



IFPRI Modeling Systems

Informing future pathways and priorities

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

Model documentation for version 3.6

Modeling Systems Technical Paper No. 1

Sherman Robinson, Shahnila Dunston, Abhijeet Mishra,
Timothy B. Sulser, Daniel Mason-D’Croz, Richard Robertson,
Nicola Cenacchi, Timothy S. Thomas, Tingju Zhu, Arthur
Gueneau, Gauthier Pitois, Keith Wiebe and Mark Rosegrant



International Food Policy Research Institute

The International Food Policy Research Institute (IFPRI), a research center of CGIAR, provides research-based policy solutions to sustainably reduce poverty and end hunger and malnutrition in low- and middle-income countries. IFPRI was established in 1975 to identify and analyze alternative national and international strategies and policies for meeting the food needs of the developing world, with particular emphasis on low-income countries and on the poorer groups in those countries. Partnerships, communications, capacity strengthening, and data and knowledge management are essential components for translating IFPRI's research to action and impact. The Institute's regional and country programs play a critical role in responding to demand for food policy research and in delivering holistic support to country-led development. IFPRI collaborates with partners around the world.

www.ifpri.org

CGIAR

CGIAR is a global research partnership for a food-secure future, dedicated to transforming food, land, and water systems in a climate crisis. CGIAR science aims to reduce poverty, enhance food and nutrition security, and improve natural resources and ecosystem services. As the world's largest agricultural innovation network, its research is carried out by 15 CGIAR Centers working around the world in close collaboration with hundreds of partners, including national and regional research institutes, civil society organizations, academia, development organizations, and the private sector.

www.cgiar.org

Authors

Sherman Robinson (s.robinson@cgiar.org) is a Research Fellow Emeritus at the Director General's Office of the International Food Policy Research Institute, Washington, D.C., USA.

Shahnila Dunston was formerly a Senior Research Analyst at the Foresight and Policy Modeling unit of the International Food Policy Research Institute, Washington, D.C., USA. Shahnila is an Applied Economist - Climate Fellow at the Economic Research Service of the United States Department of Agriculture.

Abhijeet Mishra (a.mishra@cgiar.org) is an Associate Research Fellow at the Foresight and Policy Modeling unit of the International Food Policy Research Institute, Washington, D.C., USA.

Timothy B. Sulser (t.sulser@cgiar.org) is a Senior Scientist at the Foresight and Policy Modeling unit of the International Food Policy Research Institute, Washington, D.C., USA.

Daniel Mason-D'Croz was formerly a Senior Research Analyst at the Environment and Production Technology Division the International Food Policy Research Institute, Washington, D.C., USA. Daniel is a Senior Research Associate at the Department of Global Development of the College of Agriculture and Life Sciences at Cornell University, Ithaca, New York, USA.

Richard Robertson (r.robertson@cgiar.org) is a Research Fellow at the Foresight and Policy Modeling unit of the International Food Policy Research Institute, Washington, D.C., USA.

Nicola Cenacchi (n.cenacchi@cgiar.org) is a Senior Research Analyst at the Foresight and Policy Modeling unit of the International Food Policy Research Institute, Washington, D.C., USA.

Tim Thomas (tim.thomas@cgiar.org) is a Senior Research Fellow at the Foresight and Policy Modeling unit of the International Food Policy Research Institute, Washington, D.C., USA.

Tingju Zhu was formerly a Research fellow in the Environment and Production Technology Division of the International Food Policy Research Institute, Washington, D.C., USA.

Arthur Gueneau was formerly a Research Analyst in the Development Strategy and Governance Division of the International Food Policy Research Institute, Washington, D.C., USA.

Gauthier Pitois was formerly a Research Analyst in the Development Strategy and Governance Division of the International Food Policy Research Institute, Washington, D.C., USA.

Keith Wiebe (k.wiebe@cgiar.org) is a Senior Research Fellow at the Foresight and Policy Modeling unit of the International Food Policy Research Institute, Washington, D.C., USA and Lead of the CGIAR Research Initiative on Foresight.

Mark Rosegrant (m.rosegrant@cgiar.org) is an IFPRI–Emeritus Fellow at the Director General's Office of the International Food Policy Research Institute, Washington, D.C., USA.

Copyright: © 2024 International Food Policy Research Institute (IFPRI).



This publication is licensed for use under a [Creative Commons Attribution 4.0 International License \(CC BY 4.0\)](https://creativecommons.org/licenses/by/4.0/).

Disclaimer: The boundaries, names, and designations used in this publication do not imply official endorsement or acceptance by the authors, the International Food Policy Research Institute (IFPRI), or its partners and donors.

Recommended Citation: Robinson, S; Dunston, S; Mishra, A; Sulser, TB; Mason-D’Croz, D; Robertson, R; Cenacchi, N; Thomas, TS; Zhu, T; Gueneau, A; Pitois, G; Wiebe, K; Rosegrant, MW. 2024. *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model documentation for version 3.6*. International Food Policy Research Institute. Modeling Systems Technical Paper No. 1. <https://hdl.handle.net/10568/148953>

International Food Policy Research Institute
1201 Eye Street, NW
Washington, DC 20005-3915 USA
www.ifpri.org

Contents

	Abstract	i
	Acknowledgments	ii
	Abbreviations	iii
1	Introduction	1
2	History of the IMPACT model	5
3	Scenario analysis	8
4	IMPACT multimarket model	11
	4.1 Commodity supply	11
	4.2 Crop production	12
	4.3 Livestock production	18
	4.4 Production of processed goods	19
	4.5 Commodity supply and demand	20
	4.6 Markets, Trade, and Equilibrium Prices	25
5	IMPACT model system	29
	5.1 IMPACT data management and estimation system	31
	5.2 Food security modules	31
	5.3 Crop models	33
	5.4 Water models	34
6	Summary	39

Appendices **40**

- Appendix A: Geography 41
- Appendix B: Activities and commodities 75
- Appendix C: Data inputs and outputs 83
- Appendix D: Crop models 87
- Appendix E: Non-exhaustive list of publications using IMPACT 3.x to 3.6 92

List of Figures

1.1	Spatial scale of IMPACT model's operation	3
1.2	IMPACT modeling framework and interactions	4
3.1	Forecasting vs. scenario analysis	8
4.1	The palm oil value chain in the IMPACT activity-commodity framework	12
4.2	Price structure in IMPACT.	26
5.1	Detailed schematic of the IMPACT multimarket model	30
5.2	Detailed schematic of IMPACT global hydrology model	35
5.3	Detailed schematic of IMPACT water basin simulation model	36
5.4	Linking IMPACT to water models	38
A1	Map of CGIAR regions	50
A2	Map of countries/regions in Central and West Asia and North Africa	51
A3	Map of countries/regions in West and Central Africa	52
A4	Map of countries/regions in Latin America and the Caribbean	53
A5	Map of countries/regions in South Asia	54
A6	Map of countries/regions in East and Southern Africa	55
A7	Map of countries/regions in East and Southeast Asia and the Pacific	56
A8	Map of FPU in Central and West Asia and North Africa	69
A9	Map of FPU in West and Central Africa	70
A10	Map of FPU in Latin America and the Caribbean	71

A11	Map of FPU's in South Asia	72
A12	Map of FPU's in East and Southern Africa	73
A13	Map of FPU's in East and Southeast Asia and the Pacific	74

List of Tables

2.1	IMPACT model versions over time	6
3.1	Socioeconomic, environmental, political, and technological framework applied in IMPACT scenarios	9
A1	Country and region codes and names in IMPACT along with their FAO counterparts .	42
A2	List of FPU in IMPACT	57
B1	IMPACT activity list with their FAO codes.	76
B2	Mapping of activities to commodities in IMPACT	79
C1	IMPACT data requirements in the model base year	84
C2	Key IMPACT behavioral and scenario parameters and assumptions	85
C3	Standard IMPACT multimarket model outputs	86
D1	Mapping DSSAT crop model results to IMPACT	90

Abstract

The International Food Policy Research Institute's IMPACT model is a robust tool for analyzing global and regional challenges in food, agriculture, and natural resources. Continuously updated and refined, IMPACT version 3.6 is the latest update to the model for continuously improving the treatment of complex issues, including climate change, food security, and economic development. IMPACT 3.6 multimarket model integrates climate, crop simulation, and water models into a comprehensive system, providing decision-makers with a flexible platform to assess the potential impacts of various scenarios on 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, global hydrology, water basin management, water stress simulation, crop simulation modeling

Acknowledgments

Funding

This work was undertaken by the International Food Policy Research Institute (IFPRI) with support from the CGIAR Initiative on Foresight.

Author contributions

Abhijeet Mishra updated IMPACT v3.6 documentation based on IMPACT v3.0 documentation by Robinson et al. [2015b](#).

Shahnila Dunston, Abhijeet Mishra and Timothy B. Sulser contributed to the coding of the IMPACT 3.6 model system components.

All authors contributed to the research design of IMPACT 3.6.

Additional acknowledgments

We acknowledge that IMPACT 3.6 was built upon the extensive work carried out in previous versions of the model. IMPACT has seen growing usage among multidisciplinary researchers beyond IFPRI. We extend our gratitude to those who have contributed to the model's improvement, including many of our colleagues at IFPRI for their valuable expertise and support. We also acknowledge the assistance and feedback from Claudia Ringler and Nicostratos Perez.

We would also like to especially thank Athanasios Petsakos (Alliance of Bioversity International and the International Center for Tropical Agriculture) for helpful suggestions and comments while reviewing this documentation.

Abbreviations

AR4	Fourth assessment report of the IPCC
AR5	Fifth assessment report of the IPCC
AR6	Sixth assessment report of the IPCC
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
ISIMIP	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 Socio-economic 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 Robinson et al. 2015b.

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), water models (hydrology, water basin management, and water stress models), crop simulation models like 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. The IMPACT model system integrates information flows among the component modules in a consistent equilibrium framework that supports longer-term scenario analysis.

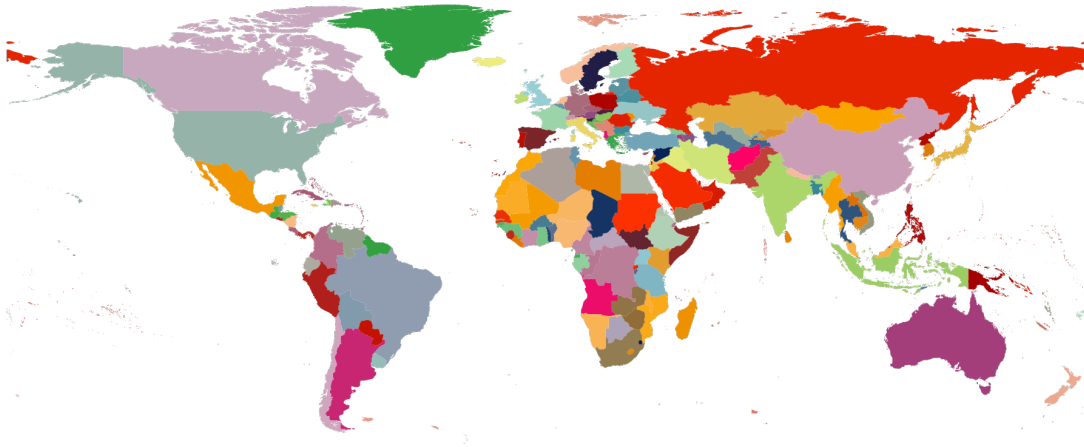
Some of the model communication among IMPACT model’s components (*modules*) is one way, with no feedback links (for example, climate scenarios to hydrology models and crop simulation models), while other links require capturing feedback loops (for example, water demand from the core multimarket model and water supply from the water models must be reconciled to estimate water stress impacts on crop yields). 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.

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.

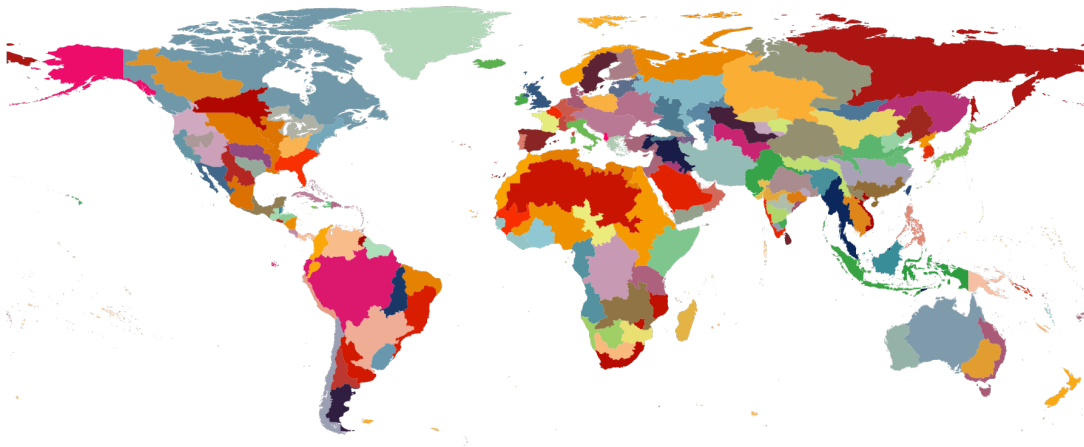
The core multimarket model focuses on national and global markets including 158 countries. Agricultural production is specified by models of land supply, allocation of land to irrigated and rainfed crops, and determination of yields. Production is modeled at a sub-national level, including 320 regions called food production units (FPUs). FPU's correspond to water basins within national boundaries of these 158 countries (see Fig. 1.1 for a geography overview and [Appendix A: Geography](#) for more detailed IMPACT geography). The multimarket model simulates 62 agricultural commodity markets, representing the bulk of food and cash crops (see [Appendix B: Activities and commodities](#) for a full list of commodities).

Fig. 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 (Fig. 5.1) as well as a more detailed description of the integration of different modules within the IMPACT system can be seen in Section 5.

