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The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)

Model Description for Version 3

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ABSTRACT

The International Food Policy Research Institute's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) supports analysis of long-term challenges and opportunities for food, agriculture, and natural resources at global and regional scales. IMPACT is continually being updated and improved to better inform the choices that decisionmakers face today. This document describes the latest version of the model. IMPACT version 3 expands the geographic and commodity scope of the model in response to desires expressed by researchers and policymakers to address more complex questions involving climate change, food security, and economic development into the future. IMPACT 3 is an integrated modeling system that links information from climate models (Earth System Models), crop simulation models (for example, Decision Support System for Agrotechnology Transfer), and water models linked to a core global, partial equilibrium, multimarket model focused on the agriculture sector. This model system supports longer-term scenario analysis through the integration of these multidisciplinary modules to provide researchers and policymakers with a flexible tool to assess and compare the potential effects of changes in biophysical systems, socioeconomic trends, technologies, and policies.

Keywords: IMPACT model, ex ante analysis, scenario analysis, economic modeling, agriculture, international trade, food security, climate change, multimarket model, modular modeling approach, welfare analysis, global hydrology, water basin management, water stress simulation, crop simulation modeling

ABBREVIATIONS AND ACRONYMS

AR5	Fifth assessment report
CGE	Computable general equilibrium
CSE	Consumer support estimate
DSSAT	Decision Support System for Agrotechnology Transfer
ESM	Earth System Model
FAO	Food and Agriculture Organization of the United Nations
FPU	Food production unit
GAMS	General Algebraic Modeling System
GDP	gross domestic product
GFSF	Global Futures and Strategic Foresight
ICWASM	IMPACT crop water allocation and stress model
IFPRI	International Food Policy Research Institute
IGHM	IMPACT global hydrology model
IIASA	International Institute for Applied Systems Analysis
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
IPCC	International Panel on Climate Change
IPR	Intrinsic productivity growth rate
IRR	Internal rate of return
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
IWSM	IMPACT water basin simulation model
MM	Marketing margin
NIRWD	Net irrigation water demand
OECD	Organisation for Economic Co-operation and Development
PSE	Producer support estimate
RCP	Representative Concentration Pathway
SPAM	Spatial Production Allocation Model
SSP	Shared Socioeconomic Pathway
W/m^2	watts per square meter
WDI	World Bank's World Development Indicators

1. INTRODUCTION

The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) was developed at the International Food Policy Research Institute (IFPRI) at the beginning of the 1990s to address a lack of long-term vision and consensus among policymakers and researchers about the actions necessary to feed the world in the future, reduce poverty, and protect the natural resource base. Over time, this economic model has been expanded and improved, and IMPACT is now a system of linked models around a core multimarket economic model of global production, trade, demand, and prices for agricultural commodities. This document updates and replaces previous technical reports that served as model documentation for IMPACT, in particular Rosegrant and IMPACT Development Team (2012) and Rosegrant et al. (2008).

The multimarket model simulates the operation of national and international markets, solving for production, demand, and prices that equate supply and demand across the globe. The core model is linked to a number of "modules" that include climate models (Earth System Models, ESMs),[1] water models (hydrology, water basin management, and water stress models), crop simulation models (for example, Decision Support System for Agrotechnology Transfer [DSSAT]), value chain models (for example, sugar, oils, livestock), land use (pixel-level land use, cropping patterns by regions), nutrition and health models, and welfare analysis. The IMPACT model system integrates information flows among the component modules in a consistent equilibrium framework that supports longer-term scenario analysis. Some of the model communication is one way, with no feedback links (for example, climate scenarios to hydrology models to crop simulation models), while other links require capturing feedback loops (for example, water demand from the core multimarket model and water supply from the water models must be reconciled to estimate water stress impacts on crop yields). Section 5 and Appendixes E, F, and H provide details about the separate models and how they are linked.

The IMPACT model is designed for scenario analysis rather than forecasting—a distinction discussed in more detail in Section 3. It is a "structural" model in the sense that it simulates the operation of commodity markets and the behavior of economic "agents" (for example, producers and consumers) that determine supply and demand for agricultural commodities in those markets. In particular, it provides a detailed specification of production technology and shocks affecting productivity (for example, water shortages and changes in temperature). It is a partial equilibrium model in that it deals only with agricultural commodities and so covers only part of overall economic activity. Computable general equilibrium (CGE) models, another class of long-run simulation models, cover the entire economy and hence are "complete" in the sense that they specify all economic flows and include all commodity markets and usually all factor markets (for example, labor and capital markets). The two types of models have different strengths and weaknesses for scenario analysis and have proven to be complementary in analysis of long-run trends under climate change (see Robinson et al. 2014, which compares the two model types, focusing on the specification of production).

Given its modular structure, the IMPACT model supports integrated analysis of the implications of physical, biophysical, and socioeconomic trends and phenomena, allowing for varied and in-depth analysis on a variety of key issues of interest to policymakers. As a flexible policy analysis tool, IMPACT has been used to research linkages between agriculture production and food security at the national and regional levels. IMPACT also has been used in commodity-level analyses and has contributed to thematic and interdisciplinary scenario-based projects. Box 1.1 lists some examples of the analysis done using IMPACT, and a more complete list of publications using IMPACT can be seen in Appendix I.

[1] Earth System Models were formerly called *General Circulation Models* (GCM), which is the term widely used in the literature. We use the new term, *Earth System Model,* in this paper.

Box 1.1 Examples of IMPACT analysis

National Analysis of Food Security

- Africa Agriculture and Climate Change Research Monographs (Waithaka et al. 2013; Hachigonta et al. 2013; Jalloh et al. 2013)
- Analysis of China (Ye et al. 2014), South Africa (Dube et al. 2013), and United States (Takle et al. 2013)

Regional Analysis of Food Security

- Food security issues in the Arab region (Sulser et al. 2011)
- "Looking Ahead: Long-term Prospects for Africa's Agricultural Development and Food Security" (Rosegrant, Cline, et al. 2005)
- Irrigation technologies in OECD countries (Ignaciuk and Mason-D'Croz 2014)

Commodity Analysis

- Alternative Futures for World Cereal and Meat Consumption (Rosegrant, Leach, and Gerpacio 1999)
- Global Projections for Root and Tuber Crops to the Year 2020 (Scott, Rosegrant, and Ringler 2000)
- Livestock to 2020: The next food revolution (Delgado et al. 1999)

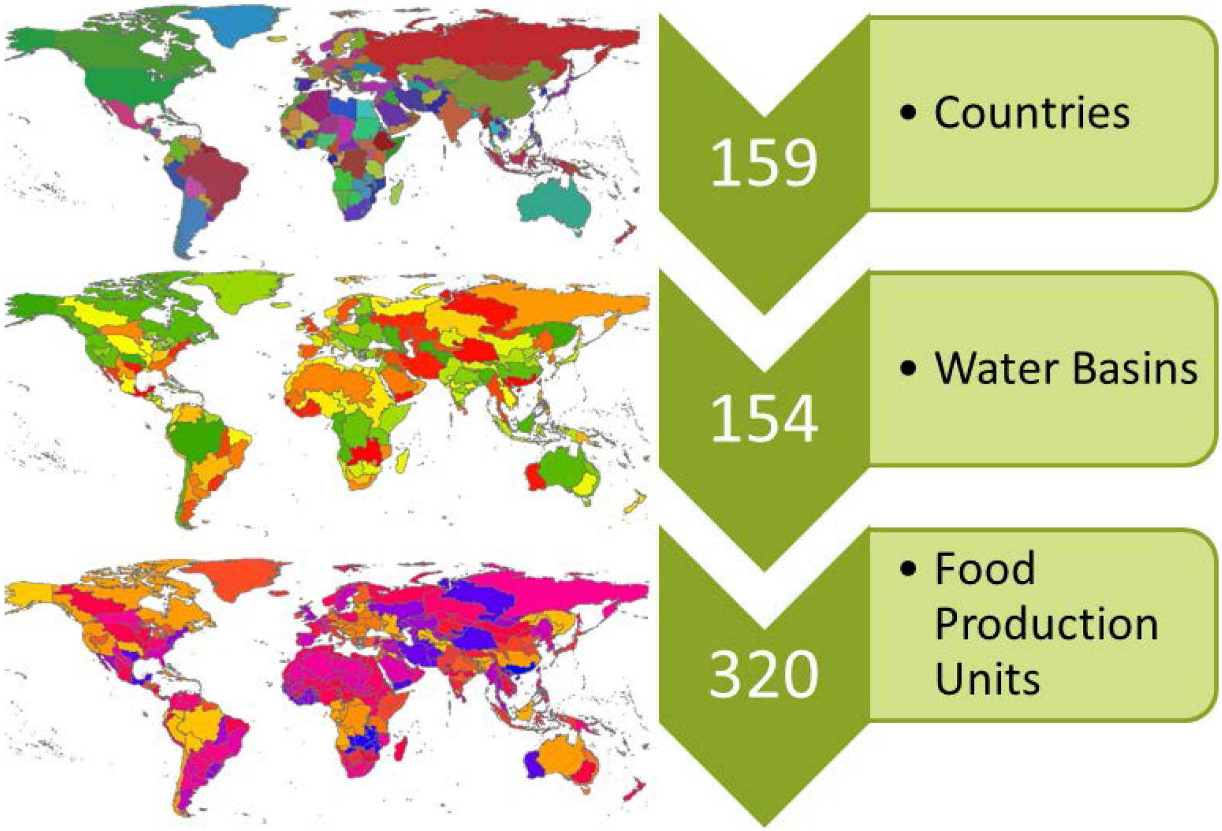
Thematic and Interdisciplinary Analysis

- IFPRI-IWMI book *World Water and Food to 2025: Dealing with Scarcity* (Rosegrant, Cai, and Cline 2002)
- Food security and climate change (Nelson et al. 2010)
- Global assessments such as the International Assessment of Agricultural Science and Technology for Development (2009), *World Development Report 2008: Agriculture for Development* (World Bank 2007), CGIAR's Strategic Results Framework (SRF 2009), and the Agriculture Model Intercomparison and Improvement Project (Nelson et al. 2014; Wiebe et al. 2015).

Source: Authors.
Note: IFPRI = International Food Policy Research Institute; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; IWMI = International Water Management Institute; OECD = Organisation for Economic Co-operation and Development.

The core multimarket model focuses on national and global markets including 159 countries. Agricultural production is specified by models of land supply, allocation of land to irrigated and rainfed crops, and determination of yields (which is described in more detail in Section 3). Production is modeled at a subnational level, including 320 regions called food production units (FPUs). FPUs are defined to link to the water models and correspond to water basins within national boundaries—154 basins (that is, Nile, Amazon, and so forth) and 159 countries (see Figure 1.1 for a geography overview and Appendix A for more detailed IMPACT geography). The multimarket model simulates 62 agricultural commodity markets, an expansion of more than 15 new commodities from the previous version of IMPACT, representing the bulk of food and cash crops (see Appendix B for a full list of commodities). New additions under consideration include expanding cash crops like coffee and cacao as well as further disaggregating dryland pulses that have important food and feed uses in the developing world.

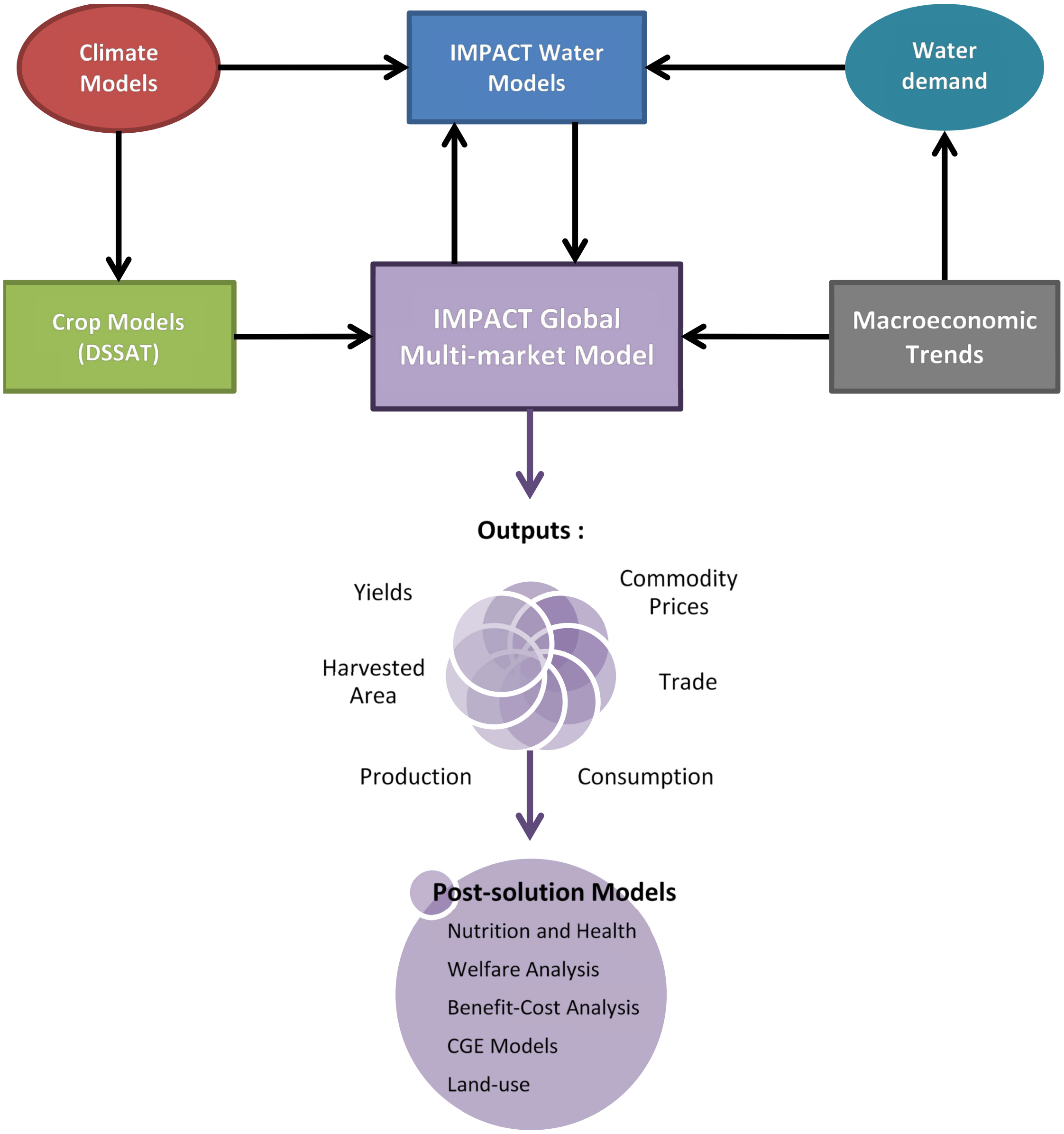
Figure 1.1 Geography of the IMPACT model



Source: Authors.
Note: IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

Figure 1.2 summarizes the links between major component modules and the core multimarket model, with arrows indicating information flows. The climate models (ESMs) provide climate data (temperature and precipitation) as inputs to the water and crop simulation models. Macroeconomic trends reflect projections from demographic and economic growth models. These links are one way, from these models to the multimarket and water models. The water models are dynamically linked to the multimarket model, with two-way flows of information over time. Other modules (for example, value chains, land allocation to crops) are integrated within periods with the core multimarket model. Finally, a set of post-solution modules calculates the results from scenario solution, with one-way communication from the multimarket model. A detailed schematic of the multimarket core model as well as a more detailed description of the integration of different modules within the IMPACT system can be seen in Section 5.

Figure 1.2 The IMPACT system of models: Climate, crops, and water



Source: Authors.
Note: CGE = computable general equilibrium.

2. IMPACT MODEL HISTORY

IMPACT was developed at IFPRI at the beginning of the 1990s to do medium- to long-term scenario analysis. In 1993, IFPRI launched the 2020 Vision for Food, Agriculture, and the Environment Initiative, and in 1995 the first results using IMPACT were published as a 2020 Vision discussion paper: *Global Food Projections to 2020: Implications for Investment* (Rosegrant, Agcaoili-Sombilla, and Perez 1995), which analyzed the effects of population, investment, and trade scenarios on food security and nutrition status, especially in developing countries.

IMPACT continues to serve as the basis for research at IFPRI, examining the links between production of key food commodities and food security at the national level in the context of scenarios of future trends, including climate change. Studies focus on regional issues, commodity-level analyses, and crosscutting thematic issues. New developments in computational and modeling capacity, as well as new thematic questions, have spurred development of the IMPACT model system to ensure that it remains a relevant policy analysis tool.

Since 1995 IMPACT has gone through a process of constant expansion and improvement. New components and modules have been added, expanding the domain of applicability of the model system (Table 2.1 summarizes the major model developments over time). First, water and aquaculture[2] were added in the first half of the 2000s. The full integration of an explicit water module in the modeling framework, in particular, was critical and was a focus of several IMPACT studies investigating the long-term dynamics of how water demand and availability would affect future food production, demand, and trade. The water model consists of three separate modules: (1) a global hydrology model, (2) water basin management models, and (3) water stress models that determine the impact of changes in water supply on crop yields. Later, links were added to food security modules to estimate changes in the number of undernourished children and crop models to allow for systematic analysis of climate change impacts on agriculture productivity and changes in food security. IMPACT 3 is now adding agricultural land markets, linking with land-use models to better handle competing demands for land and changes in greenhouse gas emissions due to land-use change in future analysis.

Improving availability of data and greater computing capacity has allowed for increasing coverage of commodity markets, expanding from the original 17 commodities and 35 countries to the current 62 commodities (and growing) and 159 countries. The model has increased not only the breadth of coverage but also the depth of the commodity markets, with each subsequent version building on previous work to better model basic value chains. For example, the first version started with two aggregate processed commodities: food oils and oil meals. IMPACT 3 now simulates six oilseed complexes (groundnut, palm, rapeseed, soybean, sunflower, and other oilseeds). The model also includes the value chain for livestock, from feed grains to dressed meat and dairy. The IMPACT 3 model includes a general treatment of value chains that provides a flexible framework that will allow for the addition of future processing sectors.

This focus on increasing the breadth and depth of IMPACT's modeling capacity has required significant data work. As part of the transition to IMPACT 3, a new data management and estimation system was developed to handle the increased volume and complexity of data needed to support the model. This system is treated as a separate module that includes diagnostic tools to analyze and clean the data and estimation procedures to generate a consistent database. Appendix C summarizes the current sources of data used in IMPACT, and a full explanation of the data management and estimation system is provided in a separate IFPRI discussion paper.[3]

The core multimarket model and many of the linked modules are written in General Algebraic Modeling System (GAMS). The multimarket model code has gone through several major revisions moving from using a Gauss-Seidel solution method in IMPACT 1 to using sophisticated nonlinear solvers called GAMS that greatly improve solution robustness and speed. In addition, software design that

[2] This was subsequently dropped but is currently under development for IMPACT 3.

[3] See Mason-D'Croz. Robinson, and Islam (2015).

incorporates best practices of modularity has become critical in the design of the latest version (IMPACT 3), laying the foundation for future model development. The user community of the IMPACT model, including model users and those interested in sharing scenario results, has grown significantly since 1995. In response to increased interest in sharing this tool with others to improve policymaking worldwide, IFPRI has held a series of IMPACT training workshops all over the world. The first publicly available version of IMPACT was released in 2005.[4] More recent versions of IMPACT have incorporated major developments in user interface to ease the use of IMPACT. IMPACT 3, for example, has an Excel interface that allows users to design and run scenarios for IMPACT without having to learn the GAMS modeling language (see Section 5 for more details about the Excel interface). Significant efforts also have been made in developing web interfaces for running IMPACT as well as sophisticated data visualization tools to facilitate and encourage the use of IMPACT in policy analysis.[5]

Table 2.1 IMPACT development over time

IMPACT version family	Solver method	Geographic scope	Commodity scope	Time scope	Linked models and modules	Model description
IMPACT 1	Gauss-Seidel	35 countries	17 total 8 crop 6 livestock 3 processed[a]	1995–2020		Rosegrant, Agcaoili-Sombilla, and Perez (1995)
		36 countries 69 FPUs	32 total 14 crop 6 livestock 2 processed 10 aquaculture	2000–2025	• Water • Value chains (processing)	Rosegrant, Sulser. et al. (2005)
		115 countries 281 FPUs	44 total 23 crop 6 livestock 15 processed	2000–2050	• Water • Crop • Food security • Value chains (processing)	Rosegrant et al. (2008)
IMPACT 2	Path[b]	115 countries 281 FPUs	45 total 24 crop 6 livestock 15 processed	2000–2050	• Water • Crop • Food security • Value chains (processing)	Rosegrant and IMPACT Development Team (2012)
IMPACT 3	Path	159 countries 320 FPUs	62 total 39 crops 6 livestock 17 processed	2005–2050	• Water • Crop • Food security • Value chains (processing) • Land use	Robinson et al. (2015)[c]

Source: Authors.

Note: FPU = food production unit; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.
[a] Processed commodities currently include food oils (that is, soybean oil), oil meals (soybean meal or cake), and sugar. The livestock value chain includes feed crops, livestock, and meat/dairy commodities. [b] The multimarket model and many modules are coded in General Algebraic Modeling System, providing the interface with the nonlinear equation solvers (the Path solver is the default solver used for the model). [c] Current paper.

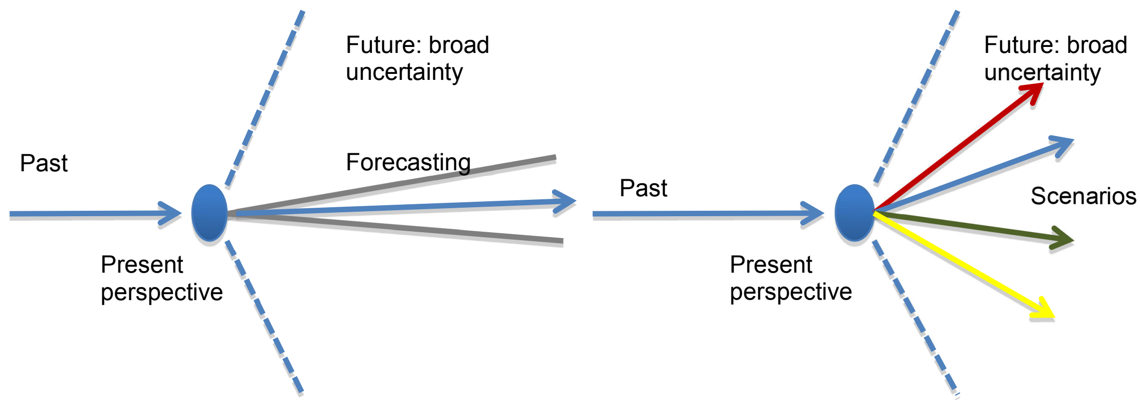
[4] This version is no longer supported due to the high cost of maintaining a user interface compatible with constantly advancing software and operating systems.

[5] Examples are (1) Agritech Toolbox (http://apps.harvestchoice.org/agritech-toolbox) and (2) IMPACT Scenario viewer (http://impactmodel.cgiar.org).

3. SCENARIO ANALYSIS

Ex ante analysis of global agricultural markets several decades into the future requires a flexible, scenario-based approach that involves specification of the impacts of long-run drivers (such as changes in population, income, consumer behavior, climate, and technology development) whose nature is highly uncertain. Scenario analysis is a powerful analytical tool that allows policymakers to explore plausible futures in a systematic manner, considering future uncertainties. Scenario analysis is distinct from forecasting analysis in that the objective is not to predict the most likely outcome (usually extrapolating from historical experience). Instead, scenario analysis focuses on system dynamics, generating logically consistent future pathways that include trends and nonlinear interactions that may deviate significantly from past experience. Figure 3.1 illustrates the difference in the range of possibilities that are considered in scenario analysis versus traditional forecasting.

Figure 3.1 Forecasting versus scenario analysis



Source: Vervoort et al. (2013).

Scenario analysis with simulation models allows policymakers to explore the robustness of different policies by testing them against alternative futures focused on key uncertainties (for example, different climates). Scenario analysis is also an appropriate approach for exploring the effects of extreme events, whose probability may be low at any particular point in time but whose effects can be catastrophic (Maack 2001).

Simulation models like IMPACT are designed explicitly for scenario analysis and provide powerful tools for developing scenarios. They include strong logical, consistent constructs around which scenario narratives can be built, providing continuous checks for internal consistency of the scenario's logic. They also allow the scenarios to be quantified and then simulated, permitting them to be tested and refined. The empirical results from simulating these scenarios then can give policymakers information not only about the direction of change but also about the magnitude of change suggested by the scenarios. These scenario results can be useful for informing policy decisions as well as providing many global and regional contexts for more detailed scenario development. The IMPACT model supports analysis of a variety of alternative scenarios within the global agricultural economy. IMPACT has been used extensively for analyzing the effects of changes in socioeconomic trends, the environment, and technology. It is also designed to consider scenarios of changes in public investment patterns and trade policy. IMPACT specifically allows for analyzing alternative scenarios about how population, income, climate, and technologies may change over time. Borrowing from the scenario analysis literature, we can group these traditional scenarios into four categories: socioeconomic, environmental, political, and technological. This framework is similar to the one for identifying environmental forces proposed by Ian Wilson (1998) and is summarized in Table 3.1 (with a few examples described in Box 3.1).

Table 3.1 The socioeconomic, environmental, political, and technological framework applied in IMPACT scenarios

Domain	Examples in IMPACT
Socioeconomic	• Population growth • Education levels • Urban-rural migrations • Gross domestic product and economic development • Income distribution across households • Consumer behavior • Price transmission and exchange rates • Input (fertilizers, pesticides, energy, and so forth) costs
Environmental	• Availability and use of key resources like water and land • Climate change
Political	• Public investment in agriculture research and development • Trade policy (taxes, tariffs, and consumer and producer support policies)
Technological	• Changes in agricultural productivity due to improved genetics, and management practices

Source: Authors, adapted from Wilson (1998).
Note: IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

Box 3.1 IMPACT scenarios in practice

Over time, IMPACT has been used for long-term scenario analysis of the implications of evolving physical, biophysical, and socioeconomic trends on agriculture. As a flexible policy analysis tool, IMPACT has been used to research linkages between agriculture production and food security at the national and regional levels (Waithaka et al. 2013; Hachigonta et al. 2013; Sulser et al. 2011).

Nelson et al. (2010) used the IMPACT model system to investigate the effects of population and gross domestic product (GDP) growth as well as climate change on future agricultural productivity, crop area expansion, trade, and human well-being. Three population and GDP growth scenarios were used in combination with three climate scenarios, at global and regional scales.

Following this work, the IMPACT was used to simulate the effects of large-scale adoption of agricultural technologies consistent with sustainable intensification. Technology scenarios were built by simulating the adoption of no-till, integrated soil fertility management; drought- and heat-tolerant crop varieties; and several improved irrigation technologies. The model then estimated global and regional effects on agricultural productivity, commodity prices, and food security indicators under climate change conditions (Rosegrant et al. 2014). Further analysis of technology adoption was done in the context of adaptation to climate change in the Organisation for Economic Co-operation and Development countries, where IMPACT was used to compare the effects on yields, prices, and food security of research and development and changes in irrigation technology as adaptation strategies (Ignaciuk and Mason-D'Croz 2014).

IMPACT has been used to assess and compare investment policies, such as in in Rosegrant et al. (2015), where cost-benefit analysis was done to compare the value of investments in decreasing postharvest loss versus the value of increased investment in agricultural research and development.

IMPACT also has been used to assess the potential effects of changes in consumer preferences and diets in a variety of studies, often in combination with changing productivity and socioeconomic factors (Rosegrant, Leach, and Gerpacio 1999; Delgado et al. 1999; Rosegrant, Tokgoz, and Bhandary 2013). IMPACT also has contributed to interdisciplinary scenario-based projects, for instance, by quantifying socioeconomic scenarios for policy development under climate change designed through stakeholder engagement in Africa, Asia, and Latin America (Palazzo et al. 2014).

Source: Authors.
Note: IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

IMPACT has been used extensively in developing and simulating regional as well as global scenarios. The core set of scenarios for which IMPACT is calibrated is global and has evolved over time as new topics of concern have arisen. For example, the potential effects of uncertain climate change have become a major issue of interest globally, and the most recent core scenarios for both IMPACT 2 and IMPACT 3 have been based on scenarios from the global community. For IMPACT 2, these were based on the *Millennium Ecosystem Assessment* (MA, 2005) and the International Panel on Climate Change's (IPCC's) fourth assessment report (Core Writing Team, Pachauri, and Reisinger 2007). For IMPACT 3, they are based on IPCC's fifth assessment report (AR5; IPCC 2013; Edenhofer et al. 2014). For more details about the current suite of core socioeconomic and climate scenarios see Appendix G, which summarizes IPCC's AR5 scenarios used in IMPACT 3.

Structural simulation models like IMPACT and global CGE models that focus on long-run scenario analysis are inherently difficult to validate. Validation for short-run forecasting models (for example, reduced-form, macroeconometric models) is easier in principle, involving simulating the model for recent years for which data are available (back-casting) and doing statistical analysis of the quality of the results. In econometric models, estimation and validation often go together—model parameters are estimated to maximize a measure of goodness of fit of the model to the data used in estimation. For long-run structural models, however, this approach is essentially infeasible. Structural simulation models involve many parameters and functional forms that are hard to estimate econometrically, and the models are designed to be used for scenario analysis that is often outside the domain of historical data. In this situation, validation necessarily involves (1) evaluating the validity of the structural design of the model, (2) assessing the quality of estimates of parameters using a variety of data sources, and (3) testing model projections with historical data when feasible. Testing with historical data is difficult since structural simulation models solve for long-run trends, while historical data often include shocks that are not part of the model design (for example, business cycle shocks that are not specified in a long-run trend model).

Validation of any model also must include a specification of the domain of applicability of the model—the universe for which the model can be applied. For an econometric model, the domain of applicability is essentially provided by the dataset used in model estimation. It is well understood that extrapolation of an econometric model outside the domain of its estimation dataset must be done with great care. For structural simulation models, specifying the domain of applicability is a major part of the model design and provides the starting point for model specification. Validation of a simulation model must reflect its intended domain of applicability.

4. IMPACT MULTIMARKET MODEL

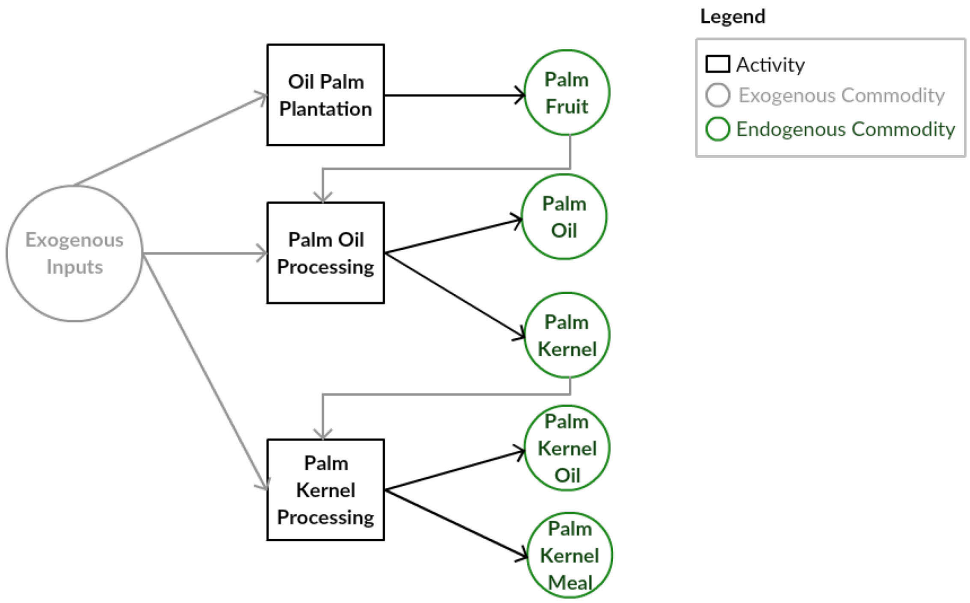
The IMPACT model system, as described in the preceding sections, is organized around a core global partial equilibrium multimarket model of agricultural production, demand, trade, and prices. The multimarket model simulates the operation of national and global markets for agricultural commodities, solving for equilibrium prices and quantities. The model specifies supply and demand behavior in all markets. This section describes the elements of that model.

Commodity Supply

One of the major changes from IMPACT 2 to IMPACT 3 is the full implementation of an activity-commodity framework, borrowed from the CGE literature (Lofgren, Harris, and Robinson 2002), to organize the supply side, incorporating value chains from crops to produced commodities. This framework allows for a general approach that can encompass a wide array of commodities and different technologies, methods, or both in producing these commodities. Currently in IMPACT, there are three main types of commodities (crops, livestock, and processed) that each has a unique method of production but that can still be summarized by the activity-commodity framework. The key to understanding this framework is to separate the process (activity) from the output of this process (commodity). For example, a soybean farm is an activity. It demands a variety of inputs such as land, fertilizer, seeds, and labor, and it produces soybeans, which are demanded and traded in commodity markets (domestic and potentially international). Individual activities can produce more than one commodity. For example, the soybean value chain processing activity uses soybeans as an input and produces both soybean oil and soybean meal. Conversely, a given commodity can be produced by more than one activity. For example, there are separate sugar beet and sugarcane value chain processing activities that produce the same commodity, processed sugar, which is consumed and traded.

This framework allows for potentially complex interlinking of activity inputs and outputs (managed through input-output matrixes), to simulate agricultural value chains. An example of this interlinking is illustrated in Figure 4.1, illustrating the oil palm sector value chain. The palm plantation activity produces palm fruit that is demanded by the palm fruit–processing sector that produces palm oil and a palm kernel by-product. Palm kernel is, in turn, an input into the palm kernel–processing sector that produces palm kernel oil and palm kernel meal. For a full list of activities and the commodities produced in IMPACT see Appendix B. This framework also allows IMPACT to consider the role of commodities outside of the agriculture sector in the production process (that is, fertilizer, labor) that can be treated as exogenous commodities with exogenous supply, prices, or both.

Figure 4.1 The palm oil value chain in the IMPACT activity-commodity framework



Source: Authors.

Crop Production

Crop production in IMPACT is simulated through area[6] and yield response functions. The choice of specifying crop production in this way has a long history in IMPACT and facilitates interaction with commodity experts and land-use specialists, who work in natural units (hectares, tons per hectare). Crop production in IMPACT is specified subnationally with the area and yield functions at the level of FPUs. This regional disaggregation permits linking with water models and provides the added benefit of smaller geographical units for aggregating climate change results, which can vary significantly from one location to another. Land used for crop production is divided into irrigated and rainfed systems, capturing the significant differences in yields observed across these cultivation systems and linking directly with the water models, which treat irrigated and rainfed water supplies separately.

A new feature of IMPACT 3 is the implementation of a land market to manage competing demands for agricultural land from different crops, as well as providing new linkage points to land-use models that work with broader land-use changes, such as conversion of forest to grasslands and agricultural land. It also allows us to separate total area supply (irrigated and rainfed) from individual crop area demands and allows equilibrium conditions to determine the best economic use of the available land. The total supply of land is assumed to be a function of the scarcity value or shadow price index of land, which can also be considered a summary of changes in crop prices. The shadow price (WF) is indexed to 1 in the first year and changes based on changing demands from all crops for land area.

