 (O'Neill et al., 2014). The SSPs are coherent scenarios of macroeconomic drivers that give plausible projections to 2100. They have been used as a common source for socioeconomic drivers under the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Nelson et al., 2014a; von Lampe et al., 2014; Wiebe et al., 2015).

The first studies using the structural approach were limited by data, computing power, downscaling techniques, and level of commodity and regional disaggregation, among other critical elements (Fernández and Blanco, 2015). Earlier studies use the IPCC AR4 SRES scenarios for the socioeconomic projections while some research uses the UN median population and World Bank income growth projections as their business-as-usual scenario (Nelson et al., 2014a; Rosegrant et al., 2014). The number of climate change scenarios modeled ranges from two (Parry et al., 1999) to fourteen (Fischer et al., 2005). Studies also vary in their regional scope, with some covering five regions in Europe (Ciscar et al., 2009; Ciscar et. al., 2011) or focusing on European countries only (Shrestha et al., 2013), while others cover as many as 159 countries (Wiebe et al., 2015; Ignaciuk et al., 2015; Springmann et al., 2016). The time horizon for the studies also varies, most going to 2050 or 2080 with some intermediate results provided for 2020 and 2030. Crop simulation modeling serves as an intermediate step in the structural approach (Nelson et al., 2010; Nelson et al., 2014a; Wiebe et al., 2015). Although crop simulation modeling might use historical climate data for calibration, the results generated are for future time periods.

Research conducted under AgMIP by Nelson et al. (2014a, 2014b) and von Lampe et al. (2014), harmonized input data and provided results from five CGE and four PE models. These studies are also cutting edge in that they used outputs from a variety of crop models and harmonized their results to use as inputs into the economic models (under a high emissions pathway). This allowed for more direct comparison of the results to highlight how production and food security may be affected by climate change from various perspectives. Further analysis compared the impacts of climate change on yields, production, area, prices, and trade across multiple socioeconomic and emissions pathways (Wiebe et al., 2015).

The studies that use the structural approach find that the addition of economic modeling decreases the yield changes that result from purely biophysical modeling through economic feedback mechanisms in production and consumption (Blanco et al., 2014; Nelson et al., 2010). Globally aggregated results from these economic analyses show that the world is producing enough food to feed the growing population currently, and moving into the future (Witzke et al., 2014). However, regional differences in production are likely to be exacerbated due to climate change and differences in impacts and adaptive capacity are expected to create a growing wedge between developed and developing countries (Parry et al., 1999; Parry et al., 2004; Tesfaye et al., 2015).

Given the complexity of climate impacts on crop yields and food production, there is an increasing need to link biophysical and economic methods and results. Considerable work has explored the impact of climate change on yields under alternative socioeconomic and climate pathways. However, not as much work has used this methodology to simulate the potential effects of new crop technologies as a means of adapting to climate change. Different authors have signaled the need for improvements along the chain of the structural approach, from greater efforts in representing the effects of adaptation policies and strategies (Fernández and Blanco, 2015), or, more specifically, in properly translating results from field trials into crop modeling so that biophysical models can effectively simulate the improved traits that are currently sought by agronomists (Challinor et al., 2010). Only a couple of studies so far, e.g. Rosegrant et al. (2014) and Nedumaran et al. (2014), actually model explicit adaptation technologies in an economic modeling framework.

## 3. Case study – modeling the effect of new crop technologies on the impact of climate change

Significant progress has been made in implementing structural approaches for evaluating technology adoption in agriculture. Building on the method published by Nelson et al. (2009), researchers at IFPRI simulated the productivity and food security effects from the expanded adoption of several agricultural technologies and practices considered representative of a sustainable intensification approach (Rosegrant et al., 2014). The study by Rosegrant et al. (2014) is global and regional in scope and relies on scenarios in which technologies are adopted globally in wheat, maize, and rice producing areas. For the case study highlighted in this section, we followed the approach of Rosegrant et al. (2014) by estimating the productivity effects of improved crop varieties focused on specific regions, but with more nuanced scenarios of adoption informed by a collaboration between several CGIAR centers as part of the Global Futures and Strategic Foresight (GFSF) program. The improvements represented by crop varieties are represented as additive gains on top of the exogenous baseline assumptions on yield growth.