158 Countries/regions



161 Water basins



320 FPU's

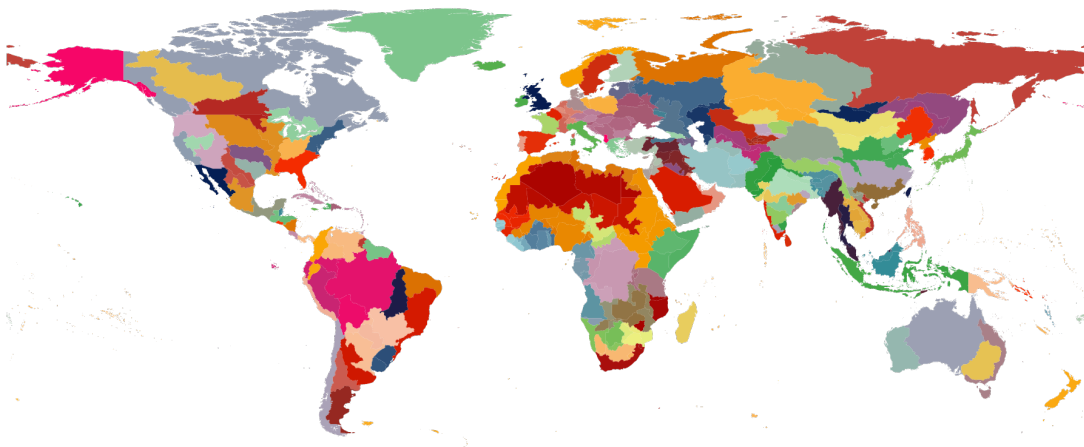


Figure 1.1: Spatial scale of IMPACT model's operation. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

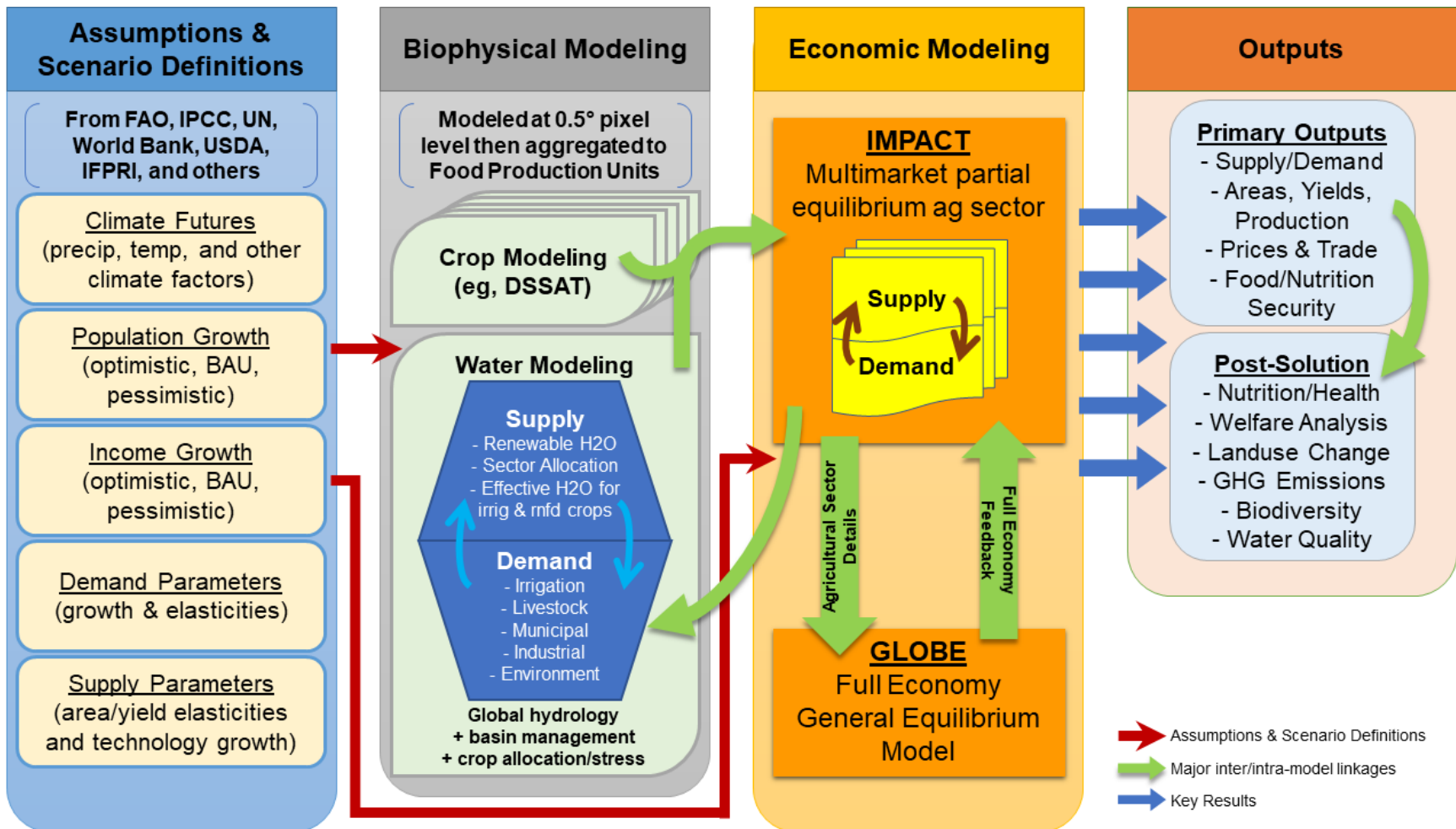


Figure 1.2: IMPACT modeling framework and interactions

2 History of the IMPACT model

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 long-term foresight modeling 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 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.

The latest version of IMPACT, i.e., v3.6 brings forward additional capabilities to the modeling framework. These include the latest climate impact projections from AR6 of IPCC, version 3 of the Shared Socioeconomic Pathways, ability to model planetary health diets, and, inclusion of post harvest losses in our food systems.

Table 2.1: IMPACT model versions over time

Version	Solver	Scope	Commodities	Time scope	Linkages	<i>changelog</i>	Model description
1 to 1.x	Gauss-Seidel	35 countries	17 total 8 crop 6 livestock 3 processed	1995 - 2020			Rosegrant, Agcaoili-Sombilla, and Perez (1995)
		36 countries 69 FPU	32 total 14 crop 6 livestock 2 processed	2000 - 2025	Water Value chains (processing)		Rosegrant, Sulser. et al. (2005)
		115 countries 281 FPU	44 total 23 crop 6 livestock 15 processed	2000 - 2050	Water Crop Food security Value chains (processing)		Rosegrant et al. (2008)
2 to 2.x	Path	115 countries 281 FPU	45 total 24 crop 6 livestock 15 processed	2000 - 2050	Water Crop Food security Value chains (processing)		Rosegrant and IMPACT development team (2012)
3	Path	158 countries 320 FPU	62 total 39 crop 6 livestock 17 processed	2005 - 2050	Water Crop Food security Value chains (processing)		Robinson et al. 2015
3.6+	Path	158 countries 320 FPU	62 total 39 crop 6 livestock 17 processed	2020 - 2050	Water Crop Food security Value chains (processing)	AR6 climate impacts; SSP version 3; Planetary health diets; Post harvest losses; IPRs linked to SSPs (GDP per capita changes)	Current paper

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 158 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 and above, 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: Data inputs and outputs](#) summarizes the current sources of data used in IMPACT.

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 (PATH solver) that greatly improve solution robustness and speed. In addition, software design that 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. More recent versions of IMPACT have incorporated major developments in user interface to ease the use of IMPACT.

Significant efforts also have been made in developing interfaces for running IMPACT as well as sophisticated data visualization tools to facilitate and encourage the use of IMPACT in policy analysis. One such visualization tool is App for IMPACT (ARIA - **A**pp for **R** **I**mp**A**ct). This tool is developed in-house by the Foresight and Policy Modeling Unit at IFPRI and is made available as an open-source tool. Source code of ARIA is hosted on GitHub at github.com/ifpri/aria and its documentation is available via IFPRI's R-universe at ifpri.r-universe.dev/ARIA (Mishra 2024).

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. Fig. 3.1 illustrates the difference in the range of possibilities that are considered in scenario analysis versus traditional forecasting.

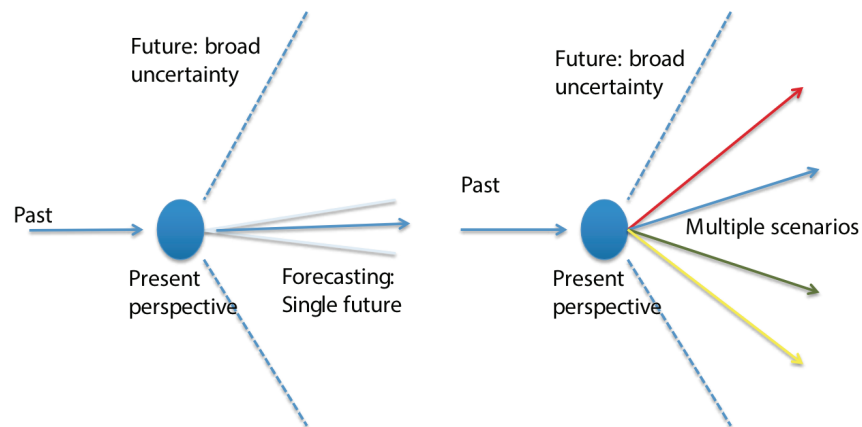


Figure 3.1: Forecasting vs. scenario analysis. Source Vervoort et al. 2013.

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.

Table 3.1: The socioeconomic, environmental, political, and technological framework applied in IMPACT scenarios. Source: Authors, with adaptation from Wilson 1998.

Domain	Examples in IMPACT
Socioeconomic	Population growth Urban-rural households Gross domestic product and economic development Income distribution across households Consumer behaviour Price transmission and exchange rates Input (fertilizers, pesticides, energy etc.)
Environmental	Water and land availability Climate change
Political	Investment in agriculture research and development Trade policies (taxes, tariffs, consumer & producer support policies)
Technological	Change in agricultural productivity due to improved genetics and management

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 (Sarukhán et al. 2005) and the Intergovernmental Panel on Climate Change’s (IPCC’s) fourth assessment report (AR4). For IMPACT 3, they are based on IPCC’s fifth assessment report (AR5). For IMPACT 3.6, they are based in IPCC’s sixth assessment report (AR6).

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, macro-econometric 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.

4.1 Commodity supply

IMPACT since update to version 3 carries a 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), and each has a unique method of production but that can still be summarized by the activity-commodity framework. This framework is described in Box 4.1.

Box 4.1. Activity-Commodity framework in IMPACT.

The key to understanding the activity-commodity framework is to separate the process (activity) from the output of this process (commodity).

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.

The framework described in box 4.1 allows for potentially complex interlinking of activity inputs and outputs (managed through input-output matrices), to simulate agricultural value chains. An example of this interlinking is illustrated in Fig. 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: Activities and commodities](#). 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.

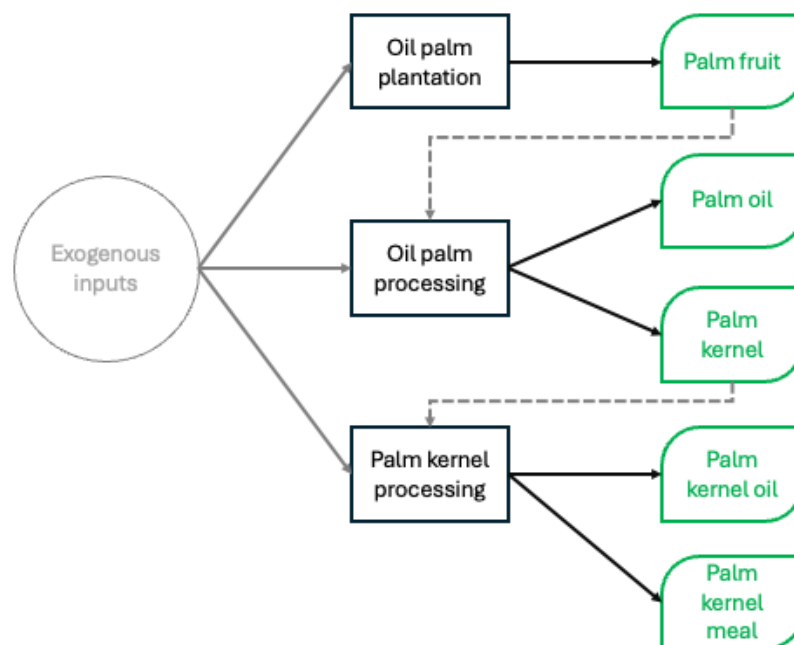


Figure 4.1: Conceptual diagram explaining the palm oil value chain in the IMPACT activity-commodity framework. Boxes in black are activities. Irregular boxes in green are commodities in IMPACT.

4.2 Crop production

Crop production in IMPACT is simulated through area¹ 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 sub-nationally with the area and yield functions at the level of FPU. 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 version 3 and above 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

¹In 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.

changes in crop prices. The shadow price (WF in equation 1) is indexed to 1 in the first year and changes based on changing demands from all crops for land area.

4.2.1 Equations

Equation 1 describes the land supply in IMPACT. 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.

$$QFS_{fpu, lnd} = QFSInt_{fpu, lnd} * QFSInt2_{fpu, lnd} * QFSInt3_{fpu, lnd} * (WF_{fpu, lnd})^{L_\gamma} \quad (1)$$

where:

- QFS = Land supply
- $QFSInt$ = Land supply intercept i.e., base year supply of land
- $QFSInt2$ = Endogenous land supply growth multiplier
- $QFSInt3$ = Exogenous land supply growth multiplier
- WF = Shadow price index of land
- L_γ = Elasticity of land supply
- fpu = Food production unit
- lnd = Land type (irrigated or rainfed)

Additionally, equations 2a and 2b are applied at the end of each year before solving for land supply for a new year. Note that the index t and $t+1$ for the simulation time step are only illustrative in equations 2a and 2b to denote updates of parameters in IMPACT from one year to another.

$$QFSInt2_{fpu, lnd, t+1} = QFSInt2_{fpu, lnd, t} * (1 + Landgr_{fpu, lnd}) \quad (2a)$$

$$QFSInt3_{fpu, lnd, t+1} = \left(\frac{\sum_{t=1}^t WF_{fpu, lnd, t}}{3} \right)^{L_\gamma, t} \quad (2b)$$

where:

- $QFSInt2$ = Land supply growth multiplier
- $Landgr$ = Exogenous land supply growth rate
- WF = Shadow price index of land
- $\sum_{t=1}^3 WF_{fpu, lnd, t}/3$ = Average shadow price of past three years
- L_γ = Elasticity of land supply
- fpu = Food production unit
- lnd = Land type (irrigated or rainfed)
- t = Simulation time step

From equation 3, crop area is driven by an area demand function with respect to changes in the marginal revenue product, changes in land cost, and exogenous non-price 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.

$$MRP_{j,fpulnd} = Yld_{j,fpulnd} * \sum_{cty}^{fpu} PNET_{j,cty} \quad (3)$$

where:

MRP = Marginal revenue product of land
Yld = Crop yield
PNET = Net price for the activity at the country-level
j = Activity (crops)
fpu = Food production unit
lnd = Land type (irrigated or rainfed)
cty = Countries

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 non-agricultural uses. The combination of these endogenous and exogenous factors in area demand are described in equation 4.

$$Area_{j,fpulnd} = AreaInt_{j,fpulnd} * AreaInt2_{j,fpulnd} * (WF_{fpulnd})^{WF_{\epsilon}} * \left(\frac{MRP_{j,fpulnd}}{MRP0_{j,fpulnd}} \right)^{A_{\epsilon}} \quad (4)$$

where:

Area = Solution for crop area
AreaInt = Crop area intercept (base year crop area)
AreaInt2 = Exogenous crop area growth multiplier
WF_ε = Elasticity of demand with respect to land shadow price
MRP = Marginal revenue product of land
MRP0 = Base year marginal revenue product of land (used to index prices)
A_ε = Elasticity of area demand with respect to marginal revenue product
j = Activity (crops)
fpu = Food production unit
lnd = Land type (irrigated or rainfed)

Assumptions for exogenous trends are determined by a combination of historical changes in land use and expert judgment on potential future regional dynamics as described in equation 5. They are represented as compound growth from the base and are applied between years. Note that the

index t and $t+1$ for the simulation time step is only illustrative in equation 5 to denote updates of parameters in IMPACT from one year to another.

$$AreaInt2_{j,fpu,lnd,t+1} = AreaInt2_{j,fpu,lnd,t} * (1 + Areagr_{j,fpu,lnd,t+1}) \quad (5)$$

where:

$AreaInt2$ = Exogenous crop area growth multiplier
 $Areagr$ = Exogenous area demand growth rate
 j = Activity (crops)
 fpu = Food production unit
 lnd = Land type (irrigated or rainfed)
 t = Simulation time step

Competing demands from different crops are handled through equation 6. This equilibrium equation that determines the land allocation and ensures that all crop area demand sums up to the total land supply for each FPU.

$$QFS_{fpu,lnd} = \sum_j Area_{j,fpu,lnd} \quad (6)$$

where:

QFS = Land supply
 $Area$ = Solution for crop area
 j = Activity (crops)
 fpu = Food production unit
 lnd = Land type (irrigated or rainfed)

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, Pray, and Rosegrant 1998.