[6] In IMPACT, area is treated as harvested area, which is the total area planted and harvested within a year, and may include multicropping or multiple harvests and differ from total arable land or reported physical area.

$$\begin{aligned} QFS_{\text{fpu,lnd}} &= QFSInt_{\text{fpu,lnd}} \times QFSInt2_{\text{fpu,lnd}} \\ QFS &= \text{Land supply} \\ QFSInt &= \text{Land supply intercept (base year supply)} \\ QFSInt2 &= \text{Land supply growth multiplier} \\ fpu &= \text{Food production unit} \\ lnd &= \text{Land type (i.e. irrigated, rainfed)} \end{aligned} \tag{1}$$

The supply of land is considered exogenous within each year, meaning that farmers are not allowed to adjust the total crop area in the middle of the year. The total land supply over time is driven by exogenous trends on the availability of area for agriculture as well as endogenous responses to changes in area demand, which is handled in between years. The following equation is applied at the end of each year before solving for a new year.

$$\begin{aligned} QFSInt2_{\text{fpu,lnd,t+1}} &= QFSInt2_{\text{fpu,lnd,t}} \times \left(1 + Landgr_{\text{fpu,lnd}}\right) \times \left(\frac{WF_{\text{fpu,lnd,t}}}{\left\langle WF_{\text{fpu,lnd,t}} \right\rangle_{t-3}} \right)^{L\gamma} \\ Landgr &= \text{Exogenous land supply growth rate} \\ \left\langle WF_{\text{fpu,lnd,t}} \right\rangle_{t-3} &= \text{Average shadow price of past 3 years} \\ L\gamma &= \text{Land supply elasticity} \end{aligned} \tag{2}$$

Crop area is specified as an area demand function with respect to changes in the marginal revenue product, changes in land cost, and exogenous nonprice trends in harvested area. Crop area elasticities simulate the supply response to changes in the marginal revenue of land represented by the following equation as the interaction of the net price of an activity and the productivity of the activity in using an additional hectare of land.

$$\begin{aligned} MRP_{\text{j,fpu,lnd}} &= Yld_{\text{j,fpu,lnd}} \times PNET_{\text{j,cty}} \\ MRP &= \text{Marginal revenue product of land} \\ Yld &= \text{Crop yield} \\ PNET &= \text{Net price for the activity at the country-level mapped to fpu} \\ j &= \text{Activity (crop)} \\ cty &= \text{Country} \end{aligned} \tag{3}$$

The exogenous trend in harvested area captures changes in area resulting from factors other than direct market effects, such as government programs encouraging cropping expansion, contraction due to soil degradation, or conversion of land from agriculture to nonagricultural uses. The combination of these endogenous and exogenous factors in area demand are described in the following equation.

$$\begin{aligned} Area_{\text{j,fpu,lnd}} &= AreaInt_{\text{j,fpu,lnd}} \times AreaInt2_{\text{j,fpu,lnd}} \times WF_{\text{fpu,lnd}}^{\;WF\varepsilon} \times \left(\frac{MRP_{\text{j,fpu}}}{MRP0_{\text{j,fpu}}} \right)^{A\varepsilon} \\ Area &= \text{Final crop area} \\ AreaInt &= \text{Crop area intercept (base year crop area)} \\ AreaInt2 &= \text{Exogenous crop area growth multiplier} \\ WF\varepsilon &= \text{Elasticity of demand with respect to land shadow price} \\ MRP0 &= \text{Base year marginal revenue product (used to index prices)} \\ A\varepsilon &= \text{Elasticity of area demand with respect to marginal revenue product} \end{aligned} \tag{4}$$

Assumptions for exogenous trends are determined by a combination of historical changes in land use and expert judgment on potential future regional dynamics. They are represented as compound growth from the base and are applied between years.

$$AreaInt2_{j,fpu,lnd,t+1} = AreaInt2_{j,fpu,lnd,t} \times \left(1 + Areagr_{fpu,lnd}\right) \tag{5}$$

$Areagr$ = Exogenous area demand growth rate

Competing demands from different crops are handled through an equilibrium equation that determines the land allocation and ensures that all crop area demand sums up to the total land supply for each FPU.

$$QFS_{fpu,lnd} = \sum_{j} Area_{j,fpu,lnd} \tag{6}$$

Crop yields are a function of commodity prices, prices of inputs, available water, climate, and exogenous trend factors. The IMPACT model includes five ways that changes in yields are achieved. First, the model assumes a scenario of underlying improvements in yields over time that, to varying degrees, continue trends observed during the past 50 to 60 years in an informed extrapolation following the concepts introduced in Evenson and Rosegrant (1995) and Evenson et al. (1999). These long-run trends, or intrinsic productivity growth rates, are intended to reflect the expected increases in inputs, improved seeds, and improvements in management practices. These trends differ and generally are higher for developing countries, where there is considerable scope to narrow the gap in yields compared to developed countries. These intrinsic productivity growth rates are exogenous to the model, and changes in them are specified as part of the definition of different scenarios. We assume that these underlying trends vary by crop and region and that they will decline somewhat during the next 50 years as the pace of technological improvements in developed countries slows and as developing countries catch up to yields in developed countries.

Second, the IMPACT model includes a short-run (annual), endogenous, response of yields to changes in both input and output prices. These yield response functions specify the change in yield as a constant elasticity function of the changes in output prices, with elasticity parameters that can vary by crop and region. The underlying assumption is that farmers will respond to changes in prices by varying the use of inputs, including inputs such as fertilizer, chemicals, and labor that will, in turn, change yields.

Third, climate is assumed to affect yields through two mechanisms. The first is through the effects of changes in temperature and weather due to climate change on crop yields for rainfed and irrigated crops, as calculated from the solution of a crop simulation model (DSSAT, see Hoogenboom et al. 2012; Jones et al. 2003) for different climate change scenarios. These crop simulations vary by crop type. The DSSAT model is run with detailed time, geographic, and crop disaggregation for different climate change scenarios that are downscaled to include weather variation in small geographic areas. This analysis gives changes in average yields due to climate change that are then averaged to generate yield shocks by crop and region (FPU) in the IMPACT model. These long-run climate scenarios generate yield shocks that are assumed to follow simple trends over time and do not consider extreme events such as droughts or floods (for more information on DSSAT see Section 5 and Appendix F).

The fourth mechanism by which climate change affects yields is through variation in water availability for agriculture year by year in different climate scenarios. This mechanism is modeled through the use of the IMPACT water models. These include (1) a global hydrology model that determines runoff to the river basins included in the IMPACT model; (2) water basin management models for each FPU that optimally allocate available water to competing nonagricultural and agricultural uses, including irrigation; and (3) a water allocation and stress model that allocates available irrigation water to crops and, when the water supply is less than demand by crop, computes the impact of the water shortage on crop yields, accounting for differences among crops and varieties. These yields shocks are then passed to the IMPACT model, affecting year-to-year crop yields (Appendix E).

$$Yield_{j,fpu,lnd} = YieldInt_{j,fpu,lnd} \times YieldInt2_{j,fpu,lnd} \times WatShk_{j,fpu,lnd} \times CliShk_{j,fpu,lnd} \times \left(\frac{PNET_{j,cty}}{PNET0_{j,cty}}\right)^{Y\varepsilon} \times PF^{F\varepsilon}$$

$$\begin{aligned} Yield &= \text{Final yield} \\ YieldInt &= \text{Yield intercept (base year yield)} \\ YieldInt2 &= \text{Exogenous yield growth multiplier} \\ WatShk &= \text{Water stress shock (from water models)} \\ CliShk &= \text{Climate change shock (from water and crop models)} \\ Y\varepsilon &= \text{Yield supply elasticity with respect to net price} \\ PF &= \text{Input prices} \\ F\varepsilon &= \text{Yield supply elasticity with respect to input prices} \end{aligned} \tag{7}$$

Finally, IMPACT includes the possibility of introducing new technologies such as drought- and/or heat-tolerant crop varieties (Robinson et al. 2015). These are included as new crop- and region-specific activities in the model. We assume (as part of technology adoption scenarios) that the share of production using the new activities increases over time, usually following a logistic adoption function. Given these adoption functions, the effect of the new activities on average yields is exogenous in the multimarket model, but they will be affected by climate shocks that vary over time (that is, different crop varieties will vary in their yield reaction to climate shocks). These multiple technologies are handled in IMPACT through nested equations, where each technology's yield is calculated in equation 8, and a region-weighted average yield (based on share of total area using each technology) is calculated.

$$\begin{aligned} Yield_{j,fpu,lnd} &= \sum_{tech}\left(TechShare_{j,fpu,lnd,tech} \times TechYield_{j,fpu,lnd}\right) \\ TechShare &= \text{Share of crop area adopting the technology} \\ tech &= \text{Crop production technology} \end{aligned} \tag{8}$$

Final crop production for each FPU and crop (j) is estimated as the product of the solution for its respective area and yield equations, with national production ($QS_{j,cty}$) equal to the summation of the production in all of the relevant FPUs in that country.

$$QS_{j,cty} = \sum_{fpu,lnd}\left(Area_{j,fpu,lnd} \times Yield_{j,fpu,lnd}\right) \tag{9}$$

Livestock Production

Livestock production is modeled at the FPU level and includes animal numbers, with associated feed demands, and meat/dairy production based on processing the animals. Similar to the crop sector, this specification allows for easier translation of information from livestock experts who are used to working with herd-size and feeding requirements. In the current version of the model, there is no modeling of herd dynamics—herd size over time is set exogenously.

Feed demand is a function of the livestock's own price, the prices of intermediate (feed) inputs, and a trend variable reflecting growth in livestock herds (slaughter rates are implicitly assumed to stay more or less constant over time). The price elasticities in the livestock supply function are derived in a fashion similar to how the crop area and yield elasticities are derived.

$$
\begin{aligned}
&Animals_{\text{j,fpu,livsys}} = AnimalInt_{\text{j,fpu,livsys}} \times AnimalInt2_{\text{j,fpu,livsys}} \times \left(\frac{PNET_{\text{j,cty}}}{PNET0_{\text{j,cty}}}\right)^{AN\varepsilon} \times \prod_{\text{cfeeds}} \left(\frac{PC_{\text{c,cty}}}{PC0_{\text{c,cty}}}\right)^{Feed\varepsilon} \\
&Animals = \text{Number of producing animals} \\
&AnimalInt = \text{Animal intercept (initial number of animals)} \\
&AnimalInt2 = \text{Exogenous population growth} \\
&PC = \text{Consumer prices} \\
&PC0 = \text{Intial consumer prices} \\
&Feed\varepsilon = \text{Supply elasticity with respect to changes in feed prices} \\
&livsys = \text{Livestock production systems} \\
&cfeeds = \text{Feed commodities demanded by livestock sector}
\end{aligned}
\tag{10}
$$

Livestock yields are determined through exogenous growth due to improved animals and management practices. Currently, all price responses in the livestock sector are accounted for in the animal number equations.

$$
\begin{aligned}
&AnimalYield_{\text{j,fpu,livsys}} = AnimalYieldInt_{\text{j,fpu,livsys}} \times AnimalYieldInt2_{\text{j,fpu,livsys}} \\
&AnimalYield = \text{Animal yields} \\
&AnimalYieldInt = \text{Initial animal yields} \\
&AnimalYieldInt2 = \text{Exogenous yield growth}
\end{aligned}
\tag{11}
$$

Total national production ($QS_{\text{j,cty}}$) is calculated by multiplying the number of slaughtered animals by the yield per head and summing across FPU and livestock system.

$$
QS_{\text{j,cty}} = \sum_{\text{fpu,livsys}} \left(Animals_{\text{j,fpu,livsys}} \times AnimalYield_{\text{j,fpu,livsys}}\right) \tag{12}
$$

There is work under way to improve the livestock model, incorporating more animal types; a number of feed systems that include pastures, fodders, processed feeds, and feed grains; and a more detailed representation of the value chain from feeds to herds to final demand commodities.

Production of Processed Goods

Modeling of processed goods (that is, food oils, oil meals, sugar) has been an active area of improvement for IMPACT 3, and the development of the activity-commodity framework allows for a general handling of all processed goods in IMPACT through input-output matrixes and the use of net prices. The input-output matrixes represent technical coefficients on input requirements, are specified by quantities of inputs per unit of output (that is, metric tons of soybeans per metric tons of soybean oil), and are calculated from the base data. The net price is the price the producer receives net of input costs. The net price will equal the producer price of the activity whenever there are no intermediate inputs.[7]

$$
\begin{aligned}
&PNET_{\text{j,cty}} = PP_{\text{j,cty}} - \sum_{\text{inputs}} \left(IOMAT_{\text{inputs,j,cty}} \times \left(1 - CSEI_{\text{inputs,cty}}\right) \times PC_{\text{inputs,cty}}\right) \\
&PNET = \text{Net price} \\
&PP = \text{Producer price} \\
&PC = \text{Consumer price of inputs} \\
&CSEI = \text{Consumer support estimate on intermediate inputs} \\
&IOMAT = \text{Input-output matrix} \\
&inputs = \text{Set of commodities (c) that are inputs into activity j}
\end{aligned}
\tag{13}
$$

[7] Crops and livestock currently do not include intermediate inputs in the net price equation and instead directly take input price effects through supply elasticities in the crop yield and animal number equations.

Production of processed goods is then simulated by a supply function that incorporates both endogenous price effects and exogenous technological change. As opposed to crop and livestock production, processed goods are modeled at the country level instead of at the FPU.

$$QS_{\mathrm{j,cty}} = QSInt_{\mathrm{j,cty}} \times QSINT2_{\mathrm{j,cty}} \times \left(\frac{PNET_{\mathrm{j,cty}}}{PNET0_{\mathrm{j,cty}}} \right)^{QS\varepsilon}$$

QS = Total production
$QSInt$ = Initial production (14)
$QSInt2$ = Exogenous productivity growth
$QS\varepsilon$ = Supply elasticity with respect to net price

Commodity Supply and Demand

Total supply of commodities requires mapping from output of production activities to supply of commodities. The mapping is given by the following:

$$QSUP_{\mathrm{c,cty}} = \sum_{\mathrm{j}} JCRatio_{\mathrm{j,c}} \times QS_{\mathrm{j,cty}}$$

$QSUP$ = Total commodity supply
$JCRatio$ = Activity to commodity mapping (15)
c = Commodity
cty = Country

The parameter *JCRatio* maps from the activity output to commodities. Usually, each activity produces a matched commodity (for example, wheat-growing activity produces the commodity wheat and nothing else). The specification, however, is general. There can be many activities producing the same commodity (for example, different wheat-growing activities producing the same wheat commodity) or a single activity producing more than one commodity (for example, oil seed processing yielding both oil and meal). By convention, the units of j agree with the units of the main commodity produced by the activity (for example, output of the wheat activity yields the commodity wheat, in the same units), so that the *JCRatio* for this mapped commodity always equals 1. Other outputs, if any, from an activity in *JCRatio* are measured as ratios to the output of the main activity (for example, tons of meal per ton of production of oil in an oilseed-processing activity).

Total domestic demand for a commodity is the sum of household food demand, agricultural intermediate demand (feed and processed goods), and intermediate demand from other sectors (that is, for biofuels and industrial uses).

$$QD_{\mathrm{c,cty}} = \sum_{\mathrm{h}} \left(QH_{\mathrm{c,h,cty}} \right) + QInterm_{\mathrm{c,cty}} + QL_{\mathrm{c,cty}} + QBF_{\mathrm{c,cty}} + QOTH_{\mathrm{c,cty}}$$

QD = Total commodity demand
QH = Household food demand
$QInterm$ = Intermediate demand from Ag-processing sector (16)
QL = Feed demand from livestock sector
QBF = Intermediate demand for biofuel feedstock
$QOth$ = All other demand
h = Household type

Food demand is a function of the price of the commodity and the prices of other competing commodities, per capita income, and total population. Per capita income and population increase annually according to country-specific population and income growth rates. Population and gross domestic product (GDP) trends vary by scenario and are drawn from the Shared Socioeconomic Pathway (SSP) database representing socioeconomic scenarios from IPCC's AR5 (Edenhofer et al. 2014; see Appendix G for more details). The IMPACT demand elasticities are originally based on United States Department of

Agriculture–estimated elasticities and adjusted to represent a synthesis of average, aggregate elasticities for each region, given the income level and distribution of urban and rural population (United States Department of Agriculture 1998). Over time the elasticities are adjusted to accommodate the gradual shift in demand from staples to high-value commodities like meat, especially in developing countries. This assumption is based on expected economic growth, increased urbanization, and continued commercialization of the agricultural sector. IMPACT is designed to simulate multiple types of households (that is, rural, urban, rich, poor, and so forth); however, currently, IMPACT treats household demand with one representative consumer per country.

$$QH_{c,h,cty} = QHInt_{c,h,cty} \times \left(\frac{pcGDP_{h,cty}}{pcGDP0_{h,cty}} \right)^{Inc\varepsilon} \times \left(\frac{(1-CSE_{c,cty}) \times PC_{c,cty}}{(1-CSE0_{c,cty}) \times PC0_{c,cty}} \right)^{HF\varepsilon}$$

$$\times \prod_{cc \neq c} \left(\frac{(1-CSE_{cc,cty}) \times PC_{cc,cty}}{(1-CSE0_{cc,cty}) \times PC0_{cc,cty}} \right)^{HF\varepsilon} \times \frac{PopH_{h,cty}}{PopH0_{h,cty}}$$

QH = Household food demand

$QHInt$ = Initial household food demand

$pcGDP$ = Per capita GDP

$pcGDP0$ = Initial per capita GDP

CSE = Consumer support estimate

$CSE0$ = Initial consumer support estimate

$PopH$ = Population disaggregated by household type

$PopH0$ = Initial household population

$Inc\varepsilon$ = Income demand elasticity

$HF\varepsilon$ = Price demand elasticty

$\left(\frac{(1-CSE) \times PC}{(1-CSE0) \times PC0} \right)^{HF\varepsilon}$ = Own-price response

$\prod_{cc \neq c} \left(\frac{(1-CSE) \times PC}{(1-CSE0) \times PC0} \right)^{HF\varepsilon}$ = Cross-price response (17)

Feed demand is a derived intermediate demand. It is determined by two components: (1) animal feed requirements determined by livestock production and livestock feed requirements and (2) price effects that take into account potential substitution possibilities among different feeds. The equation also incorporates a technology parameter that indicates improvements in feeding efficiencies over time.

$$QL_{c,cty} = \sum_{jlvst} \left(QS_{jlvst,cty} \times \mathrm{Re}\,q_{jlvst,c,cty} \right) \times \prod_{cfeeds} \left(\frac{PC_{c,cty}}{PC0_{c,cty}} \right)^{LFD\varepsilon}$$

QL = Total feed demand for livestock sector

QS = Total production of each livestock activity (18)

$\mathrm{Re}\,q$ = Feed requirements for each livestock activity

$LFD\varepsilon$ = Price elasticity of demand for feed

$jlvst$ = Set of livestock producing activities

Intermediate demand is a derived demand that is based on the demand for final processed goods, such as food oils and sugar. The input-output matrix determines the proportions of inputs (c) required for each producing activity (j).

$$QDInterm_{c,cty} = \sum_{j} \left(IOMat_{c,j,cty} \times QS_{j,cty} \right)$$
$$QDInterm = \text{Intermediate demand}$$
$$IOMat = \text{Input-Output matrix} \quad (19)$$

Exogenous biofuel feedstock demand is determined through exogenous growth rates, which represent government mandates to encourage the production of biofuels, though adjusted in various scenarios where the mandates are infeasible or adjusted to reflect scenarios on the role of first- or second-generation biofuels. The biofuel feedstock demand equation also allows for a price response for biofuels to allow for substitution across different potential feedstocks as well as to reflect the reality that increasing food prices would put pressure to ease biofuel mandates.

$$QBF_{c,cty} = QBFInt_{c,cty} \times QBFINT2_{c,cty} \times \prod_{c} \left(\frac{PC_{c,cty}}{PC0_{c,cty}} \right)^{BF\varepsilon}$$
$$QBF = \text{Biofuel feedstock demand}$$
$$QBFInt = \text{Initial demand from biofuel sector}$$
$$QBFInt2 = \text{Exogenous growth in demand from biofuels}$$
$$BF\varepsilon = \text{Price elasticity of demand for biofuel feedstock} \quad (20)$$

Other demand summarizes all other demands for agricultural products from sectors outside of the focus of IMPACT (for example, seeds, industrial use). It is simulated under two equations. The primary method follows the household food demand equation and is sensitive to changes in income, population, and prices.

$$QOth_{c,cty} = QOthInt_{c,cty} \times \left(\frac{pcGDP_{cty}}{pcGDP0_{cty}} \right)^{IOth\varepsilon} \times \left(\frac{POP_{cty}}{POP0_{cty}} \right) \times \prod_{cc} \left(\frac{PC_{c,cty}}{PC0_{c,cty}} \right)^{POth\varepsilon}$$
$$QOth = \text{Other Demand}$$
$$QOthInt = \text{Initial other demand}$$
$$IOth\varepsilon = \text{Income demand elasticity for other demand}$$
$$POth\varepsilon = \text{Price demand elasticity for other demand} \quad (21)$$

The second method is used in a few cases where other demand historically has not shown much of a response to prices and is instead a function of changes in per capita GDP from the previous year (*pcGDP*1).

$$QOth_{c,cty} = QOth1_{c,cty} \times \frac{pcGDP_{cty}}{pcGDP1_{cty}}$$
$$QOth = \text{Other demand}$$
$$QOth1 = \text{Lagged other demand}$$
$$pcGDP1 = \text{Lagged per capita GDP} \quad (22)$$

Markets, Trade, and Equilibrium Prices

The system of equations is written in the GAMS programming language (GAMS 2012). The solution of these equations is achieved by the Path solver, which is included in the GAMS system. This procedure finds a set of domestic and world prices for all crops that clear domestic and international commodity markets. The world price of a commodity is the equilibrating mechanism for traded commodities—when an exogenous shock is introduced in the model, world price will adjust to clear world markets, and each adjustment is passed back to the effective producer and consumer prices via the price transmission equations. Changes in domestic prices subsequently affect commodity supply and demand, necessitating their iterative readjustments until world supply and demand balance and world net trade again equals 0. For nontraded commodities, domestic prices in each country adjust to equate supply and demand within the country.

IMPACT assumes a closed world economy—at the end of every year the world's production must equal the world's demand. This constraint is ensured by the following equation, where the sum of net trade over the globe must equal 0.

$$\sum_{cty} NT_{c,cty} = 0 \qquad (23)$$

$$NT = \text{Net Trade}$$

National production and demand for tradable commodities are linked to world markets through trade. Commodity trade by country (cty) is a function of domestic production, domestic demand, and stock change.[8] Regions with positive net trade are net exporters, while those with negative values are net importers. This specification does not permit a separate identification of international trade by country of origin and destination—all countries export to and import from a single global market.

$$NT_{c,cty} = QSUP_{c,cty} - QD_{c,cty} - QSt_{c,cty}$$

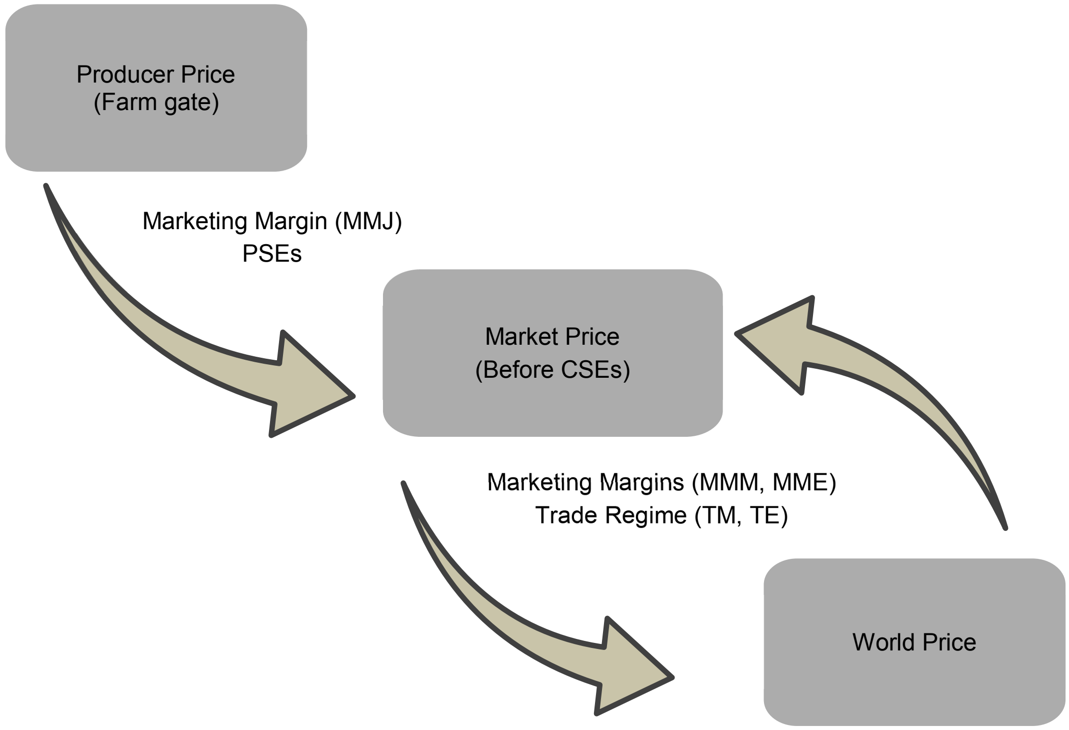
$$NT = \text{Net trade} \qquad (24)$$

$$QSt = \text{Change in stocks}$$

Prices are endogenous in the system of equations for food and are calibrated to 2005 commodity prices (OECD Agricultural Market Access Database 2010). Prices are in constant 2005 US dollars. Domestic prices of tradable commodities are a function of world prices, adjusted by the effect of trade policy represented by taxes and tariffs, and price policies are expressed in terms of producer support estimates (PSEs), consumer support estimates (CSEs), and the cost of moving products from one market to another represented by marketing margins (MMs). Export taxes and import tariffs are drawn from data from the Global Trade Analysis Project at Purdue University and reflect trade policies at the national level (Narayanan and Walmsley 2008; International Trade Center 2006; Boumellassa, Laborde, and Mitaritonna 2009). PSEs and CSEs represent public policies to support production and consumption by creating wedges between world and domestic prices. PSEs and CSEs are based on Organisation for Economic Co-operation and Development (OECD) estimates and are adjusted by expert judgment to reflect regional trade dynamics (OECD 2014). MMs reflect other factors such as transport and marketing costs of getting goods to various markets and are based on expert opinion on the quality and availability of transportation, communication, and market infrastructure. Figure 4.2 illustrates the pricing system in IMPACT and where the appropriate price wedges are applied.

[8] Note stocks are constant and exogenous.

Figure 4.2 IMPACT price structure



Source: Authors.
Note: CSEs = consumer support estimates; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; MME = Export marketing margin; MMJ = Farm-gate to market marketing margin; MMM = Import marketing margin; PSEs = producer support estimates; TE = Export taxes; TM = Import Tarrifs.

The model includes three markets: (1) the farm gate, where producers sell their output to purchasers in producer prices; (2) a national market, where the purchasers then take the commodity, incurring any taxes/subsidies and trade/transportation costs; and (3) the port where exports are sold to foreigners and imports are bought from them at world market prices. Moving commodities to and from the port incurs MMs and any taxes/subsidies/tariffs. In the model, PSEs, CSEs, and MMs are expressed as percentages (ad valorem) of the world price. To calculate producer prices the appropriate wedges are applied to the domestic consumer prices (*PC*) and represent the markup observed in domestic markets from the farm-gate or factory-gate prices producers receive. The producer price of an activity is the weighted sum of the prices of the commodities associated with that activity.

$$PP_{\text{j,cty}} \times \left(1 + MMJ_{\text{j,cty}}\right) = \left(1 + PSE_{\text{j,cty}}\right) \times \sum_{\text{c}} JCRatio_{\text{j,c,cty}} \times PC_{\text{c,cty}} \tag{25}$$

PP = Producer price

MMJ = Farm(factory)-gate to domestic market Marketing Margin (MM)

PSE = Producer support estimate, ad valorem component

$JCRatio$ = mapping from activities (j) to commodities (c)

How consumer prices are determined in IMPACT depends on the state of tradability of the commodity. Commodities can be specified as either tradable or nontradable. Traded commodity prices are determined in international markets. Nontraded commodities are those commodities whose prices are determined in national markets, without direct links to international markets. Examples include sugarcane, sugar beets, and grass, where all demand is intermediate demand from domestic sectors (sugar processing and livestock). These commodity prices are determined endogenously by country and ensure that domestic supply equals domestic demand.

$$QSUP_{c,cty} = QD_{c,cty} \tag{26}$$

Nontraded commodities are indirectly linked to world markets through the demand for final products (that is, sugar), and potential substitution from tradable commodities (that is, grass and other feeds). IMPACT 3 also has been designed to allow the tradability of a commodity to be determined endogenously. As the IMPACT model includes price wedges between domestic and international markets, the prices of exports received by producers and of imports paid by consumers can be modeled in separate equations.

$$\begin{aligned}
PM_{c,cty} &= PW_c \times EXR_{cty} \times \left(1+TM_{c,cty}\right) \times \left(1+MMM_{c,cty}\right) \\
PE_{c,cty} &= PW_c \times EXR_{cty} \times \left(1-TE_{c,cty}\right) \times \left(1-MME_{c,cty}\right) \\
PM &= \text{Import Price} \\
PE &= \text{Export Price} \\
PW &= \text{World Price} \\
EXR &= \text{Exchange Rate (currently =1)} \\
TM &= \text{Import tariff (ad valorem)} \\
TE &= \text{Export tax (ad valorem)} \\
MMM &= \text{Marketing margin for importing to domestic market} \\
MME &= \text{Marketing margin for exporting to international market}
\end{aligned} \tag{27}$$

If the equilibrium domestic price falls between the floor price of exports and the ceiling price of imports, then there will be no international trade. If conditions change (over time or for different scenarios) such that the equilibrium domestic price either falls to the export price or rises to the import price, the model will endogenously change the regime and clear the market through international trade. To start importing the domestic import price must equal the consumer price (global prices are lower than domestic prices), and to start exporting domestic prices must be equal to export prices (domestic prices are greater than global prices).

$$\begin{aligned}
\text{Imports if } & PC_{c,cty} \le PM_{c,cty} \\
\text{Exports if } & PC_{c,cty} \ge PE_{c,cty} \\
\text{Domestically traded if } & PE_{c,cty} \le PC_{c,cty} \le PM_{c,cty}
\end{aligned} \tag{28}$$

For purely tradable goods, where we want the commodities to always be linked to world markets,[9] this inequality is not used, the domestic consumer price is set to the import price, and the export price equation is never used.

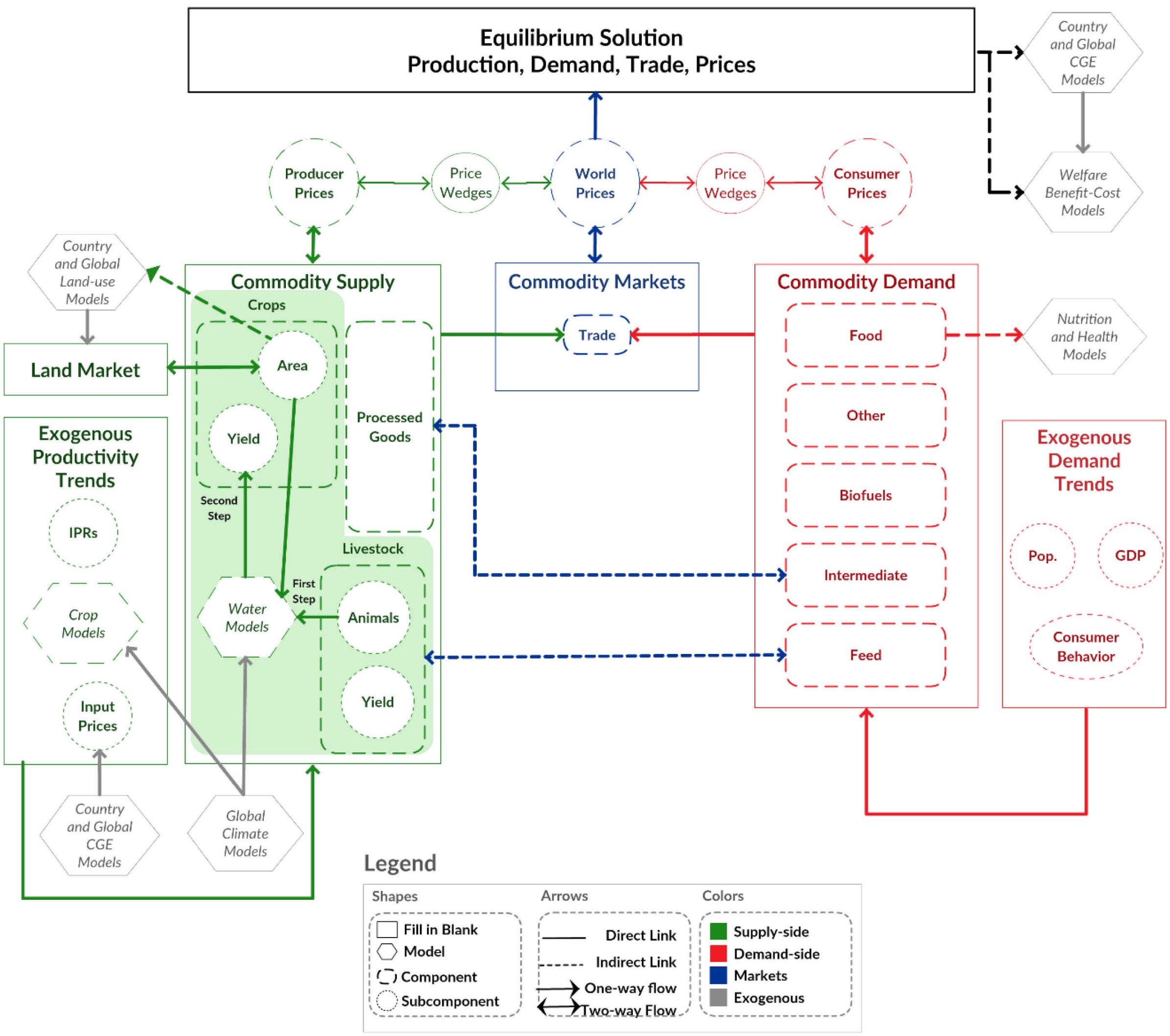
$$PC_{c,cty} = PM_{c,cty} \tag{29}$$

[9] This is the current treatment of all tradable commodities.

5. IMPACT MODEL SYSTEM

The IMPACT model system is a network of linked models. Major components include climate models, crop models, and water models, and the links between these were shown in Figure 1.1. The model system now includes a number of additional modules, and more are in development. Some of these modules are integrated into the multimarket model, and others are coded as separate modules that are linked through information flows to others. Figure 5.1, a detailed schematic of the IMPACT multimarket model, illustrates how many of these modules are interconnected. In this section, we will discuss these new modules and provide further description of the major components of the IMPACT model system such as data management and estimation, scenario specification and implementation, food security indicators, welfare analysis, crop models, and water models.[10] More detail about some of the modules, including equations, is provided in the appendixes.

Figure 5.1 Detailed IMPACT multimarket model schematic



Source: Authors.
Note: CGE = computable general equilibrium; GDP = gross domestic product; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; IPRs = intrinsic productivity growth rates.

[10] There is also work under way on new modules, including expanded livestock, land use, and fishery modules.

Specifying IMPACT as a set of linked models has required major changes in the computer code, which was completely rewritten in moving from version 2 to 3. In the next section, we discuss the design of the new model code, particularly how to implement a flexible modular system.

Modularity

In the redesign of IMPACT from version 2 to 3, great effort was made toward the implementation of best practices in software design not only to widen the domain of applicability of the model (that is, more commodities, countries, and features) but also to improve the quality of the model code and design. The object was to create a model design that was transparent and flexible, allowing for easier future model updates and improvements. Some elements of a modular approach had been used in IMPACT 2; however, in IMPACT 3 modularity has become a key design feature. Modularity is defined as the breaking up of software into separate and addressable components that are integrated to address specific problems (Pressman 2010). In an increasingly complex model such as IMPACT, not pursuing a modular approach risks creating monolithic software, which is difficult to understand, edit, debug, and maintain. Modular design has many benefits (Box 5.1) but requires careful design and discipline to implement.

Box 5.1 Benefits of modular design

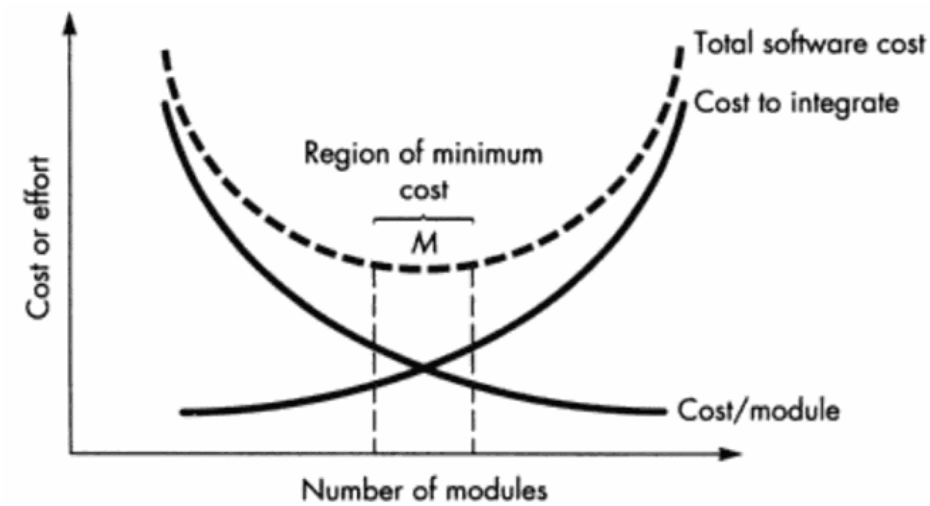
Modular software design has many benefits that not only improve the quality of the software code but also facilitate future software development. Some of the key benefits of modular design are the following:

- It facilitates breaking down complex problems into smaller and easier-to-solve subproblems.
- It allows for parallel and distributed model development, with many modelers working on different subproblems simultaneously.
- It allows for different modules, in various combinations, to be used to solve different problems.
- Modularity increases the readability of the model code, making it easier to understand, edit, debug, and maintain.
- It facilitates model updating. If integration is properly designed, one module can easily be replaced with an improved module without having to update any other part of the linked model system.
- It provides the ability to turn on and off modules that may not be needed for certain tasks, simplifying the model and improving solution time.
- The modules can be run in stand-alone mode, independently of the other linked modules, which greatly facilitates development and testing of modules.
- It facilitates multidisciplinary collaboration and utilization of wide-ranging expertise (for example, collaboration across different CGIAR centers to improve modeling of water, livestock, fish, and nutrition, among others).