The IMPACT system of models (Fig. 2) links general circulation models (GCMs), crop simulation models, water models, and a

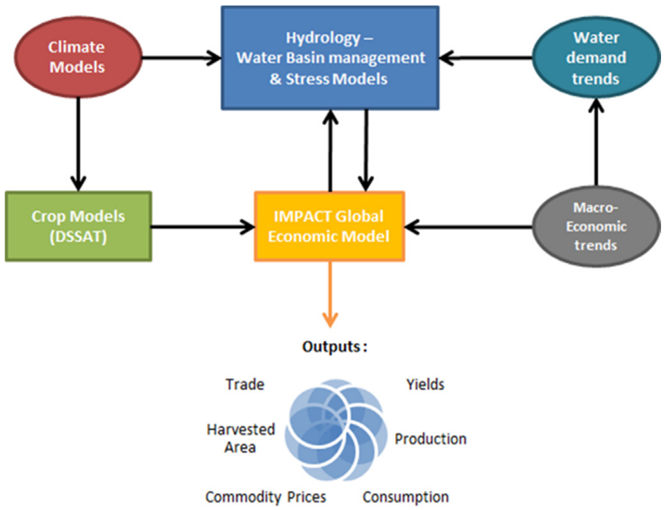


**Fig. 2.** The IMPACT system of models.
Source: Robinson et al., 2015a

global economic model in the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT, Robinson et al., 2015a). We used the IMPACT system of models to run alternative scenarios for drought and heat tolerant crop varieties under two extreme future climate scenarios. Detailed, location-specific data on climate, soil type, and physiological crop parameters are incorporated into the DSSAT crop models. Climate and technology-induced yield shocks from crop models are used as inputs into IMPACT, a partial equilibrium, multi-market, agricultural sector economic model. In addition, plausible regions of adoption and rates of adoption (maximum rates and timelines) of new technologies by farmers are solicited through center expertise and then modeled in IMPACT following logistic adoption curves (Table 1). Long–run drivers such as population and income growth (as represented in SSP2) are also used as inputs in the economic model.

The structural approach is formalized in the design of the IMPACT system of models. Importantly, the link between physiological/biological studies and crop models is made explicit in this system. Collecting data from several cropping systems (maize, wheat, potatoes, groundnuts, and sorghum), GFSF team members in three participating CGIAR centers (CIMMYT, CIP, and ICRISAT) identified specific drought and heat tolerance (DT and HT) traits as priorities for addressing climate challenges.

The climate and economic scenarios used in IMPACT draw on the work developed for the IPCC AR5 report. We analyze the effect on agricultural productivity from adoption of DT and HT improved varieties under a no climate change (NoCC) and a climate change (CC) scenario that is expected to cause significant changes to agricultural systems worldwide. Under the NoCC scenario the alternative technologies perform better than the baseline technology. However, to really test the benefits of the technologies a more extreme climate scenario is used. This extreme climate scenario was simulated using the Geophysical Fluid Dynamic Laboratory's Earth System Model (GFDL ESM2M) using RCP 8.5. This CC scenario is driest, on average across the globe and was chosen specifically to test the performance of drought tolerant varieties under conditions where the technology would be expected to be more beneficial.

Results from the IMPACT model show that improved drought and heat tolerant crop varieties have the potential to reduce the negative yield impacts from climate change. In IMPACT, yield growth over time is comprised of exogenous and endogenous effects. In our approach, climate change is treated as an independent factor that affects yield growth due to changes in precipitation and temperature; generally in RCP 8.5 climate scenarios this effect reduces crop productivity across most regions. The exception is crop production in more northern latitudes where longer and warmer growing seasons may improve yields. This can be seen with wheat, where global average yields increase due to climate change with large regional variability. The exogenous yields calculated within the IMPACT system of models are affected by climate change, water availability, and assumptions of growth implicit in the core economic model, but they are independent of market effects. When market effects are also taken into consideration, prices and trade interact with agricultural productivity worldwide, producing what are defined as endogenous yields (Robinson et al., 2015a). Market effects dampen both negative and positive impacts on yields because the price signals from changing yields influence incentives to adjust farm management.

In this study, we found that the technologies tested in many of the regions were able to partially or completely offset the negative effects of climate change on yields. For example, looking at exogenous yields, we estimate that climate change may decrease yields of rainfed maize by 6% in twelve African countries (see Table 1) with baseline technology compared to a scenario without CC (Fig. 3). In contrast, the modeled adoption of a drought tolerant maize variety under CC conditions increases yields by about 25% compared to a reference scenario with CC but without adoption of this variety.