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) 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.

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 non-agricultural 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 as shown in equation 7.

$$Yield_{j,fpulnd} = YieldInt_{j,fpulnd} * YieldInt2_{j,fpulnd} * WatShk_{j,fpulnd} * CliShk_{j,fpulnd} * \left(\frac{PNET_{j,cty}}{PNET0_{j,cty}} \right)^{Y_\epsilon} * (PF)^{F_\epsilon} \quad (7)$$

where:

- Yield* = Final yield
- YieldInt* = Yield intercept (base year yield)
- YieldInt2* = Exogenous yield growth multiplier
- WatShk* = Water stress shock (from water models)
- CliShk* = Climate change shock (from water and crop models)
- PNET* = Net price for the activity at the country-level
- PNET0* = Base year net price for the activity at the country-level (used to index prices)
- PF* = Input prices
- F_ε* = Yield supply elasticity with respect to net price
- j* = Activity (crops)
- fpu* = Food production unit
- lnd* = Land type (irrigated or rainfed)
- cty* = Countries

IMPACT also includes the possibility of introducing new technologies such as drought and/or heat tolerant crop varieties (Robinson et al. 2015a). 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.

$$Yield_{j,fpu,lnd} = \sum_{tech} (TechShare_{j,fpu,lnd,tech} * TechYield_{j,fpu,lnd}) \quad (8)$$

where:

Yield = Final yield
TechShare = Share of crop area adopting the technology
TechYield = Yield from technology
j = Activity (crops)
fpu = Food production unit
lnd = Land type (irrigated or rainfed)
tech = Crop production technology

Final crop production for each FPU and activity or crop (j) is estimated as the product of the solution for its respective area and yield equations, with national production equal to the summation of the production in all of the relevant FPUs in that country. This is modeled as shown in equation 9.

$$QS_{j,cty} = \sum_{fpu}^{cty} \left(\sum_{lnd} (Area_{j,fpu,lnd} * Yield_{j,fpu,lnd}) \right) \quad (9)$$

where:

QS = Crop production
Area = Solution for crop area
Yield = Final yield
j = Activity (crops)
fpu = Food production unit
lnd = Land type (irrigated or rainfed)
cty = Countries

4.3 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.

4.3.1 Equations

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.

$$AnN_{j,fpulvs} = AnNInt_{j,fpulvs} * AnNInt2_{j,fpulvs} * \sum_{cty} \left[\prod_{jl} \left(\frac{PNET_{jl,cty}}{PNET0_{jl,cty}} \right)^{AN_{\epsilon}} * \prod_{cfeed} \left(\frac{PC_{cfeed,cty}}{PC0_{cfeed,cty}} \right)^{Feed_{\epsilon}} \right] \quad (10)$$

where:

- AnN = Animal Numbers
- $AnNInt$ = Animal intercept (initial number of animals)
- $AnNInt2$ = Exogenous population growth for animals
- AN_{ϵ} = Animal stock supply elasticity
- $Feed_{\epsilon}$ = Animal feed elasticity of supply
- $PNET$ = Net price for the activity at the country-level
- $PNET0$ = Base year net price for the activity at the country-level (used to index prices)
- PC = Consumer price
- $PC0$ = Base year consumer price
- j = Activity (crops)
- jl = Activity (livestock)
- fpu = Food production unit
- lvs = Livestock production systems
- cty = Countries

Livestock yields are determined through exogenous growth due to improved animals and management practices as shown in equation 11. Currently, all price responses in the livestock sector are accounted for in the animal number equations.

$$AnY_{j,fpulvs} = AnYInt_{j,fpulvs} * AnYInt2_{j,fpulvs} \quad (11)$$

where:

AnY = Animal yields
AnYInt = Initial animal yields
AnYInt2 = Exogenous yield growth
j = Activity (crops)
fpu = Food production unit
lvs = Livestock production systems

Total national production (equation 12) is calculated by multiplying the number of slaughtered animals by the yield per head and summing across FPU and livestock system.

$$QS_{j,cty} = \sum_{fpu,lvs} (AnN_{j,fpu,lvs} * AnY_{j,fpu,lvs}) \quad (12)$$

where:

QS = Production from animals
AnN = Animal numbers
AnY = Animal yields
j = Activity (crops)
fpu = Food production unit
lvs = Livestock production systems

4.4 Production of processed goods

4.4.1 Equations

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.²

$$PNET_{j,cty} = PP_{j,cty} * (1 - CSEI_{j,cty}) * \sum_{ci} (IOmat_{ci,j,cty} * PC_{ci,cty}) \quad (13)$$

where:

²Crops 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.

PNET = Net price for the activity at the country-level
PP = Producer prices
CSEI = Consumer support estimate on intermediate inputs
IOMAT = Input-output matrix
PC = Consumer prices (of inputs)
j = Activity (crops)
ci = Commodities that are inputs for activity *j*
cty = Countries

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 as shown in equation 14.

$$QS_{j,cty} = QSInt_{j,cty} * QSInt2_{j,cty} * \prod_j \left(\frac{PNET_{j,cty}}{PNET0_{j,cty}} \right)^{QS\varepsilon} \quad (14)$$

where:

QS = Production of processed goods
QSInt = Non-crop activity supply intercept
QSInt2 = Supply multiplier for non-crop activities
PNET = Net price for the activity at the country-level
PNET0 = Base year net price for the activity at the country-level (used to index prices)
QS\varepsilon = Supply price elasticities
j = Activity (processed goods)
cty = Countries

4.5 Commodity supply and demand

4.5.1 Equations

Total supply of commodities requires mapping from output of production activities to supply of commodities. The mapping is given by equation 15.

$$QSUP_{c,cty} = \sum_j (JCRatio_{j,c} * QS_{j,cty}) \quad (15)$$

where:

$QSUP$ = Total commodity supply
 $JCRatio$ = Activity to commodity mapping
 QS = Total production
 c = Commodity
 j = Activity (crops)
 cty = Countries

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 described in equation 16, and 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).

$$QD_{c,cty} = \left(\sum_h (QH_{c,h,cty}) \right) + QInterm_{c,cty} + QL_{c,cty} + QBF_{c,cty} + QOth_{c,cty} \quad (16)$$

where:

QD = Total commodity demand
 QH = Household food demand
 $QInterm$ = Intermediate demand from agricultural processing sector
 QL = Feed demand from livestock sector
 QBF = Intermediate demand for biofuel feedstock
 $QOth$ = Other demand
 h = Household type (urban or rural)
 c = Commodity
 cty = Countries

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 Socio-economic Pathway (SSP) database (version 3) representing socioeconomic scenarios.

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 (USDA 1998). Over time these elasticities have been adjusted in IMPACT 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, etc.); however, IMPACT 3.6 treats household demand with one representative consumer per country.

$$\begin{aligned}
 QH_{c,h,cty} = & QHDint_{c,h,cty} * WI_{c,cty} * QHDIInt2_{c,h,cty} * \left(\frac{pcGDP_{h,cty}}{pcGDP0_{h,cty}} \right)^{I_\varepsilon} \\
 & * \left(\frac{popH_{h,cty}}{popH0_{h,cty}} \right) \\
 & * \prod_{cc \neq c} \left(\frac{PC_{c,cty} * (1 - CSE_{c,cty})}{PC0_{c,cty} * (1 - CSE0_{c,cty})} \right)^{F_\varepsilon}
 \end{aligned} \tag{17}$$

where:

QH	= Household food demand
$QHDInt$	= Initial household food demand
WI	= Waste fraction for post harvest losses
$QHDIInt2$	= Demand adjuster for implementing change in diets
$pcGDP$	= Per capita GDP
$pcGDP0$	= Initial per capita GDP
I_ε	= Income demand elasticity
$popH$	= Household population
$popH0$	= Initial household population
$\prod_{cc \neq c} \left(\frac{PC_{c,cty} * (1 - CSE_{c,cty})}{PC0_{c,cty} * (1 - CSE0_{c,cty})} \right)^{F_\varepsilon}$	= Cross price response
F_ε	= Price demand elasticity
h	= Household type (urban or rural)
c, cc	= Commodity
cty	= Countries

Feed demand is treated as 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. As defined in equation 18, IMPACT also incorporates a technology parameter that indicates improvements in feeding efficiencies over time.

$$QL_{c,cty} = QLInt_{c,cty} * QLInt2_{c,cty} * \sum_{lvs} (QS_{lvs,cty} * FR_{lvs,c,cty}) * \prod_{c=cfeed} \left(\frac{PC_{c,cty}}{PC0_{c,cty}} \right)^{LF_\varepsilon} \tag{18}$$

where:

QL = Feed demand for livestock sector
 $QLInt$ = Initial feed demand for livestock sector
 $QLInt2$ = Livestock sector feed demand multiplier
 QS = Total production for livestock activity
 FR = Livestock feed requirement
 lvs = Livestock production systems
 c = Commodity
 $cfeed$ = Feed commodities
 cty = Countries

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) as show in equation 19.

$$QInterm_{c,cty} = \sum_j (IOMat_{c,j,cty} * QS_{j,cty}) \quad (19)$$

where:

$QInterm$ = Intermediate demand from agricultural processing sector
 $IOMAT$ = Input-output matrix
 QS = Total production
 j = Activity (crops)
 c = Commodity
 cty = Countries

Biofuel feedstock demand (equation 20) in IMPACT 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.

$$QBF_{c,cty} = QBFInt_{c,cty} * QBFInt2_{c,cty} * \prod_c \left(\frac{PC_{c,cty}}{PC0_{c,cty}} \right)^{BF_\epsilon} \quad (20)$$

where:

QBF = Biofuel feedstock demand
 $QBFInt$ = Initial demand for biofuel feedstock
 $QBFInt2$ = Exogenous growth in demand for biofuel feedstock
 BF_ϵ = Biofuel feedstock demand price elasticity
 c = Commodity
 cty = Countries

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 equation 21 and equation 22. The primary method follows the household food demand equation and is sensitive to changes in income, population, and prices.

$$QOth_{c,cty} = QOthInt_{c,cty} * QOthInt2_{c,cty} * \left(\frac{pcGDP_{cty}}{pcGDP0_{cty}} \right)^{OI_\varepsilon} * \left(\frac{pop_{cty}}{pop0_{cty}} \right) * \prod_{cc=c} \left(\frac{PC_{c,cty}}{PC0_{c,cty}} \right)^{OP_\varepsilon} \quad (21)$$

where:

- $QOth$ = Other demand
- $QOthInt$ = Initial other demand
- $QOthInt2$ = Growth in other demand
- $pcGDP$ = Per capita GDP
- $pcGDP0$ = Initial per capita GDP
- $popH$ = Household population
- $popH0$ = Initial household population
- OI_ε = Income demand elasticity for other demand
- OP_ε = Price demand elasticity for other demand
- PC = Consumer price
- $PC0$ = Initial consumer price
- c, cc = Commodity
- cty = Countries

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 (pcGDP1).

$$QOth_{c,cty} = QOth1_{c,cty} * \left(\frac{\sum_h QH_{c,h,cty}}{\sum_h QHD1_{c,h,cty}} \right) \Leftrightarrow \sum_h QHD1_{c,h,cty} + QOth1_{c,cty} * \left(\frac{pcGDP_{cty}}{pcGDP1_{cty}} \right) \Leftrightarrow \sum_h QHD1_{c,h,cty} = 0 \quad (22)$$

where:

- $QOth$ = Other demand
- $QOth1$ = Lagged other demand
- QH = Household demand
- $QHD1$ = Lagged household demand
- $pcGDP$ = Per capita GDP
- $pcGDP1$ = Lagged per capita GDP
- c = Commodity
- cty = Countries
- h = Type of household

4.6 Markets, Trade, and Equilibrium Prices

The system of equations is written in the GAMS programming language (from GAMS Development Corp. and GAMS Software GmbH, see gams.com). 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 non-traded commodities, domestic prices in each country adjust to equate supply and demand within the country.

4.6.1 Equations

In IMPACT, at the end of every year the world’s production must equal the world’s demand. This constraint is ensured by equation 23, where the sum of net trade over the globe must equal zero.