Source: Authors.

Modularity comes with some cost. It is necessary to develop standards of intermodule communication to integrate the different modules. The greater the number of modules, the easier each module is to create, but the more complicated it is to link them all. Developing and implementing linkage standards can be challenging and time consuming, so a balance must be achieved between developing more and simpler modules versus the time required to integrate them, a challenge illustrated well by Roger Pressman (2010) in Figure 5.2.

Figure 5.2 Modularity and software cost



Source: Pressman (2010, 226).

In IMPACT, we have classified modules based on the depth of their linkages. We handle module integration in three main ways, distinguished by how deeply they are integrated and the flow of information between the modules.

1. One-way information flow: This type of module integration occurs when the results of one module are inputs into another module and there are no feedback loops. We can think of these interactions as exogenous or external exchanges of information from one module to another. Data transfers between modules occur through data files, and neither module directly changes other module values. Examples of one-way information flow are crop-modeled climate shocks into the multimarket model, water flows in river basins from the global hydrology model, and postprocessing food security modules that take results of the multimarket model as inputs to estimate changes in undernourished children and risk of hunger.
2. Iterative two-way information flow: This type of coupling is needed when there needs to be some type of feedback loop. This type of integration illustrates sequential cohesion between modules, where the outputs of one module serve as inputs into the next module (van Vliet 2007) and the outputs of this second module need to be fed back as inputs into the original module. Examples of this type of integration can be seen with how the multimarket model is connected with the IMPACT water basin management and water stress models, where economic results each year serve as inputs to the water models and then the results of the water models are fed back to the multimarket model to simulate the effects of changes in irrigated water supply.
3. Dynamic and endogenous information flow: This type of integration is required when complete integration of modules is required. This reflects "content coupling, where each module directly affects the working of another module" (van Vliet 2007). This integration is needed when modules must be solved simultaneously and all information between modules must be freely shared. Examples of this type of integration are the integration of commodity demand, trade, and production, which are solved simultaneously within the multimarket model.

We have already covered in detail the dynamic and endogenous modules in IMPACT in Section 4. The rest of this section will present how other critical modules function within the IMPACT model system. The design of these modules has followed several key standards, which are outlined in Box 5.2. New modules should be developed following these design standards and should aim to have a distinct research publication describing the module, its uses, and how it fits into the IMPACT model system. Modules used in stand-alone mode, treating inputs from other modules and the IMPACT multimarket model as exogenous, can be useful research tools within their own disciplines (for example, water models, detailed livestock models, land-use models).

Box 5.2 IMPACT module design requirements

A module in the IMPACT model system should be designed to

- read its own parameters,
- initialize its own variables,
- accept variables passed to it from other modules,
- pass variables computed within the module to other modules,
- own its set of state variables (information hiding in software design parlance), and
- be able to operate in stand-alone mode without being dynamically coupled to other modules.

Source: Authors.
Note: IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

IMPACT Data Management and Estimation System

While pursuing a modular design in IMPACT, there has been a focus on making data processing independent from the behavioral model system. The goal is that any module should have standard data requirements and that the data sources could be changed as long as they conform to deliver standard data inputs of the modules. This standardization of data inputs has allowed the breaking up of processing the IMPACT database into a series of specific data-processing modules, each focused on preparing one part of the IMPACT database. These data modules are linked into a separate IMPACT Data Management and Estimation System that provides all the data needed to implement the IMPACT model system. For more details on the data sources used in IMPACT see Appendix C. These data processing modules include the following:

- Food and Agriculture Organization of the United Nations (FAO) production, trade, and demand estimation program: An estimation module that uses cross-entropy estimation techniques to estimate a consistent and balanced base year database for IMPACT from FAOSTAT, AquaStat, IFPRI-SPAM, and other data sources. For more information about this module see Mason-D'Croz, Robinson, and Islam (2015)
- Population and GDP processing module: An aggregation module that takes data for population, GDP, and growth rates from a variety of sources, including the World Bank's World Development Indicators (WDIs), UN population statistics, Central Intelligence Agency World Factbook, and the SSP database, and puts them into an IMPACT-ready format
- Price-processing module that reads in data from OECD Agricultural Market Access Database and maps them to IMPACT commodities
- Trade parameter–processing module that reads in data from OECD and Global Trade Analysis Project at Purdue University to IMPACT commodities and countries

- Model calibration modules that join GAMS, Excel, and Tableau[11] to generate complex data visualizations, which are used to compare IMPACT results to historical trends and to inform model calibration to adjust IMPACT parameters in response to these trends and new expert judgment
- Climate data processing module, which reads in results from crop models aggregated to the FPU level and then processes them into average annual climate shocks for all IMPACT commodities (for more information about crop models see Appendix F)

IMPACT Scenario Environment

By designing standards for coupling of data in IMPACT, it has been possible to develop a more user-friendly interface for handling common and repetitive tasks, such as scenario design and specification and compiling and generating result files and data visualizations. For IMPACT 3, elaborate graphical user interfaces were developed in Excel and use a visual basic actionscript backend to read in data and output GAMS files that can be executed directly from Excel. This feature now allows IMPACT to be used by a wider set of users, as it no longer requires knowledge of GAMS to run IMPACT. This work builds on efforts done in IMPACT 2 to develop an Excel interface to run the model. The IMPACT Scenario Environment has two primary components: (1) the scenario development and specification tool and (2) the report and outputting tool.

The scenario development and specification tool allows users to easily specify scenario drivers to define a wide array of scenarios. This tool allows users to easily adjust assumptions on growth rates on agricultural productivity, agricultural land, population, and economic development. Users also can change assumptions in the IMPACT water models to simulate changes in irrigation infrastructure and technology. In addition, users can include various climate assumptions from processed crop model results.

The report and outputting tool allows users to easily read in IMPACT result files (in GAMS data exchange files or GDXs) and execute a variety of standard postprocessing and outputting programs. This facilitates the process of merging, aggregating, and presenting results from one or more IMPACT scenario result files. Currently, the report and outputting tool provides the following functionality:

- Executing the welfare-benefit-cost module (see below for more details) and outputting its results in Excel
- Generating StatPlanet[12] interactive web data visualizations
- Generating static and publication-ready maps, line graphs, and box-whisker graphs using R statistical package
- Generating Excel pivot tables of results aggregated to user-defined aggregations of regions and commodities

Food Security Modules

Food security is an important aspect analyzed with IMPACT. Understanding the interplay of commodity production, trade, and demand is valuable, but understanding some of the potential human welfare implications of these changes is also important to better understand consequences of difference scenarios. In IMPACT, there are two food security modules that were designed to give policymakers a sense of how countries were progressing toward the Millennium Development Goals (goal 1, target 2). The first module, based on work by Smith and Haddad (2000), estimates changes in child wasting (underweight) based on changes in food availability at the country level. The second module, based on work by Fischer et al. (2005), estimates changes in the share of population at risk of hunger based on changes in food availability. Both modules are examples of one-way postprocessing modules, where information from the

[11] See www.tableau.com for more information about this data visualization software package.
[12] See www.statsilk.com for more details.

multimarket model (food availability, population, GDP, and so forth) serves as an input to the module and the results are not feedback into the economic module.

Undernourished Children[13]

The percentage of undernourished children younger than five is estimated from the average per capita calorie consumption, female access to secondary education, the quality of maternal and child care, and health and sanitation (Rosegrant et al. 2001). Observed relationships between all of these factors were used to create the semi-log functional mathematical model, allowing an accurate estimate of the number of undernourished children to be derived from data describing the average per capita calorie consumption, female access to secondary education,[14] quality of maternal and child care, and health and sanitation. The precise relationship used to project the percentage of undernourished children is based on a cross-country regression relationship of Smith and Haddad (2000).

$$\begin{aligned}\Delta UndNrsh_{\mathrm{t,t0}} &= -25.24 \times \ln\frac{KCAL_{\mathrm{t}}}{KCAL_{\mathrm{t0}}} - \left(71.76 \times \Delta LFER_{\mathrm{t,t0}}\right) - \left(0.22 \times \Delta SCH_{\mathrm{t,t0}}\right) \\ &\quad - \left(0.08 \times \Delta \mathrm{WAT}_{\mathrm{t,t0}}\right) \\ UndNrsh &= \text{Percent change in undernourished children} \\ KCAL &= \text{per capita kilocalorie availability} \\ LFER &= \text{Ratio of female-male life expectancy at birth} \\ SCH &= \text{Gross female secondary school enrollment rate} \\ WAT &= \text{\% of population with access to safe water} \\ \Delta_{\mathrm{t,t0}} &= \text{Difference between time t and 2005}\end{aligned} \tag{30}$$

The data used in this calculation come from a variety of sources. The base values for undernourished children originally come from the World Bank's WDIs (World Bank 2014). The base values for female-male life expectancy ratio, female secondary school enrollment, and access to safe water come from the WDIs (World Bank 2014). The projections of changes in female-male life expectancy come from the United Nations Populations Prospects medium variant (United Nations 2011). The projections of changes in female secondary school enrollment and access to clean water come from the Technogarden Baseline Scenario (MA 2005).

The per capita kilocalorie availability is derived from two sources: (1) the amount of calories obtained from commodities included in the IMPACT-Food model and (2) the calories from commodities outside the model (FAO 2015).

After the percentage of undernourished children has been calculated, the total number of undernourished children is calculated as the product of equation 29, with the population of children (0–5 years old) coming from the appropriate SSP scenario (International Institute for Applied Systems Analysis [IIASA] 2013).

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[13] In previous versions of IMPACT this was synonymous with *malnourished children,* but we have changed this to the more precise term *undernourished.*

[14] This is total female enrollment in secondary education (any age group) as a percentage of the female age group corresponding to national regulations for secondary education.

Share at Risk of Hunger

The share at risk is the percentage of the total population that is at risk of suffering from undernourishment. This calculation is based on a strong empirical correlation between the share of undernourished within the total population and the relative availability of food and is adapted from the work done by Fischer et al. in the IIASA World Food System used by IIASA and FAO (Fischer et al. 2005).[15]

$$
\begin{aligned}
ShareAtRisk &= \alpha RelativeKCal^2 + \beta RelativeKCal + int + \varepsilon \\
\alpha &= 89.63 \\
\beta &= -319.69 \\
\text{int} &= 288.16 \\
\varepsilon &= \text{Estimation error} \\
RelativeKCal &= \frac{KCal}{MinKCal} \\
Kcal &= \text{Food supply} \\
MinKcal &= \text{Minimum food requirement}
\end{aligned} \tag{31}
$$

It should be noted that due to the quadratic nature of this equation it is necessary to apply an upper and lower bound to the share at risk. The lower bound is defined as 0, and the upper bound is 100. Developed countries unsurprisingly have low share at risk, so for simplicity we treat all countries with less than 4 percent share at risk of hunger as if they had 0 percent share of hunger. The relative availability of food has been bounded to ensure realistic results on the quadratic curve: when the ratio of calories available to calories required, RelativeKCal, is greater than 1.7, we assume that the share at risk of hunger is effectively 0.

Welfare Analysis Module

The welfare module in IMPACT follows a traditional economic welfare analysis approach to estimate the benefits to society on the consumer and producer side. It allows policymakers to disentangle some of the effects of alternative plausible futures in changes to agricultural commodity prices as well as quantities produced and consumed. Similar to the food security modules, the welfare analysis module is a one-way postprocessing module, taking in the results from the multimarket model as inputs for welfare calculations.

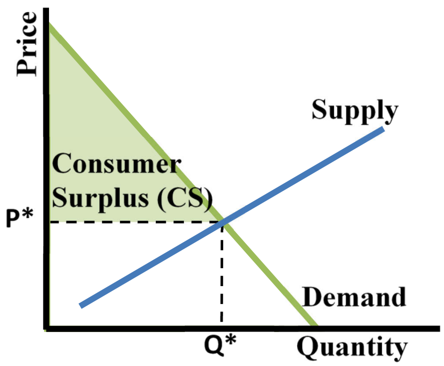
On the demand side a consumer surplus is calculated to estimate changes faced by consumers from changes in agricultural markets. Calculating the consumer surplus in IMPACT is straightforward, as we measure the area below the demand curve (see Appendix H for full details on welfare calculations) and above the market price for each agricultural commodity and region (Figure 5.3). These consumer surpluses can be aggregated to give a measure of national and global consumer surplus.

The producer surplus is the area above the supply curve and under the equilibrium price. In IMPACT, calculating this area directly is relatively complicated; thus, the producer surplus is calculated using agricultural revenue (market price multiplied by quantity) minus total cost of production, which is the area under the supply curve (Figure 5.4). Similar to the consumer surplus, the producer surplus is aggregated to national and global levels. Total welfare is the combination of the supply- and demand-side effects, which is calculated by summing the consumer and the producer surplus.

The welfare metrics were designed to be used in a comparative context to give policymakers insight into different welfare effects of alternative futures. Thus, total welfare and consumer and producer surplus are expressed as changes from one scenario to another.

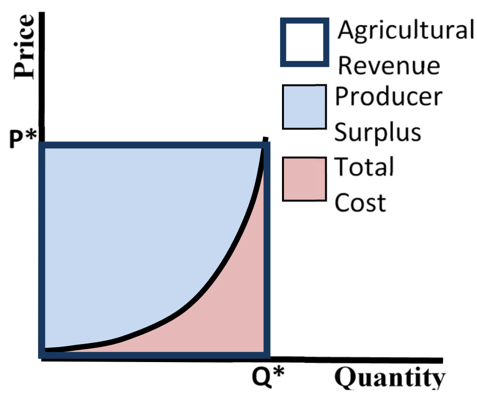
[15] The estimated values of the parameter and intercept values are not the same as the ones used by Fischer et al. (2005). These parameters have been adjusted to better fit data from IMPACT. Nevertheless, the parameters are similar.

Figure 5.3 Visual representation of consumer surplus



Source: Authors.
Note: P* = market price; Q* = quantity.

Figure 5.4 Visual representation of producer surplus



Source: Authors.
Note: P* = market price; Q* = quantity.

Crop Models

The effect of climate change on crop yields starts by running the DSSAT family of crop models across a gridded representation of the world. Yield maps for groundnuts, maize, potatoes, rice, sorghum, soybeans, and wheat are compiled under both rainfed and irrigated conditions. Driving the model is a large collection of data. Some of the data represent soil characteristics and conditions as well as basic management decisions while others characterize the climatic conditions under which the crops were grown.

The climate data are maps of monthly climate data that allow the random generation of daily weather data for each location typical of what might be expected for conditions of the near recent past (2005) as well as those of the future (2050). The baseline climate information comes from Jones, Thornton, and Heinke (2009). The future climate information is derived from data processed by the Inter-sectoral Impact Model Intercomparison Project (Hempel et al. 2013; Piani, Haerter, and Coppola 2010; Weedon et al. 2011). The two datasets were combined by extracting the appropriate changes from the climate model data and imposing them on the common baseline climate. The crop models can then make projections about possible yields under the different climate circumstances.

The grid-based yields for each climate and crop combination are then aggregated within regions appropriate for the economic portions of the model. Specifically, they are computed as production-area-weighted averages using maps of production areas from the Spatial Production Allocation Model as weights (You et al. 2014). These are then used as weights in the multimarket model to estimate final yield impacts. This follows the general approach for incorporating projected yield changes from biophysical models into economics models as outlined in Müller and Robertson (2014). For more information about crop models and IMPACT see Appendix F.

Water Models

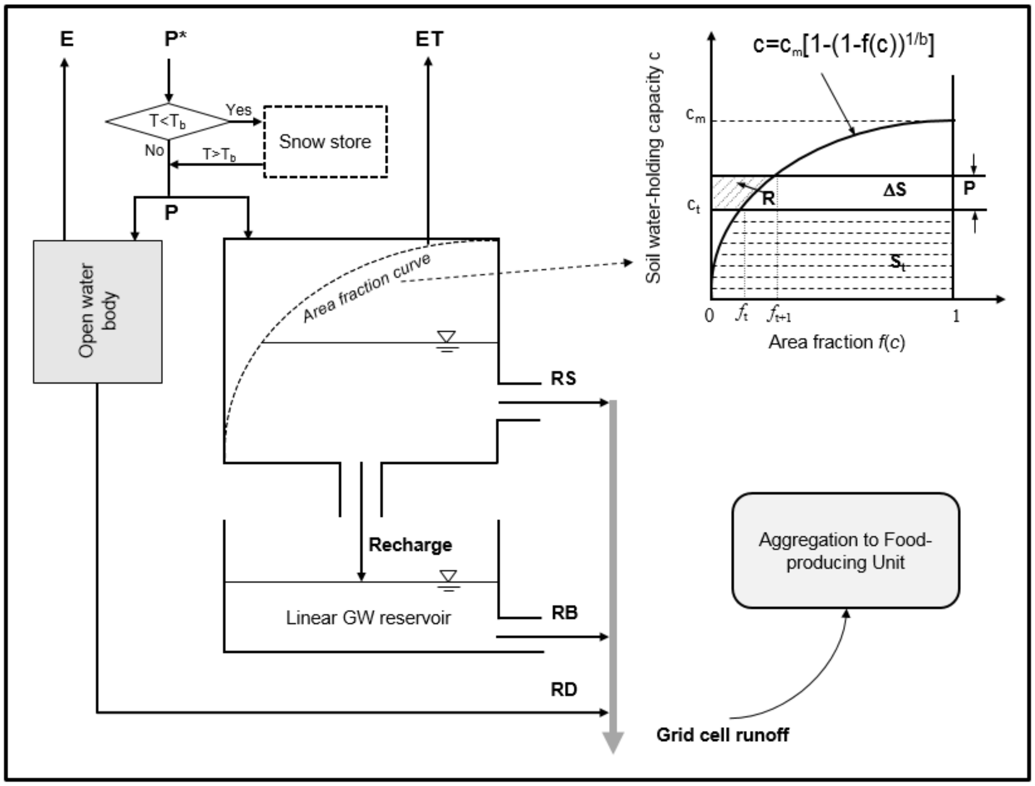
The water models in the IMPACT Modeling System include (1) the IMPACT global hydrology model (IGHM) that simulates snow accumulation and melt and rainfall-runoff processes, (2) the IMPACT water basin simulation model (IWSM) that simulates operation of aggregate surface water reservoir and water supplies to economic sectors including irrigation, and (3) the IMPACT crop water allocation and stress model (ICWASM) that allocates available net irrigated water to crops and estimates the impact of water shortages on yields. These three models enable the IMPACT multimarket model to assess the effects on global food and water systems of hydroclimatic variability and change, socioeconomic change–driven water demand growth, investment in water storage and irrigation infrastructure, and technological improvements.

IGHM is driven by climate-forcing data and computes effective rainfall, potential and actual evapotranspiration, and runoff to river basins. The IGHM-simulated hydrologic outputs are then provided in a one-way link to IWSM, which optimally manages water basin storage and provides irrigated water supply in a one-way link to ICWASM, which then provides the IMPACT multimarket model with water stress-induced crop yield reductions for both irrigated and rainfed crops. The solution of IGHM depends only on climate inputs and is completely independent of the other water models and the IMPACT multimarket model. However, there is two-way communication between IWSM and the IMPACT multimarket model—the demand for water in IWSM depends on the allocation of land to crops, which is part of the solution of the IMPACT multimarket model. In turn, changes in water availability from IWSM affect water allocation and stress in ICWASM. The communication between these models to capture this endogeneity is discussed below.

IGHM

As described in the following schematic (Figure 5.5), IGHM is a semidistributed parsimonious model. It simulates monthly soil moisture balance, evapotranspiration, and runoff generation on each 0.5˚ latitude by 0.5˚ longitude grid cell spanning the global land surface except the Antarctic. Gridded output of hydrological fluxes—namely, effective rainfall, evapotranspiration, and runoff—are spatially aggregated to FPUs within the river basin and weighted by grid cell areas.

Figure 5.5 IMPACT global hydrology model schematic illustrating vertical water balance of the land and open water fraction of a grid cell



Source: Authors.

Note: E = evaporation (millimeters per month [mm/m]); ET = evapotranspiration (mm/m); GW = groundwater; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; P = effective precipitation (mm/m); P^* = precipitation (mm/m); R = total runoff (mm/m); RB = base flow (mm/m); RD = direct runoff from open water body (mm/m); RS = surface runoff (mm/m); S = soil moisture content (millimeters); T = temperature (°C); T_b = base temperature (°C), used as threshold to determine incoming precipitation as rain or snow.

The most important climatic drivers for water availability are precipitation and evaporative demand determined by net radiation at ground level, atmospheric humidity, wind speed, and temperature. In IGHM, the Priestley-Taylor equation (Priestley and Taylor 1972) is used to calculate potential evapotranspiration. Soil moisture balance is simulated for each grid cell using a single layer water bucket. To represent subgrid variability of soil water-holding capacity, we assume it spatially varies within each grid cell, following a parabolic distribution function.

Actual evapotranspiration is determined jointly by the potential evapotranspiration and the relative soil moisture state in a grid cell. The generated runoff is divided into a surface runoff component and a deep percolation component using a partitioning factor. The base flow is linearly related to storage of the groundwater reservoir. The total runoff to the streams in a month is the sum of surface runoff and base flow.

IWSM

Water Demand

The water demand module calculates water demand for crops, industry, households, and livestock at the FPU level. Irrigation water demand is assessed as the portion of crop water requirement not satisfied by precipitation or soil moisture based on hydrologic and agronomic characteristics. Crop water requirement is calculated for each crop using evapotranspiration and effective rainfall from IGHM. It relies on the FAO crop coefficient approach (Allen et al. 1998) to calculate water requirement for each crop every month. Irrigation demand in the FPU is calculated for a given cropping pattern after taking into account the basin efficiency of the irrigation system. The IMPACT multimarket model solves endogenously for the allocation of land to different crops while IWSM requires information about the cropping pattern to calculate irrigation water demand and hence water stress that is then an input into the multimarket model, which requires two-way communication between the models (as mentioned earlier).

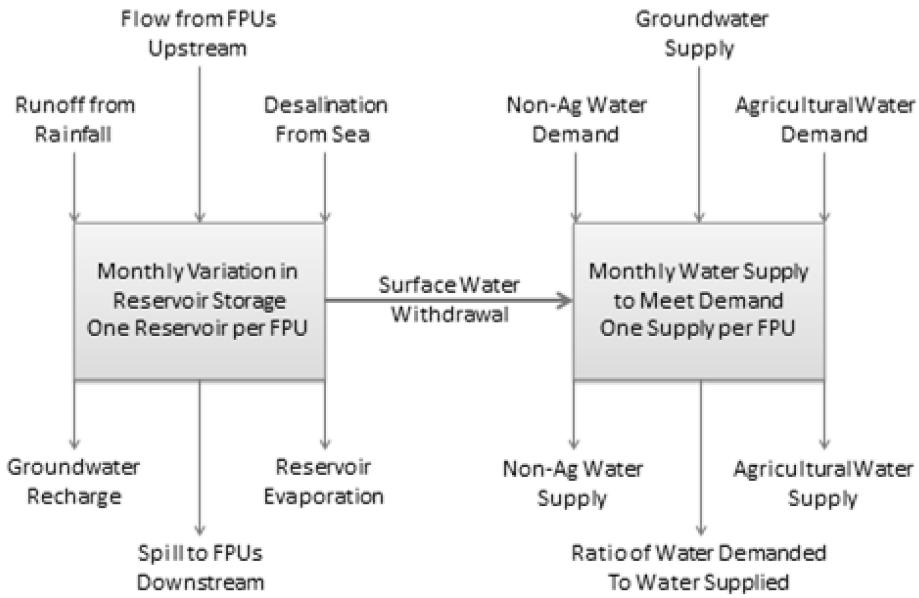
Industrial water demand is modeled for the manufacturing and energy sectors using growth rates for the value-added by sector and energy production values for the electricity sector from the Emissions Prediction and Policy Analysis Model version 6 (EPPA6) of the MIT Joint Program on the Science and Policy of Global Change (Chen et al. 2015). For many countries in Africa south of the Sahara, the projected industrial water demands are substantially lower than those in IMPACT 2, suggesting an underestimation. Therefore, for countries in Africa south of the Sahara we retained the projection method of IMPACT 2 for industrial water demand, which is modeled as a nonlinear function of gross domestic production per capita and technology change.

Future domestic water demands are based on projections of population and income growth. In each region or basin income elasticities of demand for domestic water use are synthesized based on the literature and available estimates (de Fraiture 2007; Rosegrant, Cai, and Cline 2002). These elasticities of demand measure the propensity to consume water with respect to increases in per capita income. The elasticities also capture both direct income effects and conservation of domestic water use through technological and management change. Livestock water demand is proportional to the number of animals raised as calculated by the multimarket model.

Water Supply

IWSM is a water basin management model. For FPUs where there is surface water storage capacity (for example, dams), the model specifies a single reservoir that summarizes all water storage capacity. For a given water basin that includes more than one FPU, IWSM manages storage in all those FPUs to maximize the ratio of water supply to water demand in the water basin. IWSM uses the runoff calculated by IGHM, the climatic data, and the water demands presented above to allocate available water to different uses. The schematic in Figure 5.6 provides an overview of the model. In each FPU, IWSM solves for a balance between the change in the amount of water stored in the reservoirs, the entering water flows (runoff from precipitation, water from nontraditional sources such as desalination, and inflows from FPUs situated upstream), the exiting water flows (groundwater recharge from the stream, evaporation from the reservoirs, outflows to the FPU downstream or the ocean), and the water withdrawn for human use (surface water depletion). The model uses a simple hedging rule to avoid leaving empty storage for the next year.

Figure 5.6 IMPACT water basin simulation model



Source: Authors.

Note: FPU = food production unit; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; Non-Ag = nonagricultural.

Surface water depletion added to the pumped groundwater (which is limited by the monthly capacity of tubewells and other pumps) is used to meet various water demands. The model solves by maximizing the ratio of water supplied to water demanded by water basin during a year in all FPUs. Solving for water supply in all FPUs simultaneously, IWSM assumes that linked FPUs within the same water basins are operated cooperatively, optimally allocating water between upstream and downstream demanders (qualified by imposing constraints on water delivery to downstream demanders). The model is parameterized to use available storage to smooth the distribution of water over months to avoid dramatic swings in monthly water delivery, if possible.

Following standard practice, IWSM incorporates the basic rule that nonagricultural water demands have priority over agricultural water demands. Any shortage in water supply is absorbed by agriculture first. If the shortage is larger than irrigation water demand, then livestock and domestic and industrial supplies are reduced proportionally.

ICWASM

ICWASM then allocates water among crops in an area, given the economic value of the crop. We use the FAO approach (Doorenbos and Kassam 1979) to measure water stress at monthly intervals to include seasonality of water stress. Because optimizing total value of production given fixed prices leads to a tendency for specializing in high-value crops, we include a measure of risk aversion for farmers in the objective function, which preserves a diversified production structure even in case of a drought. The stress model produces a measure of yield stress for every crop—both irrigated and rainfed—in each FPU where that crop is grown. The yield stress for the base year is recorded, and the model defines for subsequent years the yield shock as the ratio of that year's yield stress to the base year yield stress. This allows for a consistent modeling framework while making sure that the base year yields from the multimarket model dataset are preserved.

Linking the IMPACT Water and Multimarket Models

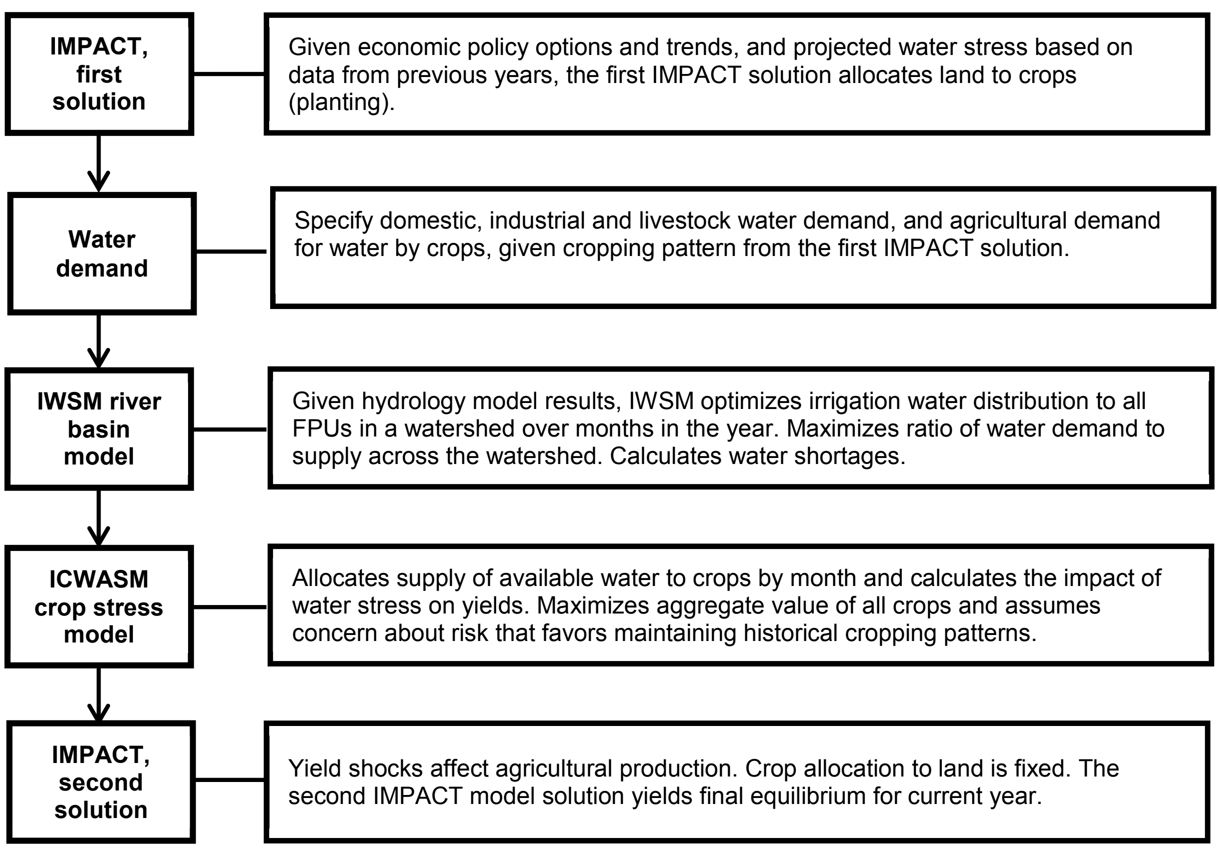
Communication between the water models and the multimarket model is shown in Figure 5.7. In a given year, the IMPACT multimarket model is first solved assuming exogenous trends on various parameters, yielding projected production, prices, and allocation of land to crops. For this first run, expected water stress is set to the average of the previous four years, which sets harvest expectations for the allocation of land to different crops. This solution can be seen as providing projections that farmers use to make their cropping decisions.

The water demand module then calculates water demand for crops, industry, households, and livestock. Agricultural and nonagricultural water demands are then calculated as outlined above. IWSM (Figure 5.6) uses these water demands, along with river flows provided by IGHM (Figure 5.5), to provide the monthly repartition of water among FPUs given the objective function described above.

ICWASM then allocates water among crops in an area, given the economic value of the crop. The stress model produces a measure of water stress on yield for every crop—both irrigated and rainfed—in each of the FPUs and then multiplies by the temperature stress obtained from DSSAT to represent the total climate yield shock.

Finally, the new yield shocks are applied to the IMPACT multimarket model, which is solved a second time for the final equilibrium, only now assuming that the allocation of land to crops is fixed since farmers cannot change their decisions after planting. This solution yields all economic variables, including quantities and prices of outputs and inputs, and all trade flows. The model then moves to the next year, updates various parameters on trend, and starts the process again.

Figure 5.7 Linking IMPACT to water models: Dynamic two-way communication year by year



Source: Authors.

Note: FPUs = food production units; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; IWSM = IMPACT water basin simulation model; ICWASM = IMPACT crop water allocation and stress model.

6. SUMMARY AND DISCUSSION

Work on the IMPACT model began more than 20 years ago in response to the need to look at long-run issues related to poverty alleviation, rural development, and food security. This need for tools to do long-run scenario analysis has only grown over time, with new challenges to the global food system like climate change coming to the forefront. This growing demand combined with improvements in computer hardware and software (methods) have spurred model growth and improvement to address new and ever-more-complex questions. In response to these growing demands IMPACT's domain of applicability has grown significantly with the disaggregation of IMPACT's core database to account for nearly 50 additional countries and 20 agricultural commodity markets (see Table 2.1 for evolution of IMPACT over time). IMPACT 3 builds on the work of previous versions while consolidating these changes in a more flexible design that borrows from the best practices in the modeling literature (for example, adopting the activity-commodity framework from the CGE literature) and from software design with greater implementation of modular design, readable coding practices (see Box 6.1 for a summary of readable code), and a graphical interface.

Box 6.1 What is readable code?

Readable code is code that minimizes the time and effort required by others to understand, debug, and modify it. Readable code is characterized by having

- modular design including a logical organization of model files and directories;
- well-named variables, parameters, and methods;
- consistent formatting that incorporates white space and line breaks to facilitate reading;
- clear in-code documentation with relevant and descriptive comments; and
- a logical flow of model execution with minimal nesting and branching.

Source: Author summary from Boswell and Foucher (2011).

These changes have been made to make IMPACT more flexible for future additions and improvements while at the same time making the model more transparent and accessible to a broader community of users. The benefits of these improvements have already proven beneficial, allowing a relatively small modeling team to better incorporate model feedback and new data and expert opinion—for example, the CGIAR Research Program on Policies, Institutions, and Markets review on agricultural modeling (CGIAR–Independent Evaluation Arrangement 2015) and the Global Futures and Strategic Foresight (GFSF)–led review of IMPACT exogenous assumptions on productivity growth. IMPACT is continually being improved as we incorporate new data and expertise to allow the model to be used in new and more complex ways. Currently a series of parallel efforts is being pursued to expand and improve on IMPACT and will become a part of future versions of IMPACT. Some of these improvements will lead to new modules and others to improvements to current modules. Table 6.1 summarizes the current IMPACT improvements that are in the pipeline.

Table 6.1 Summary of ongoing IMPACT developments

Model improvement	Summary	Collaborators
Aquaculture module	The aquaculture module was dropped in the transition from IMPACT 1 to IMPACT 2. An exogenous module for fish was developed based on IMPACT 2 (Msangi et al 2013), and there is ongoing work to extend this module and fully integrate it into IMPACT 3.	WorldFish
Further elaboration of CGIAR mandate commodities	This involves collaborating with CGIAR centers to review the behavior of new IMPACT 3 commodities and make adjustments to take into account new and detailed commodity expertise available in the CGIAR centers. This work may lead to more commodity disaggregation (for example, millet into pearl and finger millets) or the addition of new behaviors to capture shallow value chains (for example, the addition of starch to better simulate the global cassava market).	CGIAR centers participating in GFSF[16]
Integrating GLOBE with IMPACT	GLOBE is a global CGE model. Many issues related to poverty alleviation and welfare are difficult to answer when only focusing on the agriculture sector. To be able to assess welfare effects as well as important interactions between the agriculture sector and other sectors of the economy, GLOBE is being calibrated and linked to IMPACT.	Institute of Development Studies
Livestock module	Update the current handling of livestock in IMPACT to better reflect livestock production systems around the world. In addition incorporate more detailed handling of livestock diets and the direct and indirect effects of climate change.	ILRI, CSIRO
Nutrition and health	Questions about nutrition are critical if we are to analyze food security. IMPACT 3 currently has modules that can assess trends on changes in undernourishment. These measures are being expanded to include new data, to look at nutrient deficiency, obesity, and updating the current food security module. In addition, we are linking IMPACT food demand to health modules to look at the changes diets may have on noncommunicable diseases.	CIMSANS, CSIRO, and Oxford University

Source: Authors.
Note: CIMSANS = Center for Integrated Modeling of Sustainable Agriculture and Nutrition Security; CSIRO = Commonwealth Scientific and Industrial Research Organization; GFSF = Global Futures and Strategic Foresight; GLOBE = Global CGE model ILRI = International Livestock Research Institute; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

IMPACT has been attracting greater interest from the policymaking and research community in having greater access not only to IMPACT scenario results but also to the model itself. This growing demand has led to the development of a standard IMPACT 3 training program (Mason-D'Croz and Islam 2014), which has built on the training efforts done with IMPACT 2 as part of the GFSF project (Palazzo, Mason-D'Croz, and Sulser 2012). In 2014 and 2015, five IMPACT 3 training workshops were given in four countries (Colombia, Malaysia, Russia, and the United States) to more than 40 participants from more than 23 institutions. Table 6.2 summarizes participation in IMPACT 3 training to date.

