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

Shahnila Islam[a], Nicola Cenacchi[a], Timothy B. Sulser[a], Sika Gbegbelegbe[b], Guy Hareau[c], Ulrich Kleinwechter[d], Daniel Mason-D'Croz[a], Swamikannu Nedumaran[e], Richard Robertson[a], Sherman Robinson[a], Keith Wiebe[a,*]

[a] International Food Policy Research Institute, 2033 K St NW, Washington DC 20006, USA
[b] International Institute of Tropical Agriculture, PMB 5320, Ibadan, Oyo State, Nigeria
[c] International Potato Center, Avenida La Molina 1895, La Molina, Apartado Postal 1558, Lima, Peru
[d] formerly International Potato Center, Avenida La Molina 1895, La Molina, Apartado Postal 1558, Lima, Peru
[e] International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502324, Telangana, India

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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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* Corresponding author.
E-mail address: K.Wiebe@cgiar.org (K. Wiebe).

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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 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).

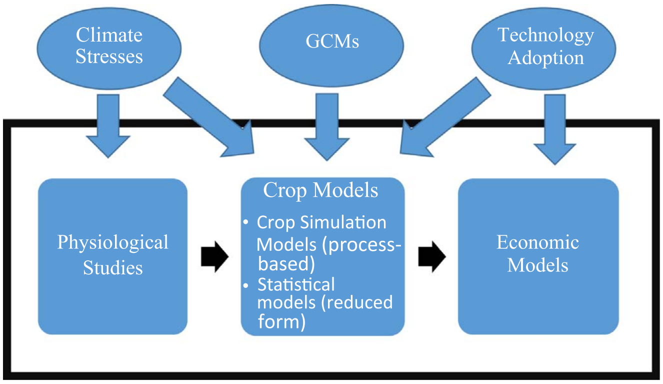

Fig. 1. Primary components of the structural approach used in research on climate impacts in agriculture and food systems.

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 and 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