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

where:

NT = Net trade of commodities

c = Commodity

cty = Countries

Additionally, 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. 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 as shown in equation 24.

$$NT_{c,cty} = QSUP_{c,cty} - QD_{c,cty} - QSt_{c,cty} \quad (24)$$

where:

NT = Net trade of commodities

$QSUP$ = Total commodity supply

QD = Total commodity demand

QSt = Total change in stocks

c = Commodity

cty = Countries

IMPACT prices are in constant base year US dollars (for IMPACT 3.6, 2020 is the base year). 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 (GTAP) at Purdue University and reflect trade policies at the national level. 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. 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. Fig. 4.2 illustrates the pricing system in IMPACT and where the appropriate price wedges are applied. Abbreviations used in Fig. 4.2 are as follows:

- MMJ is **M**arketing **M**argins for activities (**j**)
- PSE is **P**roducer **S**ubsidy **E**quivalents
- CSE is **C**onsumer **S**ubsidy **E**quivalents.
- MMM is **M**arketing **M**argins for **I**mports
- MME is **M**arketing **M**argins for **E**xports
- TM is **T**ariffs on **I**mports, and,
- TE is **T**axes on **E**xports

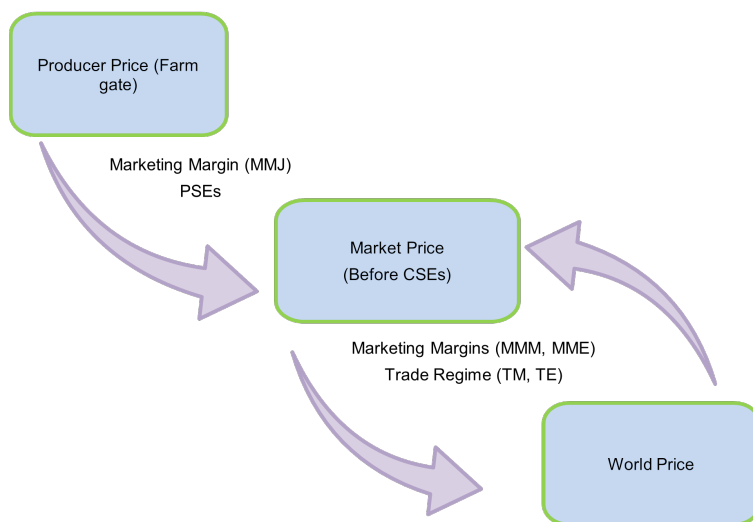


Figure 4.2: Price structure in IMPACT.

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 as shown in equation 25.

$$PP_{j,cty} * (1 + MMJ_{j,cty}) = (1 + PSE_{j,cty}) * \sum_c (JCRatio_{j,c,cty} * PC_{c,cty}) \quad (25)$$

where:

PP = Producer price
MMJ = Farm(factory)-gate to domestic market Marketing Margin (MM)
PSE = Producer support estimate, ad valorem component
JCRatio = Mapping between activities (j) and commodities (c)
j = Activity (crops)
cty = Countries

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 every country and ensure that domestic supply equals domestic demand as shown in equation 26.

$$QSUP_{c,cty} = QD_{c,cty} \quad (26)$$

where:

QSUP = Domestic supply
QD = Domestic demand
c = Commodity
cty = Countries

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 3.6, like IMPACT 3 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 price of imports paid by consumers can be modeled in separate equations with similar specifications as shown in equation 27.

$$PM_{c,cty} = PW_c * EXR_{cty} * (1 + TM_{c,cty}) * (1 + MMM_{c,cty}) \quad (27a)$$

$$PE_{c,cty} = PW_c * EXR_{cty} * (1 - TE_{c,cty}) * (1 - MME_{c,cty}) \quad (27b)$$

where:

PM = Import price

PE = Export price

PW = World market price

EXR = Exchange rate (normalized to 1)

TM = Import tariff (ad valorem)

TE = Export tariff (ad valorem)

MMM = Import marketing margin for domestic market

MME = Export marketing margin for international market

c = Commodity

cty = Countries

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, IMPACT 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). In summary:

- No import happens while $PM_{c,cty} > PC_{c,cty}$, imports begin at $PM_{c,cty} \leq PC_{c,cty}$
- No export happens while $PC_{c,cty} > PE_{c,cty}$, exports begin at $PC_{c,cty} \leq PE_{c,cty}$
- Domestic trade happens if $PE_{c,cty} \leq PC_{c,cty} \leq PM_{c,cty}$

For purely tradable goods, where we want the commodities to always be linked to world markets³, this inequality is not used, the domestic consumer price is set to the import price (equation 28), and the export price equation is never used.

$$PC_{c,cty} = PM_{c,cty} \quad (28)$$

where:

PC = Consumer price

PM = Import demand

c = Commodity

cty = Countries

³This is done for all traded commodities in IMPACT v3.6

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 Fig. 1.2. 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. Fig. 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. More detail about some of the modules, including equations, is provided in the appendixes.

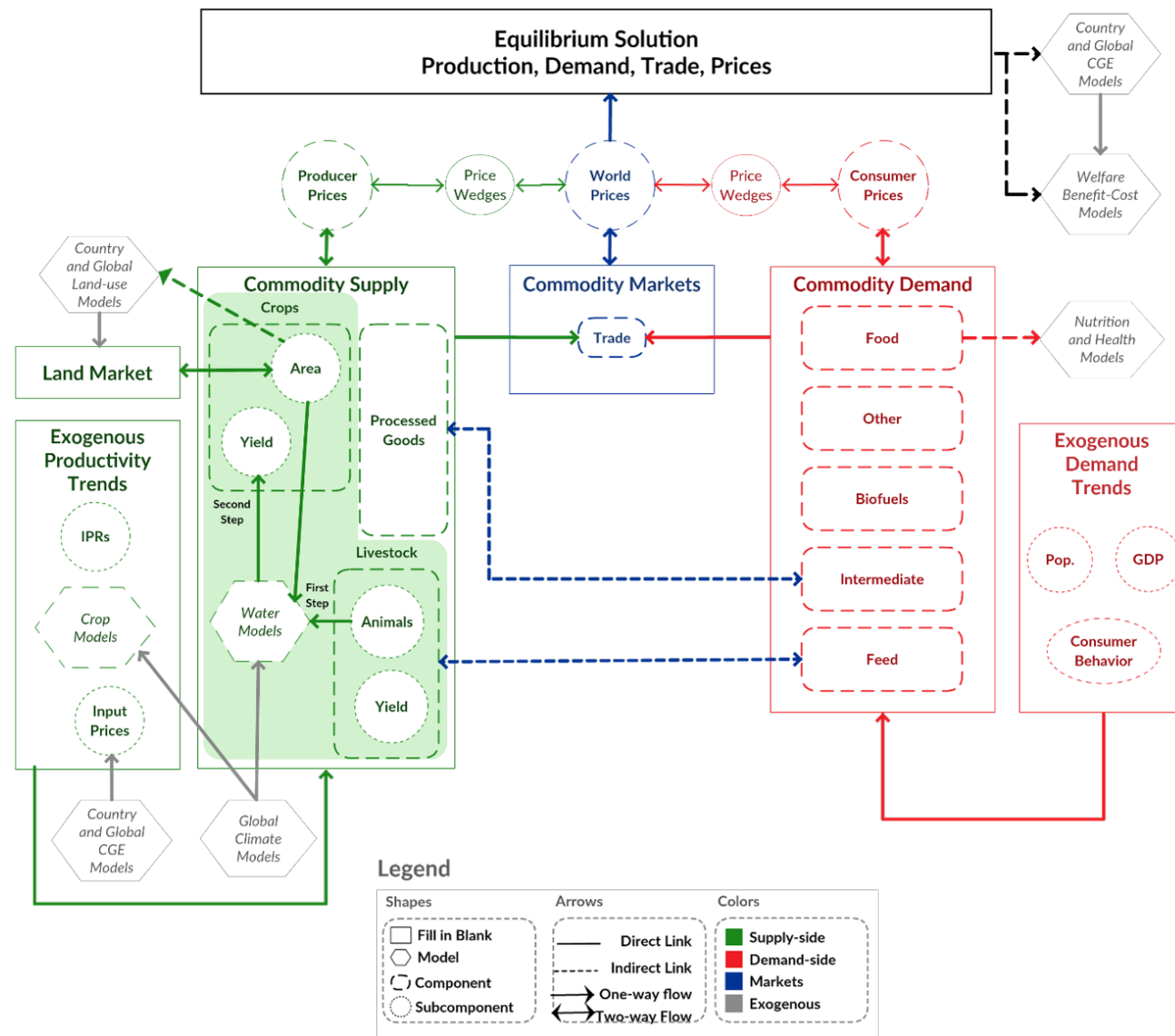


Figure 5.1: Detailed schematic of the IMPACT multimarket model. CGE = computable general equilibrium; GDP = gross domestic product; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; IPRs = intrinsic productivity growth rates.

5.1 IMPACT data management and estimation system

Modeling philosophy in IMPACT also focuses on making data processing independent from the behavioral model system. The goal is that any model component of IMPACT 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. 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 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.

5.2 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 Sustainable Development Goals.

The malnutrition module is based on Smith and Haddad [2000](#), and estimates changes in child wasting (underweight) based on changes in food availability at the country level. The population

at risk of hunger module is based on Fischer et al. 2005, and estimates changes in the share of population at risk of hunger based on changes in food availability. Both modules are examples of postprocessing modules in IMPACT, where information from the multimarket model (food availability, population, GDP, etc.) serves as an input to the module and the results are not feedback into the economic module.

5.2.1 Undernourished children

The percentage of children younger than five who are undernourished 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, 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.

$$\Delta UndNrsh_{t,t0} = -25.54 * \ln \frac{kcal_t}{kcal_{t0}} - (71.76 * \Delta LFER_{t,t0}) - (0.22 * \Delta SCH_{t,t0}) - (0.08 * \Delta WAT_{t,t0}) \quad (29)$$

where:

- UndNrsh* = Percent change in undernourished children
- kcal* = per capita kilocalorie availability
- LFER* = Ratio of female-male life expectancy at birth
- SCH* = Gross female secondary school enrollment rate
- WAT* = % of population with access to safe water
- $\Delta t, t0$ = Difference between time step t and base year (2019 for IMPACT v3.6)

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 World Development Indicators (WDIs). The base values for female-male life expectancy ratio, female secondary school enrollment, and access to safe water come from the WDIs. The projections of changes in female-male life expectancy come from the United Nations Populations Prospects (medium variant). The projections of changes in female secondary school enrollment and access to clean water come from the Technogarden Baseline Scenario (MEA 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 (FAOSTAT database).

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 (KC et al. 2024).

5.2.2 Share of population 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 Fischer et al. 2005⁴.

$$ShrRisk_{cty,t} = \beta_0 + (\beta_1 * rKcal_{cty,t}) + (\beta_2 * rKcal_{cty,t}^2) + \varepsilon \quad (30)$$

where:

<i>ShrRisk</i>	= Share of population at risk of hunger
β_0	= Constant term (288.1)
β_1	= -319.7
β_2	= 89.7
ε	= Estimation error
<i>cty</i>	= Countries
<i>t</i>	= Simulation time step

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 3 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.

5.3 Crop models

Estimating 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 grid-based yields for each climate and crop combination are 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. Crop models are further discussed in [Appendix D: Crop models](#).

⁴The 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.

5.4 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.

5.4.1 IMPACT global hydrology model (IGHM)

As described in the following schematic (Fig. 5.2), 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 FPU within the river basin and weighted by grid cell areas.

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.

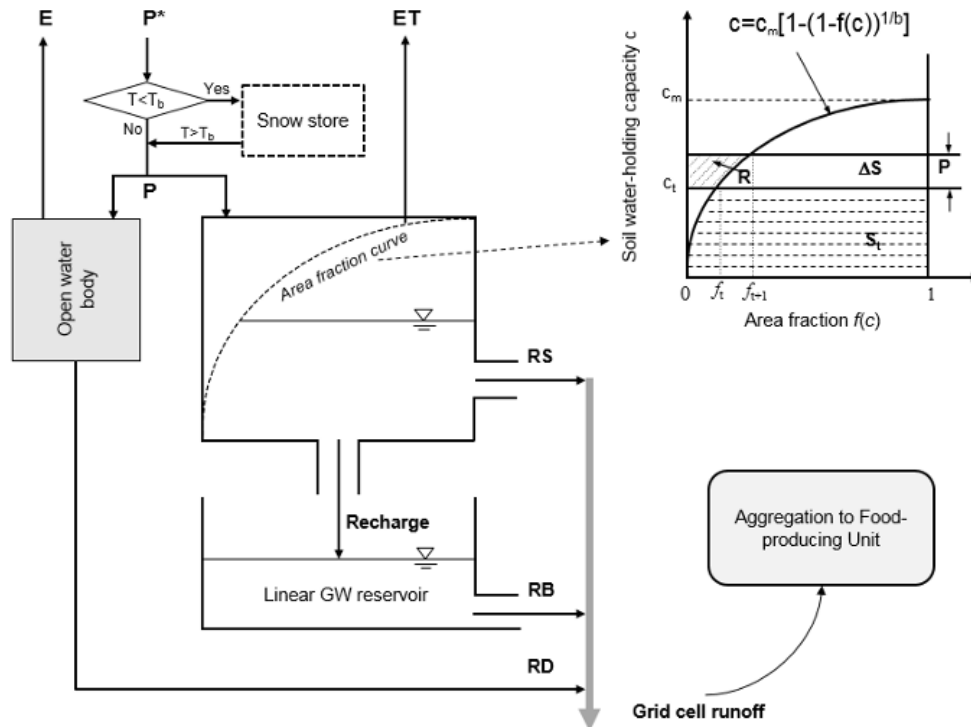


Figure 5.2: IMPACT global hydrology model schematic illustrating vertical water balance of the land and open water fraction of a grid cell. E = evaporation (millimeters per month [mm/m]); ET = evapotranspiration (mm/m); GW = groundwater; IMPACT = International Model for Policy Analysis of Agricultural 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); Tb = base temperature (°C), used as threshold to determine incoming precipitation as rain or snow.

5.4.2 IMPACT water basin simulation model (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.

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). 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 (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 FPU's 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 FPU's 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 Fig. 5.3 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 FPU's 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.