**Table 1**
Promising and alternative crops and traits considered in this paper.

| Crop | Trait | Countries (region) | Final adoption | Share of global production |
|---|---|---|---|---|
| Maize | Drought tolerance | Angola, Benin, Ethiopia, Ghana, Kenya, Malawi, Mozambique, Uganda, United Republic of Tanzania, Zambia, Zimbabwe | 30% | 6% |
| | Heat tolerance | Bangladesh, India, Nepal, Pakistan | 30% | |
| Wheat | Drought tolerance | Iran, Turkey | 35% | 23% |
| | Heat tolerance | India, Pakistan | 30% | |
| | Drought and heat tolerance | Argentina, South Africa | 30% | |
| Potato | Drought Tolerance | Bangladesh, China, Kyrgyzstan, India, Nepal, Pakistan, Tajikistan, Uzbekistan | 4–40% | 33% |
| | Heat tolerance | | 4–40% | |
| | Drought and heat tolerance | | 4–40% | |
| Sorghum | Drought tolerance | Burkina Faso, Eritrea, Ethiopia, India, Mali, Nigeria, Sudan, United Republic of Tanzania | 20–80% | 44% |
| Groundnut | Drought tolerance | Burkina Faso, Ghana, India, Malawi, Mali, Myanmar, Niger, Nigeria, Uganda, | 40–60% | 35% |
| | Heat tolerance | United Republic of Tanzania, Viet Nam | 40–60% | |
| | Drought and heat tolerance, high yielding | | 40–60% | |

Note: Final adoption rates for potatoes, sorghum, and groundnuts vary by country. The final adoption refers to the share of crop area that adopts the alternative technology.

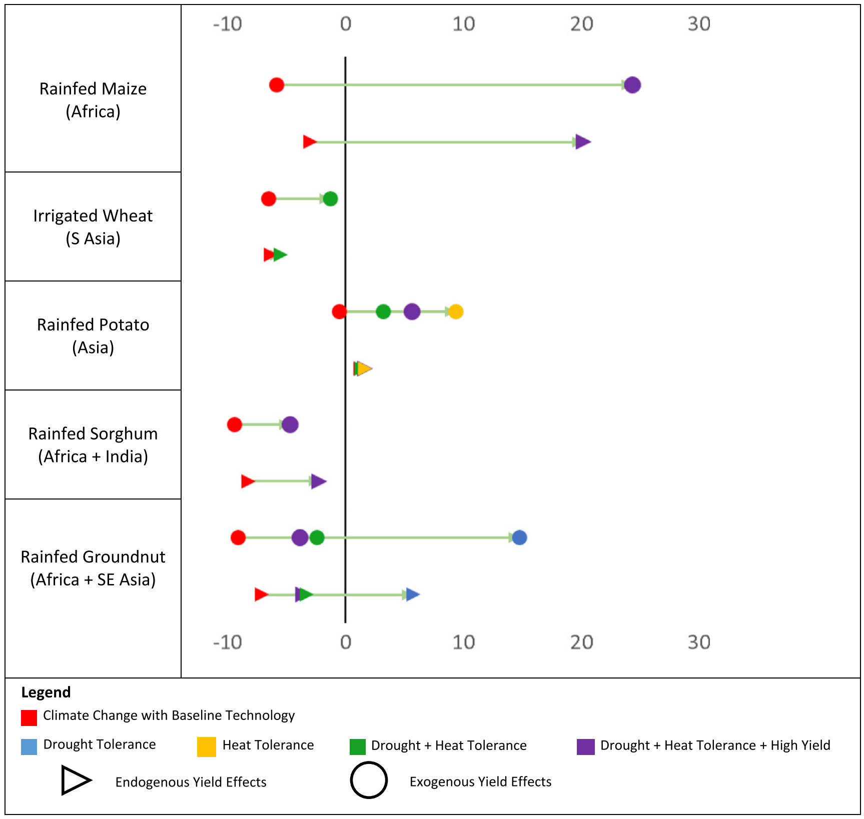


**Fig. 3.** Effects of Climate Change and Promising Technologies on Yields in 2050 Compared to Reference Scenario (with and without market effects). Note: Regions of adoption identified in Table 1. Circles represent exogenous yield effects, triangles represent endogenous yield effects.