[16] For more information on work being done for GFSF go to http://globalfutures.cgiar.org.

Table 6.2 IMPACT 3 training summary by type of institution

Type of institution	Number of institutions	Countries represented	Number of participants
CGIAR	9	Colombia, India, Jordan, Kenya, Malaysia, Peru, Sri Lanka, United States, and Vietnam	26
Government agencies	2	Tajikistan and Uzbekistan	3
Nongovernmental organizations, think tanks, and multilateral organizations	3	France, Russia, and Uzbekistan	4
Universities	6	Germany, Kazakhstan, Kyrgyzstan, Russia, United Kingdom, Uzbekistan	11

Source: Authors.
Note: IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

These training workshops have helped increase the visibility of IMPACT, which in turn has increased the demand to learn more about IMPACT and how to use it. Already there is demand for additional training, and to meet these demands IFPRI offers periodic training workshops.[17] Not all users are interested in learning how to use the model. Many are interested in using IMPACT results to inform policy. Work in collaborative scenario-building exercises has brought national and regional policymakers in contact with IMPACT scenarios, leading to direct interactions and use of IMPACT 3 results in a growing number of countries and regions. In the past, most of the demand has come from CGIAR and academia. This will likely continue, although there has been growing demand from government agencies and regional entities to develop foresight-modeling capacity using IMPACT, as awareness of IMPACT has increased. To meet this greater demand for IMPACT scenario results as inputs into policymaking and informing activities data visualization tools have been developed to allow for more varied and nuanced outputs.

[17] For more information about IMPACT training please contact ifpri-impact-model@cgiar.org.

APPENDIX A: INTERNATIONAL MODEL FOR POLICY ANALYSIS OF AGRICULTURAL COMMODITIES AND TRADE (IMPACT) GEOGRAPHY

Table A.1 IMPACT countries

IMPACT code	IMPACT name	ISO name	ISO code
AFG	Afghanistan	Afghanistan	AFG
AGO	Angola	Angola	AGO
ALB	Albania	Albania	ALB
ARG	Argentina	Argentina	ARG
ARM	Armenia	Armenia	ARM
AUS	Australia	Australia	AUS
AUT	Austria	Austria	AUT
AZE	Azerbaijan	Azerbaijan	AZE
BDI	Burundi	Burundi	BDI
BEN	Benin	Benin	BEN
BFA	Burkina Faso	Burkina Faso	BFA
BGD	Bangladesh	Bangladesh	BGD
BGR	Bulgaria	Bulgaria	BGR
BLR	Belarus	Belarus	BLR
BLT	Baltic States	Estonia	EST
		Lithuania	LTU
		Latvia	LVA
BLX	Belgium-Luxembourg	Belgium	BEL
		Luxembourg	LUX
BLZ	Belize	Belize	BLZ
BOL	Bolivia	Bolivia	BOL
BRA	Brazil	Brazil	BRA
BTN	Bhutan	Bhutan	BTN
BWA	Botswana	Botswana	BWA
CAF	Central African Republic	Central African Republic	CAF
CAN	Canada	Canada	CAN
CHL	Chile	Chile	CHL
CHM	China Plus	China	CHN
		Hong Kong	HKG
		Macao	MAC
		Taiwan	TWN
CHP	Switzerland Plus	Switzerland	CHE
		Liechtenstein	LIE
CIV	Ivory Coast	Ivory Coast	CIV
CMR	Cameroon	Cameroon	CMR
COD	Democratic Republic of Congo	Democratic Republic of Congo	COD
COG	Congo	Congo	COG
COL	Colombia	Colombia	COL

Table A.1 Continued

IMPACT code	IMPACT name	ISO name	ISO code
CRB	Other Caribbean	Aruba	ABW
		Anguilla	AIA
		Netherlands Antilles (obsolete)	ANT
		Antigua	ATG
		Bonaire, Sint Eustatius, and Saba	BES
		Bahamas	BHS
		St. Barthélemy	BLM
		Barbados	BRB
		Curacao	CUW
		Cayman Islands	CYM
		Dominica	DMA
		Guadeloupe	GLP
		Grenada	GRD
		St. Kitts and Nevis	KNA
		St. Lucia	LCA
		Saint Martin	MAF
		Montserrat	MSR
		Martinique	MTQ
		Puerto Rico	PRI
		Sint Maarten	SXM
		Turks and Caicos Islands	TCA
		Trinidad and Tobago	TTO
		St. Vincent and Grenadines	VCT
		British Virgin Islands	VGB
		U.S. Virgin Islands	VIR
CRI	Costa Rica	Costa Rica	CRI
CUB	Cuba	Cuba	CUB
CYP	Cyprus	Cyprus	CYP
CZE	Czech Republic	Czech Republic	CZE
DEU	Germany	Germany	DEU
DJI	Djibouti	Djibouti	DJI
DNK	Denmark	Denmark	DNK
DOM	Dominican Republic	Dominican Republic	DOM
DZA	Algeria	Algeria	DZA
ECU	Ecuador	Ecuador	ECU
EGY	Egypt	Egypt	EGY
ERI	Eritrea	Eritrea	ERI
ETH	Ethiopia	Ethiopia	ETH
FJI	Fiji	Fiji	FJI
FNP	Finland Plus	Aland Islands	ALA
		Finland	FIN

Table A.1 Continued

IMPACT code	IMPACT name	ISO name	ISO code
FRP	France Plus	France	FRA
		Monaco	MCO
GAB	Gabon	Gabon	GAB
GEO	Georgia	Georgia	GEO
GHA	Ghana	Ghana	GHA
GIN	Guinea	Guinea	GIN
GMB	Gambia	Gambia	GMB
GNB	Guinea-Bissau	Guinea-Bissau	GNB
GNQ	Equatorial Guinea	Equatorial Guinea	GNQ
GRC	Greece	Greece	GRC
GRL	Greenland	Greenland	GRL
GSA	Guyanas South America	French Guiana	GUF
		Guyana	GUY
		Suriname	SUR
GTM	Guatemala	Guatemala	GTM
HND	Honduras	Honduras	HND
HRV	Croatia	Croatia	HRV
HTI	Haiti	Haiti	HTI
HUN	Hungary	Hungary	HUN
IDN	Indonesia	Indonesia	IDN
IND	India	India	IND
IRL	Ireland	Ireland	IRL
IRN	Iran	Iran	IRN
IRQ	Iraq	Iraq	IRQ
ISL	Iceland	Iceland	ISL
ISR	Israel	Israel	ISR
ITP	Italy Plus	Italy	ITA
		Malta	MLT
		San Marino	SMR
		Vatican City	VAT
JAM	Jamaica	Jamaica	JAM
JOR	Jordan	Jordan	JOR
JPN	Japan	Japan	JPN
KAZ	Kazakhstan	Kazakhstan	KAZ
KEN	Kenya	Kenya	KEN
KGZ	Kyrgyzstan	Kyrgyzstan	KGZ
KHM	Cambodia	Cambodia	KHM
KOR	South Korea	South Korea	KOR
LAO	Laos	Laos	LAO
LBN	Lebanon	Lebanon	LBN
LBR	Liberia	Liberia	LBR

Table A.1 Continued

IMPACT code	IMPACT name	ISO name	ISO code
LBY	Libya	Libya	LBY
LKA	Sri Lanka	Sri Lanka	LKA
LSO	Lesotho	Lesotho	LSO
MDA	Moldova	Moldova	MDA
MDG	Madagascar	Madagascar	MDG
MEX	Mexico	Mexico	MEX
MLI	Mali	Mali	MLI
MMR	Myanmar	Myanmar	MMR
MNG	Mongolia	Mongolia	MNG
MOR	Morocco Plus	Western Sahara	ESH
		Morocco	MAR
MOZ	Mozambique	Mozambique	MOZ
MRT	Mauritania	Mauritania	MRT
MWI	Malawi	Malawi	MWI
MYS	Malaysia	Malaysia	MYS
NAM	Namibia	Namibia	NAM
NER	Niger	Niger	NER
NGA	Nigeria	Nigeria	NGA
NIC	Nicaragua	Nicaragua	NIC
NLD	Netherlands	Netherlands	NLD
NOR	Norway	Norway	NOR
NPL	Nepal	Nepal	NPL
NZL	New Zealand	New Zealand	NZL
OAO	Other Atlantic Ocean	Bermuda	BMU
		Bouvet Island	BVT
		Cape Verde	CPV
		Falkland Islands	FLK
		Faroe Islands	FRO
		South Georgia and South Sandwich Islands	SGS
		Saint Helena, Ascension, and Tristan de Cunha	SHN
		Svalbard and Jan Mayen	SJM
		Saint Pierre and Miquelon	SPM
		Sao Tome and Principe	STP
OBN	Other Balkans	Bosnia-Herzegovina	BIH
		Macedonia (FYR)	MKD
		Montenegro	MNE
		Serbia	SRB

Table A.1 Continued

IMPACT code	IMPACT name	ISO name	ISO code
OIO	Other Indian Ocean	Southern Territories	ATF
		Keeling Islands	CCK
		Comoros	COM
		Christmas Island	CXR
		Heard and McDonald Islands	HMD
		British Indian Ocean Territory	IOT
		Maldives	MDV
		Mauritius	MUS
		Mayotte	MYT
		Réunion	REU
		Seychelles	SYC
OPO	Other Pacific Ocean	American Samoa	ASM
		Cook Islands	COK
		Micronesia	FSM
		Guam	GUM
		Kiribati	KIR
		Marshall Islands	MHL
		Northern Mariana Islands	MNP
		New Caledonia	NCL
		Norfolk Island	NFK
		Niue	NIU
		Nauru	NRU
		Pitcairn	PCN
		Palau	PLW
		French Polynesia	PYF
		Tokelau	TKL
		Tonga	TON
		Tuvalu	TUV
		Minor Outlying Islands	UMI
		Wallis and Futuna	WLF
		Samoa	WSM
OSA	Other Southeast Asia	Brunei	BRN
		Singapore	SGP
PAK	Pakistan	Pakistan	PAK
PAN	Panama	Panama	PAN
PER	Peru	Peru	PER
PHL	Philippines	Philippines	PHL
PNG	Papua New Guinea	Papua New Guinea	PNG
POL	Poland	Poland	POL
PRK	North Korea	North Korea	PRK
PRT	Portugal	Portugal	PRT

Table A.1 Continued

IMPACT code	IMPACT name	ISO name	ISO code
PRY	Paraguay	Paraguay	PRY
PSE	Occupied Palestinian Territory	Occupied Palestinian Territory	PSE
RAP	Rest of Arab Peninsula	United Arab Emirates	ARE
		Bahrain	BHR
		Kuwait	KWT
		Oman	OMN
		Qatar	QAT
ROU	Romania	Romania	ROU
RUS	Russia	Russia	RUS
RWA	Rwanda	Rwanda	RWA
SAU	Saudi Arabia	Saudi Arabia	SAU
SDN	Sudan Plus	Sudan	SDN
		South Sudan[a]	SSD
SEN	Senegal	Senegal	SEN
SLB	Solomon Islands	Solomon Islands	SLB
SLE	Sierra Leone	Sierra Leone	SLE
SLV	El Salvador	El Salvador	SLV
SOM	Somalia	Somalia	SOM
SPP	Spain Plus	Andorra	AND
		Spain	ESP
		Gibraltar	GIB
SVK	Slovakia	Slovakia	SVK
SVN	Slovenia	Slovenia	SVN
SWE	Sweden	Sweden	SWE
SWZ	Swaziland	Swaziland	SWZ
SYR	Syria	Syria	SYR
TCD	Chad	Chad	TCD
TGO	Togo	Togo	TGO
THA	Thailand	Thailand	THA
TJK	Tajikistan	Tajikistan	TJK
TKM	Turkmenistan	Turkmenistan	TKM
TLS	Timor-L'este	Timor-L'este	TLS
TUN	Tunisia	Tunisia	TUN
TUR	Turkey	Turkey	TUR
TZA	Tanzania	Tanzania	TZA
UGA	Uganda	Uganda	UGA
UKP	Great Britain Plus	Great Britain	GBR
		Guernsey	GGY
		Isle of Man	IMN
UKP	Great Britain Plus	Jersey	JEY
UKR	Ukraine	Ukraine	UKR

Table A.1 Continued

IMPACT code	IMPACT name	ISO name	ISO code
URY	Uruguay	Uruguay	URY
USA	United States	United States	USA
UZB	Uzbekistan	Uzbekistan	UZB
VEN	Venezuela	Venezuela	VEN
VNM	Vietnam	Vietnam	VNM
VUT	Vanuatu	Vanuatu	VUT
YEM	Yemen	Yemen	YEM
ZAF	South Africa	South Africa	ZAF
ZMB	Zambia	Zambia	ZMB
ZWE	Zimbabwe	Zimbabwe	ZWE

Source: Authors.
Note: IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; ISO = International Organization for Standardization. [a]South Sudan gained independence in 2011 and is not represented in the base 2005 data.

Table A.2 IMPACT water basin and food production units (FPUs)

Country code	Country	FPU	Basin code	Basin
AFG	Afghanistan	AMD_AFG	AMD	Amudarja
AFG	Afghanistan	WAI_AFG	WAI	Western Asia Iran
AGO	Angola	CAF_AGO	CAF	Central African
AGO	Angola	CON_AGO	CON	Congo
AGO	Angola	ZAM_AGO	ZAM	Zambezi
ALB	Albania	ALB_ALB	ALB	Albania
ARG	Argentina	PAR_ARG	PAR	Parana
ARG	Argentina	RIC_ARG	RIC	Rio Colorado
ARG	Argentina	SAL_ARG	SAL	Salada Tierra
ARG	Argentina	TIE_ARG	TIE	Tierra
ARM	Armenia	ARM_ARM	ARM	Armenia
AUS	Australia	CAU_AUS	CAU	Central Australia
AUS	Australia	EAU_AUS	EAU	Eastern Australia
AUS	Australia	MAU_AUS	MAU	Murray Australia
AUS	Australia	WAU_AUS	WAU	Western Australia
AUT	Austria	DAN_AUT	DAN	Danube
AZE	Azerbaijan	AZE_AZE	AZE	Azerbiajan
BDI	Burundi	EAC_BDI	EAC	East African Coast
BEN	Benin	NIG_BEN	NIG	Niger
BEN	Benin	VOT_BEN	VOT	Volta
BFA	Burkina Faso	NIG_BFA	NIG	Niger
BFA	Burkina Faso	VOT_BFA	VOT	Volta
BGD	Bangladesh	BRT_BGD	BRT	Brahmaputra
BGD	Bangladesh	GAN_BGD	GAN	Ganges

Table A.2 Continued

Country code	Country	FPU	Basin code	Basin
BGD	Bangladesh	TMM_BGD	TMM	Thai Myan Malay
BGR	Bulgaria	DAN_BGR	DAN	Danube
BLR	Belarus	DNI_BLR	DNI	Dnieper
BLT	Baltic States	BAL_BLT	BAL	Baltic
BLX	Belgium-Luxembourg	RHI_BLX	RHI	Rhine
BLZ	Belize	BLZ_BLZ	BLZ	Belize
BOL	Bolivia	AMA_BOL	AMA	Amazon
BOL	Bolivia	PAR_BOL	PAR	Parana
BRA	Brazil	AMA_BRA	AMA	Amazon
BRA	Brazil	NEB_BRA	NEB	Northeast Brazil
BRA	Brazil	PAR_BRA	PAR	Parana
BRA	Brazil	SAN_BRA	SAN	San Francisco
BRA	Brazil	TOC_BRA	TOC	Toc
BRA	Brazil	URU_BRA	URU	Uruguay
BTN	Bhutan	BRT_BTN	BRT	Brahmaputra
BWA	Botswana	KAL_BWA	KAL	Kalahari
BWA	Botswana	LIM_BWA	LIM	Limpopo
BWA	Botswana	ZAM_BWA	ZAM	Zambezi
CAF	Central African Republic	CAF_CAF	CAF	Central African
CAF	Central African Republic	CON_CAF	CON	Congo
CAF	Central African Republic	LCB_CAF	LCB	Lake Chad
CAN	Canada	CAN_CAN	CAN	Canadian Arctic
CAN	Canada	COB_CAN	COB	Columbia
CAN	Canada	GLA_CAN	GLA	Great Lakes
CAN	Canada	MCK_CAN	MCK	Mackenzie
CAN	Canada	RWI_CAN	RWI	Red Winnipeg
CHL	Chile	CHC_CHL	CHC	Chilean Coast
CHM	China Plus	AMR_CHM	AMR	Amur
CHM	China Plus	BRT_CHM	BRT	Brahmaputra
CHM	China Plus	CHJ_CHM	CHJ	Chang Jiang
CHM	China Plus	GAN_CHM	GAN	Ganges
CHM	China Plus	HAI_CHM	HAI	Hail He
CHM	China Plus	HUA_CHM	HUA	Hual He
CHM	China Plus	HUN_CHM	HUN	Huang He
CHM	China Plus	IND_CHM	IND	Indus
CHM	China Plus	LAJ_CHM	LAJ	Langcang Jiang
CHM	China Plus	LMO_CHM	LMO	Lower Mongolia
CHM	China Plus	OBB_CHM	OBB	Ob

Table A.2 Continued

Country code	Country	FPU	Basin code	Basin
CHM	China Plus	SON_CHM	SON	Songhua
CHM	China Plus	TWN_CHM	TWN	Tawain
CHM	China Plus	YHE_CHM	YHE	Yili He
CHM	China Plus	YRD_CHM	YRD	Yuan Red River
CHM	China Plus	ZHJ_CHM	ZHJ	Zhu Jiang
CHP	Switzerland plus	RHI_CHP	RHI	Rhine
CIV	Ivory Coast	NIG_CIV	NIG	Niger
CIV	Ivory Coast	VOT_CIV	VOT	Volta
CIV	Ivory Coast	WAC_CIV	WAC	West African Coast
CMR	Cameroon	CAF_CMR	CAF	Central African
CMR	Cameroon	LCB_CMR	LCB	Lake Chad
CMR	Cameroon	NIG_CMR	NIG	Niger
COD	Democratic Republic of Congo	CON_COD	CON	Congo
COD	Democratic Republic of Congo	EAC_COD	EAC	East African Coast
COD	Democratic Republic of Congo	ZAM_COD	ZAM	Zambezi
COG	Congo	CAF_COG	CAF	Central African
COG	Congo	CON_COG	CON	Congo
COL	Colombia	AMA_COL	AMA	Amazon
COL	Colombia	NWS_COL	NWS	Northwest South America
COL	Colombia	ORI_COL	ORI	Orinoco
CRB	Other Caribbean	CRB_CRB	CRB	Other Caribbean
CRI	Costa Rica	CRI_CRI	CRI	Costa Rica
CUB	Cuba	CUB_CUB	CUB	Cuba
CYP	Cyprus	EME_CYP	EME	Eastern Mediterranean
CZE	Czech Republic	DAN_CZE	DAN	Danube
DEU	Germany	DAN_DEU	DAN	Danube
DEU	Germany	ELB_DEU	ELB	Elbe
DEU	Germany	ODE_DEU	ODE	Oder
DEU	Germany	RHI_DEU	RHI	Rhine
DJI	Djibouti	NLL_DJI	NLL	Nile
DNK	Denmark	ELB_DNK	ELB	Elbe
DOM	Dominican Republic	DOM_DOM	DOM	Dominican Republic
DZA	Algeria	NAC_DZA	NAC	North African Coast
DZA	Algeria	SAH_DZA	SAH	Sahara
ECU	Ecuador	AMA_ECU	AMA	Amazon
ECU	Ecuador	NWS_ECU	NWS	Northwest South America
EGY	Egypt	EME_EGY	EME	Eastern Mediterranean
EGY	Egypt	NAC_EGY	NAC	North African Coast
EGY	Egypt	NLL_EGY	NLL	Nile

Table A.2 Continued

Country code	Country	FPU	Basin code	Basin
EGY	Egypt	SAH_EGY	SAH	Sahara
ERI	Eritrea	NLL_ERI	NLL	Nile
ETH	Ethiopia	HOA_ETH	HOA	Horn of Africa
ETH	Ethiopia	NLL_ETH	NLL	Nile
FJI	Fiji	FJI_FJI	FJI	Fiji
FNP	Finland Plus	FNP_FNP	FNP	Finland plus
FRP	France plus	LBO_FRP	LBO	Loire Bordeaux
FRP	France plus	RHI_FRP	RHI	Rhine
FRP	France plus	RHO_FRP	RHO	Rhone
FRP	France plus	SEI_FRP	SEI	Seine
GAB	Gabon	CAF_GAB	CAF	Central African
GEO	Georgia	GEO_GEO	GEO	Georgia
GHA	Ghana	VOT_GHA	VOT	Volta
GIN	Guinea	NIG_GIN	NIG	Niger
GIN	Guinea	SEN_GIN	SEN	Senegal
GIN	Guinea	WAC_GIN	WAC	West African Coast
GMB	Gambia	WAC_GMB	WAC	West African Coast
GNB	Guinea-Bissau	WAC_GNB	WAC	West African Coast
GNQ	Equatorial Guinea	CAF_GNQ	CAF	Central African
GRC	Greece	GRC_GRC	GRC	Greece
GRL	Greenland	GRL_GRL	GRL	Greenland
GSA	Guyanas South America	GSA_GSA	GSA	Guyanas South America
GTM	Guatemala	GTM_GTM	GTM	Guatemala
HND	Honduras	HND_HND	HND	Honduras
HRV	Croatia	DAN_HRV	DAN	Danube
HTI	Haiti	HTI_HTI	HTI	Haiti
HUN	Hungary	DAN_HUN	DAN	Danube
IDN	Indonesia	BOR_IDN	BOR	Borneo
IDN	Indonesia	INE_IDN	INE	Indonesia East
IDN	Indonesia	INW_IDN	INW	Indonesia West
IND	India	BRT_IND	BRT	Brahmaputra
IND	India	CAV_IND	CAV	Cauvery
IND	India	CHO_IND	CHO	Chota-Nagpui
IND	India	EGH_IND	EGH	Easten Ghats
IND	India	GAN_IND	GAN	Ganges
IND	India	GOD_IND	GOD	Godavari
IND	India	IEC_IND	IEC	India East Coast
IND	India	IND_IND	IND	Indus
IND	India	KRI_IND	KRI	Krishna

Table A.2 Continued

Country code	Country	FPU	Basin code	Basin
IND	India	LUN_IND	LUN	Luni
IND	India	MAT_IND	MAT	Mahi Tapti
IND	India	MHN_IND	MHN	Mahanadi
IND	India	SAY_IND	SAY	Sahyada
IRL	Ireland	IRL_IRL	IRL	Ireland
IRN	Iran	TIG_IRN	TIG	Tigris Euphrates
IRN	Iran	WAI_IRN	WAI	Western Asia Iran
IRQ	Iraq	ARA_IRQ	ARA	Arabian Peninsula
IRQ	Iraq	TIG_IRQ	TIG	Tigris Euphrates
ISL	Iceland	ISL_ISL	ISL	Israel
ISR	Israel	EME_ISR	EME	Eastern Mediterranean
ITP	Italy plus	ITA_ITP	ITA	Italy
JAM	Jamaica	JAM_JAM	JAM	Jamaica
JOR	Jordan	EME_JOR	EME	Eastern Mediterranean
JPN	Japan	JAP_JPN	JAP	Japan
KAZ	Kazakhstan	AMD_KAZ	AMD	Amudarja
KAZ	Kazakhstan	LBA_KAZ	LBA	Lake Balkhash
KAZ	Kazakhstan	OBB_KAZ	OBB	Ob
KAZ	Kazakhstan	SYD_KAZ	SYD	Syrdarja
KAZ	Kazakhstan	URA_KAZ	URA	Ural
KAZ	Kazakhstan	VOG_KAZ	VOG	Volga
KAZ	Kazakhstan	YHE_KAZ	YHE	Yili He
KEN	Kenya	HOA_KEN	HOA	Horn of Africa
KGZ	Kyrgyzstan	LBA_KGZ	LBA	Lake Balkhash
KGZ	Kyrgyzstan	SYD_KGZ	SYD	Syrdarja
KHM	Cambodia	MEK_KHM	MEK	Mekong
KOR	South Korea	SKP_KOR	SKP	South Korean Penisula
LAO	Laos	MEK_LAO	MEK	Mekong
LBN	Lebanon	EME_LBN	EME	Eastern Mediterranean
LBR	Liberia	WAC_LBR	WAC	West African Coast
LBY	Libya	NAC_LBY	NAC	North African Coast
LBY	Libya	SAH_LBY	SAH	Sahara
LKA	Sri Lanka	SRL_LKA	SRL	Sri Lanka
LSO	Lesotho	ORA_LSO	ORA	Orange
MDA	Moldova	DAN_MDA	DAN	Danube
MDG	Madagascar	MAD_MDG	MAD	Madagascar
MEX	Mexico	MIM_MEX	MIM	Middle Mexico
MEX	Mexico	RIG_MEX	RIG	Rio Grande
MEX	Mexico	UME_MEX	UME	Upper Mexico
MEX	Mexico	YUC_MEX	YUC	Yucatan
MLI	Mali	NIG_MLI	NIG	Niger

Table A.2 Continued

Country code	Country	FPU	Basin code	Basin
MLI	Mali	SAH_MLI	SAH	Sahara
MLI	Mali	SEN_MLI	SEN	Senegal
MLI	Mali	VOT_MLI	VOT	Volta
MMR	Myanmar	MEK_MMR	MEK	Mekong
MMR	Myanmar	TMM_MMR	TMM	Thai Myan Malay
MNG	Mongolia	LMO_MNG	LMO	Lower Mongolia
MNG	Mongolia	UMO_MNG	UMO	Upper Mongolia
MOR	Morocco	NWA_MOR	NWA	Northwest Africa
MOR	Morocco	SAH_MOR	SAH	Sahara
MOZ	Mozambique	LIM_MOZ	LIM	Limpopo
MOZ	Mozambique	SAF_MOZ	SAF	Southeast Africa
MOZ	Mozambique	ZAM_MOZ	ZAM	Zambezi
MRT	Mauritania	NWA_MRT	NWA	Northwest Africa
MRT	Mauritania	SAH_MRT	SAH	Sahara
MRT	Mauritania	SEN_MRT	SEN	Senegal
MWI	Malawi	ZAM_MWI	ZAM	Zambezi
MYS	Malaysia	BOR_MYS	BOR	Borneo
MYS	Malaysia	TMM_MYS	TMM	Thai Myan Malay
NAM	Namibia	CAF_NAM	CAF	Central African
NAM	Namibia	KAL_NAM	KAL	Kalahari
NAM	Namibia	ORA_NAM	ORA	Orange
NAM	Namibia	ZAM_NAM	ZAM	Zambezi
NER	Niger	LCB_NER	LCB	Lake Chad
NER	Niger	NIG_NER	NIG	Niger
NER	Niger	SAH_NER	SAH	Sahara
NGA	Nigeria	LCB_NGA	LCB	Lake Chad
NGA	Nigeria	NIG_NGA	NIG	Niger
NIC	Nicaragua	NIC_NIC	NIC	Nicaruagua
NLD	Netherlands	RHI_NLD	RHI	Rhine
NOR	Norway	NOR_NOR	NOR	Norway
NPL	Nepal	GAN_NPL	GAN	Ganges
NZL	New Zealand	NZE_NZL	NZE	New Zealand
OAO	Other Atlantic Ocean	OAO_OAO	OAO	Other Atlantic Ocean
OBN	Other Balkans	DAN_OBN	DAN	Danube
OIO	Other Indian Ocean	OIO_OIO	OIO	Other Indian Ocean
OPO	Other Pacific Ocean	OPO_OPO	OPO	Other Pacific Ocean
OSA	Other Southeast Asia	TMM_OSA	TMM	Thai Myan Malay
PAK	Pakistan	IND_PAK	IND	Indus
PAK	Pakistan	WAI_PAK	WAI	Western Asia Iran
PAN	Panama	PAN_PAN	PAN	Panama

Table A.2 Continued

Country code	Country	FPU	Basin code	Basin
PER	Peru	AMA_PER	AMA	Amazon
PER	Peru	PEC_PER	PEC	Peru Coastal
PHL	Philippines	PHI_PHL	PHI	Philippines
PNG	Papua New Guinea	PAO_PNG	PAO	Papau Oceania
POL	Poland	ODE_POL	ODE	Oder
PRK	North Korea	NKP_PRK	NKP	North Korean Penisula
PRT	Portugal	PRT_PRT	PRT	Portugal
PRY	Paraguay	PAR_PRY	PAR	Parana
PSE	Occupied Palestinian Territory	EME_PSE	EME	Eastern Mediterranean
RAP	Rest of Arab Peninsula	RAP_RAP	RAP	Rest of Arab Peninsula
ROU	Romania	DAN_ROU	DAN	Danube
RUS	Russia	AMR_RUS	AMR	Amur
RUS	Russia	BAL_RUS	BAL	Baltic
RUS	Russia	BLA_RUS	BLA	Black Sea
RUS	Russia	DNI_RUS	DNI	Dnieper
RUS	Russia	NER_RUS	NER	North Europe-Russia
RUS	Russia	OBB_RUS	OBB	Ob
RUS	Russia	ODE_RUS	ODE	Oder
RUS	Russia	RRS_RUS	RRS	Rest of Russia
RUS	Russia	UMO_RUS	UMO	Upper Mongolia
RUS	Russia	URA_RUS	URA	Ural
RUS	Russia	VOG_RUS	VOG	Volga
RUS	Russia	YEN_RUS	YEN	Yenisey
RWA	Rwanda	EAC_RWA	EAC	East African Coast
SAU	Saudi Arabia	SAU_SAU	SAU	Saudi Arabia
SDN	Sudan	NLL_SDN	NLL	Nile
SDN	Sudan	SAH_SDN	SAH	Sahara
SEN	Senegal	SEN_SEN	SEN	Senegal
SEN	Senegal	WAC_SEN	WAC	West African Coast
SLB	Solomon Islands	SLB_SLB	SLB	Solomon Islands
SLE	Sierra Leone	WAC_SLE	WAC	West African Coast
SLV	El Salvador	SLV_SLV	SLV	El Salvador
SOM	Somalia	HOA_SOM	HOA	Horn of Africa
SPP	Spain plus	SPP_SPP	SPP	Spain plus
SSD	South Sudan	NLL_SSD	NLL	Nile
SVK	Slovakia	DAN_SVK	DAN	Danube
SVN	Slovenia	DAN_SVN	DAN	Danube
SWE	Sweden	SWE_SWE	SWE	Sweden
SWZ	Swaziland	SAC_SWZ	SAC	South African Coast

Table A.2 Continued

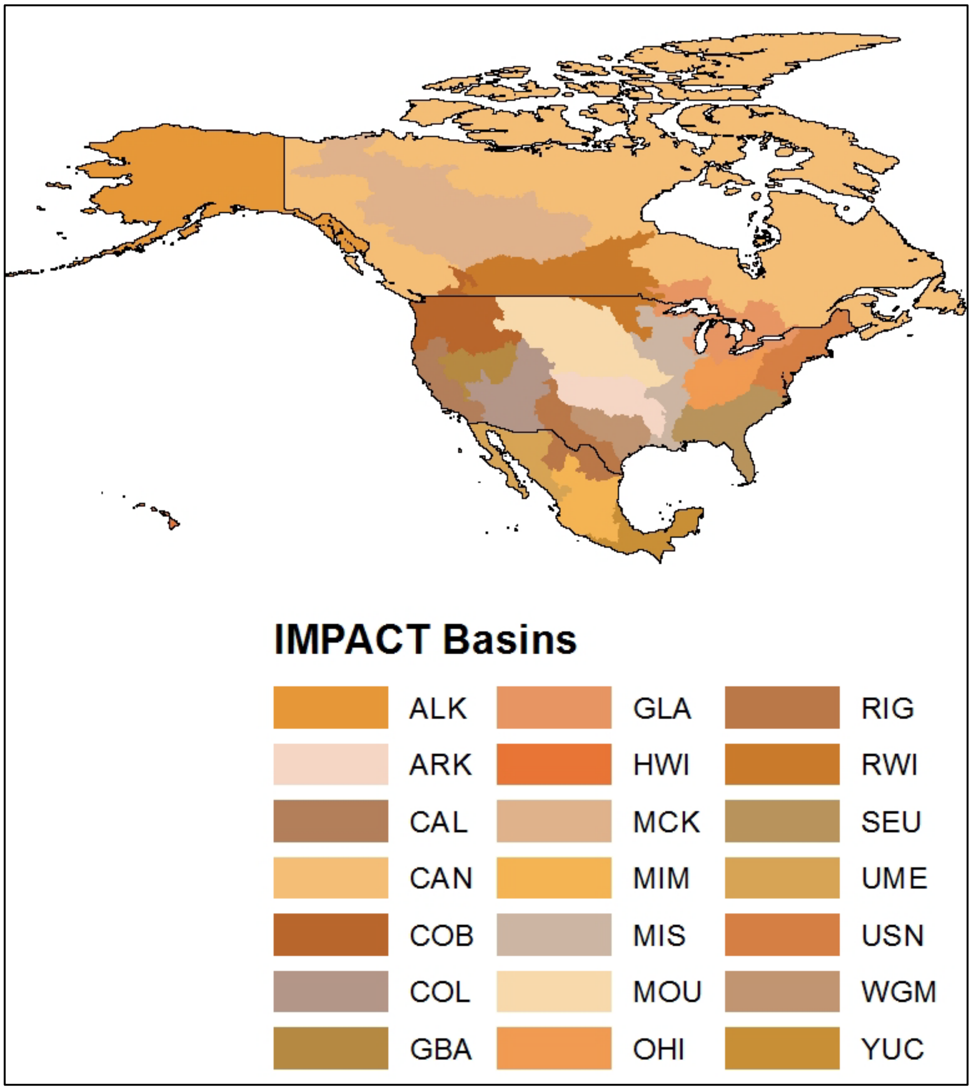
Country code	Country	FPU	Basin code	Basin
SYR	Syria	EME_SYR	EME	Eastern Mediterranean
SYR	Syria	TIG_SYR	TIG	Tigris Euphrates
TCD	Chad	LCB_TCD	LCB	Lake Chad
TCD	Chad	NIG_TCD	NIG	Niger
TCD	Chad	SAH_TCD	SAH	Sahara
TGO	Togo	VOT_TGO	VOT	Volta
THA	Thailand	MEK_THA	MEK	Mekong
THA	Thailand	TMM_THA	TMM	Thai Myan Malay
TJK	Tajikistan	AMD_TJK	AMD	Amudarja
TKM	Turkmenistan	AMD_TKM	AMD	Amudarja
TKM	Turkmenistan	URA_TKM	URA	Ural
TKM	Turkmenistan	WAI_TKM	WAI	Western Asia Iran
TLS	Timor-L'este	TLS_TLS	TLS	Timor-L'este
TUN	Tunisia	NAC_TUN	NAC	North African Coast
TUR	Turkey	BLA_TUR	BLA	Black Sea
TUR	Turkey	DAN_TUR	DAN	Danube
TUR	Turkey	EME_TUR	EME	Eastern Mediterranean
TUR	Turkey	TIG_TUR	TIG	Tigris Euphrates
TZA	Tanzania	EAC_TZA	EAC	East African Coast
TZA	Tanzania	SAF_TZA	SAF	Southeast Africa
TZA	Tanzania	ZAM_TZA	ZAM	Zambezi
UGA	Uganda	NLL_UGA	NLL	Nile
UKP	Great Britain plus	UKP_UKP	UKP	Great Britain plus
UKR	Ukraine	BLA_UKR	BLA	Black Sea
UKR	Ukraine	DAN_UKR	DAN	Danube
UKR	Ukraine	DNI_UKR	DNI	Dnieper
URY	Uruguay	URU_URY	URU	Uruguay
USA	United States	ALK_USA	ALK	Alaska
USA	United States	ARK_USA	ARK	Arkansas
USA	United States	CAL_USA	CAL	California
USA	United States	COB_USA	COB	Columbia
USA	United States	COL_USA	COL	Colorado
USA	United States	GBA_USA	GBA	Great Basin
USA	United States	GLA_USA	GLA	Great Lakes
USA	United States	HWI_USA	HWI	Hawaii
USA	United States	MIS_USA	MIS	Mississippi
USA	United States	MOU_USA	MOU	Missouri
USA	United States	OHI_USA	OHI	Ohio
USA	United States	RIG_USA	RIG	Rio Grande
USA	United States	RWI_USA	RWI	Red Winnipeg
USA	United States	SEU_USA	SEU	Southeast US

Table A.2 Continued

Country code	Country	FPU	Basin code	Basin
USA	United States	USN_USA	USN	US Northeast
USA	United States	WGM_USA	WGM	Western Gulf of Mexico
UZB	Uzbekistan	AMD_UZB	AMD	Amudarja
UZB	Uzbekistan	SYD_UZB	SYD	Syrdarja
VEN	Venezuela	ORI_VEN	ORI	Orinoco
VEN	Venezuela	RVE_VEN	RVE	Rest of Venezuela
VNM	Vietnam	MEK_VNM	MEK	Mekong
VNM	Vietnam	RVN_VNM	RVN	Rest of Vietnam
VNM	Vietnam	YRD_VNM	YRD	Yuan Red River
VUT	Vanuatu	VUT_VUT	VUT	Vanuatu
YEM	Yemen	YEM_YEM	YEM	Yemen
ZAF	South Africa	KAL_ZAF	KAL	Kalahari
ZAF	South Africa	LIM_ZAF	LIM	Limpopo
ZAF	South Africa	ORA_ZAF	ORA	Orange
ZAF	South Africa	SAC_ZAF	SAC	South African Coast
ZMB	Zambia	ZAM_ZMB	ZAM	Zambezi
ZWE	Zimbabwe	LIM_ZWE	LIM	Limpopo
ZWE	Zimbabwe	SAF_ZWE	SAF	Southeast Africa
ZWE	Zimbabwe	ZAM_ZWE	ZAM	Zambezi

Source: Authors.
Note: IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

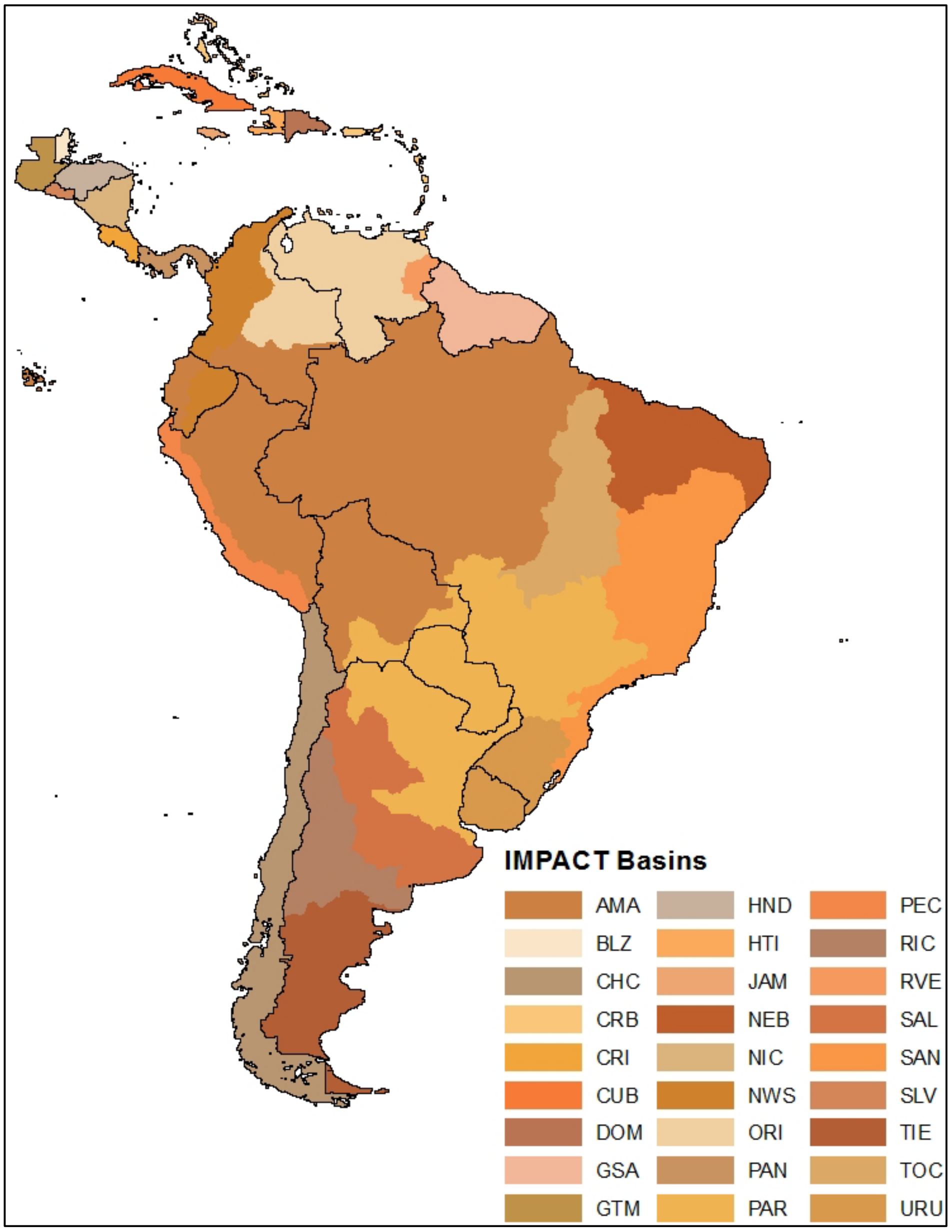
Figure A.1 Map of food production units in North America



Source: Authors.