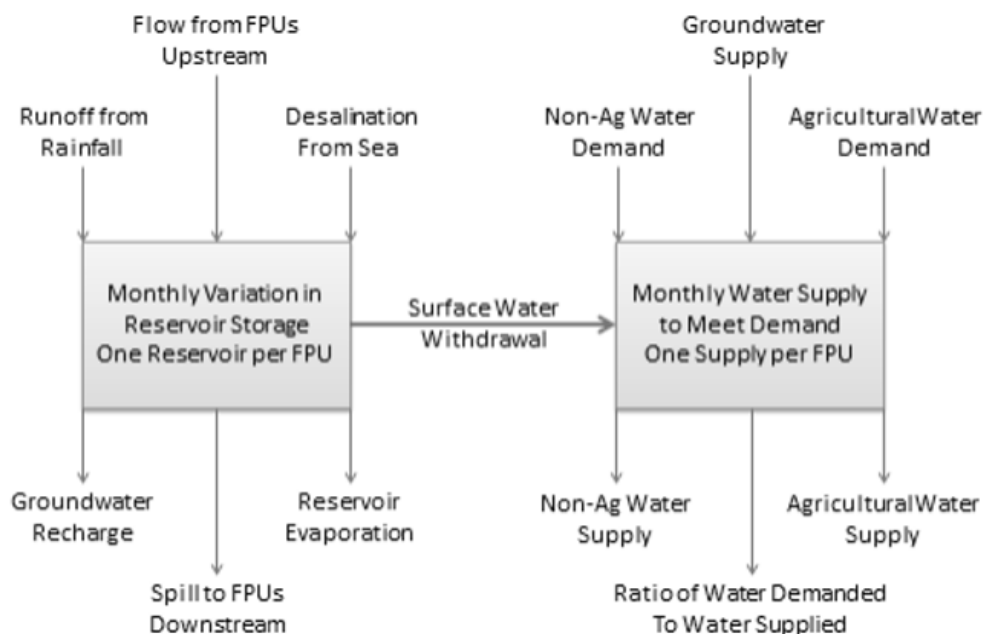


Figure 5.3: IMPACT water basin simulation model. FPU = food production unit; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; Non-Ag = nonagricultural

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 FPU. Solving for water supply in all FPU simultaneously, IWSM assumes that linked FPU 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.

5.4.3 IMPACT crop water allocation and stress model (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.

5.4.4 Linking the IMPACT Water and Multimarket Models

Communication between the water models and the multimarket model is shown in Fig. 5.4. 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 (Fig. 5.3) uses these water demands, along with river flows provided by IGHM (Fig. 5.2), to provide the monthly repartition of water among FPU 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 FPU 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.

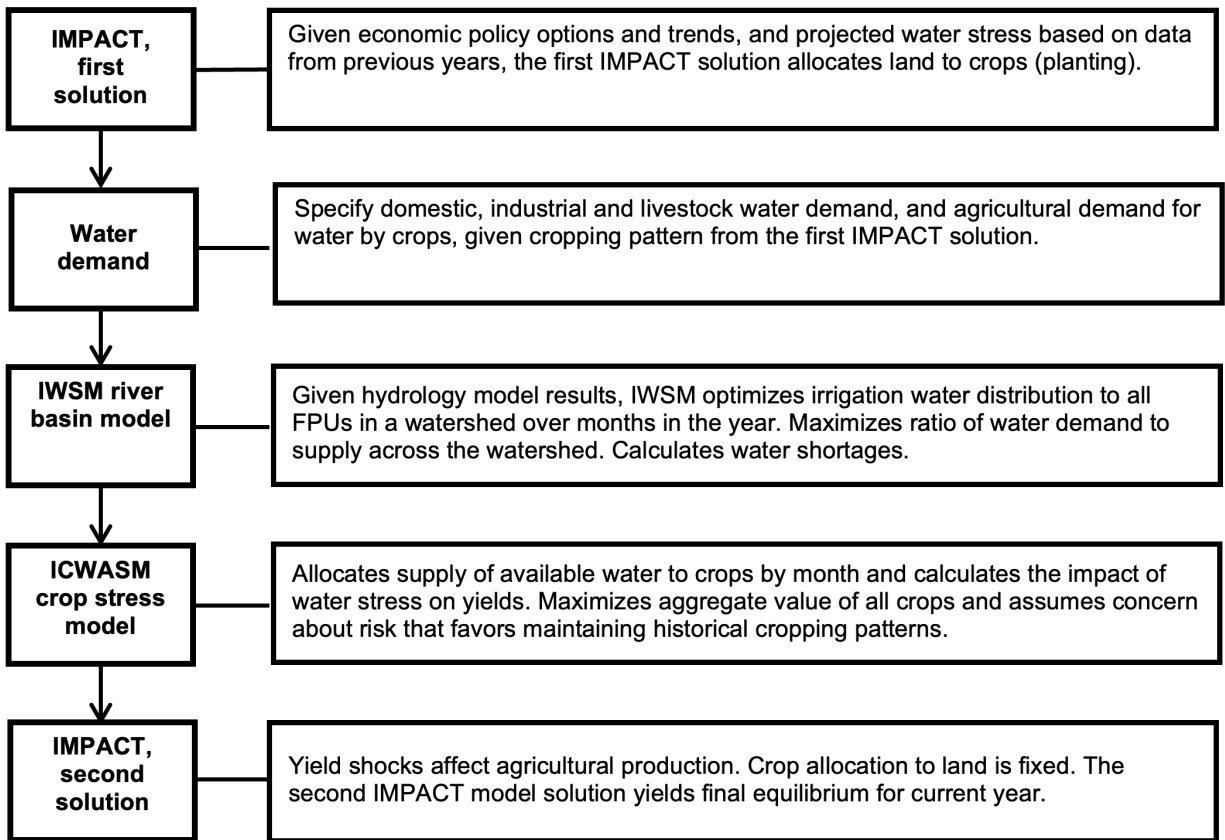


Figure 5.4: Linking IMPACT to water models: Dynamic two-way communication year by year. FPU's = food production units; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; IWSM = IMPACT water basin simulation model; ICWASM = IMPACT crop water allocation and stress model.

6 Summary

IFPRI began work on the IMPACT model about 30 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. IMPACT 3.6 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.

These changes have made 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. These improvements have already proven beneficial, allowing a relatively small modeling team to better incorporate model feedback, new data and expert opinion. 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, including improvements to current modules and development of new modules, is being pursued to expand and improve on IMPACT.

Appendices

Appendix A: Geography

Table A1: Country and region codes and names in IMPACT along with their FAO counterparts.

See fao.org/faostat/en/#definitions (section "Country/Region") for full list of FAO codes and definitions.

FAO country code	Country name (FAO)	Country / Region code (IMPACT)	Country / Region name (IMPACT)
1	Armenia	ARM	Armenia
2	Afghanistan	AFG	Afghanistan
3	Albania	ALB	Albania
4	Algeria	DZA	Algeria
5	American Samoa	OPO	Other Pacific Ocean
7	Angola	AGO	Angola
8	Antigua and Barbuda	CRB	Other Caribbean
9	Argentina	ARG	Argentina
10	Australia	AUS	Australia
11	Austria	AUT	Austria
12	Bahamas	CRB	Other Caribbean
13	Bahrain	RAP	Rest of Arab Peninsula
14	Barbados	CRB	Other Caribbean
16	Bangladesh	BGD	Bangladesh
17	Bermuda	OAO	Other Atlantic Ocean
18	Bhutan	BTN	Bhutan
19	Bolivia	BOL	Bolivia
20	Botswana	BWA	Botswana
21	Brazil	BRA	Brazil
22	Aruba	CRB	Other Caribbean
23	Belize	BLZ	Belize
25	Solomon Islands	SLB	Solomon Islands
26	Brunei	OSA	Other Southeast Asia
27	Bulgaria	BGR	Bulgaria
28	Myanmar	MMR	Myanmar
29	Burundi	BDI	Burundi
32	Cameroon	CMR	Cameroon
33	Canada	CAN	Canada

Table A1 continued from previous page

FAO country code	Country name (FAO)	Country / Region code (IMPACT)	Country / Region name (IMPACT)
35	Cape Verde	OAO	Other Atlantic Ocean
36	Cayman Islands	CRB	Other Caribbean
37	Central African Republic	CAF	Central African Republic
38	Sri Lanka	LKA	Sri Lanka
39	Chad	TCD	Chad
40	Chile	CHL	Chile
44	Colombia	COL	Colombia
45	Comoros	OIO	Other Indian Ocean
46	Republic of Congo	COG	Congo
47	Cook Islands	OPO	Other Pacific Ocean
48	Costa Rica	CRI	Costa Rica
49	Cuba	CUB	Cuba
50	Cyprus	CYP	Cyprus
52	Azerbaijan	AZE	Azerbaijan
53	Benin	BEN	Benin
54	Denmark	DNK	Denmark
55	Dominica	CRB	Other Caribbean
56	Dominican Republic	DOM	Dominican Republic
57	Belarus	BLR	Belarus
58	Ecuador	ECU	Ecuador
59	Egypt	EGY	Egypt
60	El Salvador	SLV	El Salvador
61	Equatorial Guinea	GNQ	Equatorial Guinea
63	Estonia	BLT	Baltic States
64	Faroe Islands	UKP	Great Britain and nearby protectorates
65	Falkland Islands	OAO	Other Atlantic Ocean
66	Fiji	FJI	Fiji
67	Finland	FNP	Finland Plus
68	France	FRP	France plus

Table A1 continued from previous page

FAO country code	Country name (FAO)	Country / Region code (IMPACT)	Country / Region name (IMPACT)
69	French Guiana	GSA	Guyanas South America
70	French Polynesia	OPO	Other Pacific Ocean
72	Djibouti	DJI	Djibouti
73	Georgia	GEO	Georgia
74	Gabon	GAB	Gabon
75	Gambia	GMB	Gambia
79	Germany	DEU	Germany
80	Bosnia and Herzegovina	OBN	Other Balkans
81	Ghana	GHA	Ghana
83	Kiribati	OPO	Other Pacific Ocean
84	Greece	GRC	Greece
85	Greenland	GRL	Greenland
86	Grenada	CRB	Other Caribbean
87	Guadeloupe	CRB	Other Caribbean
88	Guam	OPO	Other Pacific Ocean
89	Guatemala	GTM	Guatemala
90	Guinea	GIN	Guinea
91	Guyana	GSA	Guyanas South America
93	Haiti	HTI	Haiti
95	Honduras	HND	Honduras
97	Hungary	HUN	Hungary
98	Croatia	HRV	Croatia
99	Iceland	ISL	Iceland
100	India	IND	India
101	Indonesia	IDN	Indonesia
102	Iran	IRN	Iran
103	Iraq	IRQ	Iraq
104	Ireland	IRL	Ireland
105	Israel	ISR	Israel

Table A1 continued from previous page

FAO country code	Country name (FAO)	Country / Region code (IMPACT)	Country / Region name (IMPACT)
106	Italy	ITP	Italy plus
107	Cote d'Ivoire	CIV	Ivory Coast
108	Kazakhstan	KAZ	Kazakhstan
109	Jamaica	JAM	Jamaica
110	Japan	JPN	Japan
112	Jordan	JOR	Jordan
113	Kyrgyzstan	KGZ	Kyrgyzstan
114	Kenya	KEN	Kenya
115	Cambodia	KHM	Cambodia
116	North Korea	PRK	North Korea
117	South Korea	KOR	South Korea
118	Kuwait	RAP	Rest of Arab Peninsula
119	Latvia	BLT	Baltic States
120	Lao People's Democratic Republic	LAO	Laos
121	Lebanon	LBN	Lebanon
122	Lesotho	LSO	Lesotho
123	Liberia	LBR	Liberia
124	Libya	LBY	Libya
125	Liechtenstein	CHP	Switzerland plus
126	Lithuania	BLT	Baltic States
127	Marshall Islands	OPO	Other Pacific Ocean
129	Madagascar	MDG	Madagascar
130	Malawi	MWI	Malawi
131	Malaysia	MYS	Malaysia
132	Maldives	OIO	Other Indian Ocean
133	Mali	MLI	Mali
134	Malta	ITP	Italy plus
135	Martinique	CRB	Other Caribbean
136	Mauritania	MRT	Mauritania

Table A1 continued from previous page

FAO country code	Country name (FAO)	Country / Region code (IMPACT)	Country / Region name (IMPACT)
137	Mauritius	OIO	Other Indian Ocean
138	Mexico	MEX	Mexico
141	Mongolia	MNG	Mongolia
142	Montserrat	CRB	Other Caribbean
143	Morocco	MOR	Morocco
144	Mozambique	MOZ	Mozambique
145	Micronesia	OPO	Other Pacific Ocean
146	Moldova	MDA	Moldova
147	Namibia	NAM	Namibia
148	Nauru	OPO	Other Pacific Ocean
149	Nepal	NPL	Nepal
150	Netherlands	NLD	Netherlands
151	Netherlands Antilles	CRB	Other Caribbean
153	New Caledonia	OPO	Other Pacific Ocean
154	The former Yugoslav Republic of Macedonia	OBN	Other Balkans
155	Vanuatu	VUT	Vanuatu
156	New Zealand	NZL	New Zealand
157	Nicaragua	NIC	Nicaragua
158	Niger	NER	Niger
159	Nigeria	NGA	Nigeria
160	Niue	OPO	Other Pacific Ocean
161	Norfolk Island	OPO	Other Pacific Ocean
162	Norway	NOR	Norway
165	Pakistan	PAK	Pakistan
166	Panama	PAN	Panama
167	Czech Republic	CZE	Czech Republic
168	Papua New Guinea	PNG	Papua New Guinea
169	Paraguay	PRY	Paraguay
170	Peru	PER	Peru

Table A1 continued from previous page

FAO country code	Country name (FAO)	Country / Region code (IMPACT)	Country / Region name (IMPACT)
171	Philippines	PHL	Philippines
173	Poland	POL	Poland
174	Portugal	PRT	Portugal
175	Guinea-Bissau	GNB	Guinea-Bissau
176	East Timor	TLS	Timor-L'este
177	Puerto Rico	CRB	Other Caribbean
178	Eritrea	ERI	Eritrea
179	Qatar	RAP	Rest of Arab Peninsula
181	Zimbabwe	ZWE	Zimbabwe
182	Réunion	ZWE	Zimbabwe
183	Romania	ROU	Romania
184	Rwanda	RWA	Rwanda
185	Russia	RUS	Russia
186	Serbia and Montenegro	RUS	Russia
187	Saint Helena	OAO	Other Atlantic Ocean
188	Saint Kitts and Nevis	CRB	Other Caribbean
189	Saint Lucia	CRB	Other Caribbean
190	Saint Pierre and Miquelon	OAO	Other Atlantic Ocean
191	Saint Vincent and the Grenadines	OAO	Other Atlantic Ocean
193	Sao Tome and Principe	OAO	Other Atlantic Ocean
194	Saudi Arabia	SAU	Saudi Arabia
195	Senegal	SEN	Senegal
196	Seychelles	OIO	Other Indian Ocean
197	Sierra Leone	SLE	Sierra Leone
198	Slovenia	SVN	Slovenia
199	Slovakia	SVK	Slovakia
200	Singapore	OSA	Other Southeast Asia
201	Somalia	SOM	Somalia
202	South Africa	ZAF	South Africa