Increased production lowers prices, ceteris paribus. Price changes affect both consumer and producer behavior, with consumers increasing consumption and producers decreasing production. In IMPACT, producers respond to changing commodity price by adjusting land allocation (extensive response) and/or input levels (intensive response). In this exercise, the intensive response to lower prices dominates for all crops except sorghum, with farmers achieving smaller yield gains than suggested by the crop models. Generally, we still see large positive yield increases in all crops (between 10% and 27%) with the new technologies (Fig. 3). For example, for rainfed maize in Africa we see the intensive response in action: exogenous yield increases alone would lead to an expected 24% improvement, but once market effects are taken into account, we observe only a 20% increase. In the case of sorghum, producers achieve higher than expected yield improvements and follow a land-sparing strategy reducing area allocated to the crop by one percent (316,000 ha). In the crop model, there can either be adoption or non-adoption in a unit area based on whether or not the technology provides a yield benefit compared to non-adoption. Therefore, the exogenous results in IMPACT are only based on the suitability of the technology as shown by the biophysical model (DSSAT). Biophysical suitability is just one factor that farmers will consider when deciding to adopt a new technology. Farmers weigh the benefits against the costs, and their choice is not entirely binary, as they may adopt a new technology partially. In IMPACT, we take this into account through the endogenous feedbacks of market prices on yields (Fig. 3). As a result, for wheat and potatoes, the endogenous results show very little change in aggregate yields as the adoption rate in the region is low (e.g. only four percent of area in China and Bangladesh). Overall, the new stress-resistant varieties reduce the adverse effects of declining water availability and increasing temperature. The resulting increase in production leads to lower prices relative to the case without the new varieties. Lower prices are a net gain to consumers, particularly poor consumers who spend a larger share of their income on food, and may reduce the prevalence of hunger. The effect of lower prices on producers is less clear as declines in unit prices may be offset by increased productivity. Small farmers are generally still net food consumers, and as such, the losses in farm revenue may still be less than gains farmers see from lower food prices.

Endogenous yield effects are one of the key outputs of the structural approach, but they are not the only output that has a bearing on future scenarios of food security. When a productivity shock is introduced in the IMPACT economic model, world commodity prices and trade flows are affected. In our case study, adoption of improved varieties is simulated only in selected regions based on suitability and, as a result, the impact on global prices is fairly moderate. However, changes in productivity do affect national supply and demand, and therefore trade flows are affected.

To summarize results shown in detail in Robinson et al. (2015b), adopting regions improve their productivity faster than projected changes in national-level demand when compared to a baseline without technology adoption. This translates into improving terms of trade where net importers are displacing imports with own production and net exporters are increasing their exports. This is a benefit at the national and local level that gets hidden in more aggregated analyses. While the new drought-tolerant and heat-tolerant technologies are likely to have important food security implications for adopting farmers and regions, food security in most countries, and globally, will be influenced more by changes in broader, global drivers such as population, income, productivity, and climate change.

## 4. Discussion

Linking physiological, crop simulation, and economic models is increasingly important in a world facing the complexities of climate change. The structural approach helps in estimating the impact of climate change on crop yields across different locations and cropping systems and offers the ability to simulate the effects of alternative adaptation strategies (Challinor et al., 2010; Nelson et al., 2009; Nelson et al., 2014; Rosegrant et al., 2014; Wiebe et al., 2015). This includes the adoption of alternative technologies that have not yet been developed to their full potential, by using physiological knowledge from agronomic and biological studies combined with a range of modeling tools. The availability of powerful computation allows researchers to simulate the uncertainty implicit in future climate conditions by linking biophysical and economic models to climate models. These represent a range of future climatic conditions and, in turn, are also linked to a suite of socioeconomic scenarios that represent key drivers of future change, such as population and GDP. Linking to economic models allows for market effects to be taken into account and is critical for policy-makers undertaking ex-ante assessments of technologies, particularly over the longer term.

The case study represents the latest version of a methodological development process which resulted in an improved integration of crop, water, and economic models. The hard-link (Reilly and Willenbockel, 2010) between water allocation and water stress models on one side and the core economic model on the other allows for a more complete representation of climate risks across rainfed and irrigated systems (Calzadilla et al., 2013), while also simulating conditions where drivers other than climate change (e.g., competition from other sectors of the economy) are affecting water supply to the agriculture sector. To date, few studies have tried to estimate the effects of adaptation options, whether whole, comprehensive policies or single-targeted measures (Easterling et al., 2007; Fernández and Blanco, 2015). Our approach also seeks to fill a gap noted by previous authors (Challinor et al., 2010) whereby the expertise of plant breeders, agronomists, and crop modelers could be pulled together via the GFSF network across the CGIAR centers to identify key climate-tolerant traits to show the potential of DT and HT varieties.