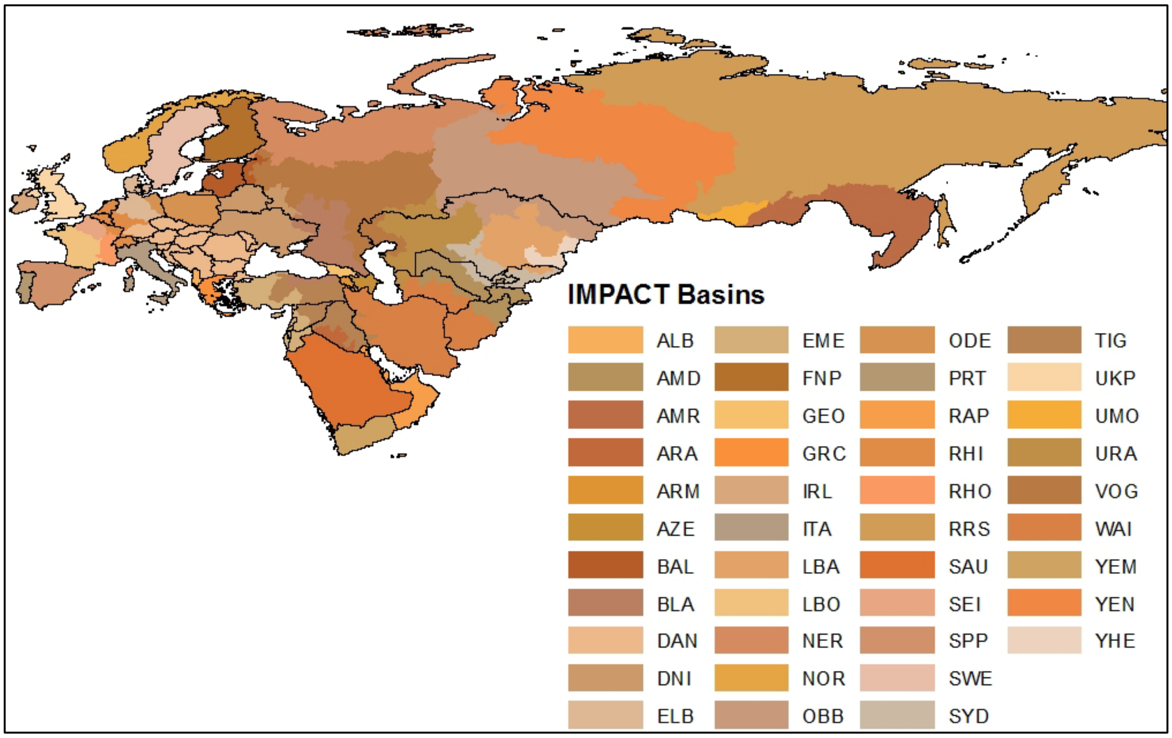
Note: Refer to Table A.2 for basin name correspondence. IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

Figure A.2 Map of food production units in Latin America and Caribbean



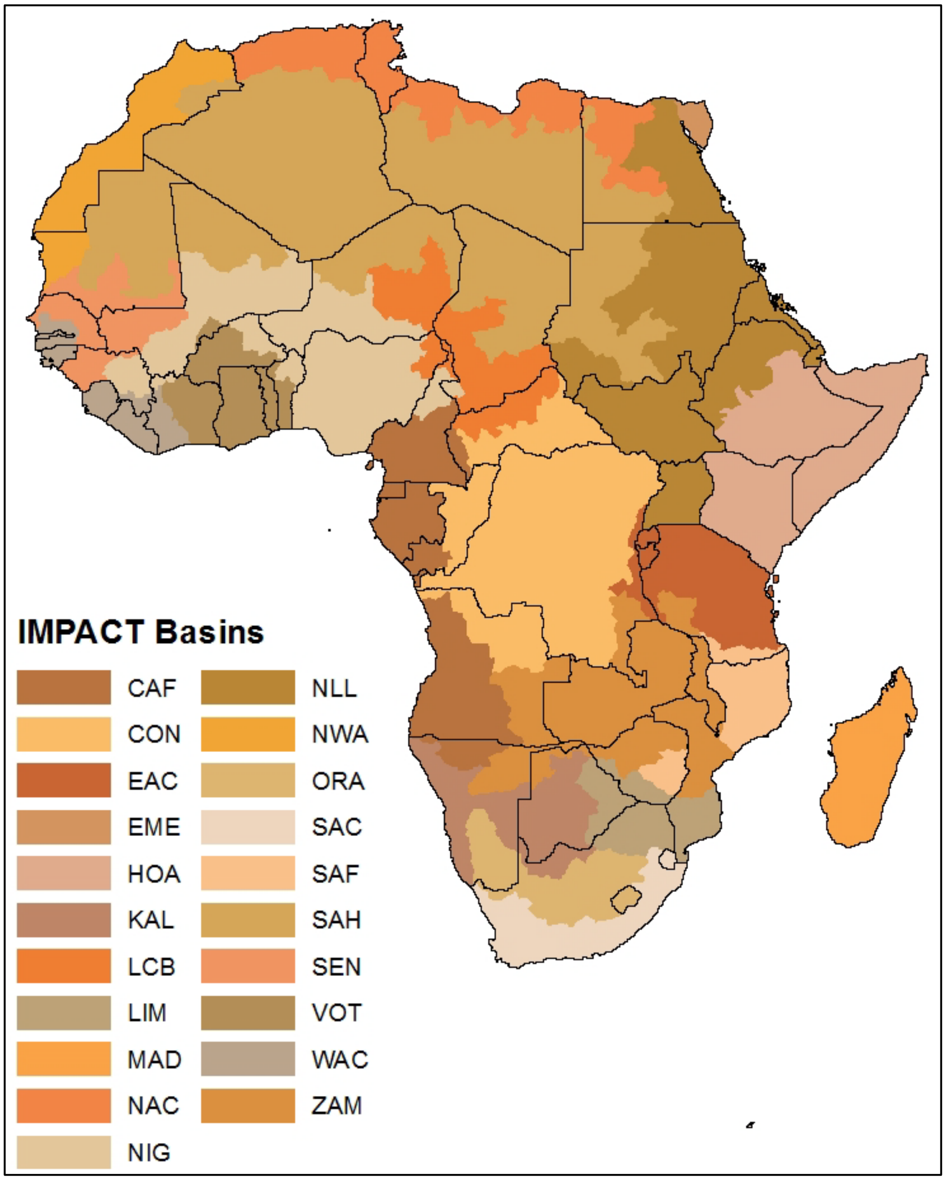
Source: Authors.
Note: Refer to Table A.2 for basin name correspondence. IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

Figure A.3 Map of food production units in Europe and the Middle East



Source: Authors.
Note: Refer to Table A.2 for basin name correspondence. IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

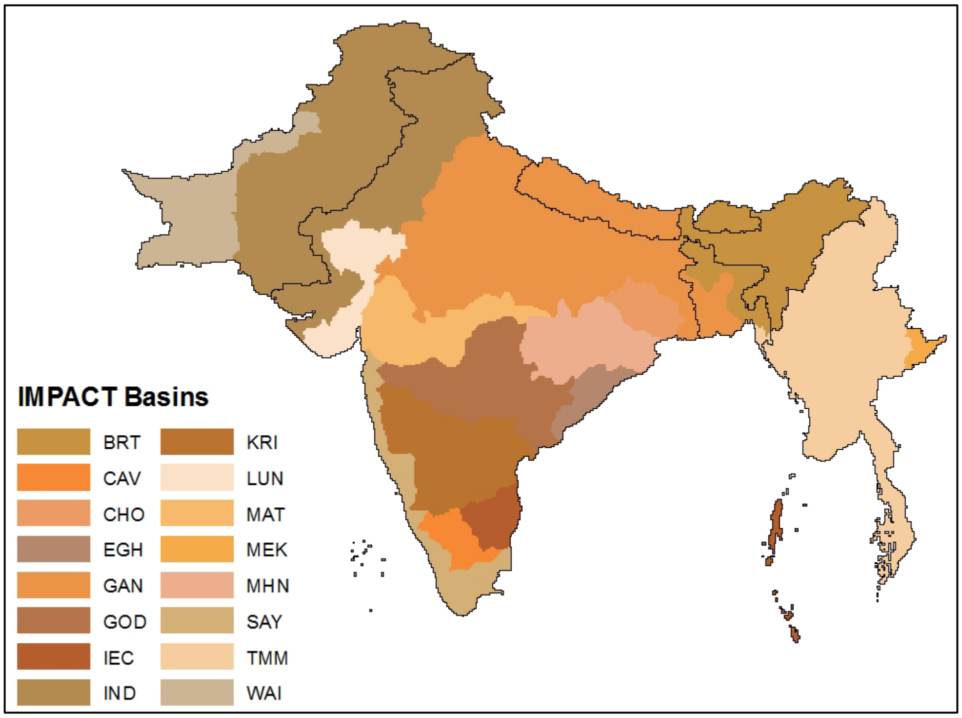
Figure A.4 Map of food production units in Africa



Source: Authors.

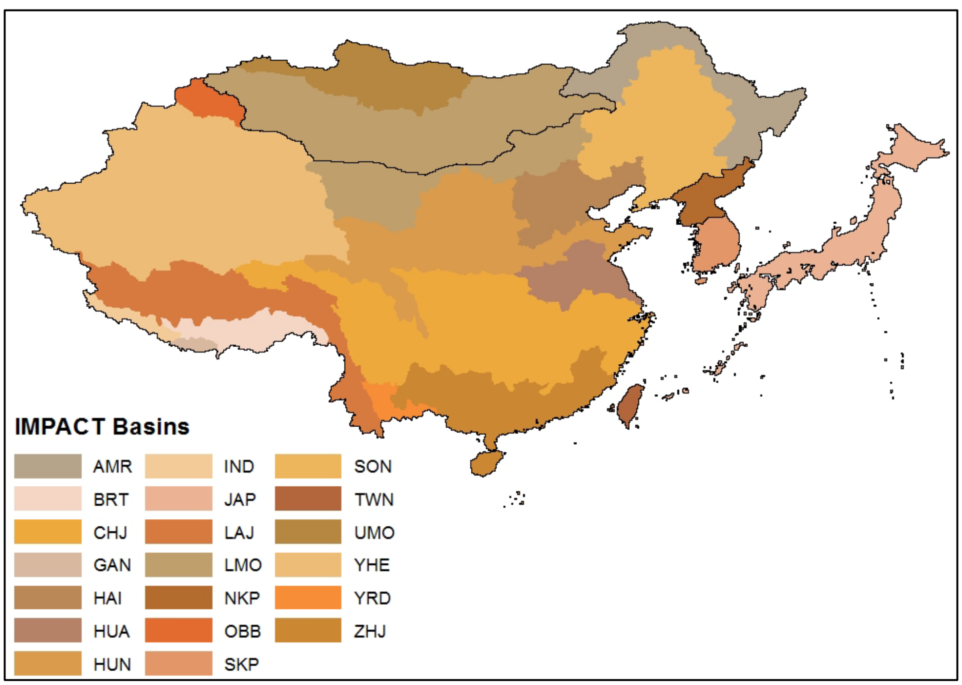
Note: Refer to Table A.2 for basin name correspondence. IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade

Figure A.5 Map of food production units in South Asia



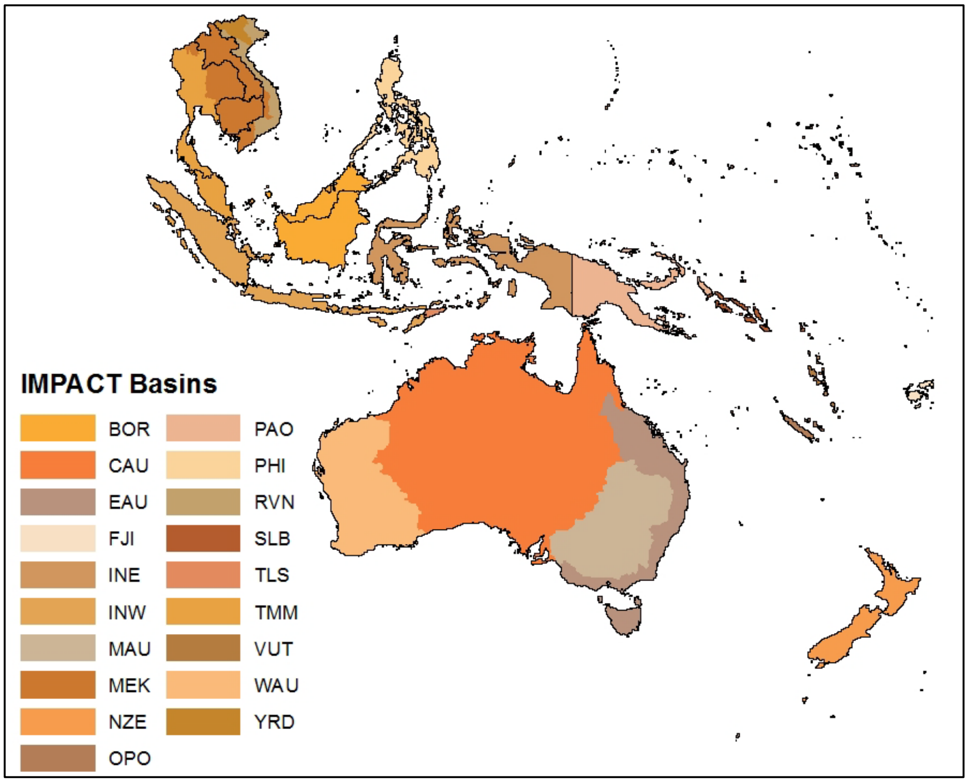
Source: Authors.
Note: Refer to Table A.2 for basin name correspondence. IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

Figure A.6 Map of food production units in East Asia



Source: Authors.
Note: Refer to Table A.2 for basin name correspondence. IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

Figure A.7 Map of food production units in Southeast Asia and Oceania



Source: Authors.
Note: Refer to Table A.2 for basin name correspondence. IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade.

APPENDIX B: INTERNATIONAL MODEL FOR POLICY ANALYSIS OF AGRICULTURAL COMMODITIES AND TRADE (IMPACT) ACTIVITIES AND COMMODITIES

Table B.1 IMPACT activities and commodities

Group	Activity[a]	Description		Commodity	Description
Animal products	jbeef[b]	Cattle ranch	→	cbeef	Cattle
Animal products	jeggs	Egg production	→	ceggs	Eggs
Animal products	jlamb[b]	Sheep, lamb, goat production	→	clamb	Sheep and goats
Animal products	jmilk	Dairy production	→	cmilk	Dairy
Animal products	jpork[b]	Pigs	→	cpork	Pigs
Animal products	jpoul[b]	Poultry	→	cpoul	Poultry
Cereals	jbarl	Barley farm	→	cbarl	Barley
Cereals	jmaiz	Maize farm	→	cmaiz	Maize
Cereals	jmill	Millet farm	→	cmill	Millet
Cereals	jocer	Other cereal farm	→	cocer	Other cereals
Cereals	jrice[c]	Rice	→	crice	Rice
Cereals	jsorg	Sorghum farm	→	csorg	Sorghum
Cereals	jwhea	Wheat farm	→	cwhea	Wheat
Fruits and vegetables	jbana	Banana plantation	→	cbana	Bananas
Fruits and vegetables	jplnt	Plantains	→	cplnt	Plantains
Fruits and vegetables	jsubf	(Sub)tropical fruit production	→	csubf	(Sub)tropical fruits
Fruits and vegetables	jtemf	Temperate fruit production	→	ctemf	Temperate fruits
Fruits and vegetables	jvege	Vegetable production	→	cvege	Vegetables
Oilseeds (traded)	jgrnd[d]	Groundnut farm	→	cgrnd	Groundnuts
Oilseeds (traded)	jrpsd	Rapeseed farm	→	crpsd	Rapeseed
Oilseeds (traded)	jsoyb	Soybean farm	→	csoyb	Soybeans
Oilseeds (traded)	jsnfl	Sunflower farm	→	csnfl	Sunflower seeds
Oilseeds (traded)	jtols	Total other oilseed production	→	ctols	Total other oilseeds
Oilseeds (nontraded)	jgdnt[d]	Groundnut farm	→	cgdnt	Groundnuts for oil
Oilseeds (nontraded)	jpalm	Oil palm plantation	→	cpalm	Oil palm fruit
Oilseeds (nontraded)	jrpnt	Rapeseed farm	→	crpnt	Rapeseed for oil
Oilseeds (nontraded)	jsbnt	Soybean farm	→	csbnt	Soybeans for oil
Oilseeds (nontraded)	jsfnt	Sunflower farm	→	csfnt	Sunflower seeds for oil
Oilseeds (nontraded)	jtont	Total other oilseed production	→	ctont	Total other oilseeds for oil
Oilseed processing[e]	jgdol jgdolnt	Groundnut processing	→	cgdol	Groundnut oil
			→	cgdml	Groundnut meal
Oilseed processing	jplol	Palm fruit processing	→	cplol	Palm oil
			→	cpkrl	Palm kernel
Oilseed processing	jpkol	Palm kernel processing	→	cpkol	Palm kernel oil
			→	cpkml	Palm kernel meal
Oilseed processing	jrpol jrpolnt	Rapeseed processing	→	crpol	Rapeseed oil
			→	crpml	Rapeseed meal

Table B.1 IMPACT activities and commodities

Group	Activity[a]	Description		Commodity	Description
Oilseed processing	jsbol jsbolnt	Soybean processing	→	csbol	Soybean oil
			→	csbml	Soybean meal
Oilseed processing	jsfol jsfolnt	Sunflower oil processing	→	csfol	Sunflower oil
			→	csfml	Sunflower meal
Oilseed processing	jtool jtoolnt	Total other oilseed processing	→	ctool	Total other oils
			→	ctoml	Total other oilseed meal
Other	jcafe	Coffee plantation	→	ccafe	Coffee
Other	jcoco	Cocoa plantation	→	ccoco	Cocoa
Other	jcott[f]	Cotton plantation	→	ccott	Cotton
Other	jfodr	Fodder production	→	cfodr	Fodders
Other	jothr	Other crop production	→	cothr	Other crops
Other	jpstr	Pasture and meadows	→	cgrss	Grass
Other	jteas	Tea plantation	→	cteas	Tea
Pulses	jbean	Bean farm	→	cbean	Beans
Pulses	jchkp	Chickpea farm	→	cchkp	Chickpeas
Pulses	jcowp	Cowpea farm	→	ccowp	Cowpeas
Pulses	jlent	Lentil farm	→	clent	Lentils
Pulses	jopul	Other pulse farm	→	copul	Other pulses
Pulses	jpigp	Pigeonpea farm	→	cpigp	Pigeonpeas
Roots and tubers	jcass	Cassava Farm	→	ccass	Cassava and other roots and tubers
Roots and tubers	jorat	Other roots and tuber production	→	corat	Other roots and tubers
Roots and tubers	jpota	Potato farm	→	cpota	Potato
Roots and tubers	jswpt	Sweet potato farm	→	cswpt	Sweet potatoes
Roots and tubers	jyams	Yam farm	→	cyams	Yams
Sugar	jsugb	Sugarbeet farm	→	csugb	Sugarbeet
Sugar	jsugc	Sugarcane plantation	→	csugc	Sugarcane
Sugar	jsugr	Sugar processing	→	csugr	Refined sugar

Source: Authors.

Note: IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade. [a] Activities (j) produce commodities (c), which are traded and consumed. [b] All meat activities and commodities are treated in dressed meat or carcass weight. [c] Rice is treated as milled equivalent. [d] Groundnuts are treated as shelled equivalent. [e] Oil-processing sector takes both domestically traded and international traded oilseeds. [f] Cotton activity and commodity are treated in terms of cotton lint only.

Table B.2 Commodity mapping FAOSTAT to IMPACT 3

IMPACT code	IMPACT name	FAO name	FAO code
jbana	Bananas	Bananas	2615
jbarl	Barley	Barley	2513
jbean	Beans	Beans	2546
jbeef	Beef[a]	Bovine Meat	2731
jbeef	Beef[a]	Buffalo meat	947
jbeef	Beef[a]	Cattle meat	867
jcafe	Coffee	Coffee	2630
jcass	Cassava	Cassava	2532
jchkp	Chickpeas[b]	Chick peas	191
jcoco	Cocoa	Cocoa Beans	2633
jcott	Cotton[c]	Cotton Lint	2661
jcowp	Cowpeas[b]	Cow peas, dry	195
jeggs	Eggs	Eggs	2744
jeggs	Eggs	Hen eggs in shell (weight)	1062
jeggs	Eggs	Other bird eggs in shell (weight)	1091
jgdml	Groundnut Meal	Groundnut Cake	2591
jgdol	Groundnut Oil	Groundnut Oil	2572
jgrnd	Groundnut[d]	Groundnuts (Shelled Eq)	2556
jlamb	Sheep-Lamb-Goat[a]	Mutton & Goat Meat	2732
jlamb	Sheep-Lamb-Goat[a]	Goat meat	1017
jlamb	Sheep-Lamb-Goat[a]	Sheep meat	977
jlent	Lentils[a]	Lentils	201
jmaiz	Maize	Maize	2514
jmilk	Dairy	Milk - Excluding Butter	2848
jmilk	Dairy	Buffalo milk whole fresh	951
jmilk	Dairy	Camel milk whole fresh	1130
jmilk	Dairy	Cow milk whole fresh	882
jmilk	Dairy	Goat milk whole fresh	1020
jmilk	Dairy	Sheep milk whole fresh	982
jmill	Millet	Millet	2517
jocer	Other Cereals	Rye	2515
jocer	Other Cereals	Oats	2516
jocer	Other Cereals	Cereals, Other	2520
jopul	Other Pulses[a]	Beans, dry	176
jopul	Other Pulses[a]	Broad beans, horse beans, dry	181
jopul	Other Pulses[a]	Peas, dry	187
jopul	Other Pulses[a]	Bambara beans	203
jopul	Other Pulses[a]	Vetches	205
jopul	Other Pulses[a]	Lupins	210
jopul	Other Pulses[a]	Pulses, nes	211
jorat	Other Roots & Tubers	Roots, Other	2534

Table B.2 Continued

IMPACT code	IMPACT name	FAO name	FAO code
jothr	Other	Nuts	2551
jothr	Other	Cloves	2642
jothr	Other	Spices, Other	2645
jothr	Other	Jute	2662
jothr	Other	Jute-Like Fibers	2663
jothr	Other	Soft-Fibers, Other	2664
jothr	Other	Sisal	2665
jothr	Other	Abaca	2666
jothr	Other	Hard Fibers, Other	2667
jothr	Other	Tobacco	2671
jothr	Other	Rubber	2672
jpigp	Pigeon Peas[a]	Pigeon peas	197
jpkml	Palm Kernel Meal	Palm kernel Cake	2595
jpkol	Palm Kernel Oil	Palm kernel Oil	2576
jpkrl	Palm Kernel	Palm kernels	2562
jplnt	Plantains	Plantains	2616
jplol	Palm Oil	Palm Oil	2577
jpork	Pork[a]	Pig meat	2733
jpork	Pork[a]	Pig meat	1035
jpota	Potatoes	Potatoes	2531
jpoul	Poultry[a]	Poultry Meat	2734
jpoul	Poultry[a]	Chicken meat	1058
jpoul	Poultry[a]	Duck meat	1069
jpoul	Poultry[a]	Goose and guinea fowl meat	1073
jpoul	Poultry[a]	Pigeons Other Birds	1083
jpoul	Poultry[a]	Turkey meat	1080
jrice	Rice[e]	Rice (Milled Equivalent)	2805
jrpml	Rapeseed Meal	Rape and Mustard Cake	2593
jrpol	Rapeseed Oil	Rape and Mustard Oil	2574
jrpsd	Rapeseed	Rape and Mustard seed	2558
jsbml	Soybean Meal	Soybean Cake	2590
jsbol	Soybean Oil	Soybean Oil	2571
jsfml	Sunflower Meal	Sunflower seed Cake	2592
jsfol	Sunflower Oil	Sunflower seed Oil	2573
jsnfl	Sunflower	Sunflower seed	2557
jsorg	Sorghum	Sorghum	2518
jsoyb	Soybeans	Soybeans	2555
jsubf	(Sub)-Tropical Fruits	Oranges, Mandarins	2611
jsubf	(Sub)-Tropical Fruits	Lemons, Limes	2612
jsubf	(Sub)-Tropical Fruits	Grapefruit	2613
jsubf	(Sub)-Tropical Fruits	Citrus, Other	2614

Table B.2 Continued

IMPACT code	IMPACT name	FAO name	FAO code
jsubf	(Sub)-Tropical Fruits	Pineapples	2618
jsubf	(Sub)-Tropical Fruits	Dates	2619
jsubf	(Sub)-Tropical Fruits	Fruit, other	2625
jsugb	Sugar Beets	Sugar Beet	2537
jsugc	Sugarcane	Sugar Cane	2536
jsugr	Sugar	Sugar (Raw Equivalent)	2542
jswpt	Sweet Potatoes	Sweet Potatoes	2533
jteas	Tea	Tea	2635
jtemf	Temperate Fruits	Apples	2617
jtemf	Temperate Fruits	Grapes	2620
jtemf	Temperate Fruits	Fruit, other	2625
jtemf	Temperate Fruits	Fruits - Excluding Wine	2919
jtols	Total Other Oilseeds	Coconuts - Incl Copra	2560
jtols	Total Other Oilseeds	Sesame seed	2561
jtols	Total Other Oilseeds	Olives	2563
jtols	Total Other Oilseeds	Oil crops, Other	2570
jtoml	Total Other Oil meals	Cottonseed Cake	2594
jtoml	Total Other Oil meals	Copra Cake	2596
jtoml	Total Other Oil meals	Sesame seed Cake	2597
jtoml	Total Other Oil meals	Oilseed Cakes, Other	2598
jtool	Total Other Oils	Cottonseed Oil	2575
jtool	Total Other Oils	Coconut Oil	2578
jtool	Total Other Oils	Olive Oil	2580
jtool	Total Other Oils	Oil crops Oil, Other	2586
jtool	Total Other Oils	Sesame seed Oil	2579
jvege	Vegetables	Tomatoes	2601
jvege	Vegetables	Onions	2602
jvege	Vegetables	Vegetables, Other	2605
jvege	Vegetables	Pepper	2640
jvege	Vegetables	Pimento	2641
jwhea	Wheat	Wheat	2511
jyams	Yams	Yams	2535

Source: Compiled by authors

Note: FAO = Food and Agriculture Organization of the United Nations; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade. [a] All meat activities are expressed in terms of dressed meat or carcass weight. [b] Demand for pulses is aggregated to total pulses in FAOSTAT and was disaggregated using FAOSTAT production shares. [c] Cotton is treated as cotton lint only in IMPACT 3, with cottonseed not currently included in the model. [d] Groundnuts are treated as shelled equivalent. [e] Rice in IMPACT 3 is treated as milled equivalent.

APPENDIX C: INTERNATIONAL MODEL FOR POLICY ANALYSIS OF AGRICULTURAL COMMODITIES AND TRADE (IMPACT) DATA—INPUTS AND OUTPUTS

Table C.1 IMPACT data requirements in the model base year

Data source	Geographic scope	IMPACT parameter	Commodity requirement	Unit
OECD Agricultural Market Access Database[a]	Global	World prices	All commodities	US dollars per mt
WDI[b] and	National	Population	—	Million
CIA World Factbook[c]		GDP	—	Billion US dollars
FAOSTAT[d] commodity balances	National	Total supply	All commodities	000 mt
		- Animal numbers	Livestock only	000 producing animals
		- Harvest AREA	Crops only	000 ha
		- Yield	Crops and livestock	mt/ha
		Total demand	All commodities	000 mt
		- Food demand	All commodities	000 mt
		- Feed demand	All commodities	000 mt
		- Intermediate demand	All commodities	000 mt
		- Other demand	All commodities	000 mt
		Stock change	All commodities	000 mt
		Net trade	All commodities	000 mt
FAOSTAT food supply	National	Calorie availability	—	kcal/person/day
		Food supply quantity	Food commodities	kilgrams/capita/year
		Food supply	Food commodities	kcal/commodity/person/day
FAO AquaStat[e] and OECD[f]	National	Total irrigated area		000 ha
		Irrigated crop area	Crops only	000 ha
IFPRI SPAM[g]	FPU (aggregated from pixels)	By production system (irrigated and rainfed):		
		- Harvest area	Crops only	000 ha
		- Yield	Crops only	mt/ha
		- Production	Crops only	000 mt

Source: Authors.
Note: CIA = Central Intelligence Agency; FAO = Food and Agriculture Organization of the United Nations; FPU = food production unit; GDP = gross domestic product; IFPRI SPAM = International Food Policy Research Institute Spatial Production Allocation Model; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; ha = hectare; mt = metric ton; kcal = kilocalorie; OECD = Organisation for Economic Co-operation and Development; WDI = World Development Indicator. [a] OECD Agricultural Market Access Database (OECD 2010). [b] World Bank's World Development Indicators (World Bank 2014). [c] US CIA World Factbook used when data missing from World Bank (Central Intelligence Agency 2014). [d] FAO's FAOSTAT database (FAO 2013; FAO 2015). [e] FAO's AquaStat database (FAO 2014). [f] OECD Agriculture Statistics (OECD-FAO 2013). [g] IFPRI SPAM (You et al. 2014).

Table C.2 Key IMPACT behavioral and scenario parameters and assumptions

Parameter/Assumption	Data source	Explanation
Demand elasticities (price and income)	USDA and expert opinion	Determine demand responses to changes in prices and income: They have been adjusted over time to reflect changing preferences for high-value goods over staples due to economic growth. In addition, they are calibrated to be consistent with Engle's Law, where food expenditure falls as a share of total expenditure with economic growth
Supply elasticities	Expert opinion	Determine production response to changes in commodity prices
Marketing margins	OECD and expert opinion	Represent the cost of transporting commodities from the point of production to national and international markets
Producer and consumer support estimates	OECD and expert opinion	Represent subsidies and other national policies that create price wedges between national and international markets
Export taxes and import tariffs	GTAP 7 database	Represent national trade policies and contribute to the price wedge between national and international markets
Exogenous yield growth rates (IPRs)	Expert opinion	Assumptions about how crop and livestock productivity will change over time due to advances in technology: The methodology for calculating IPRs is based on Evenson and Rosegrant (1995) and Evenson et al. (1999). In addition, they have been adjusted over time through consultation with experts and economic model comparison projects.
Population growth rates	SSP database	IMPACT is calibrated to the IIASA SSP 2 population scenario.
GDP growth rates	SSP database	IMPACT is calibrated to the OECD SSP 2 GDP scenario.

Source: Authors.

Note: GTAP = Global Trade Analysis Project at Purdue University; IIASA = International Institute for Applied Systems Analysis; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; OECD = Organisation for Economic Co-operation and Development; SSP = Shared Socioeconomic Pathway; USDA = United States Department of Agriculture.