Table A1 continued from previous page

FAO country code	Country name (FAO)	Country / Region code (IMPACT)	Country / Region name (IMPACT)
203	Spain	SPP	Spain plus
205	Western Sahara	MOR	Morocco
206	Sudan	SDN	Sudan
207	Suriname	GSA	Guyanas South America
208	Tajikistan	TJK	Tajikistan
209	Swaziland	SWZ	Swaziland
210	Sweden	SWE	Sweden
211	Switzerland	CHP	Switzerland plus
212	Syria	SYR	Syria
213	Turkmenistan	TKM	Turkmenistan
215	Tanzania	TZA	Tanzania
216	Thailand	THA	Thailand
217	Togo	TGO	Togo
218	Tokelau	OPO	Other Pacific Ocean
219	Tonga	OPO	Other Pacific Ocean
220	Trinidad and Tobago	CRB	Other Caribbean
221	Oman	RAP	Rest of Arab Peninsula
222	Tunisia	TUN	Tunisia
223	Turkey	TUR	Turkey
225	United Arab Emirates	RAP	Rest of Arab Peninsula
226	Uganda	UGA	Uganda
227	Tuvalu	OPO	Other Pacific Ocean
229	United Kingdom	UKP	Great Britain and nearby protectorates
230	Ukraine	UKR	Ukraine
231	United States	USA	United States
233	Burkina Faso	BFA	Burkina Faso
234	Uruguay	URY	Uruguay
235	Uzbekistan	UZB	Uzbekistan
236	Venezuela	VEN	Venezuela

Table A1 continued from previous page

FAO country code	Country name (FAO)	Country / Region code (IMPACT)	Country / Region name (IMPACT)
237	Vietnam	VNM	Vietnam
238	Ethiopia	ETH	Ethiopia
239	British Virgin Islands	CRB	Other Caribbean
240	US Virgin Islands	CRB	Other Caribbean
243	Wallis and Futuna Islands	CRB	Other Caribbean
244	Samoa	OPO	Other Pacific Ocean
249	Yemen	YEM	Yemen
250	Democratic Republic of the Congo	COD	Democratic Republic of Congo
251	Zambia	ZMB	Zambia
255	Belgium	BLX	Belgium-Luxembourg
256	Luxembourg	BLX	Belgium-Luxembourg
272	Serbia	OBN	Other Balkans
273	Montenegro	OBN	Other Balkans
299	Palestine	PSE	Occupied Palestinian Territory
351	China	CHM	China Hong Kong Macao Taiwan

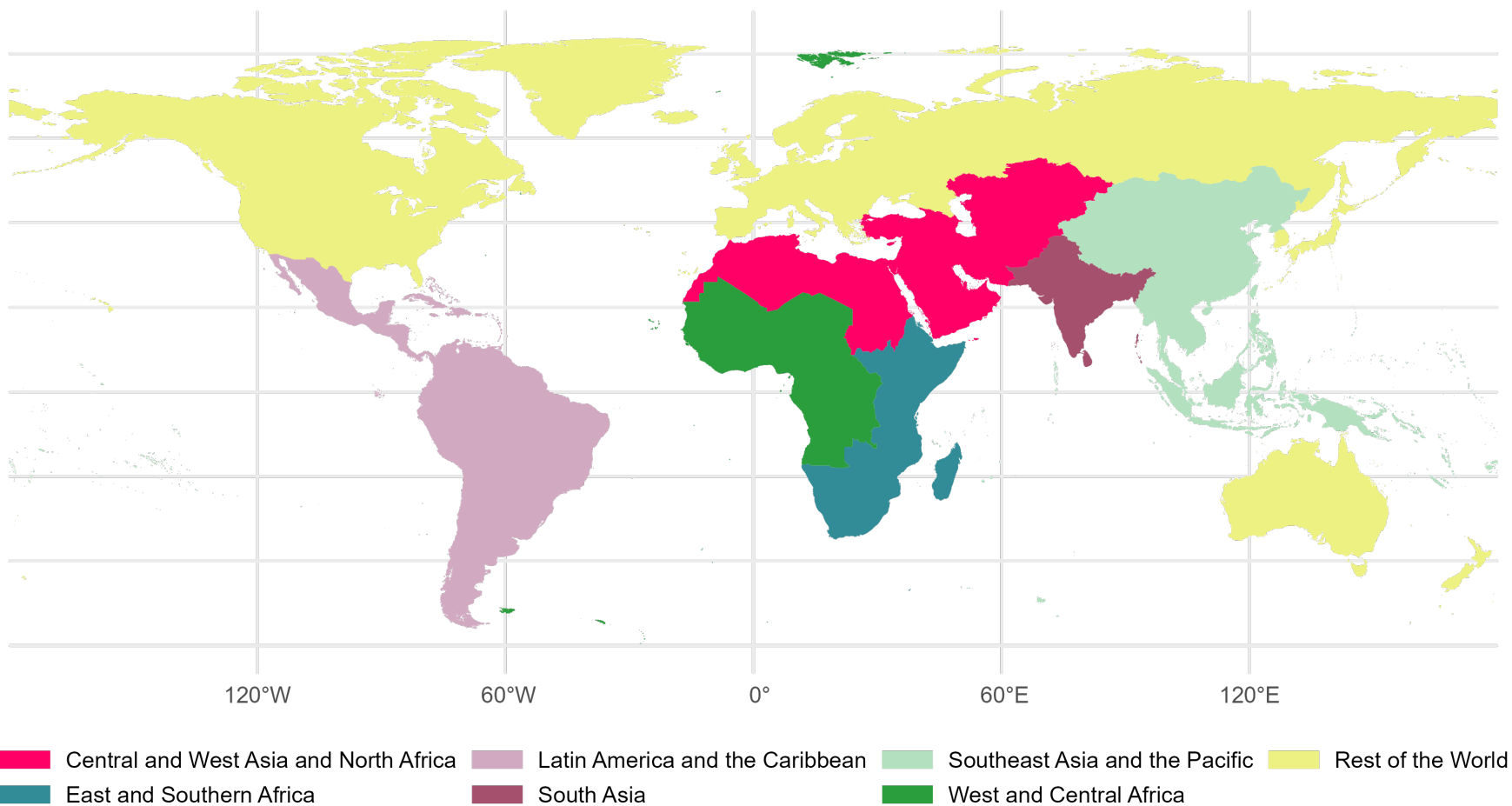


Figure A1: Map of CGIAR regions. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in CGIAR regional definitions. See cgiar.org/research/cgiar-regions for more details and description of CGIAR regions.

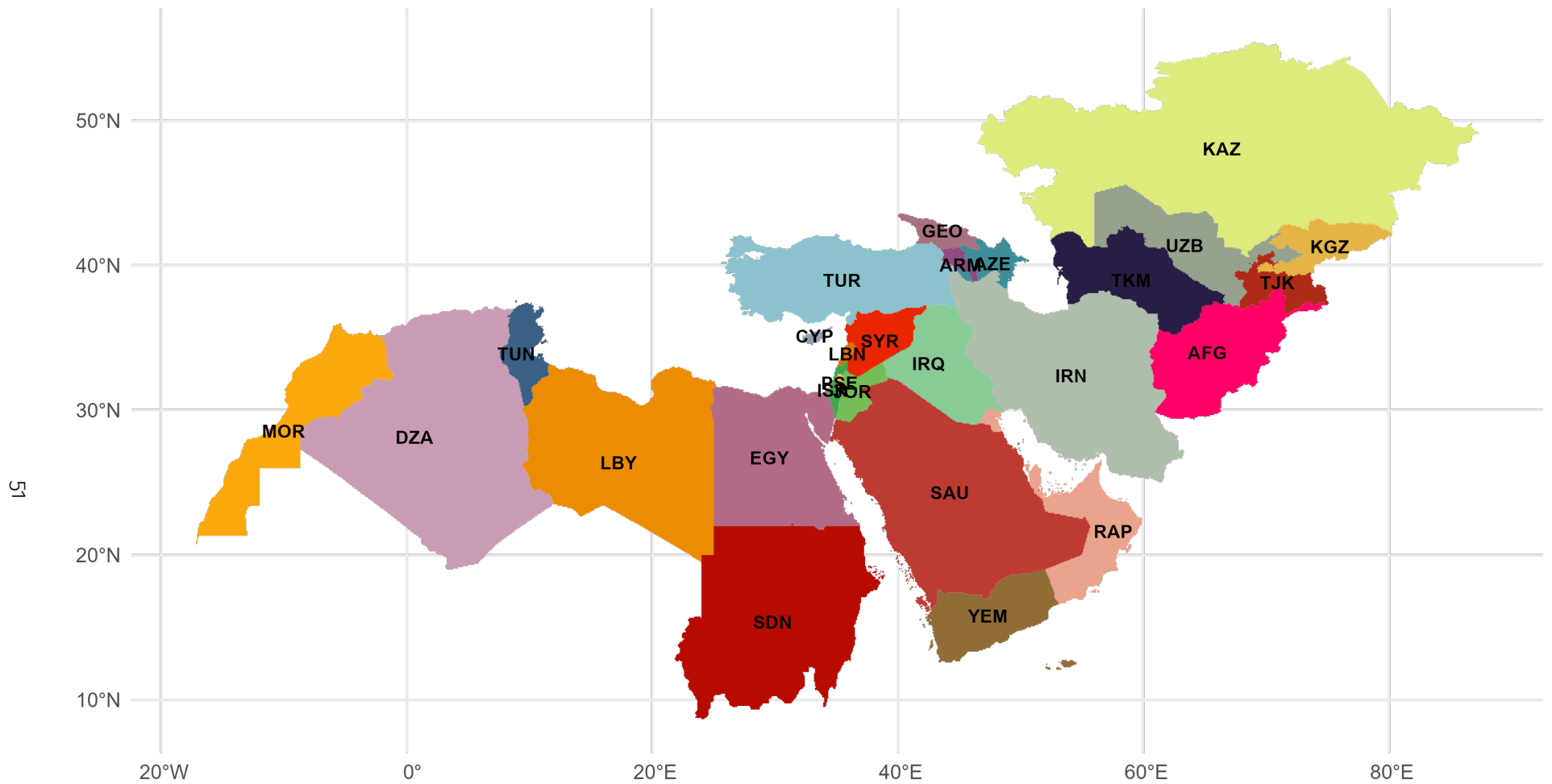


Figure A2: Map of countries/regions in Central and West Asia and North Africa. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

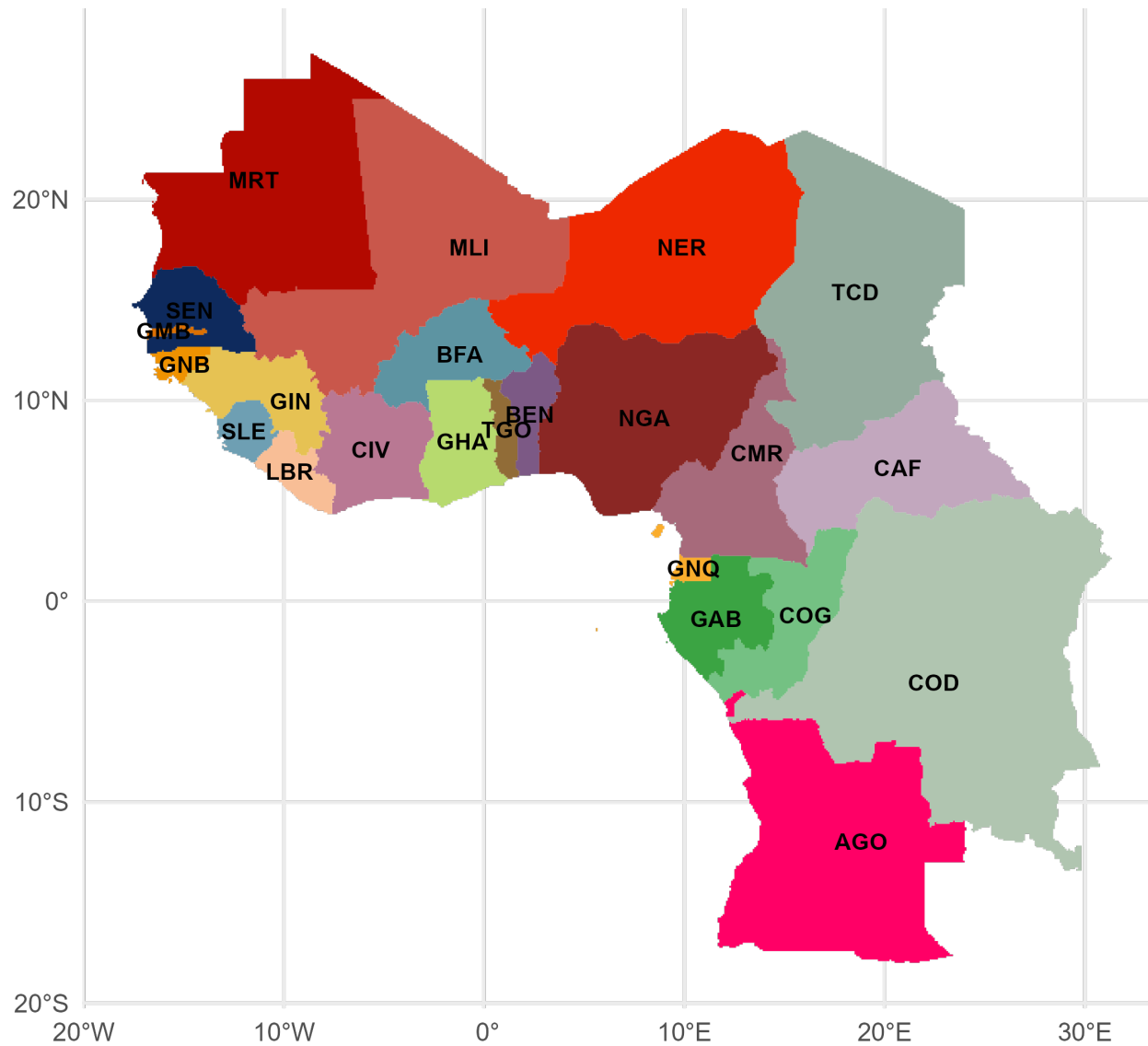


Figure A3: Map of countries/regions in West and Central Africa. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