While continued development is necessary (and in progress) in all these areas, the current system provides a flexible framework to explicitly analyze new crop varieties as well as other agricultural technologies and practices. The modeling of new crop traits first in crop models and then in the economic model as independent scenarios, separate from reference or business-as-usual scenarios, helps to isolate and identify the effects of specific interventions and produce a stepwise analysis of complex adaptation strategies. This work was made possible through collaboration among CGIAR centers with diverse mandates and expertise, which provided detailed information on countries of adoption for each improved variety as well as estimated adoption rates which take into account technical and socioeconomic feasibility dimensions that influence adoption. Further collaboration in quantification of input parameters that describe the alternative technologies and their adoption during the scenario design process would benefit the comparison of technologies by using a consistent framework for drivers specified by the various CGIAR centers. Centers could also provide a range of adoption pathways for each of the crops in order to test the sensitivity of endogenous yield improvements and mitigation capabilities of specific technologies.

In order to capture the effects of climate-induced changes in crop productivity, the structural approach relies greatly on the results of crop simulation models. These models are a powerful tool as their high geographic resolution and combination of climate and soil data allows researchers to develop highly-specific scenarios to better capture local conditions. The detailed nature of the models, however, requires large input datasets, including a thorough description of crop variety characteristics, management practices, and soil properties. This can be a challenge even for regions with strong data collection institutions (Thornton et al., 2010; Rosegrant et al., 2014).

In the face of climate change and growing competing demands on both natural and financial resources, policy-makers need to prioritize investments. The structural approach can be used for decision-support in priority setting analyses. However, scenario design will play a critical role in how technologies can be compared. The design must capture key variables while limiting the number of differences across scenarios in order to isolate the effects of adoption of a particular technology. In the case presented here, for example, it would be difficult to conclude that one technology provided greater benefits than another because crops are adopted in different regions with varying adoption rates, while each of the regions is facing markedly different expected climate change effects. Future work will need to be designed with specific prioritization needs in mind.

Cost is also important in the economic decision of whether or not to develop or adopt a specific technology. In order to prioritize, a policy-maker will need to look at development costs and weigh them against potential benefits. A welfare module that looks at these costs and benefits has already been developed as a post process to the IMPACT model and could be used as a next step to address the question of which technologies might be the best investments.

It is recognized that food security is a multi-dimensional issue, including 1) food availability 2) access to food 3) stability and 4) food utilization (FAO, 2008). However, most simulation studies only capture one aspect of insecurity when looking at climate change impacts, i.e. availability (Schmidhuber and Tubiello, 2007). This is also a limitation in our study. We recognize that productivity increases are insufficient to address aspects such as access and the quality of food. Linkages to CGE models are being developed to measure the effects of changing incomes on food security. Scenarios exploring changes in diet are also important. Links between IMPACT results on climate and changing diets and a health model developed at Oxford University allow for much broader estimates of dietary risk factor and health outcomes (Springmann et al., 2016). Further connection to diet composition models focused on a wide range of macro and micronutrients will also improve these models' abilities to explore food security impacts of technology adoption.

## 5. Conclusion

The combination of climate, crop, and economic models allows researchers to estimate changes in yields and other parameters that include both biophysical and socioeconomic factors. The final yields capture the influence of GCMs, the interactions between soil, climate, and crop management, as well as market effects and the impact of socioeconomic (population and GDP) drivers. Adding to this approach is the modeling of specific traits (e.g. drought and heat tolerance) explicitly in both the crop and economic models. This allows us to estimate the effect of specific options for adaptation to climate change, which can help policy-makers better understand the consequences of targeted actions in their priority setting exercises.

Historical data and field level trial data can be used to calibrate and validate models in this structural framework. However, in order to help policy-makers and farmers adapt to climate change, these must be translated into forward looking simulations and scenarios. There is more than one way to model adoption of technologies but, to provide the strongest case for adoption, analysis of climate change effects needs to incorporate economic feedback to capture socioeconomic as well as biophysical interactions. Finally, to better inform decision-making, the structural approach needs to be further developed to improve post-processing of economic information on supply and demand to estimate effects on food security, nutrition, environmental impacts, and welfare.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.gfs.2016.08.003.

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