Table C.3 Standard IMPACT multimarket model outputs

IMPACT result	Unit	Geographic scope	Time scope
Prices			
World prices	2005 US$/mt	Global	Annual
Consumer prices	2005 US$/mt	National	Annual
Producer prices	2005 US$/mt	National	Annual
Supply			
Total supply	000 mt	National, FPU	Annual
Harvest area	000 ha	National, FPU	Annual
Animal numbers	000 producing animals	National, FPU	Annual
Yield	mt/ha or mt/animal	National, FPU	Annual
Demand			
Total demand	000 mt	National	Annual
Food demand	000 mt	National	Annual
Feed demand	000 mt	National	Annual
Intermediate demand	000 mt	National	Annual
Biofuel demand	000 mt	National	Annual
Other demand	000 mt	National	Annual
Trade			
Net trade	000 mt	National	Annual
Net exports	000 mt	National	Annual
Net imports	000 mt	National	Annual
Trade share of production	%	National	Annual
Trade share of demand	%	National	Annual
Food security			
Food availability	kilogram/person	National	Annual
Kilocalorie availability	kcal/person/day	National	Every 5 years
Undernourished children	million	National	Every 5 years
Share at risk of hunger	%	National	Every 5 years
Population at risk of hunger	million	National	Every 5 years

Source: Authors.
Note: FPU = food production unit; ha = hectare; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; kcal = kilocalorie; mt = metric ton.

Table C.4 Standard IMPACT regional aggregations

Region code[a]	Country codes[b]
EAP	AUS, CHM, FJI, IDN, JPN, KHM, KOR, LAO, MMR, MNG, MYS, NZL, OIO, OPO, OSA, PHL, PNG, PRK, SLB, THA, TLS, VNM, VUT
EUR	ALB, AUT, BGR, BLT, BLX, CHP, CYP, CZE, DEU, DNK, FNP, FRP, GRC, HRV, HUN, IRL, ISL, ITP, NLD, NOR, OBN, POL, PRT, ROU, SPP, SVK, SVN, SWE, UKP
FSU	ARM, AZE, BLR, GEO, KAZ, KGZ, MDA, RUS, TJK, TKM, UKR, UZB
LAC	ARG, BLZ, BOL, BRA, CHL, COL, CRB, CRI, CUB, DOM, ECU, GSA, GTM, HND, HTI, JAM, MEX, NIC, PAN, PER, PRY, SLV, URY, VEN
MEN	DZA, EGY, IRN, IRQ, ISR, JOR, LBN, LBY, MOR, MRT, PSE, RAP, SAU, SYR, TUN, TUR, YEM
NAM	CAN, GRL, USA
SAS	AFG, BGD, BTN, IND, LKA, NPL, PAK
SSA	AGO, BDI, BEN, BFA, BWA, CAF, CIV, CMR, COD, COG, DJI, ERI, ETH, GAB, GHA, GIN, GMB, GNB, GNQ, KEN, LBR, LSO, MDG, MLI, MOZ, MWI, NAM, NER, NGA, OAO, RWA, SDN, SEN, SLE, SOM, SWZ, TCD, TGO, TZA, UGA, ZAF, ZMB, ZWE

Source: Authors.

Note: IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade. [a] EAP = East Asia and Pacific; EUR = Europe; FSU = Former Soviet Union; LAC = Latin America and Caribbean; MEN = Middle East and North Africa; NAM = North America SAS = South Asia; SSA = Africa south of the Sahara. [b] IMPACT country codes are defined in Table A.1.

APPENDIX D: INTERNATIONAL MODEL FOR POLICY ANALYSIS OF AGRICULTURAL COMMODITIES AND TRADE (IMPACT) MODEL DECLARATION IN GENERAL ALGEBRAIC MODELING SYSTEM

```
Variables
* Price Variables
PPV(j,cty)     producer price of activity j
PNETV(j,cty)   Net price of activity j
PWV(c)         world price of commodity c
PCV(c,cty)     consumer price of commodity c
PMV(c,cty)     domestic price of imports
PEV(c,cty)     domestic price of exports
WFV(fpu,fctr)  shadow price index of land by fpu and land type
* Supply Variables
QFSV(fpu,fctr)    supply of land by fpu and land type
AREAV(j,fpu,fctr) crop area by fpu and land type lnd
YLDV(j,fpu,fctr)  crop yields by fpu and land type lnd
YLDTECHV(j,fpu,fctr,tech) crop yields by tech
QSV(j,cty)        total production of activities
WQSV(j)           sum of production across all countries for each crop
QSUPV(c,cty)      commodity supply
* Demand Variables
 QDV(c,cty)     final demand for commodity
 QHDV(c,h,cty)  household demand
 QLV(c,cty)     livestock sector feed demand
 QINTV(c,cty)   intermediate demand for commodity
 EHV(h,cty)     Household Expenditure per capita
 STV(c,cty)     stock change for each country
 QOTHRV(c,cty)  Other demand
* Trade Variables
QNV(c,cty)     net trade for each country and traded commodity
QEV(c,cty)     exports for each country and traded commodity
QMV(c,cty)     imports for each country and traded commodity
NTRADEV(c)     sum of net trade across all countries for each crop
;

Equations
* Prices
PPEqn(j,cty)    producer price
PMDEqn(c,cty)   domestic price of imports
PEDEqn(c,cty)   domestic price of exports
PMEqn(c,cty)    consumer price LE to domestic price of imports
PMNTEqn(c,cty)  consumer price EQ PM if tradable but not non traded
PEEqn(c,cty)    consumer price GE to domestic price of exports
PNETEqn(j,cty)  net price of activity j
* Supply
QFSEqn(fpu,lnd)    supply of land by fpu and land type lnd
AreaEqn(j,fpu,lnd) area for crops by fpu and land type lnd
LandEqn(fpu,lnd)   land allocation equilibrium
YldEqn(j,fpu,lnd)  yield for crops by fpu and land type lnd
YldEqn2(j,fpu,lnd) average yield for crops by fpu lnd across tech
YldTechEqn(j,fpu,lnd,tech) yield for crops by fpu lnd and tech
QSEqn1(j,cty)      supply for cty from area times yield in fpu and lnd
QSEqn2(j,cty)      supply by cty as function of PNETV
QSEqn3(j,cty)      supply by cty as function of PPV and PCV of inputs
```

```
QsEqn4(j,cty)      supply by cty from AnmlNum and anmlyld in fpu and lvsys
PcostEqn(j,cty)    link between intermediate input price and output price
QSUPEqn(c,cty)   commodity supply
WQSEqn(j)        total world supply production
* Commodity demand
QINTEqn(c,cty)   total intermediate demand for commodity in activity
QHEqn1(c,h,cty)  household demand with standard demand functions
QOthrEqn1(c,cty) Other demand
QOthrEqn2(c,cty) Other demand for milk
QDEqn(c,cty)     Total demand
* Trade and commodity market equilibrium conditions
QNEqn(c,cty)     country level net trade
QNEqn2(c,cty)    supply demand balance for non traded commodities
QNEqn2A(c,cty)   supply demand balance for non traded commodities with PCV.LO
QNEqn3(c,cty)    net trade equals QE minus QM
NTRADEEqn(c)     total world net trade
NetTradeEqn(c)   equilibrium condition on net trade
;

*++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
* Price Equations
*++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
* Producer prices
PPEqn(j,cty1)$iprod(j,cty1).. PPV(j,cty1)*(1 + MMJ(j,cty1)) =E=
 (1 + PSE(j,cty1))*sum[c$jcratio(j,c,cty1), jcratio(j,c,cty1)*PCV(c,cty1)]
 ;

* Define domestic price of exports and imports
PMDEqn(c,cty1)$ctrade(c).. PMV(c,cty1) =E= PWV(c)*exr(cty1)*
 (1 + tm(c,cty1))*(1 + MMM(c,cty1)) ;
PEDEqn(c,cty1)$ctrade(c).. PEV(c,cty1) =E= PWV(c)*exr(cty1)*
 (1 - te(c,cty1))*(1 - MME(c,cty1)) ;

* Consumer prices for traded goods, linked to world prices
* Adjusted world price for imports must exceed adjusted world price for
* exports. For imports, domestic price of imports =G= PCV. If =E=, then
* country imports
PMEqn(c,cty1)$ctrdnt(c,cty1).. PMV(c,cty1) =G= PCV(c,cty1) ;

* For purely tradable goods, PCV always equals PMV and PEV is not used
PMNTEqn(c,cty1)$(ctrade(c) and not ctrdnt(c,cty1)).. PCV(c,cty1) =E=
PMV(c,cty1) ;

* For exports, PCV =G= domestic price of exports, If =E=, then country
exports
PEEqn(c,cty1)$ctrdnt(c,cty1)..   PCV(c,cty1) =G= PEV(c,cty1) ;

* Complementarity relationships for PMEqn and PEEqn
 QMV.LO(c,cty1)$ctrdnt(c,cty1) = 0 ;
 QEV.LO(c,cty1)$ctrdnt(c,cty1) = 0 ;

* Net price equation. Output price minus intermediate input costs
* Special treatment for sugar processing as an option below
* Note that PNET will equal PPV whenever there are no intermediate inputs,
* and intermediate inputs can be non-produced commodities (e.g.
* fertilizer).
PNETEqn(j,cty1)$iprod(j,cty1).. PNETV(j,cty1) =G= PPV(j,cty1) -
```

```
 ( 1 - CSEINT(j,cty1)) *
 SUM[c$iomat(c,j,cty1), iomat(c,j,cty1)*PCV(c,cty1)] ;

*++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
* Land, Area and Yield equations
*++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
* Supply of factor land by type. Assumed to be a function of the
* "scarcity value" or "shadow price index" of land (WFV).
QFSEqn(fpu1,lnd)$(fpuLnd(fpu1,lnd)   and
         (not wlndfx(fpu1,lnd)) and
         (twostep ne 2))..
 QFSV(fpu1,lnd) =E= QFSInt(fpu1,lnd)*
   QFSInt2(fpu1,lnd)*WFV(fpu1,lnd)**QFSElas(fpu1,lnd) ;

* Demand of factor land by type. The equation takes account of the
possibility
* that land demand is fixed, with all AreaElas parameters equal to zero.
AreaEqn(j,fpu1,lnd)$(ftech(j,fpu1,lnd) and (twostep ne 2))..
 AREAV(j,fpu1,lnd) =E=
 [(Area1(j,fpu1,lnd)*AreaLagInt2(j,fpu1,lnd))**(AreaLagElas(j,fpu1,lnd))] *
* [(Area1(j,fpu1,lnd))**(AreaLagElas(j,fpu1,lnd))] *
 {
 AreaInt(j,fpu1,lnd)*AreaInt2(j,fpu1,lnd)*
 WFV(fpu1,lnd)**WFElas(j,fpu1,lnd)*
  IFTHEN{AreaElasChk(j,fpu1,lnd),
   SUM{cty1$fpu2cty(fpu1,cty1),
     PROD[jj$AreaElas(j,jj,fpu1,lnd),
        ([PNETV(jj,cty1)]/[PNET00(jj,cty1)])**AreaElas(j,jj,fpu1,lnd)
*
([YldV(jj,fpu1,lnd)*PNETV(jj,cty1)]/[Yld00(jj,fpu1,lnd)*PNET00(jj,cty1)])**
    AreaElas(j,jj,fpu1,lnd)
       ]
    },
  1} }**(1-AreaLagElas(j,fpu1,lnd))
 ;



* Land allocation equilibrium
LandEqn(fpu1,lnd)$(fpuLnd(fpu1,lnd)   and
*          (not wlndfx(fpu1,lnd)) and
         (twostep ne 2))..
 SUM(j$ftech(j,fpu1,lnd), AREAV(j,fpu1,lnd)) =E= QFSV(fpu1,lnd) ;

* Yield equations for non-cultivar specification.
* Intermediate input prices are taken into account through
* the net price equation, PNET. No cross-price elasticities.
YldEqn(j,fpu1,lnd)$(ftech(j,fpu1,lnd) eq 1).. YLDV(j,fpu1,lnd) =E=
 YLDint(j,fpu1,lnd)*YldInt2(j,fpu1,lnd)*YldShk(j,fpu1,lnd)*
 YldCliShk(j,fpu1,lnd)*
 IFTHEN[YldElasWFChk(j,fpu1,lnd),
  PROD(pfac$YldElasWF(j,fpu1,lnd,pfac),
  WFV(fpu1,pfac)**YldElasWF(j,fpu1,lnd,pfac)), 1]*
 SUM[cty1$fpu2cty(fpu1,cty1),
  (PNETV(j,cty1)/PNET00(j,cty1))**YldElas(j,fpu1,lnd)]
 ;
```

```
* Yield equations by fpu if there are cultivars. Average across cultivars.
YldEqn2(j,fpu1,lnd)$(ftech(j,fpu1,lnd) eq 2).. YLDV(j,fpu1,lnd) =E=
 SUM(tech$jTechShr(j,fpu1,lnd,tech),
 YldTechV(j,fpu1,lnd,tech)*jTechShr(j,fpu1,lnd,tech))
 ;

* Yield equation by cultivar, if used.
YldTechEqn(j,fpu1,lnd,tech)$((ftech(j,fpu1,lnd) eq 2) and
              YldTech00(j,fpu1,lnd,tech))..
 YldTechV(j,fpu1,lnd,tech) =E=
 YldTechInt(j,fpu1,lnd,tech)*YldTechInt2(j,fpu1,lnd,tech)*
 YldTechInt3(j,fpu1,lnd,tech)*YldTechShk(j,fpu1,lnd,tech)*
 YldCliShk(j,fpu1,lnd)*
 IFTHEN[YldElasWFChk(j,fpu1,lnd),
  PROD(pfac$YldElasWF(j,fpu1,lnd,pfac),
  WFV(fpu1,pfac)**YldElasWF(j,fpu1,lnd,pfac)), 1]*
 SUM[cty1$fpu2cty(fpu1,cty1),
   (PNETV(j,cty1)/PNET00(j,cty1))**YldTechElas(j,fpu1,lnd,tech)]
 ;

*++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
* Supply Equations
*++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

* Supply for crops. Aggregate output across fpu1 and lnd in each cty1
QSEqn1(j,cty1)$(jtech(j,cty1) eq 1).. QSV(j,cty1) =E=
 SUM[(fpu1,lnd)$(ftech(j,fpu1,lnd) and fpu2cty(fpu1,cty1)),
 YLDV(j,fpu1,lnd)*AREAV(j,fpu1,lnd)]
 ;

* Include cross-price supply elasticities for non-crop supply functions
* Regional activity Supply Equations, if jtech(j,cty1) eq 2
QSEqn2(j,cty1)$(jtech(j,cty1) eq 2).. QSV(j,cty1) =E=
 QSInt(j,cty1)*QSInt2(j,cty1)*
 PROD[jj$QSElas(j,jj,cty1),
 (PNETV(jj,cty1)/PNET00(jj,cty1))**QSElas(j,jj,cty1)]
 ;

* Total commodity supply from production
QSUPEqn(cj,cty1)$csup(cj,cty1)..  QSUPV(cj,cty1) =E=
 SUM(j$jcratio(j,cj,cty1), jcratio(j,cj,cty1)*QSV(j,cty1))
 ;

* World Supply Equation by activity
WQSEqn(j).. WQSV(j) =E= SUM(cty1, QSV(j,cty1)) ;

*++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
* Demand Equations
*++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

* Intermediate demand
QINTEqn(c,cty1)$SUM(j, iomat(c,j,cty1)).. QINTV(c,cty1) =E=
 SUM(j$iomat(c,j,cty1), iomat(c,j,cty1)*QSV(j,cty1))
 ;

* Standard demand curve
```

```
QHEqn1(c,h,cty1)$(PopH(h,cty1) and hdmnd(c,h,cty1) and (hdmnd2(h,cty1) =
1))..
 QHDV(c,h,cty1) =E=
 QHDInt(c,h,cty1)
 * [(pcGDPH(h,cty1)/pcGDPH00(h,cty1))**IncDmdElasH(c,h,cty1)]
 * PROD[cc$FDElasH(c,cc,h,cty1),
  [(PCV(cc,cty1)*(1 - CSE(cc,cty1))) /
  (PC00(cc,cty1)*(1 - CSE(cc,cty1)))]**FDElasH(c,cc,h,cty1)]
 * [PopH(h,cty1) / PopH00(h,cty1)] ;

* Other demand that grow with a trend on the lag and is not price sensitive
(small demand)
QOTHREqn1(c,cty1)$[QOTHR00(c,cty1) and IDMND(c,cty1) and (not
Cothdmd(c,cty1))]..
 QOTHRV(c,cty1) =E=
  [QOthr1(c,cty1) *
(sum(h,QHDV(c,h,cty1))/sum(h,QHD1(c,h,cty1)))]$sum(h,QHD1(c,h,cty1)) +
  [QOthr1(c,cty1) * (pcGDP(CTY1)/pcGDP1(cty1))]$(sum(h,QHD1(c,h,cty1)) eq 0)
;

* Other demand that is price sensitive
QOTHREqn2(c,cty1)$[QOTHR00(c,cty1) and IDMND(c,cty1) and Cothdmd(c,cty1)]..
QOTHRV(c,cty1) =E=
 QOTHRInt(c,cty1) * QOTHRInt2(c,cty1) *
 ((pcGDP(cty1)/pcGDP00(cty1))**OthDmdIElas(c,cty1)) * (Pop(cty1)/Pop00(cty1))
*
 PROD[cc$OthDmdPElas(c,cc,cty1),
  (PCV(cc,cty1)/PC00(cc,cty1))**OthDmdPElas(c,cc,cty1)]
;

* Total Demand
QDEqn(c,cty1).. QDV(c,cty1) =E=
 SUM(h, QHDV(c,h,cty1)) + QINTV(c,cty1) + QLV(c,cty1) + QBFV(c,cty1) +
 QOTHRV(c,cty1)
;

*+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
* Trade and commodity market equilibrium conditions
*+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

* Regional Net Trade for traded goods
QNEqn(c,cty1)$ctrade(c).. QNV(c,cty1) =E=
 QSUPV(c,cty1) - QDV(c,cty1) - STV(c,cty1) ;

* Equation links QNV to exports and imports since both must be positive
QNEqn3(c,cty1)$ctrdnt(c,cty1).. QNV(c,cty1) =E=
 QEV(c,cty1) - QMV(c,cty1) ;

* Supply-demand balance for non-traded goods, which determines PCV
QNEqn2(c,cty1)$((not ctrade(c)) and csup(c,cty1) and (NOT cLow(c,cty1)) )..
 QSUPV(c,cty1) =E= QDV(c,cty1) + STV(c,cty1) ;

* Supply-demand balance for non-traded goods, which determines PCV
QNEqn2A(c,cty1)$((not ctrade(c)) and csup(c,cty1) and cLow(c,cty1))..
 QSUPV(c,cty1) =G= QDV(c,cty1) + STV(c,cty1) ;
```

```
* World Sum of Net Trade
NetTradeEqn(cj)$(ctrade(cj)   and
        (card(cty1) ne 1) and
        (NOT cpwfx(cj)))..   NTRADEV(cj) =E= 0 ;

*++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
* Model definition
*++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
Model IMPACT3_Crop
/
* Prices
 PPEqn.PPV
 PMDEqn.PMV
 PEDEqn.PEV
 PMEqn.QMV
 PMNTEqn.PCV
 PEEqn.QEV
 PNETEqn.PNETV
* Supply
 QFSEqn.QFSV
 AREAEqn.AREAV
 LandEqn
 YLDEqn.YldV
 YLDEqn2.YldV
 YLDTechEqn.YldTechV
 QSEqn1.QSV
 QSEqn2.QSV
 QSEqn3.QSV
 PcostEqn.QSV
 QSUPEqn.qsupv
 WQSEqn.WQSV
* Commodity Demand
 QothrEqn1.QothrV
 QothrEqn2.QothrV
 QINTEqn.QINTV
 QHEqn1.QHDV
 QBFEqn.QBFV
 QDEqn.QDV
* Trade and commodity market equilibrium
 QNEqn.QNV
 QNEqn2.PCV
 QNEqn2A.PCV
 QNEqn3.PCV
 NTRADEEqn.NTRADEV
 NETTRADEEqn.PWV
/ ;
```

APPENDIX E: INTERNATIONAL MODEL FOR POLICY ANALYSIS OF AGRICULTURAL COMMODITIES AND TRADE (IMPACT) WATER MODELS

The IMPACT global hydrology model (IGHM) was first described in the IMPACT 2 technical description (Rosegrant and IMPACT Development Team 2012) and its main structure has remained the same. The explanation of the equations from Rosegrant and IMPACT Development Team (2012) follows. The IMPACT water basin simulation model (IWSM) has been modified between IMPACT 2 and IMPACT 3 to account for new ways of optimizing water allocation across a river basin.

IGHM

IGHM is a semidistributed parsimonious model. It simulates snow accumulation and melt, soil moisture balance, evapotranspiration, and runoff generation at monthly intervals and on each 0.5˚ latitude by 0.5˚ longitude grid cell spanning the global land surface except the Antarctic. Gridded output of hydrological fluxes, namely, effective rainfall (for calculating net irrigation water requirement in IWSM), potential and actual evapotranspiration, and runoff are spatially aggregated to food production units (FPUs) within the river basin, weighted by grid cell areas, and then incorporated into IWSM.

The most dominant climatic drivers for water availability are precipitation and evaporative demand determined by net radiation at ground level, atmospheric humidity, wind speed, and temperature. In IGHM, the Priestley-Taylor equation is used to calculate potential evapotranspiration:

IGHM Equation 1: Potential Evapotranspiration

$$PET = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G) \tag{IGHM.1}$$

In the above equation (IGHM.1), *PET* is potential evapotranspiration in millimeters per day; the value of α is 1.26 in humid climates and 1.74 in arid locations. The humid and arid conditions are defined as having relative humidity greater or less than 60 percent in the month with peak evapotranspiration, Δ is the slope of the vapor pressure curve in kPa °C – 1, γ is the psychrometric constant in kPa °C – 1, R_n is net radiation at the land surface in millimeters per day, and *G* is soil heat flux density in millimeters per day.

Soil moisture balance is simulated at each grid cell using a single-layer water bucket. To represent subgrid variability of soil water-holding capacity *c* we assume that it varies spatially within each grid cell following a parabolic distribution function (IGHM.2).

IGHM Equation 2: Soil Water-holding Capacity

$$f(c) = 1 - \left(1 - \frac{c}{C_m}\right)^b \tag{IGHM.2}$$

where f(c) is the fraction of area in a grid cell that has soil water-holding capacity values lower than *c*, C_m is the maximum soil water-holding capacity value across all points within the grid cell, and *b* is the shape parameter that defines the degree of spatial variability of soil moisture-holding capacity *c*.

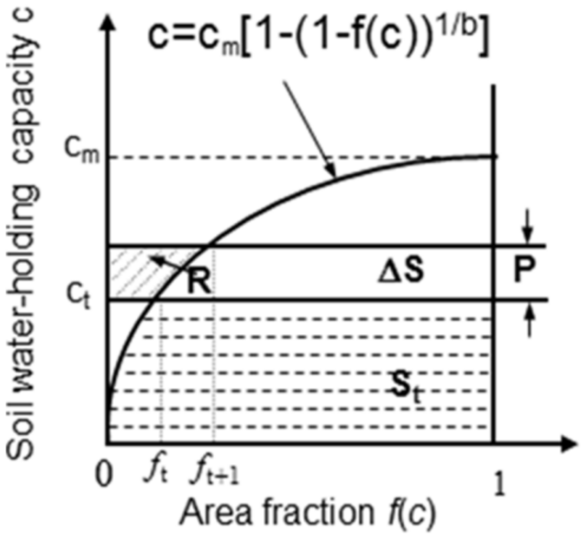
The maximum amount of water that can be held in the grid cell is

IGHM Equation 3: Maximum Water-holding Capacity

$$S_m = \int_0^{C_m} [1 - f(c)]\, dc = \frac{C_m}{1 + b} \tag{IGHM.3}$$

In Figure E.1, S_m equals the area between the parabolic curve and the x-axis with area fraction values of the x-axis ranging from 0 to 1.

Figure E.1 Statistical distribution of soil water-holding capacity and runoff generation in a grid cell



Source: Modified from Zhao (1992) and Wood et al. (1992).
Note: P = precipitation; R = runoff; S = soil moisture content.

Assuming that at any time *t* each point in the grid cell is either at C_m or at a constant moisture state *c* (Zhao 1992), the mean areal water storage *S* associated with soil water-holding capacity *c* at time *t* is given by the following equation:

IGHM Equation 4: Mean Areal Water Storage

$$S_t = S_m \times \left[1 - \left(1 - \frac{c_t}{C_m}\right)^{1+b}\right] \qquad \text{(IGHM.4)}$$

With precipitation P_t and actual evapotranspiration AET_t in time period *t,* runoff is determined by the following equations:

IGHM Equation 5: Calculating Runoff

If $c_t + P_t - AET < C_m$, (IGHM.5)

$$R_t = P_t - AET_t - \Delta S = P_t - AET_t - S_m \times \left[\left(1 - \frac{c_t}{C_m}\right)^{1+b} - \left(1 - \frac{c_t + P_t - AET_t}{C_m}\right)^{1+b}\right]$$

Otherwise, if $c_t + P_t - AET > C_m$,

$$R_t = P_t - AET_t - (S_m - S_t) = P_t - AET_t - S_m + S_m \times \left[\left(1 - \frac{c_t}{C_m}\right)^{1+b} - \left(1 - \frac{c_t + P_t - AET_t}{C_m}\right)^{1+b}\right]$$

The *AET* is determined jointly by the *PET* and relative soil moisture state in a grid cell at time period *t:*

IGHM Equation 6: Actual Evapotranspiration

$$AET_t = PET_t \times \frac{S_t}{S_m} \qquad \text{(IGHM.6)}$$

Runoff generated in time period *t* is divided into a surface runoff component *RS* and a deep percolation component using partitioning factor λ:

IGHM Equation 7: Runoff Partitioning

$$RS_t = \lambda \times R_t \qquad \text{(IGHM.7)}$$

A linear reservoir is assumed to model base flow *RB*. The storage of the linear reservoir is linearly related to output, namely, base flow by a storage constant β (Chow et al. 1988):

IGHM Equation 8: Reservoir Base Flow

$$RB_t = \beta \times G_t \qquad \text{(IGHM.8)}$$

where G_t is storage value in time period *t*. The change of reservoir storage during time period *t* equals the difference between deep percolation and base flow occurred in this period:

IGHM Equation 9: Change in Reservoir Storage

$$G_t - G_{t-1} = (1 - \lambda) \times R_t - RB_t \qquad \text{(IGHM.9)}$$

Total runoff generated in time period *t* is the sum of surface runoff and base flow:

IGHM Equation 10: Total Generated Runoff

$$R_t = RS_t + RB_t \qquad \text{(IGHM.10)}$$

In the above equations calibration parameters include the subgrid variability shape parameter *b,* the total runoff partitioning parameter λ, the storage constant β, and the average soil water-holding capacity S_m. Conceptually, S_m should equal available water—namely, field capacity less wilting point—in a soil moisture–accounting perspective. However, because of the monthly time step adopted, using measured available water rather than calibrating S_m can significantly overestimate runoff and underestimate actual evapotranspiration as found in our calibration experiments.

IWSM

IWSM includes three components: (1) water demand projections for domestic, industrial, livestock, and irrigation sectors; (2) water supply optimization; and (3) water allocation across sectors. The model can simulate water use impacts of technological and socioeconomic changes as well as climate change.

Water Demand Projection

IWSM Equation 1: Crop Water Requirement

$$ETM_{fpu,i,\mathrm{m}} = kc_{i,\mathrm{m}} \times ETo_{fpu,m} \qquad \text{(IWSM.1)}$$

where

i	=	commodity index (only for crops),
fpu	=	food production unit,
m	=	month,
ETo	=	reference evapotranspiration, and
kc	=	crop coefficient.

Irrigation Water Demand

Irrigation water demand is assessed as the portion of crop water requirement (IWSM.2) not satisfied by precipitation or soil moisture based on hydrologic and agronomic characteristics. Net irrigation water demand (NIRWD) in an FPU is calculated based on an empirical crop water requirement function (Doorenbos and Pruit 1977) and irrigated area of the crop.

IWSM Equation 2: Net Irrigation Water Requirement per Crop

$$NIRWD_{fpu,i} = \sum_m Max\left[0,\ ETM_{fpu,i,m} - PE_{fpu,m}\right] \times AI_{fpu,i} \qquad \text{(IWSM.2)}$$

where

$ETM_{fpu,i,\mathrm{m}}$	=	Maximum evapotranspiration in month m for crop i
$PE_{fpu,m}$	=	Effective rainfall in month i
$AI_{fpu,i}$	=	Irrigated area for crop i

Part or all of crop water demand can be satisfied by effective rainfall (PE), which is the rainfall infiltrated into the root zone and available for crop use. Effective rainfall for crop growth can be increased through rainfall harvesting technology.

Effective Rainfall

Effective rainfall depends on total rainfall (*PT*), previous soil moisture content (*SM*0), maximum crop evapotranspiration (*ETM*), and soil characteristics (hydraulic conductivity *K,* moisture content at field capacity Z_s, and others). *PE* is calculated by a SCS (Soil Conservation Service) method (USDA-SCS 1993), given *PT, ETM,* and effective soil water storage.

IWSM Equation 3: Effective Rainfall

$$PE = SF \times (0.70917PT^{0.82416} - 0.11556) \times 10^{0.02426 \times ETM} \qquad \text{(IWSM.3)}$$

in which SF is the soil water storage factor and is given by the following equation.

IWSM Equation 4: Soil Water Storage

$$SF = 0.531747 + (0.295167 \times D) - (0.057697 \times D^2) + (0.003804 \times D^3) \qquad \text{(IWSM.4)}$$

where D represents the usable soil water storage in inches and is generally calculated as 40 to 60 percent of available soil water capacity in the crop root zone, depending on the irrigation management practices in use (USDA-SCS 1993).

Technology scenarios can be modeled by adjusting the effective rainfall value to reflect improved rainfall harvesting technology. Rainfall harvesting is the capture, diversion, and storage of rainwater for plant irrigation and other uses and can be an effective water conservation tool, especially in arid and semiarid regions. Water harvesting can provide farmers with improved water availability, increased soil fertility, and higher crop production in some local and regional ecosystems and can also provide broader environmental benefits through reduced soil erosion. Advanced tillage practices also can increase the share of rainfall that goes to infiltration and evapotranspiration. Contour plowing, which is typically a soil-preserving technique, should act also to detain and infiltrate a higher share of the precipitation. Precision leveling also can lead to greater relative infiltration and therefore a higher percentage of effective rainfall.

Gross irrigation water demand for all crops, with consideration of effective rainfall use and salt leaching requirement, is

IWSM Equation 5: Gross Irrigation Water Demand

$$GIWD_{fpu} = \frac{\sum_i NIRWD_{fpu,i} \times AI_{fpu,i} \times (1 + LR)}{BE} \qquad \text{(IWSM.5)}$$

where

LR	=	salt-leaching factor, and
BE	=	basin efficiency.

The concept of basin efficiency was discussed and various definitions were provided by Keller, Keller and Seckler (1996). Basin efficiency is defined as the ratio of beneficial water depletion (crop evapotranspiration and salt leaching) to total irrigation water depletion at the FPU scale. Basin efficiency in the base year (2005) is calculated as the ratio of the net irrigation water demand (NIRWD, IWSM.2) to the total irrigation water depletion estimated from records (Shiklomanov 1999). Basin efficiency in future years is assumed to increase at a prescribed rate in an FPU depending on water infrastructure investment and water management improvement in the FPU.

The projection of irrigation water demand depends on the changes in irrigated area and cropping patterns,[18] basin efficiency, and effective rainfall. Global climate change affects future irrigation water demand through changes in precipitation and temperature along with other meteorological variables that affect crop evapotranspiration.

Livestock Water Demand

Livestock water demand is estimated using livestock numbers and water consumptive use per unit of livestock (w_{lv}), including beef, milk, pork, poultry, eggs, and sheep and goats (de Fraiture 2007; Steinfeld et al. 2006). The total number of live animals during a year includes slaughtered animals, the followers herd, and other categories (for example, milk-producing animals). The total number of animals is calculated based on the number of slaughtered animals (QS_{lv}) and a ratio of the number of slaughtered animals to the total number of animals (r_{lv}) (IWSM.6).

IWSM Equation 6: Total Number of Animals

$$LVWD_t = QS_{lv} \times r_{lv} \times w_{lv} \qquad \text{(IWSM.6)}$$

Industrial Water Demand

Industrial water demand is modeled for the manufacturing and energy sectors using growth rates for the value-added by sector and energy production values for the electricity sector from the EPPA6 Model of the MIT Joint Program on the Science and Policy of Global Change (Chen et al. 2015). For many countries in Africa south of the Sahara, the projected industrial water demands are substantially lower than those in IMPACT 2, suggesting an underestimation. Therefore, for countries in Africa south of the Sahara we retained the projection method of IMPACT 2—namely, the industrial water demand is modeled as a nonlinear function of gross domestic production per capita and technology change. In IWSM equation 7, ε is income elasticity of demand, and Y^t is the technology term, which is determined according to our perspectives on future industrial water demand and technological improvements in industrial water use in different regions.

IWSM Equation 7: Industrial Water Demand

$$INWD_t = \alpha \times (pcGDP_t)^{\varepsilon} \times EXP(\gamma_t) \qquad \text{(IWSM.7)}$$

Domestic Water Demand

Domestic water demand includes municipal water demand and rural domestic water demand. Annual per capita domestic water consumption is based on previous work with the International Water Management Institute (de Fraiture 2007; Rosegrant, Cai, and Cline 2002), with necessary adjustments to ensure that per capita consumption in rural and urban households is not less than 15 liters per day and 25 liters per day, respectively. Total domestic water consumption at the FPU level equals population multiplied by annual per capita consumption, as seen in IWSM equation 8. The growth of domestic per capita consumption is based on projections of per capita gross domestic product as seen in IWSM equation 9. In each region or

[18] These cropping pattern assumptions are the same as those used in the multimarket model described above.

basin, income elasticities η of demand for domestic water use are synthesized based on the literature and available estimates (de Fraiture 2007). These elasticities of demand measure the propensity to consume water with respect to increases in per capita income. The elasticities also capture both direct income effects and conservation of domestic water use through technological and management change. In higher-income countries where per capita domestic consumption is high, the elasticities of demand imply that water demand will decline with increased income growth, whereas in developing countries the elasticities imply an increase in water consumption with increased income growth.

IWSM Equation 8: Domestic Water Demand

$$DOWD_t = POP_t \times pcDOWD_t \qquad \text{(IWSM.8)}$$

IWSM Equation 9: Per Capita Domestic Water Demand

$$pcDOWD_t = pcDOWD_{t-1} \times \left(1 + \eta \times \phi_{pcGDP}\right) \qquad \text{(IWSM.9)}$$

Water Supply Optimization

IWSM is an optimization-driven simulation model with operating rules implicitly given by the objective function and constraints in the following quadratic programming model, coded in GAMS. The model runs at monthly time step and is solved for individual years using the CPLEX solver.[19] Adjacent years are linked through reservoir storage. Although the model is solved for all the 320 FPUs in the world simultaneously each year, it is the same as solving the 154 aggregated river basins individually because only FPUs within the same basin are connected through upstream-to-downstream water transport.

Table E.1 IMPACT water basin simulation model variable definitions

Variable	Definition
$INFLWV_{fpu,m}$	Monthly inflows from upstream food production units
$EVAPV_{fpu,m}$	Monthly reservoir evaporation
$STRGV_{fpu,m}$	Reservoir storage at the end of month m
$SPV_{fpu,m}$	Monthly reservoir spill
$SWDPV_{fpu,m}$	Monthly surface water depletion
$GWDPV_{fpu,m}$	Monthly groundwater depletion
$RAV_{fpu,m}$	Monthly ratio of water supply to water demand
$MINRAV_{fpu}$	The minimum ratio of monthly water supply to water demand
$IRRWUV_{fpu,m}$	Slack variable for evaporation equation
$GRWSLACKV_{fpu,m}$	Slack variable for groundwater-surface water exchange
$NIRSHORTV_{fpu,m}$	Slack variable for the shortage of nonirrigation water

Source: Authors.
Note: All variables are positive variables (greater than or equal to 0). fpu = food production unit; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; m = month.

The objective function minimizes the sum of a set of objectives summed across all FPUs, including the annual sum of squared deviations from 1 of monthly ratios of irrigation water supply to demand, squared deviation from 1 of the minimum irrigation water supply to demand ratio across all months, squared deviation from 1 of the ratio of end of year storage to reservoir storage capacity, and

[19] See GAMS Solver manual for more information www.gams.com/help/topic/gams.doc/solvers/allsolvers.pdf

penalty terms. $STCAP_{fpu}$ is reservoir storage capacity. $WFPU_{fpu}$, WRA_{fpu}, $MINRA_{fpu}$, $WSTRG_{fpu}$, $WEVSLK$, and $WNIRST$ are weighting factors. High values are assigned to the weighting factors of the slack variables to force the solution of the slack variables to zero, through the minimization.