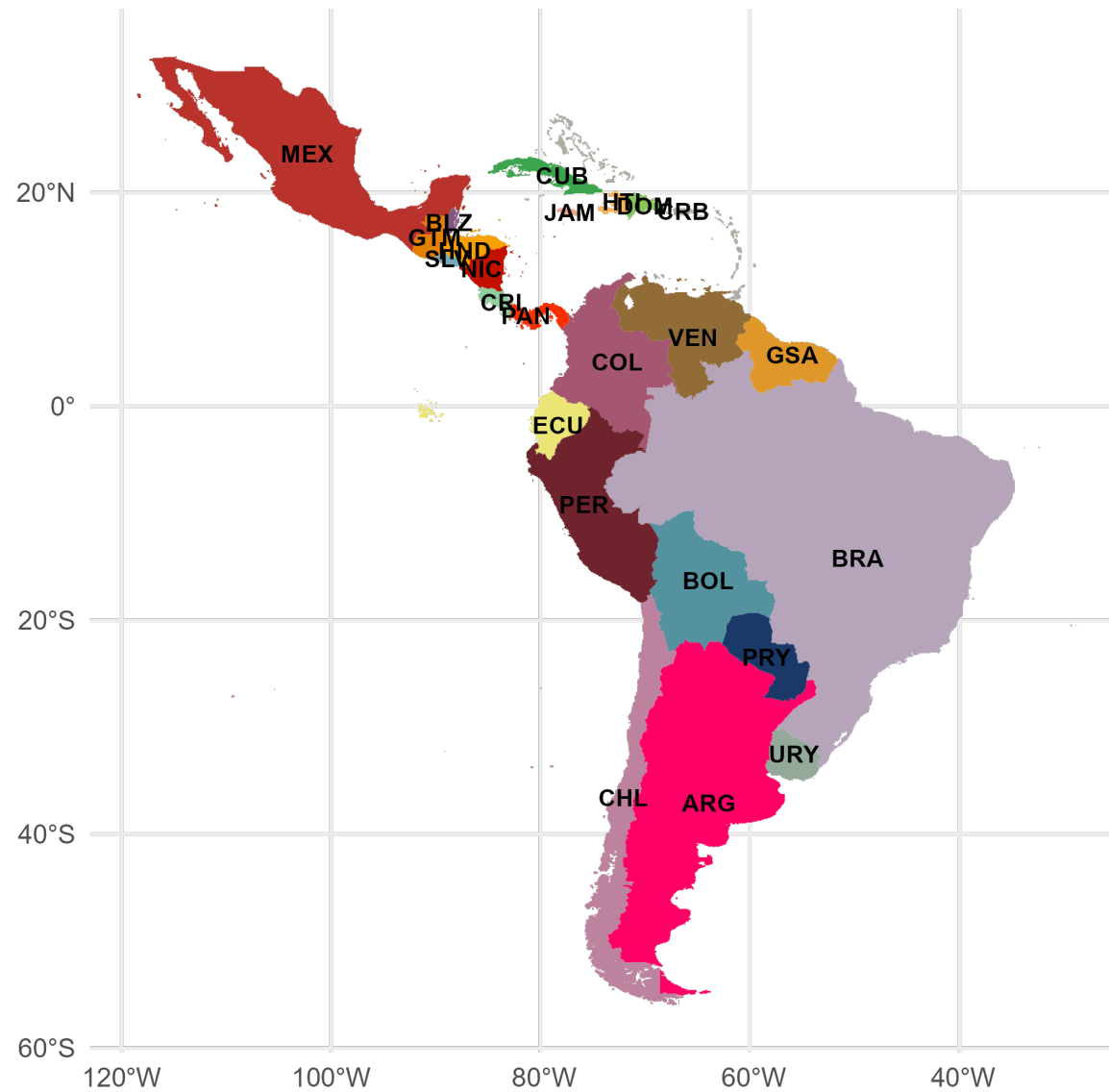


Figure A4: Map of countries/regions in Latin America and the Caribbean. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

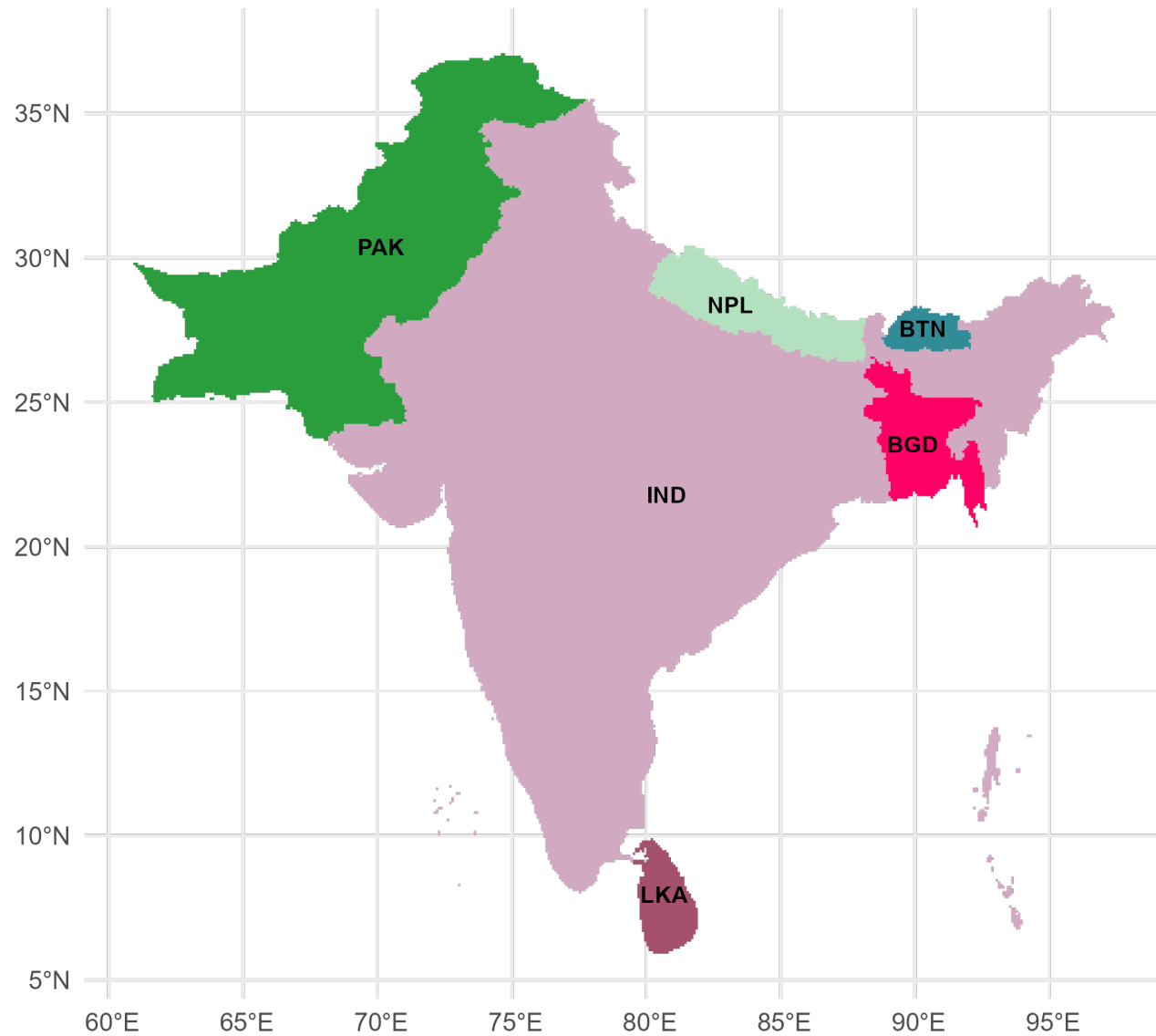


Figure A5: Map of countries/regions in South Asia. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

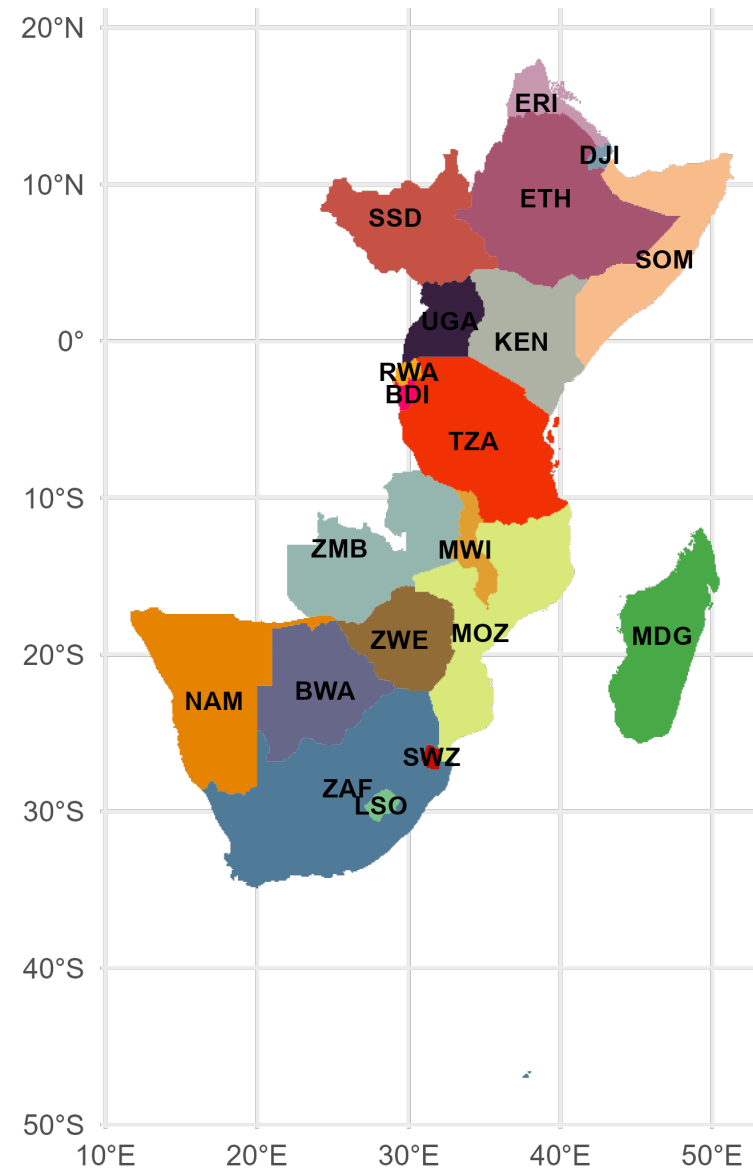


Figure A6: Map of countries/regions in East and Southern Africa. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

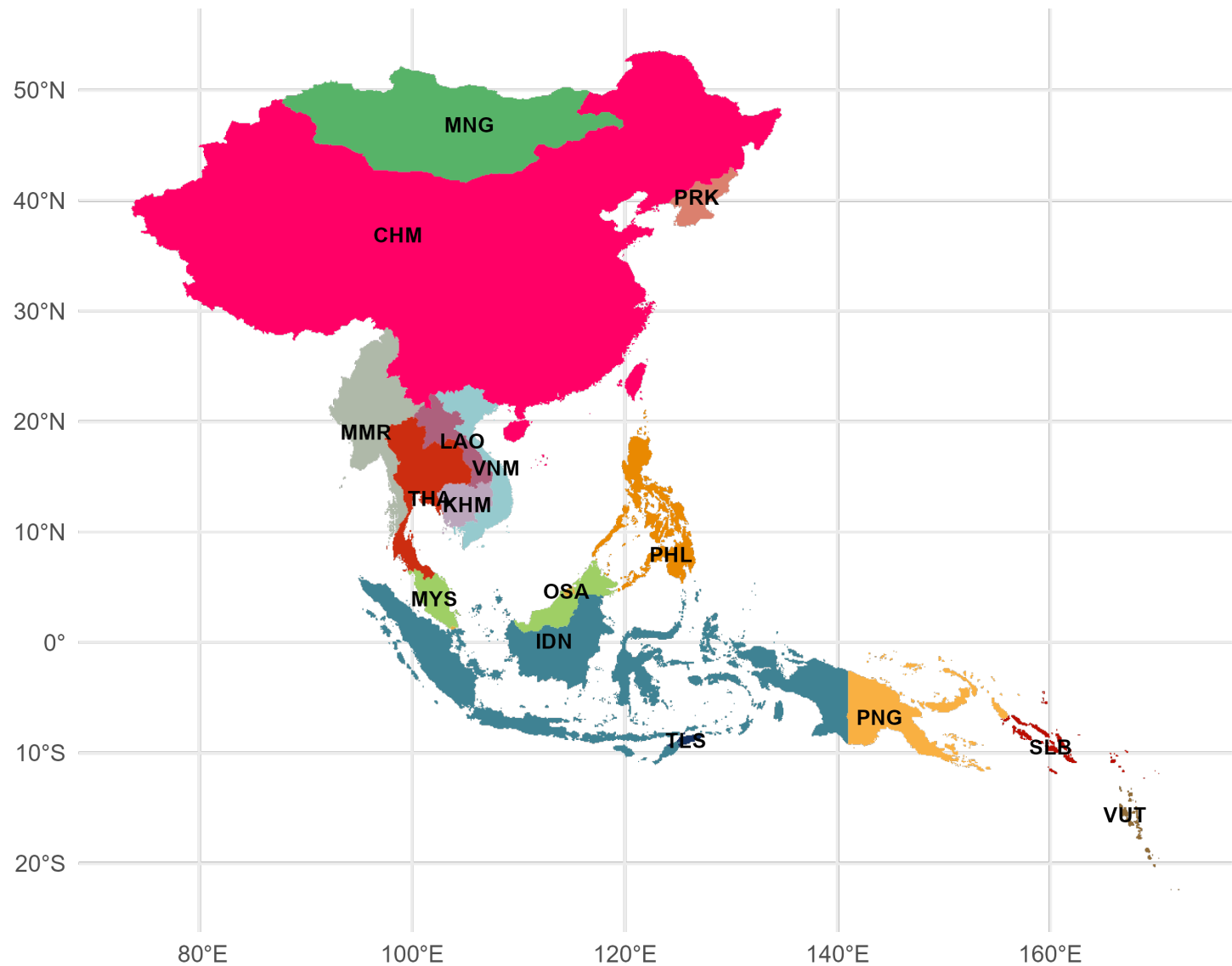


Figure A7: Map of countries/regions in Southeast Asia and the Pacific. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT. Small Atlantic and Pacific islands are not plotted in this map. See Table A1 for full list of countries/regions.