IWSM Equation 10: Objective Function

$$\min\ OBJSQV = \sum_{fpu} WFPU_{fpu} \times \left[WRA_{fpu} \times \sum_{m} \left(RAV_{fpu,m} - 1\right)^2 + MINRA_{fpu} \times \left(MINRAV_{fpu} - 1\right)^2 + WSTRG_{fpu} \times \left(\frac{STRGV_{fpu,M}}{STCAP_{fpu}} - 1\right)^2 + WEVSLK \times \sum_{m} EVAPSLACKV_{fpu,m} + WNIRST \times \sum_{m} NIRSHORTV_{fpu,m} \right] \tag{IWSM.10}$$

The reservoir monthly water balance equation states that reservoir storage at the end of a month equals storage at the beginning of the month, plus incoming flows, which include inflow from upstream FPUs within the same river basin and the surface water component of internal renewable water resource (that is, total internal renewal water resource less the overlap between surface water and groundwater, $GWX_{fpu,m}$), minus outgoing flows including reservoir surface evaporation, reservoir spill, and surface water depletion. We implicitly assume that return flow of surface water withdrawal rejoins the water system within the same month.

IWSM Equation 11: Reservoir Monthly Water Balance

$$STRGV_{fpu,m} = STRGPV_{fpu,m} + \left(IRW_{fpu,m} - GWX_{fpu,m} + INFLOWV_{fpu,m}\right) - \left(EVAPV_{fpu,m} + SPV_{fpu,m} + SWDPV_{fpu,m}\right) \tag{IWSM.11}$$

In the base year, because beginning storage is unknown, beginning storage is set as equivalent to the end-of-period storage of the last month. This is equivalent to the IWSM running an infinite number of times using base year data such that the ending storage converges to a certain value. In case it is not the base year, beginning storage of the first month is set at the ending storage of the last month of the previous year ($ISTRG_{fpu}$). For all other months, beginning storage of a month equals ending storage of the previous month.

IWSM Equation 12: Beginning-of-period Storage in the First Month

$$STRGPV_{fpu,m} = \begin{cases} STRGV_{fpu,12}, & m = 1 \text{ and Base Year} \\ ISTRG_{fpu}, & \mathrm{m} = 1 \text{ and NOT Base Year} \\ STRGV_{fpu,m-1}, & m > 1 \end{cases} \tag{IWSM.12}$$

The inflow from FPUs upstream within the basin is given by the following equation.

IWSM Equation 13: Inflow from Upstream FPUs within the Same River Basin

$$INFLOWV_{fpu,m} = \sum_{fpub \in FPUB_{fpu}} SPV_{fpub,m} \tag{IWSM.13}$$

Reservoir evaporation equals potential evaporation multiplied by reservoir surface area. Considering storage capacity growth over time, reservoir surface area equals the area of reservoir when storage is at its capacity in the base year multiplied by a coefficient that is a power function of the ratio of average storage of the current month to base-year storage capacity. The power 2/3 is applied for converting the change in three-dimensional reservoir storage to that of two-dimensional reservoir surface area. $STRGC^0_{fpu}$, $RESA^0_{fpu,m}$, and $PET_{fpu,m}$ are, respectively, reservoir storage capacity in the base year, reservoir surface area at full storage in the base year, and potential evaporation in month m of the current year. Reservoir storage capacity and reservoir surface area values in the base year are based on the GRanD database (Lehner et al. 2011).

IWSM Equation 14: Reservoir Evaporation

$$EVAPV_{fpu,m} = \left[\frac{0.5 \times \left(STRGPV_{fpu,m} + STRGV_{fpu,m}\right)}{STRGC^0_{fpu}}\right]^{2/3} \times RESA^0_{fpu,m} \times PET_{fpu,m} - EVAPSLACKV_{fpu,m} \quad \text{(IWSM.14)}$$

The sum of surface water depletion, groundwater depletion, and desalinized water, $WDSL_{fpu,m}$ (water supply by source) equals the sum of water depletion in the irrigation sector and total water depletion in nonirrigation sectors (water depletion by sector).

IWSM Equation 15: Water Supply and Demand Balance

$$SWDPV_{fpu,m} + GWDPV_{fpu,m} + WDSL_{fpu,m} = IRRWUV_{fpu,m} + WDNI_{fpu,m} - NIRSHORTV_{fpu,m} \quad \text{(IWSM.15)}$$

The ratio of irrigation water supply to gross irrigation water requirement, $GIWD_{fpu,m}$, which considers effective basin efficiency, is given by the following equation.

IWSM Equation 16: Monthly Ratio of Irrigation Water Supply to Demand

$$RAV_{fpu,m} = \frac{IRRWUV_{fpu,m}}{GIWD_{fpu,m}} \quad \text{(IWSM.16)}$$

The minimum value of monthly ratio values in a year is calculated in the following equation.

IWSM Equation 17: Minimum Monthly Ratio of Irrigation Water Supply to Demand in a Year

$$MINRAV_{fpu} \leq RAV_{fpu,m}, \ \forall m \quad \text{(IWSM.17)}$$

The total surface water withdrawal in a given year cannot exceed surface water withdrawal capacity. The capacity has been converted into a consumptive use term, using estimated depletion coefficients of domestic, industrial, and agricultural sectors. Water withdrawal data by source around year 2005 from FAO's AQUASTAT global database were used to estimate surface and groundwater withdrawal capacity values (FAO 2014), considering interannual variability of water demand at the FPU level.

IWSM Equation 18: Surface Water Withdrawal Capacity Constraint

$$\sum_m SWDPV_{fpu,m} \leq SWDCAP_{fpu} \quad \text{(IWSM.18)}$$

The total groundwater water withdrawal in a given year cannot exceed groundwater withdrawal capacity of this year. The capacity has been converted into a consumptive use term, using estimated depletion coefficients of domestic, industrial, and agricultural sectors.

IWSM Equation 19: Groundwater Withdrawal Capacity Constraint

$$\sum_m GWDPV_{fpu,m} \leq GWDCAP_{fpu} \quad \text{(IWSM.19)}$$

The reservoir release (excluding surface withdrawal) in any given month should be greater than minimum instream flow requirement, which is specified as a percentage of available surface water resource. The committed flow requirement coefficient values are based on available global study on environmental flow requirements (Smakhtin, Revenga, and Döll 2004).

IWSM Equation 20: Committed Instream Flow Requirement

$$SPV_{fpu,m} \geq CFY_{fpu} \times \sum_{m=1}^{M} \left(IRW_{fpu,m} + INFLOW_{fpu,m} - GWX_{fpu,m} - EVAPV_{fpu,m}\right) \quad \text{(IWSM.20)}$$

The reservoir storage in any month should be greater than its dead storage.

IWSM Equation 21: Reservoir Dead Storage Constraint

$$STRGV_{fpu,m} \geq STCAPMN_{fpu} \quad \text{(IWSM.21)}$$

The reservoir storage in any month should be less than its storage capacity.

IWSM Equation 22: Reservoir Storage Capacity Constraint

$$STRGV_{fpu,m} \leq STCAP_{fpu} \quad \text{(IWSM.22)}$$

Intersector Water Allocation

IWSM adopts a priority-based intersector water allocation scheme, assuming domestic water demand is the first priority, industrial and livestock demand is the second priority, and the remaining water is available for irrigation. The above water supply optimization already guarantees that nonirrigation water demand is met before irrigation water demand by forcing the shortage of supply to nonirrigation sectors to zero whenever possible. Therefore, for domestic, industrial, and livestock sectors, water supplies equal water demands if nonirrigation sector water supply shortage is zero in the IWSM water supply optimization solution. Otherwise, if shortage exists for nonirrigation sectors, water is allocated in the order of domestic, industrial, and livestock.

ICWASM

ICWASM allocates irrigation water among crops in an area. We use FAO's Ky/Kc approach (Doorenbos and Kassam 1979) to measure water stress using a monthly time step to include seasonality of water stress. The model maximizes the total value of production given fixed prices and also includes a measure of risk aversion for farmers in the objective function, which preserves a diversified production structure even in case of a drought.

Table E.2 ICWASM variable definitions

Variable	Definition
$CWDLV_{fpu,j,m}$	crop water delivered per hectare (millimeters)
$RATIOCWDV_{fpu,j,m}$	ratio of net irrigation water supply to demand by crop
$MEANRATIOV_{fpu,m}$	mean of RATIOCWDV over crops
$IYRMV_{fpu,j,m}$ [a]	monthly irrigated yield reduction rate
$IYRYV_{fpu,j}$ [b]	annual irrigated yield multiplier
$CPRODV_{fpu,j}$	annual crop production (million metric tons)
$IYRMSLKV_{fpu,j,m}$	slack variable to ensure IYRMV ≤ 1
$IYRYSLKV_{fpu,j}$	slack variable to ensure irrigated yield ≥ rainfed yield
OBJV	objective function variable (unconstrained)

Source: Authors.
Note: Notation convention is that the suffix *V* denotes a variable. fpu = food production unit; ICWASM = International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) crop water allocation and stress model; j = crop index; m = month. [a] IYRMV is the rate of reduction in yield by month, so a value of 1 means total crop loss. [b] IYRYV is the annual yield multiplier, so the new yield equals old yield times IYRY, and 1 means no crop loss.

The monthly irrigation water delivered to FPU has to be less than or equal to total water available for that FPU. This constraint on water availability is expressed by the following inequality, where AREAC is the area for crop j in the FPU, which comes from the multimarket model, and WDAG is available water, which comes from IWSM.

ICWASM Equation 1: Available Water Constraint

$$\sum_j CWDLV_{fpu,j,m} \times AREAC_{j,fpu} \leq WDAG_{fpu,m} \qquad \text{(ICWASM.1)}$$

The water supplied to each crop has to be less than or equal to the crop irrigation water demand requirement, which does not include basin efficiency.

ICWASM Equation 2: Water Supply Constraint

$$CWDLV_{fpu,j,m} \leq IWD_{fpu,j,m} \qquad \text{(ICWASM.2)}$$

ICWASM Equation 3: Water Delivery Ratio by Crop

$$RATIOCWDLV_{fpu,j,m} = \frac{CWDLV_{fpu,j,m}}{IWD_{fpu,j,m}} \qquad \text{(ICWASM.3)}$$

ICWASM Equation 4: Mean of Water Delivery Ratios across Crops

$$MEANRATIOV_{fpu,m} = \frac{1}{J} \times \sum_j RATIOCWDV_{fpu,j,m}, \qquad \text{(ICWASM.4)}$$
$$where\ J\ is\ the\ total\ number\ of\ crops$$

The monthly irrigation yield reduction is equal to the yield coefficient times the fraction of the water requirement unmet by supply for that month, given the cropping calendar. We ensure that yield reduction is less than 1, such that a yield reduction cannot lead to a negative yield. *Ky* is the yield coefficient, *precip* is monthly precipitation, and *etcrop* is the monthly crop-specific evapotranspiration (millimeters).

ICWASM Equation 5: Monthly Irrigated Yield Reduction Rate

$$IYRMV_{fpu,j,m} + IYRMSLKV_{fpu,j,m} = Ky_{fpu,j,m}\left[1 - \frac{MIN(precip_{fpu,m}, etcrop_{fpu,j,m})}{etcrop_{fpu,j,m}}\right] \qquad \text{(ICWASM.5)}$$

The next two equations (ICWASM.6 and ICWASM.7) provide alternative approaches to aggregating the monthly yield shocks to produce the annual shock. Both approaches are based on the article by Rao et al. (1988). In the first, the annual yield reduction shock equals the product during the months of 1 minus the monthly irrigated yield reductions. It is a nonlinear equation that requires that the model be solved with a nonlinear programming (NLP) solver. The second equals 1 minus the sum of the monthly irrigated yield reduction terms. The equation is linear, and the model can be solved as a quadratic programming (QCP) problem. The slack variable *IYRYSLKV* is introduced to allow setting a minimum on the irrigated yield so that it cannot be less than the rainfed yield (ICWASM.8).

ICWASM Equation 6: Multiplicative Model of Monthly Yield Shocks

$$IYRYV_{fpu,j} = \prod_m \left(1 - IYRMB_{fpu,j,m}\right) + IYRYSLKV_{fpu,j} \qquad \text{(ICWASM.6)}$$

ICWASM Equation 7: Additive Model of Monthly Yield Shocks

$$IYRYV_{fpu,j} = 1 - \sum_m IYRMV_{fpu,j,m} + IYRYSLKV_{fpu,j} \qquad \text{(ICWASM.7)}$$

ICWASM Equation 8: Irrigated-Rainfed Yield Constraint

$$IYRYV_{fpu,j} \times YldIrr_{fpu,j} \geq YldRfd_{fpu,j} \qquad \text{(ICWASM.8)}$$

YldIrr is irrigated yield and *YldRfd* is rainfed yield. Alternatively, one could replace *YldRfd* with the average of the full irrigated yield on part of the irrigated land, given the shortfall, and the rainfed yield on the rest, splitting *AREAC* into irrigated and rainfed. In effect, for this strategy, the farmer would fully irrigate as much land as possible, given water availability, and let the rest operate as rainfed.

Crop production is reduced by the value of the yield shock in ICWASM equation 9 by the following equation.

ICWASM Equation 9: Crop Production

$$CPRODV_{fpu,j} = IYRYV_{fpu,j} \times YldIrr_{fpu,j} \times AREAC_{j,fpu} \qquad \text{(ICWASM.9)}$$

The objective function of the module includes total revenue and a risk-aversion term to dampen changes in allocation of water to crops from the previous year and is represented mathematically by the following equation, where *J* is the total number of irrigated crops, *PP* is the producer price of crop j in an FPU, *FPU* is the total number of FPUs, and *TOTVAL* is the total expected value of crops in an FPU. *PP* and *TOTVAL* are both generated by the multimarket model. The first term on the right allocates available water to crops to maximize the expected value of output, given water shortages and yield shocks. The second term minimizes the variance of the ratios of supply to demand for water across crops, reflecting the desire for risk-averse farmers to maintain their initial cropping pattern. The variance will be 0 when all crops have the same ratio of supply to demand for water. The third minimizes the slack variables. The *WGHT*s are weights on the three terms. The first two terms are scaled to have comparable magnitudes so that the *WGHT*s will reflect the relative importance of revenue maximization versus variance minimization. The value of *WGHT*3 is chosen to be large, ensuring that the slack variables are positive only when *IYRMV* equals 1 and the irrigated yield equals the rainfed yield.

ICWASM Equation 10: ICWASM Objective Function

$$\begin{aligned} OBJV = {} & WGHT1 \times \frac{1}{FPU} \times \sum_{fpu} \frac{CPRODV_{fpu,j} \times PP_{j,fpu}}{TOTVAL_{fpu}} - \\ & WGHT2 \times \frac{1}{FPU \times 12} \times \sum_{fpu} \left[\frac{1}{J} \times \sum_{j} \left(RATIOCWDV_{fpu,j,m} - MEANRATIOV_{fpu,m} \right)^2 \right] - \\ & WGHT3 \times \left[\sum_{fpu,j,m} IYRMSLKV_{fpu,j,m} + \sum_{fpu,j} IYRYSLKV_{fpu,j} \right] \end{aligned} \qquad \text{(ICWASM.10)}$$

APPENDIX F: CROP MODELS

As a decision-support tool, crop systems models have potential at various levels of decisionmaking, from household (for example, irrigation scheduling in farmers' fields) to global (for example, identifying the potential breadbasket areas). Crop models mathematically describe the growth of crops and their interactions with soils, climate, and management practices. Most modern crop models can quantify, on a daily basis, various biological processes of a crop (for example, the amount of solar energy transformed into biomass; water and nutrient requirements, supply, and stresses; and growth stages) as well as physical processes around the crop (for example, soil water runoff, soil carbon sequestration, and nitrogen leaching).

Since the early 1970s, various crop models have been developed by agricultural scientists based on improved knowledge of plant photosynthesis and respiration processes. Models range from generic and simple to specific and complex. Some models use response functions (for example, yield as a function of rainfall and nutrients) at their core, while others use sets of differential equations to describe complexity of different processes and their interactions. There is no final and universal crop model. Instead, crop models are selected based on the type of research question.

Decision Support System for Agrotechnology Transfer (DSSAT) Crop Systems Model

DSSAT is a popular software package used by crop modelers. DSSAT is actually a suite of single crop models with access to unified crop, soil, and weather databases (Hoogenboom et al. 2012; Jones et al. 2003). The models integrate the effects of crop systems components and management options to simulate the states of all the components of the cropping system and their interactions. DSSAT crop models provide a framework for users to understand how the overall cropping system and its components function throughout cropping season(s) on a daily basis. Users are expected to provide at least a minimum set of data that are essential to run the crop model for each geographical location. The minimum dataset includes the following:

1. Site daily weather data for the duration of the growing season
2. Site soil data
3. Management and observed data from an experiment

Given the availability of the input dataset, DSSAT users can simulate single-season or multiseason outcomes of the crop management decisions for different crops at any location in the world.

DSSAT is one of the principal products developed by the International Benchmark Sites Network for Agrotechnology Transfer project supported by the United States Agency for International Development from 1983 to 1993. It has subsequently continued development through collaboration among scientists from multiple universities and international agricultural research institutes as well as scientists associated with the International Consortium for Agricultural Systems Applications[20] (White et al 2013).

Currently, DSSAT is a commercial open source application that provides source code to registered users. Adopting a modular modeling approach, many parts of crop models can be plugged out/in by users as necessary. The main engine of DSSAT is written in FORTRAN 90 programming language, originally compiled in a PC environment. With minimal changes in the source code, DSSAT also can be compiled and executed in any other operating system with a FORTRAN compiler.

[20] For more information about International Consortium for Agricultural Systems Applications standards go to http://icsas.net.

Linking DSSAT Crop Model Results to the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) Model

Process-based crop simulation models can be used to explore the effect of climate change and possible alternative technologies on the mechanics of crop production. For instance, the models can simulate how yields may respond to varietal choice, soil management practices (for example, residues retention, tillage depth), and length of growth period. The next level of assessment is to consider these biophysical processes in conjunction with economic factors. Shifters are calculated from the process-based models to implement supply curve shocks in the partial equilibrium environment. Process-based crop models can simulate accurately the growth of particular crops but provide no insight into the availability of a variety or technology and how farmers respond to incentives and factors beyond the crop system. They are mechanical biophysical models containing no economic factors or inputs. The challenge is then to take both management and climate change effects simulated in crop models and incorporate them into economic models alongside price effects, general technological progress, and assumptions about adaptive behavior on the part of producers.

The approach employed for the IMPACT model uses the responses of selected crops to climate, soil, and nutrients simulated by DSSAT. The yield simulations in DSSAT are performed on a high-resolution geographic grid, whereas IMPACT operates on a regional basis (food production units [FPUs]). Transformation of the detailed gridded crop modeling results into a form compatible with that of the multimarket model is accomplished using area-weighted average yields. The relative importance of each pixel is judged by the physical area allocated to the crop of interest by the Spatial Production Allocation Model (SPAM; You, Wood, and Wood-Sichra 2006; You et al. 2014). The SPAM areas are summed in the FPU to determine a total crop area. Next, the SPAM areas are multiplied (pixel by pixel) by the DSSAT simulated yields, providing pixel-level production information. These are summed in the FPU to obtain the total simulated production. Based on these, the area-weighted average yield is just total production divided by total area. These yields are computed for all combinations of cases and then transferred to IMPACT as shifters that are used in the simulations to reflect the climate change shock and the effects of technology adoption. All crop model results are applied in IMPACT using a delta method, meaning the changes in yields (deltas) observed in the crop models–simulated yields are applied to the IMPACT yields.

This approach is followed as it allows us to capture the direction and magnitude of change due to technologies (or climate change) seen in the crop models while maintaining the observed agricultural productivity reported in the FAOSTAT database.

DSSAT requires several consistent and comprehensive datasets as input. Seven crops are directly modeled (groundnuts, maize, potatoes, rice, sorghum, soybeans, and wheat) due to these crops' being particularly well developed in DSSAT and broadly accepted as globally applicable. The effects on the remaining crops in IMPACT are built up off of these core crops, based on biophysical similarities of the IMPACT crops to the core DSSAT crops (for example, pulses are legumes like groundnuts and soybeans, and sugarcane is a C4 grass like maize). Table F.1 summarizes this mapping of DSSAT crop models to IMPACT crops. Each crop is modeled under purely rainfed conditions and a stylized minimum water stress irrigation scheme. Effects of carbon dioxide concentrations are considered, using the appropriate future value and keeping it constant at the baseline levels. As modeled in DSSAT, the effects of carbon dioxide fertilization are generally optimistic compared to a world without any fertilization. The range of potential future climatic conditions is represented via a baseline climate (also known as no climate change) and specified Representative Concentration Pathways. Earth System Models (ESMs) then provide a more specific climate realization that can be used to generate future monthly and daily weather data. For each Representative Concentration Pathway and ESM combination, we have (7 crops) × (2 water sources) × ([1 baseline] + [2 CO_2 assumptions]) = 42 individual yield realizations that are used to calculate climate change impacts across the appropriate domains of the IMPACT model.

Table F.1 Mapping DSSAT crop model results to IMPACT

DSSAT crop model		IMPACT crops
C3 crops		
CERES rice	→	Rice
CERES wheat	→	Wheat
CROPGRO soybeans	→	Soybeans
CROPGRO groundnuts	→	Groundnuts
SUBSTOR potatoes	→	Potatoes
Dryland cereals[a]	→	Barley, other cereals
Dryland pulses[b]	→	Chickpeas, pigeon peas, beans, cowpeas, lentils, other pulses
C3 average[c]	→	Cotton, sugar beets, tropical fruits, temperate fruits, vegetables, bananas, plantains, cocoa, coffee, tea, rapeseed, sunflower, oil palm, other oilseeds
C3 tolerant[d]	→	Cassava, sweet potato, yams, other roots and tubers, other
C4 crops		
CERES maize	→	Maize
CERES sorghum	→	Sorghum, millet
C4 tolerant[e]	→	Sugarcane

Source: Authors.

Note: DSSAT = Decision Support System for Agrotechnology Transfer; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade. [a] Dryland cereals are represented by one-half the negative effects (full positive) of climate change from CERES wheat results. [b] Dryland pulses are represented by one-half the negative effects (full positive) of the area-weighted average of the CROPGRO soybeans and CROPGRO groundnut results. [c] C3 average is represented as the area-weighted average of all five C3 DSSAT crop models used. [d] C3 tolerant is represented by one-half the negative effects (full positive) of the C3 average. [e] C4 tolerant is represented by one-half the negative effects (full positive) of climate change from CERES maize results.

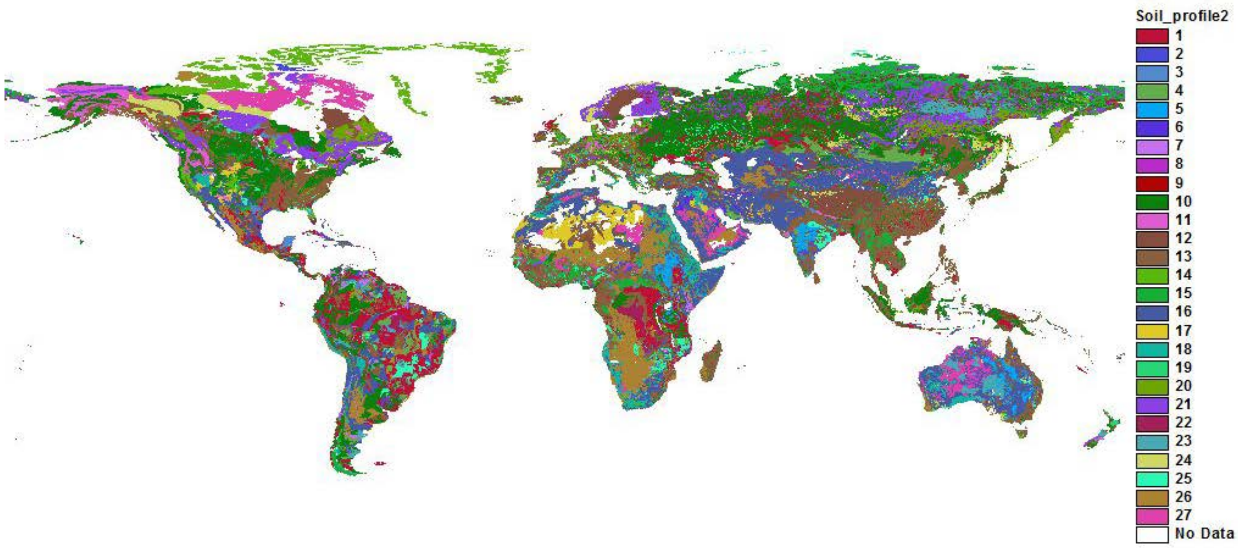
Key data sources and processing for the DSSAT-IMPACT linkage are the following:

- Climate data are derived from ESM outputs. In particular, the Inter-sectoral Impact Model Intercomparison Project (ISI-MIP) initiative provides gridded versions of ESM outputs relevant to agricultural modeling (Hempel et al. 2013; Piani, Haerter, and Coppola 2010; Weedon et al. 2011). Patterns of change from the ISI-MIP datasets are applied to a common and trusted set of baseline/historic climate data (Jones, Thornton, and Heinke, 2009) to allow for consistent comparisons and realistic baseline results.
- Soils were handled using a generic soil profile approach. The Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC 2012) was processed to provide a global gridded map of 27 generic soil types based on organic carbon content (high, medium, and low), depth (shallow, medium, deep), and texture (sand, clay, loam). Figure F.1 illustrates the global distribution of these soil types.
- Planting month assumptions are constructed as was done for Nelson et al (2010), as a combination of hard data and rules operating on them, which were calibrated to match expert and anecdotal evidence. To help account for imperfections in the approach and allow for a hint of maximizing behavior, the rule-based planting month was used as the middle of a three-month window. Each planting month was simulated and its average yield recorded. Then, for each pixel, the highest of the three monthly average yields was chosen as the final yield used for the DSSAT simulation.

- Availability of other required data inputs is sparse and must necessarily be constructed on a more ad hoc basis. Nitrogen fertilizer rates come from a combination of official sources, expert opinion, anecdotes, and iterative adjustments. Other sets of initial conditions were primarily based on expert opinion and adjusted in a way to obtain reasonable output values from the crop models.

Each of these links in the chain from raw data to crop modeling to aggregation to the multimarket model provides opportunities for investigation and improvement. As with any effort of this scale, the details are periodically modified to better incorporate lessons learned along the way.

Figure F.1 Global distribution of 27 generic soil types



Source: FAO/IIASA/ISRIC/ISSCAS/JRC (2012).

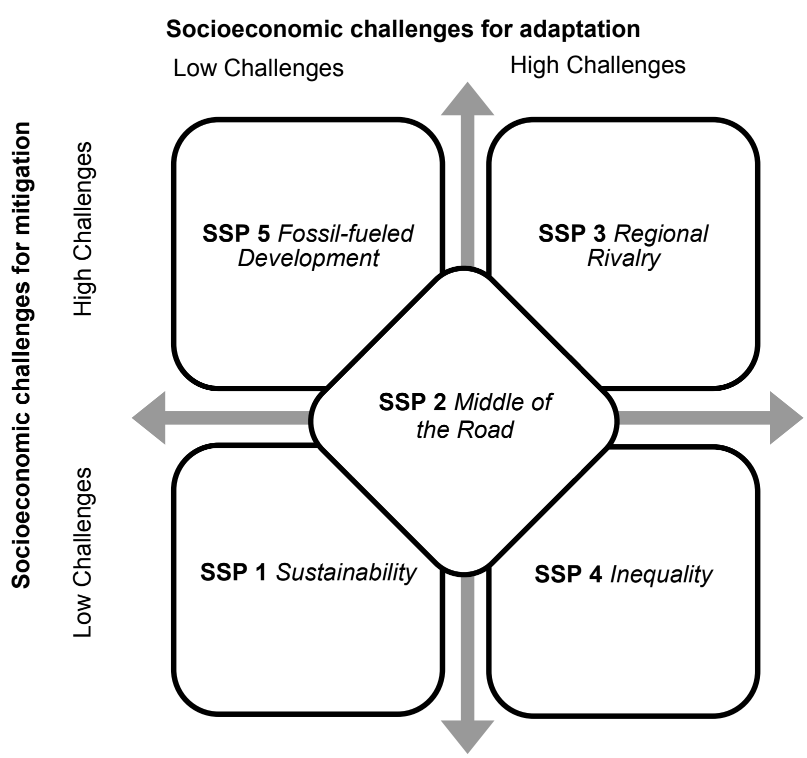
APPENDIX G: INTERNATIONAL PANEL ON CLIMATE CHANGE (IPCC) SCENARIOS

The climate and economic scenarios used in International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) draw on work developed for IPCC's fifth assessment report. These scenarios were developed to give policymakers and researchers a series of useful scenarios that can be used to test how the world would respond to future demographic, economic, and climatic changes. These scenarios are defined by two major components. First, Shared Socioeconomic Pathways (SSPs) are global pathways that represent alternative futures of societal evolution. Each SSP presents unique challenges to society for mitigating and adapting to climate change (O'Neill et al. 2014; O'Neill et al. 2015). The second component is the Representative Concentration Pathways (RCPs), which represent potential greenhouse gas emission levels in the atmosphere and the subsequent increase in solar energy that would be absorbed (radiative forcing).

Shared Socioeconomic Pathways

SSPs are scenarios of global development and contain many elements. Each scenario was given an evocative name to describe a development path the world might take and how this path would affect society's ability to respond to climate change. The following figure shows how the five SSPs were envisioned with respect to society's ability to deal with climate change.

Figure G.1 SSPs and challenges to climate change adaptation and mitigation



Source: Based on O'Neill et al. (2014, Figure 1).

Note: SSP = Shared Socioeconomic Pathway.

The scenario narratives for the SSPs were then designed to reflect a future where these different challenges would dominate in facing climate change. The following table summarizes the basic narrative elements of the five SSPs.

Table G.1 Summary narratives of the SSPs

SSP	Narrative
SSP 1	Sustainable development is realized, with relatively high levels of investment in research and development, which leads to rapid technological change (with a sustainable focus), decreasing inequality, lower energy intensity, and high land productivity. This development pathway leads to a future where society is able to relatively easily mitigate or adapt to climate change. There are a high rate of economic growth, declining population growth, and increasing levels of education globally.
SSP 2	This is a middle-of-the-road scenario that follows historical trends. Economic development continues but is not uniform. Environmental degradation continues but at a slowing pace. There is general improvement, but it is much slower than that seen in SSP 1. Climate change presents moderate challenges to both adaptation and mitigation.
SSP 3	This is a fairly negative future pathway characterized by increasing nationalism with greater levels of conflict and challenges to global and regional cooperation. Barriers to trade increase, and countries tend to look inward at the expense of global cooperation. There are lower levels of technological change. Economic development is slow, and population growth is higher. Climate change presents significant challenges for both adaptation and mitigation.
SSP 4	This is a scenario wherein current levels of inequality become entrenched and worsened over time, with inequality and stratification both within and between countries increasing. This leads to a world of pockets. Rich countries and elites in poorer countries improve significantly, but the rest lag behind. High levels of integration across elites allow for some level of global coordination, which allows society to more easily mitigate climate change. However, large segments of the population are left behind, making climate change adaptation more difficult for most.
SSP 5	This is a future characterized by fast economic industrialization. There are high levels of technological progress and improvements in education levels around the world. Globalization increases rapidly. However, the rapid industrialization is spurred on through the intense use of fossil fuels, and as such there is little effort to mitigate the effects of climate change, with the focus on adaptation through the development of new and improved technologies.

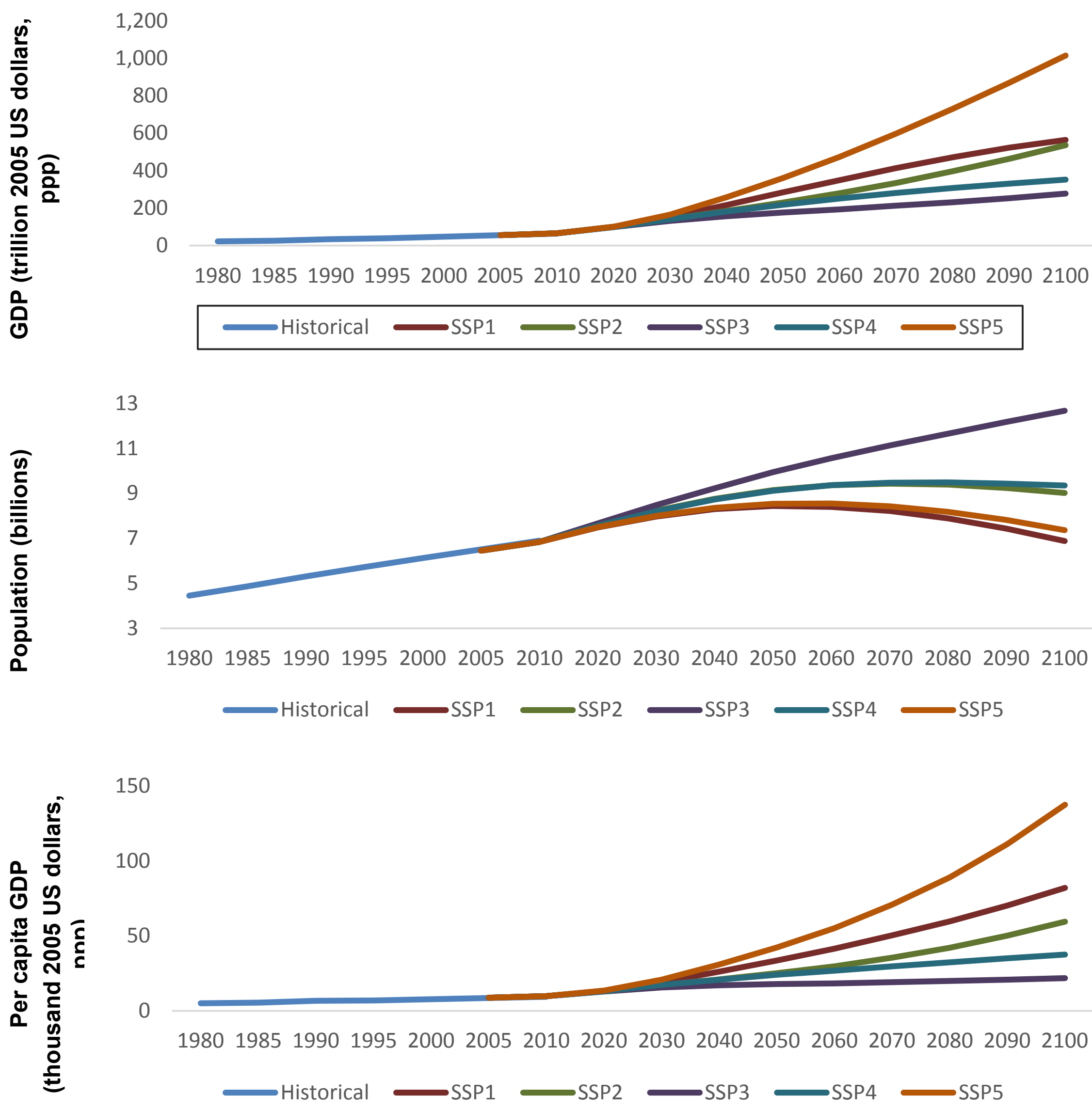
Source: Author summary of O'Neill et al.'s (2014) and O'Neill et al.'s (2015) descriptions of the SSPs.
Note: SSP = Shared Socioeconomic Pathway.

Not all of the narrative elements of the SSPs can be captured and simulated within a partial equilibrium model like IMPACT. Nevertheless, the different narrative elements of the SSPs are being used to develop more nuanced scenarios in IMPACT. Currently, the main drivers that are used from the SSPs are those that represent changes in economic development and population growth. Multiple modeling teams have quantified the SSPs for both population and gross domestic product (GDP). In IMPACT, we use the population projections from the International Institute for Applied Systems Analysis (KC and Lutz 2014), and for economic growth we use those from the Organisation for Economic Co-operation and Development (Chateau et al. 2012) up to 2050. The following figure compares the global assumptions about economic and population growth for each of the SSPs. In the five SSPs there are relatively few differences through 2030, with the average global per capita GDP between US$15,000[21] and $20,000. While the divergence between the SSPs are not as large by 2050 as they are in 2100, there are still interesting differences that can be seen. There is a clear movement from positive to negative along the diagonal line (Figure G.1) from SSP 1 to SSP 3. Along this diagonal line we go from fast economic growth and low population growth to slow economic growth and rapid population growth. This leaves a world that is significantly richer in SSP 1 than in SSP 3, where by 2050 the average per capita GDP for the world is $33,000, slightly more than $25,000, and less than $18,000, respectively, for SSP 1, SSP 2, and SSP3. SSP 4 fits between SSP 2 and SSP 3 in terms of economic development, with a per

[21] All dollars are US dollars.

capita GDP slightly more than $24,000. SSP 5, with rapid industrialization, has by far the largest GDP growth of all of the scenarios, with an average global per capita GDP more than $42,000 by 2050 (see Figure G.2 for the global scenario assumptions about GDP, population, and per capita GDP).

Figure G.2 Economic and population growth to 2100, by SSP



Source: Authors' compilation from SSP database (International Institute for Applied Systems Analysis (IIASA) 2013).
Note: GDP = gross domestic product; ppp = purchasing power parity; SSP = Shared Socioeconomic Pathway.

The global trend masks the diversity at the regional and national levels for these scenarios. Each country is quantified both to match the global scenario narrative and to account for the historical trends at the national level. For example, Africa south of the Sahara is assumed to grow at a faster pace than the global average in all five of the SSPs as the region catches up (granted at varying speeds depending on the SSP). Another example is East Asia and the Pacific, which starts off in 2010 at roughly the same economic level as Latin America at around $10,000 per capita and overtakes Latin America and catches up with Europe in SSP 1 and SSP 5.

Table G.2 Regional summary of GDP (billion 2005 US dollars), population (million), and GDP per capita (thousand US dollars per person) assumptions, by SSP

	2010	2050					Average annual growth rate (% per year)				
Region		**SSP 1**	**SSP 2**	**SSP 3**	**SSP 4**	**SSP 5**	**SSP 1**	**SSP 2**	**SSP 3**	**SSP 4**	**SSP 5**
East Asia and the Pacific											
GDP	19,236	104,096	80,045	60,608	78,950	130,284	4.31	3.63	2.91	3.59	4.90
Population	2,184	2,173	2,261	2,351	2,145	2,187	–0.01	0.09	0.18	–0.04	0.00
GDP per capita	9	48	35	26	37	60	4.32	3.54	2.72	3.64	4.89
Europe											
GDP	14,628	30,571	27,780	21,342	28,442	39,228	1.86	1.62	0.95	1.68	2.50
Population	537	592	577	498	544	662	0.24	0.18	–0.19	0.03	0.52
GDP per capita	27	52	48	43	52	59	1.61	1.43	1.14	1.64	1.96
Former Soviet Union (excluding Baltic states)											
GDP	2,855	10,603	8,984	7,551	9,174	13,750	3.33	2.91	2.46	2.96	4.01
Population	279	262	277	289	257	266	–0.15	–0.01	0.09	–0.20	–0.12
GDP per capita	10	40	32	26	36	52	3.50	2.92	2.37	3.17	4.14
Latin America and the Caribbean											
GDP	5,834	22,838	19,164	15,894	17,600	27,492	3.47	3.02	2.54	2.80	3.95
Population	585	674	742	853	705	651	0.36	0.60	0.95	0.47	0.27
GDP per capita	10	34	26	19	25	42	3.10	2.41	1.57	2.32	3.67
Middle East and North Africa											
GDP	4,551	20,566	18,631	16,006	18,550	26,763	3.84	3.59	3.19	3.58	4.53
Population	457	646	715	808	726	649	0.87	1.13	1.43	1.16	0.88
GDP per capita	10	32	26	20	26	41	2.95	2.43	1.73	2.38	3.62
North America											
GDP	14,290	33,691	29,933	24,753	32,124	44,503	2.17	1.87	1.38	2.05	2.88
Population	344	460	450	372	424	535	0.73	0.67	0.19	0.52	1.10
GDP per capita	41	73	67	67	76	83	1.43	1.19	1.19	1.52	1.76

Table G.2 Continued

	2010	2050					Average annual growth rate (% per year)				
Region		**SSP 1**	**SSP 2**	**SSP 3**	**SSP 4**	**SSP 5**	**SSP 1**	**SSP 2**	**SSP 3**	**SSP 4**	**SSP 5**
South Asia											
GDP	4,461	44,250	32,939	22,756	27,189	55,705	5.90	5.13	4.16	4.62	6.52
Population	1,630	2,108	2,373	2,720	2,289	2,087	0.65	0.94	1.29	0.85	0.62
GDP per capita	3	21	14	8	12	27	5.23	4.14	2.83	3.74	5.86
Africa south of the Sahara											
GDP	1,705	19,690	13,962	9,665	8,843	25,499	6.31	5.40	4.43	4.20	7.00
Population	863	1,564	1,793	2,084	2,055	1,543	1.50	1.84	2.23	2.19	1.46
GDP per capita	2	13	8	5	4	17	4.74	3.49	2.16	1.97	5.46
World											
GDP	67,559	286,305	231,439	178,575	220,873	363,226	3.68	3.13	2.46	3.01	4.29
Population	6,879	8,479	9,187	9,975	9,147	8,578	0.52	0.73	0.93	0.71	0.55
GDP per capita	10	34	25	18	24	42	3.14	2.38	1.51	2.27	3.72

Source: Calculated from IMPACT 3 base year population and GDP with population and GDP growth rates from International Institute for Applied Systems Analysis and Organisation for Economic Co-operation and Development.

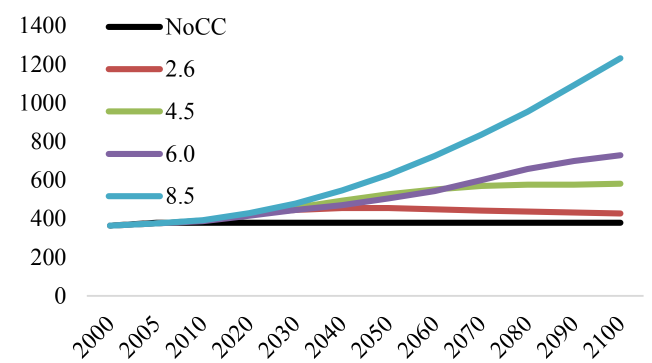
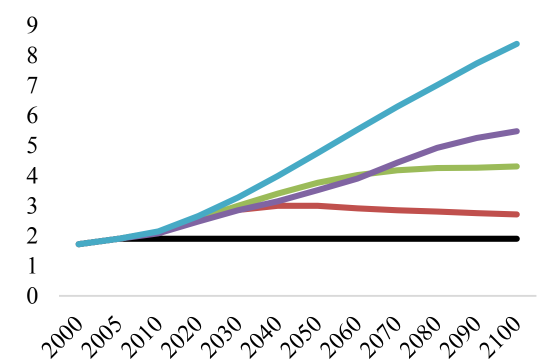
Note: GDP and GDP per capita are in purchasing power parity. Region definitions are found in Table C.4. GDP = gross domestic product; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; SSP = Shared Socioeconomic Pathway.

While all of the SSPs can be simulated in IMPACT, SSP 2 has been used as the primary reference scenario to calibrate the model. The alternative SSP scenarios are currently used to do sensitivity testing to assess potential effects of different socioeconomic trends, further analysis on the SSPs will be included in a forthcoming report.

Climate Scenarios and RCPs

RCPs describe alternative future climates depending on the levels of greenhouse gas emissions that may be observed in the 21st century. These four RCPs are quantified to 2100, although similar to SSPs, in IMPACT the projection period is only to 2050. There are four RCPs, which are named according to approximate level of radiative forcing in 2100, which ranges from 2.6 watts per square meter (W/m^2) to 8.5 W/m^2. IMPACT has traditionally also simulated a baseline scenario with historical climate (sometimes also referred to perfect mitigation or no climate change), where historical climate conditions in 2005 are assumed to continue throughout the projection period. While this assumption is not in and of itself the most realistic (greenhouse gas emissions have continued to increase since 2005), it is similar to the RCP 2.6 scenario and provides a useful counterfactual to isolate the effects of climate change from other assumptions. Figure G.3 illustrates the range of climate scenarios currently available in IMPACT.

Figure G.3 Comparing carbon dioxide concentration and radiative forcing assumptions for the Representative Concentration Pathways (RCPs)

Carbon dioxide equivalent concentration, parts per million (including all forcing agents)	Total radiative forcing (watts per square meter)
	

Source: RCP data downloaded from the RCP Database, version 2.0.5 (International Institute for Applied Systems Analysis 2015); RCP 2.6: van Vuuren et al. (2006); van Vuuren et al. (2007); RCP 4.5: Clark et al. (2007); Smith and Wigley (2006); Wise et al. (2009); RCP 6.0: Fujino et al. (2006); Hijioka et al. (2008); RCP 8.5: Riahi, Gruebler, and Nakicenovic (2007).

Note: NoCC = no climate change or perfect mitigation scenario used in International Model for Policy Analysis of Agricultural Commodities and Trade.

The consequences of this radiative forcing leads to increasing temperature, which in turn leads to greater glacier melt and rising sea levels. The projected global warming and sea level rise of the RCPs are summarized in Table G.3.

Table G.3 Likely range of global warming and sea level rise, by RCP

RCP	Midcentury[a]		End of the century[b]	
	Temperature increase	Sea level rise	Temperature increase	Sea level rise
2.6	+ 0.4–1.6	+ 0.17–0.32	+ 0.3–1.7	+ 0.26–0.55
4.5	+ 0.9–2.0	+ 0.19–0.33	+ 1.1–2.6	+ 0.32–0.63
6.0	+ 0.8–1.8	+ 0.18–0.32	+ 2.2–3.1	+ 0.33–0.63
8.5	+ 1.4–2.6	+ 0.22–0.38	+ 2.6–4.8	+ 0.45–0.82

Source: International Panel on Climate Change (2013).
Note: The no climate change scenario assumes no change in temperature or sea levels. Temperature is in degrees Celsius, and sea level rise is in meters. RCP = Representative Concentration Pathway. [a] Midcentury represents the 20 years from 2046 to 2065. [b] End of century represents the 20 years from 2081 to 2100.

Traditionally, IMPACT has used the most extreme climate scenarios to provide an envelope of potential climate impacts on agriculture (see Nelson et al. 2010; Nelson et al. 2013; Nelson et al. 2014). This strategy has the added benefit of maintaining a larger possibility space to test policies against climate change through 2050. As the three lower RCPs do not diverge significantly by midcentury in either increases in radiative forcing (3 to 3.7 W/m^2) or temperatures (0.4–2.0°C), using the no climate change scenario and RCP 8.5 provides a broader climatic range from 1.9 W/m^2 to 4.8 W/m^2 and of temperature from 0.0 to 2.6°C. Nevertheless, with continuing development and refinement of the SSPs in IMPACT, this strategy will be expanded to include other combinations of RCPs and SSPs (see Wiebe et al. 2015). IPCC has developed a measure of the compatibility of SSPs and RCPs. Table G.4 summarizes this compatibility matrix. The square with an *X* represents an SSP-RCP combination that is not considered plausible. The darker the shading, the higher would be the costs to society that would be needed to mitigate greenhouse gas emissions to allow for the compatibility of an SSP with an RCP. For example, if no climate policies are pursued to mitigate climate change under SSP 2 we would expect somewhere between RCP 6.0 and 8.5. However, with some mitigation RCP 6.0 is possible, and with heavier investment 4.5 and 2.6 may also be possible.

Table G.4 RCP and SSP compatibility matrix and cost of mitigation

Scenario Specifications	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
RCP 8.5	X				
RCP 6.0					
RCP 4.5					
RCP 2.6					

Source: International Panel on Climate Change (2013, 2014).
Note: RCP = Representative Concentration Pathway; SSP = Shared Socioeconomic Pathway.

Each RCP represents global climate change through the role of greenhouse gas emissions and radiative forcing. This is just one physical dynamic that determines climate and weather. To simulate all of these systems that determine climate and to provide weather as inputs to crop models, the RCPs must be simulated in Earth System Models (ESMs).[22] The ESMs are complex models that simulate earth's biogeochemical cycles and combine modules that simulate physical climate, atmospheric circulation, and ocean and ice dynamics. Each ESM has somewhat different assumptions about how each of these complex dynamics works and interacts, which means that each ESM's realization of the RCP will be somewhat different. This diversity of results creates model uncertainty, as it is not possible to determine

[22] ESMs were formerly called *General Circulation Models.*

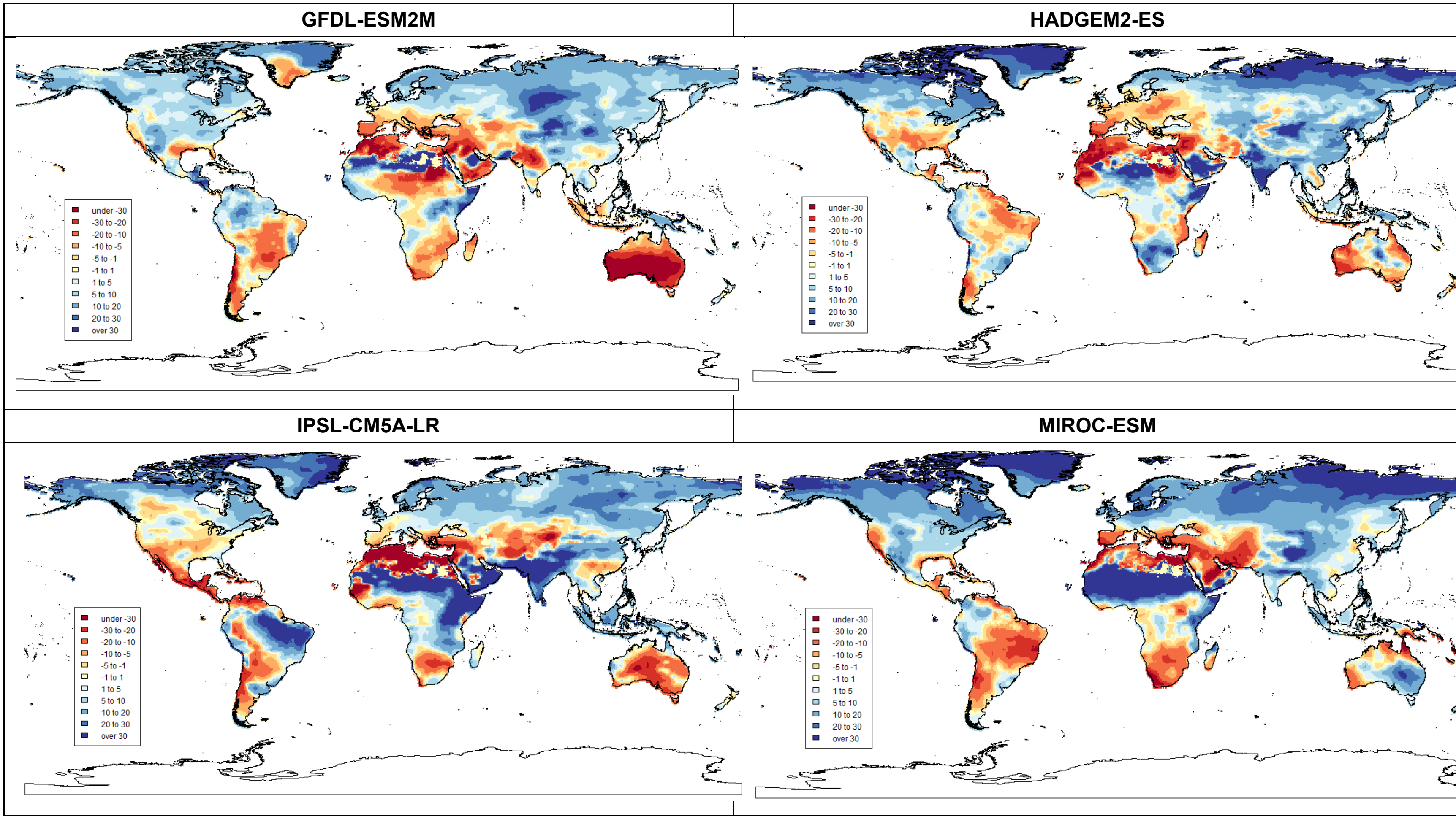
which ESM realization is more likely. To better handle this uncertainty, and to expand the climate possibility space in which IMPACT scenarios can be tested, it was decided to use multiple ESM realizations of each RCP and allow the use of a multimodel ensemble to test climate uncertainty.

The ESMs, which are currently used to provide climatic data to the Decision Support System for Agrotechnology Transfer crop models are the following:

- GFDL-ESM2M (Dunne et al. 2012)—designed and maintained by the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamic Laboratory (www.gfdl.noaa.gov/earth-system-model)
- HADGEM2-ES (Jones et al. 2011)—the Hadley Centre's Global Environment Model, version 2 (www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadgem2)
- IPSL-CM5A-LR (Dufresne et al. 2013)—the Institut Pierre Simon Laplace's ESM (http://icmc.ipsl.fr/index.php/icmc-models/icmc-ipsl-cm5)
- MIROC-ESM (Watanabe et al. 2011)—Model for Interdisciplinary Research on Climate, developed by the University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marin-Earth Science and Technology (www.geosci-model-dev-discuss.net/4/1063/2011/gmdd-4-1063-2011.pdf)

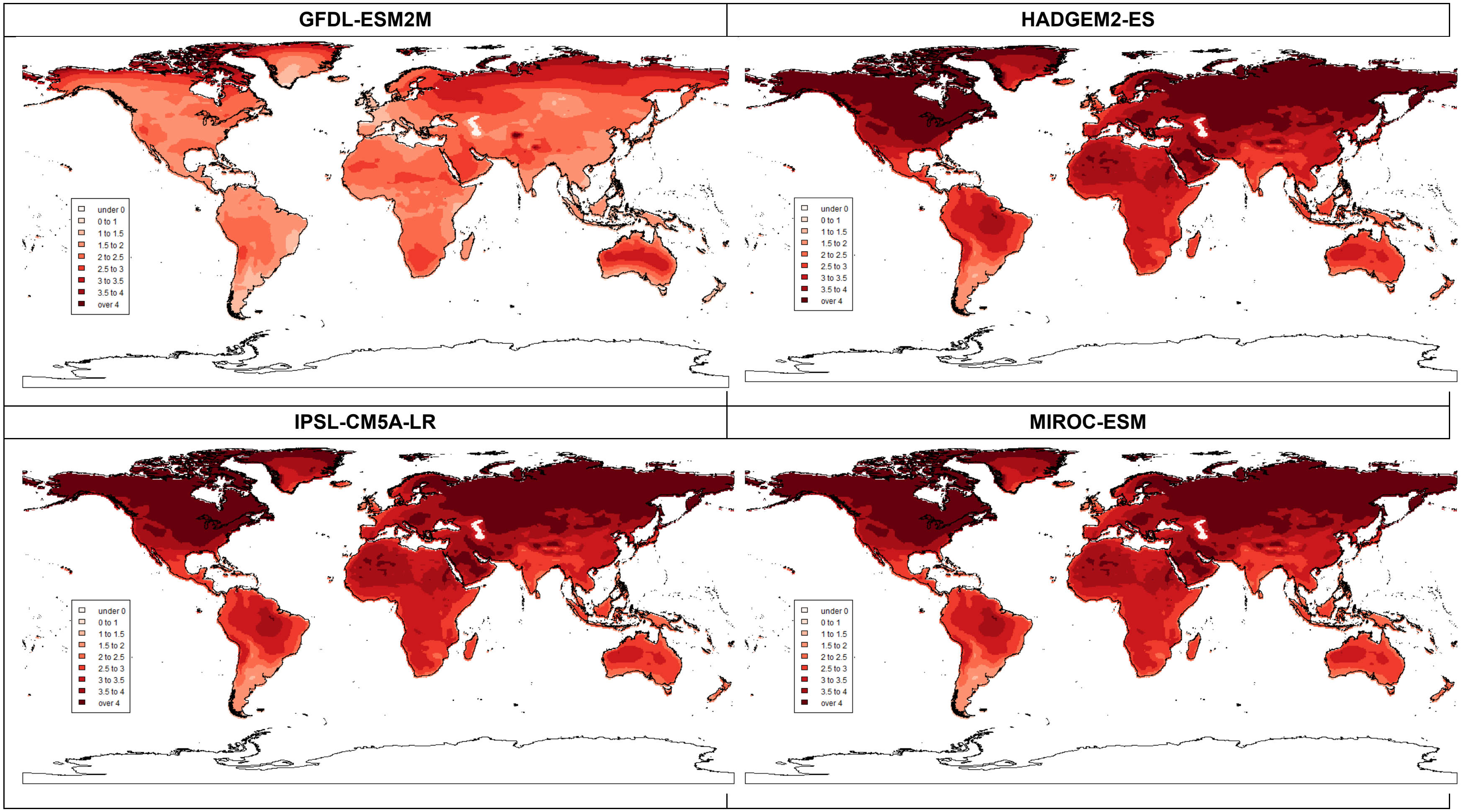
These four ESMs were selected because these modeling teams had participated in several major modeling projects as part of Coupled Model Intercomparison Project (Taylor et al. 2012) for theIPCC's fifth assessment report, the Inter-sectoral Impact Model Intercomparison Project, and the Agriculture Model Intercomparison and Improvement Project. This participation has meant that all of the results are processed and shared in the same format, allowing for better standardization of data processing and handling for use in crop models. Agriculture is dependent on weather, which is local. Using these four ESMs allows us to better test regional uncertainties with respect to climate change as each model's varying assumptions provide us with different projections of key climatic data such as precipitation and temperature. Figures G.4 and G.5 illustrate how these four ESMs can project different 2050 weather conditions for different regions.

Figure G.4 Changes in annual precipitation in 2050 compared to 2000 (millimeters) according to four Earth System Models using Representative Concentration Pathway 8.5



Source: Compiled by authors.

Figure G.5 Changes in maximum temperature in 2050 compared to 2000 (°C) according to four Earth System Models using Representative Concentration Pathway 8.5



Source: Compiled by authors.

APPENDIX H: INTERNATIONAL MODEL FOR POLICY ANALYSIS OF AGRICULTURAL COMMODITIES AND TRADE (IMPACT) WELFARE MODULES

Welfare and benefit-cost analysis is a suite of indicators that can be used to evaluate societal impacts from different scenarios. The benefit-cost component provides insight about the cost effectiveness of implementing different technologies vis-à-vis the reference scenario, permitting a more nuanced evaluation of different scenarios. These measures have been designed for a new suite of productivity simulations being generated through the Global Futures project, although the welfare analysis component will be available for use on any existing simulations.

All of these benefit-cost measures are computed in a postprocessing calculation that reads in the stored annual values. These benefit-cost measures are to be used comparatively to help determine which technologies and simulations provide the greatest social benefit and cost-effectiveness (where applicable). To do this we look at discounted benefit changes between the simulation and the reference scenario for each year.

Welfare Analysis

The welfare component of the calculations follows a traditional economic welfare analysis approach to estimate the benefits to society on the consumer and producer side. On the consumer side this is straightforward as the IMPACT model has a demand curve with demand elasticities that allows us to calculate the consumer surplus. On the producer side, it is not as straightforward, as the quantity supplied of each commodity is an area-yield equation and does not represent the traditional supply curve that reflects the producer's marginal cost curve. Therefore, we have had to create synthesized supply curves by land type (irrigated, rainfed, other) for each activity, then calculate the producer surplus for each of these supply curves, and then aggregate to the national level. We also decompose the changes in consumer and producer surplus into price and income effects to allow analysis of the respective contributions to changes in welfare from price and income shifts. The total changes in consumer and producer surplus, when combined, provide us with a benefit flow, which we can use in a benefit-cost analysis to compare a technology's overall impact in the agriculture sector.

Consumer Surplus

The demand curves in the IMPACT model have income and price elasticities and are in the following general form:

$$QF_{c,cty} = \prod \left[\left(PCV_{c,cty} \right)^{FDelas_{c,\,cty,c}} \right] * \left(pcGDP_{cty} \right)^{IncDmdElas_{c,cty}} * pop_{cty} * dmdint_{c,cty} \,,$$

where		
$QF_{c,cty}$	=	quantity demanded for commodity c
$PCV_{c,cty}$	=	consumer price for commodity c
$pcGDP_{cty}$	=	national per capita gross domestic product
pop_{cty}	=	national population
$dmdint_{c,cty}$	=	food demand intercept
$FDelas_{c,cty,c}$	=	own-price elasticity for commodity c
$IncDmdElas_{c,cty}$	=	income demand elasticity for commodity c

For each year and commodity, we compute the slope, *m,* in the equation below, of the straight line from the equilibrium point of the reference scenario (designated as subscript *ref* in the equations below) to the price axis using the food demand elasticity. In this calculation of the slope, we use the total quantity of food demand (QF) and the consumer prices (PC).

$$m_{ref} = \frac{1}{\varepsilon_{ref}} * \frac{p_{ref}}{q_{ref}}.$$

Using this slope we can now calculate the price intercept of this line. The price intercept is the upper bound of price on consumption.

$$PInt_{ref} = p_{ref} - m_{ref} * q_{ref}.$$

With the price intercept, we can now calculate the consumer surplus of the reference scenario, which will be used for all comparisons with different simulations.

$$CS_{ref} = \frac{1}{2} * \left(PInt_{ref} - p_{ref}\right) * q_{ref}.$$

We envision changes between simulations and the reference scenario to be parallel shifts of the line formed by m_{ref} and the simulations' equilibrium point.

$$P_{simulation} = m_{ref} * q_{simulation} + PInt_{simulation}.$$

We solve for $PInt_{simulation}$, which then allows us to compute the consumer surplus in the technology simulation.

$$CS_{simulation} = \frac{1}{2} * \left(PInt_{simulation} - p_{simulation}\right) * q_{simulation}.$$

The change in consumer surplus between the simulation and the reference scenario is the difference of these two triangles.
To decompose the price and income effects we have to calculate the demand of the new simulation demand curve, but at the reference scenario prices, which we will call Q*.

$$Q^* = \frac{p_{ref} - PInt_{simulation}}{m_{ref}}.$$

Now, using Q*, we can compute the areas of the price and income effects. First, we calculate the hypothetical consumer surplus if the equilibrium was at reference scenario prices and Q*.

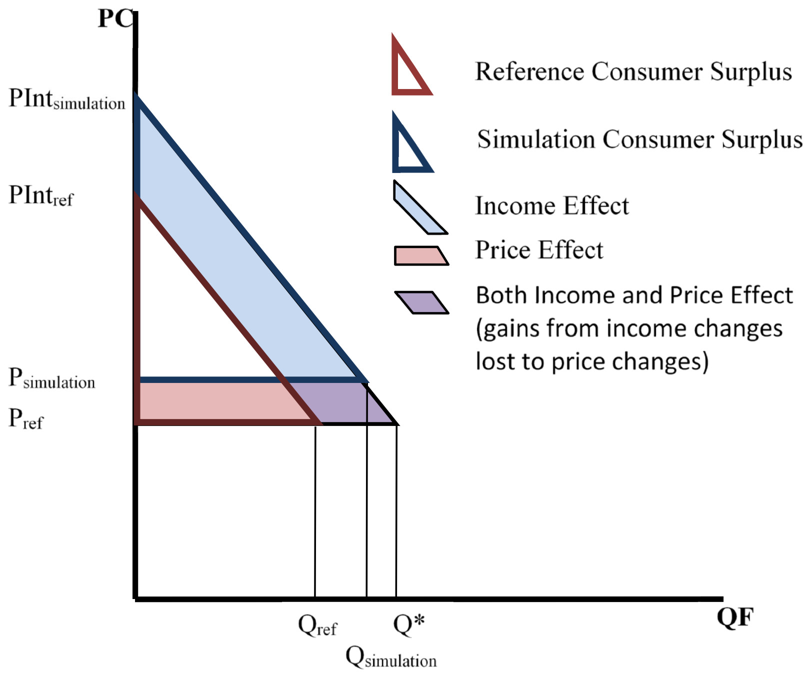
$$CS_{Q^*} = \frac{1}{2} * \left(PInt_{simulation} - p_{ref}\right) * Q^*.$$

Then we subtract triangles to calculate the price and income effects (see Figure H.1 for a graphical representation).

$$Price\ Effect = CS_{Q^*} - CS_{simulation}.$$

$$Income\ Effect = CS_{Q^*} - CS_{ref}.$$

Figure H.1 Graphic representation of consumer surplus calculation



Source: Authors.

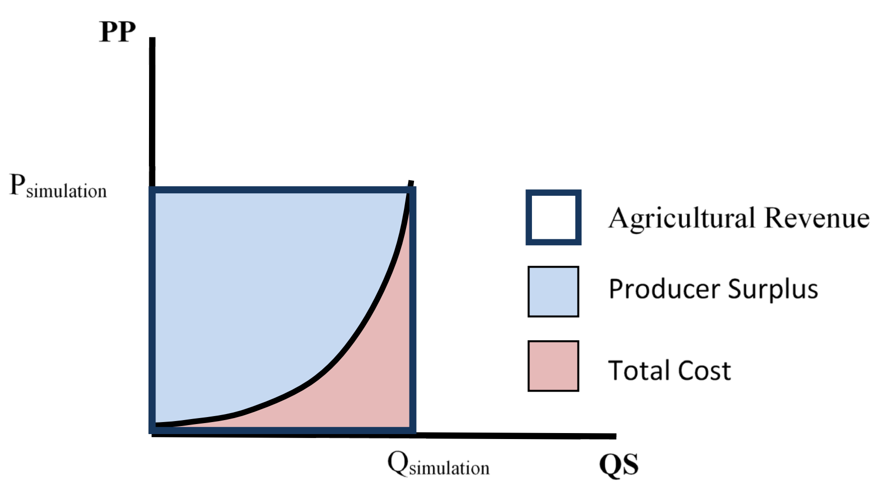
To test whether this decomposition is correct we can check to see if the following holds:

$$\Delta CS = Income\,Effect - Price\,Effect\ .$$

Producer Surplus

To calculate the producer surplus we need to be able to calculate the area above the supply curve and under the equilibrium price. In effect, we calculate the agricultural revenue at the equilibrium point and subtract the total cost of production, which is the area under the supply curve (see Figure H.2 for a visual representation of producer surplus).

Figure H.2 Graphical Representation of Producer Surplus



Source: Authors.

Without a traditional supply curve, derived directly from a marginal cost curve, we have to derive a supply curve from IMPACT's area-yield functions that, generally speaking, give us the quantity supplied (QS) in the following way.

$$QS = Area \times Yield \,.$$

To calculate the total cost, we need to make QS a function of price. The following math explains how we did this. First we put the area[22] and yield[23] equations as functions of their own price (PP).

$$Area = K_{area} * PP^{\varepsilon_{area}} \,.$$

$$Yield = K_{yield} * PP^{\varepsilon_{yield}} \,.$$

Now we can make QS a direct function of its own price.

$$QS = K * PP^{\varepsilon}, \text{ where}$$
$$K = K_{area} \times K_{yield} \text{ and}$$
$$\varepsilon = \varepsilon_{area} + \varepsilon_{yield} \,.$$

We then get the inverse supply function.

$$PP = P(Q) = K^{\left(\frac{1}{\varepsilon}-1\right)} \times QS^{\frac{1}{\varepsilon}} \,.$$

Now that we have the inverse supply function we are ready to calculate the producer surplus (PS), which is agricultural revenue (AR) less the total cost (TC) of production, the area under the inverse supply function calculated by taking the integral of P(Q).24

$$PS = AR - TC, \text{ where}$$
$$AR = P \times QS \text{ and}$$
$$TC = \int_0^{Q_0} P(Q) = \frac{1}{\left(\frac{1}{\varepsilon}+1\right)} \times (P \times QS), \text{ so}$$

$$PS = (P \times QS) - \left[\frac{1}{\left(\frac{1}{\varepsilon}+1\right)} \times (P \times QS)\right]$$
$$= \left[1 - \frac{1}{\left(\frac{1}{\varepsilon}+1\right)}\right] \times P \times QS = \left[\frac{\left(\frac{1}{\varepsilon}\right)}{\left(\frac{1}{\varepsilon}+1\right)}\right] \times P \times QS$$
$$= \frac{1}{1+\varepsilon} \times P \times QS = \frac{P \times QS}{1+\varepsilon}$$

---

[23] K_{yield} is a constant that includes growth rates, the IMPACT yield intercept, and the effects of input costs.

[24] $$\int_0^{Q_0} P(Q) = \int_0^{Q_0} K^{\left(\frac{1}{\varepsilon}-1\right)} \times QS^{\frac{1}{\varepsilon}} = \frac{K^{\left(\frac{1}{\varepsilon}-1\right)}}{\frac{1}{\varepsilon}+1} \times QS^{\left(\frac{1}{\varepsilon}+1\right)} = \left(QS \frac{1}{\frac{1}{\varepsilon}+1}\right) \times \left(K^{\left(\frac{1}{\varepsilon}-1\right)} \times QS^{\frac{1}{\varepsilon}}\right) = P(Q) \times \left(QS \frac{1}{\frac{1}{\varepsilon}+1}\right).$$

Using this equation for the producer surplus, it is a simple matter of calculating the producer surplus for all of the scenarios and comparing changes using the reference case to the new technology scenario.

$$\Delta PS = PS_{simulation} - PS_{ref}.$$

Cost

The cost of developing and implementing a new crop cultivar can be differentiated by the source of the funding and whether it is at the global or national level. Global costs are the costs of research and development that cannot be tied directly to any specific country. The role of research and development at CGIAR research centers is a good example of global costs, as the research done in developing new crop varieties is done for the benefit of many countries.

National costs are broken up into two types of expenditures. First there is the cost of adapting a new crop variety or technology to the country-specific conditions. The cost is borne at the country level, often by national research institutions and universities. Second is the cost of agricultural extension required to introduce the new technology and educate farmers in its use.

This bifurcation of the costs allows for a more nuanced analysis of benefits and costs at both the national and the global level. The national cost cash flow does not include global costs. This makes the assumption that from the perspective of the country all work done at the global level is a public good and is received by national research institutions free of charge. Global costs include both global costs and national costs.

Benefit-cost Analysis

The benefit-cost measures can be used only in simulations where there is a cost component and a defined discount rate associated with a new technology. These measures can be broken up into indicators that compare simulations with their respective costs and observed changes in

- food security and
- welfare.

Food Security Measures

There are three food security measures that provide insight into the effects of different simulations on food security. These measures compare simulations to find the greatest positive returns in improving food security. The following equations describe these measures:

- Food availability: $\dfrac{Kcal_{simulation} - Kcal_{ref}}{NPV\left(Cost_{investment}\right)}$.
- Undernourished children: $\dfrac{Undernourished_{simulation} - Undernourished_{ref}}{NPV\left(Cost_{investment}\right)}$.
- Share at risk of hunger: $\dfrac{Share_{simulation} - Share_{ref}}{NPV\left(Cost_{investment}\right)}$.

Net Benefits and Benefit-cost Ratio

To allow for better comparisons between the benefits of different technologies, we need to discount the benefits over time and compute the present value of change in consumer surplus and agricultural revenue between simulations. We do this by discounting future benefits at a given discount rate (*r*) for the years that the simulation is run.

$$NPV\left(CS_{simulation}\right)=\sum_{i=1}^{n}\frac{\Delta CS_{simulation}^{i}}{\left(1+r\right)^{i}}.$$

$$NPV\left(AR_{simulation}\right)=\sum_{i=1}^{n}\frac{\Delta AR_{simulation}^{i}}{\left(1+r\right)^{i}}.$$

$$NPV\left(Total\ Benefits_{simulation}\right)=NPV\left(CS_{simulation}\right)+NPV\left(AR_{simulation}\right).$$

We then need to do the same with cash flow of costs for implementing the changes in technology. This cost cash flow is read in from an Excel spreadsheet.

$$NPV\left(Cost_{simulation}\right)=\sum_{i=1}^{n}\frac{Cost_{simulation}^{i}}{\left(1+r\right)^{i}}.$$

Once we have a total benefits measure and a total cost measure we can create the benefit-cost ratio and calculate the net benefits of the technology for each crop and country.

- Benefit-cost ratio: $\dfrac{NPV\left(Total\ Benefits_{simulation}\right)}{NPV\left(Cost_{simulation}\right)}$.
- Net benefits: $NPV\left(Total\ Benefits_{simulation}\right)-NPV\left(Cost_{simulation}\right)$.

Summing over countries or commodities provides measures by crop and country and globally by crop, national totals, and global total.

Internal Rate of Return

In addition to the net benefits measures, we can compute the internal rates of return (IRR) of the technology simulations. The internal rate of return of the technology is the discount rate (*r*) that makes the *NPV* of total cash flows (benefits minus costs) equal 0:

$$NPV=\sum_{i=1}^{n}\frac{\left(\Delta CS_{simulation}^{i}+\Delta AR_{simulation}^{i}\right)-Cost_{simulation}^{i}}{\left(1+r\right)^{i}}=0.$$

Traditionally, solving for *r* would require using a root-solving algorithm (that is, Secant Method or Müller's Method). However, we can let the General Algebraic Modeling System solver do the work for us and solve for *r* by creating a basic model representing the previous relationship. As we are solving for a root, there is an additional requirement for computing the IRR. In addition to a cash flow, the time discounted benefits must be nonnegative, meaning no IRR can be calculated for any simulations where the benefits do not at least match the cost of investment.

APPENDIX I: SELECTED WORKS CITING INTERNATIONAL MODEL FOR POLICY ANALYSIS OF AGRICULTURAL COMMODITIES AND TRADE (IMPACT)

IMPACT Version 1

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