Table A2: List of FPU in IMPACT

FPU	Basin name	Country or region (IMPACT)	Country or region code (IMPACT)
ALB_ALB	Albania basin	Albania	ALB
ALK_USA	Alaska basin	United States	USA
AMA_BOL	Amazon basin	Bolivia	BOL
AMA_BRA	Amazon basin	Brazil	BRA
AMA_COL	Amazon basin	Colombia	COL
AMA_ECU	Amazon basin	Ecuador	ECU
AMA_PER	Amazon basin	Peru	PER
AMD_AFG	Amu darya basin	Afghanistan	AFG
AMD_TJK	Amu darya basin	Tajikistan	TJK
AMD_TKM	Amu darya basin	Turkmenistan	TKM
AMD_UZB	Amu darya basin	Uzbekistan	UZB
AMR_CHM	Amur basin	China Plus	CHM
AMR_RUS	Amur basin	Russia	RUS
ARA_IRQ	Arabian Peninsula basin	Iraq	IRQ
ARK_USA	Arkansas basin	United States	USA
ARM_ARM	Armenia basin	Armenia	ARM
AZE_AZE	Azerbaijan basin	Azerbaijan	AZE
BAL_BLT	Baltic basin	Baltic States	BLT
BAL_RUS	Baltic basin	Russia	RUS
BLA_RUS	Black Sea basin	Russia	RUS
BLA_TUR	Black Sea basin	Turkey	TUR
BLA_UKR	Black Sea basin	Ukraine	UKR
BLZ_BLZ	Belize basin	Belize	BLZ
BOR_IDN	Borneo basin	Indonesia	IDN
BOR_MYS	Borneo basin	Malaysia	MYS
BRT_BGD	Brahmaputra basin	Bangladesh	BGD
BRT_BTN	Brahmaputra basin	Bhutan	BTN
BRT_CHM	Brahmaputra basin	China Plus	CHM
BRT_IND	Brahmaputra basin	India	IND

Table A2 continued from previous page

FPU	Basin name	Country or region (IMPACT)	Country or region code (IMPACT)
CAF_AGO	Central African basin	Angola	AGO
CAF_CAF	Central African basin	Central African Republic	CAF
CAF_CMR	Central African basin	Cameroon	CMR
CAF_COG	Central African basin	Congo	COG
CAF_GAB	Central African basin	Gabon	GAB
CAF_GNQ	Central African basin	Equatorial Guinea	GNQ
CAF_NAM	Central African basin	Namibia	NAM
CAL_USA	California basin	United States	USA
CAN_CAN	Canadian Arctic basin	Canada	CAN
CAU_AUS	Central Australia basin	Australia	AUS
CAV_IND	Cauvery basin	India	IND
CHC_CHL	Chilean Coast basin	Chile	CHL
CHJ_CHM	Chang Jiang basin	China Plus	CHM
CHO_IND	Chota-Nagpui basin	India	IND
CHU_KAZ	Chu and Talas basin	Kazakhstan	KAZ
CHU_KGZ	Chu and Talas basin	Kyrgyzstan	KGZ
COB_CAN	Columbia basin	Canada	CAN
COB_USA	Columbia basin	United States	USA
COL_USA	Colorado basin	United States	USA
CON_AGO	Congo basin	Angola	AGO
CON_CAF	Congo basin	Central African Republic	CAF
CON_COD	Congo basin	Democratic Republic of Congo	COD
CON_COG	Congo basin	Congo	COG
CRB_CRB	Other Caribbean basin	Other Caribbean	CRB
CRI_CRI	Costa Rica basin	Costa Rica	CRI
CUB_CUB	Cuba basin	Cuba	CUB
DAN_AUT	Danube basin	Austria	AUT
DAN_BGR	Danube basin	Bulgaria	BGR
DAN_CZE	Danube basin	Czech Republic	CZE

Table A2 continued from previous page

FPU	Basin name	Country or region (IMPACT)	Country or region code (IMPACT)
DAN_DEU	Danube basin	Germany	DEU
DAN_HRV	Danube basin	Croatia	HRV
DAN_HUN	Danube basin	Hungary	HUN
DAN_MDA	Danube basin	Moldova	MDA
DAN_OBN	Danube basin	Other Balkans	OBN
DAN_ROU	Danube basin	Romania	ROU
DAN_SVK	Danube basin	Slovakia	SVK
DAN_SVN	Danube basin	Slovenia	SVN
DAN_TUR	Danube basin	Turkey	TUR
DAN_UKR	Danube basin	Ukraine	UKR
DNI_BLR	Dnieper basin	Belarus	BLR
DNI_RUS	Dnieper basin	Russia	RUS
DNI_UKR	Dnieper basin	Ukraine	UKR
DOM_DOM	Dominican Republic basin	Dominican Republic	DOM
EAC_BDI	East African Coast basin	Burundi	BDI
EAC_COD	East African Coast basin	Democratic Republic of Congo	COD
EAC_RWA	East African Coast basin	Rwanda	RWA
EAC_TZA	East African Coast basin	Tanzania	TZA
EAU_AUS	Eastern Australia basin	Australia	AUS
EGH_IND	Easten Ghats basin	India	IND
ELB_DEU	Elbe basin	Germany	DEU
ELB_DNK	Elbe basin	Denmark	DNK
EME_CYP	Eastern Mediterranean basin	Cyprus	CYP
EME_EGY	Eastern Mediterranean basin	Egypt	EGY
EME_ISR	Eastern Mediterranean basin	Israel	ISR
EME_JOR	Eastern Mediterranean basin	Jordan	JOR
EME_LBN	Eastern Mediterranean basin	Lebanon	LBN
EME_PSE	Eastern Mediterranean basin	Occupied Palestinian Territory	PSE
EME_SYR	Eastern Mediterranean basin	Syria	SYR

Table A2 continued from previous page

FPU	Basin name	Country or region (IMPACT)	Country or region code (IMPACT)
EME_TUR	Eastern Mediterranean basin	Turkey	TUR
FJI_FJI	Fiji basin	Fiji	FJI
FNP_FNP	Finland plus basin	Finland Plus	FNP
GAN_BGD	Ganges basin	Bangladesh	BGD
GAN_CHM	Ganges basin	China Plus	CHM
GAN_IND	Ganges basin	India	IND
GAN_NPL	Ganges basin	Nepal	NPL
GBA_USA	Great Basin basin	United States	USA
GEO_GEO	Georgia basin	Georgia	GEO
GLA_CAN	Great Lakes basin	Canada	CAN
GLA_USA	Great Lakes basin	United States	USA
GOD_IND	Godavari basin	India	IND
GRC_GRC	Greece basin	Greece	GRC
GRL_GRL	Greenland basin	Greenland	GRL
GSA_GSA	Guyanas South America basin	Guyanas South America	GSA
GTM_GTM	Guatemala basin	Guatemala	GTM
HAI_CHM	Hail He basin	China Plus	CHM
HND_HND	Honduras basin	Honduras	HND
HOA_ETH	Horn of Africa basin	Ethiopia	ETH
HOA_KEN	Horn of Africa basin	Kenya	KEN
HOA_SOM	Horn of Africa basin	Somalia	SOM
HTI_HTI	Haiti basin	Haiti	HTI
HUA_CHM	Hual He basin	China Plus	CHM
HUN_CHM	Huang He basin	China Plus	CHM
HWI_USA	Hawaii basin	United States	USA
IEC_IND	India East Coast basin	India	IND
IND_CHM	Indus basin	China Plus	CHM
IND_IND	Indus basin	India	IND
IND_PAK	Indus basin	Pakistan	PAK

Table A2 continued from previous page

FPU	Basin name	Country or region (IMPACT)	Country or region code (IMPACT)
INE_IDN	Indonesia East basin	Indonesia	IDN
INW_IDN	Indonesia West basin	Indonesia	IDN
IRL_IRL	Ireland basin	Ireland	IRL
ISL_ISL	Israel basin	Iceland	ISL
ITA_ITP	Italy basin	Italy plus	ITP
JAM_JAM	Jamaica basin	Jamaica	JAM
JAP_JPN	Japan basin	Japan	JPN
KAL_BWA	Kalahari basin	Botswana	BWA
KAL_NAM	Kalahari basin	Namibia	NAM
KAL_ZAF	Kalahari basin	South Africa	ZAF
KRI_IND	Krishna basin	India	IND
LAJ_CHM	Langcang Jiang basin	China Plus	CHM
LBA_KAZ	Lake Balkhash basin	Kazakhstan	KAZ
LBO_FRP	Loire Bordeaux basin	France plus	FRP
LCB_CAF	Lake Chad basin	Central African Republic	CAF
LCB_CMR	Lake Chad basin	Cameroon	CMR
LCB_NER	Lake Chad basin	Niger	NER
LCB_NGA	Lake Chad basin	Nigeria	NGA
LCB_TCD	Lake Chad basin	Chad	TCD
LIM_BWA	Limpopo basin	Botswana	BWA
LIM_MOZ	Limpopo basin	Mozambique	MOZ
LIM_ZAF	Limpopo basin	South Africa	ZAF
LIM_ZWE	Limpopo basin	Zimbabwe	ZWE
LMO_CHM	Lower Mongolia basin	China Plus	CHM
LMO_MNG	Lower Mongolia basin	Mongolia	MNG
LTZ_KAZ	Lake Tengiz basin	Kazakhstan	KAZ
LUN_IND	Luni basin	India	IND
MAD_MDG	Madagascar basin	Madagascar	MDG
MAT_IND	Mahi Tapti basin	India	IND

Table A2 continued from previous page

FPU	Basin name	Country or region (IMPACT)	Country or region code (IMPACT)
MAU_AUS	Murray Australia basin	Australia	AUS
MCK_CAN	Mackenzie basin	Canada	CAN
MEK_KHM	Mekong basin	Cambodia	KHM
MEK_LAO	Mekong basin	Laos	LAO
MEK_MMR	Mekong basin	Myanmar	MMR
MEK_THA	Mekong basin	Thailand	THA
MEK_VNM	Mekong basin	Vietnam	VNM
MHN_IND	Mahanadi basin	India	IND
MIM_MEX	Middle Mexico basin	Mexico	MEX
MIS_USA	Mississippi basin	United States	USA
MOU_USA	Missouri basin	United States	USA
NAC_DZA	North African Coast basin	Algeria	DZA
NAC_EGY	North African Coast basin	Egypt	EGY
NAC_LBY	North African Coast basin	Libya	LBY
NAC_TUN	North African Coast basin	Tunisia	TUN
NEB_BRA	Northeast Brazil basin	Brazil	BRA
NER_RUS	North Europe-Russia basin	Russia	RUS
NIC_NIC	Nicaragua basin	Nicaragua	NIC
NIG_BEN	Niger basin	Benin	BEN
NIG_BFA	Niger basin	Burkina Faso	BFA
NIG_CIV	Niger basin	Ivory Coast	CIV
NIG_CMR	Niger basin	Cameroon	CMR
NIG_GIN	Niger basin	Guinea	GIN
NIG_MLI	Niger basin	Mali	MLI
NIG_NER	Niger basin	Niger	NER
NIG_NGA	Niger basin	Nigeria	NGA
NIG_TCD	Niger basin	Chad	TCD
NKP_PRK	North Korean Peninsula basin	North Korea	PRK
NLL_DJI	Nile basin	Djibouti	DJI

Table A2 continued from previous page

FPU	Basin name	Country or region (IMPACT)	Country or region code (IMPACT)
NLL_EGY	Nile basin	Egypt	EGY
NLL_ERI	Nile basin	Eritrea	ERI
NLL_ETH	Nile basin	Ethiopia	ETH
NLL_SDN	Nile basin	Sudan	SDN
NLL_SSD	Nile basin	South Sudan	SSD
NLL_UGA	Nile basin	Uganda	UGA
NOR_NOR	Norway basin	Norway	NOR
NWA_MOR	Northwest Africa basin	Morocco	MOR
NWA_MRT	Northwest Africa basin	Mauritania	MRT
NWS_COL	Northwest South America basin	Colombia	COL
NWS_ECU	Northwest South America basin	Ecuador	ECU
NZE_NZL	New Zealand basin	New Zealand	NZL
OAO_OAO	Other Atlantic Ocean basin	Other Atlantic Ocean	OAO
OBB_CHM	Ob basin	China Plus	CHM
OBB_KAZ	Ob basin	Kazakhstan	KAZ
OBB_RUS	Ob basin	Russia	RUS
ODE_DEU	Oder basin	Germany	DEU
ODE_POL	Oder basin	Poland	POL
ODE_RUS	Oder basin	Russia	RUS
OHI_USA	Ohio basin	United States	USA
OIO_OIO	Other Indian Ocean basin	Other Indian Ocean	OIO
OPO_OPO	Other Pacific Ocean basin	Other Pacific Ocean	OPO
ORA_LSO	Orange basin	Lesotho	LSO
ORA_NAM	Orange basin	Namibia	NAM
ORA_ZAF	Orange basin	South Africa	ZAF
ORI_COL	Orinoco basin	Colombia	COL
ORI_VEN	Orinoco basin	Venezuela	VEN
PAN_PAN	Panama basin	Panama	PAN
PAO_PNG	Papau Oceania basin	Papua New Guinea	PNG

Table A2 continued from previous page

FPU	Basin name	Country or region (IMPACT)	Country or region code (IMPACT)
PAR_ARG	Parana basin	Argentina	ARG
PAR_BOL	Parana basin	Bolivia	BOL
PAR_BRA	Parana basin	Brazil	BRA
PAR_PRY	Parana basin	Paraguay	PRY
PEC_PER	Peru Coastal basin	Peru	PER
PHI_PHL	Philippines basin	Philippines	PHL
PRT_PRT	Portugal basin	Portugal	PRT
RAP_RAP	Rest of Arab Peninsula basin	Rest of Arab Peninsula	RAP
RHI_BLX	Rhine basin	Belgium-Luxembourg	BLX
RHI_CHP	Rhine basin	Switzerland plus	CHP
RHI_DEU	Rhine basin	Germany	DEU
RHI_FRP	Rhine basin	France plus	FRP
RHI_NLD	Rhine basin	Netherlands	NLD
RHO_FRP	Rhone basin	France plus	FRP
RIC_ARG	Rio Colorado basin	Argentina	ARG
RIG_MEX	Rio Grande basin	Mexico	MEX
RIG_USA	Rio Grande basin	United States	USA
RRS_RUS	Rest of Russia basin	Russia	RUS
RVE_VEN	Rest of Venezuela basin	Venezuela	VEN
RVN_VNM	Rest of Vietnam basin	Vietnam	VNM
RWI_CAN	Red Winnipeg basin	Canada	CAN
RWI_USA	Red Winnipeg basin	United States	USA
SAC_SWZ	South African Coast basin	Swaziland	SWZ
SAC_ZAF	South African Coast basin	South Africa	ZAF
SAF_MOZ	Southeast Africa basin	Mozambique	MOZ
SAF_TZA	Southeast Africa basin	Tanzania	TZA
SAF_ZWE	Southeast Africa basin	Zimbabwe	ZWE
SAH_DZA	Sahara basin	Algeria	DZA
SAH_EGY	Sahara basin	Egypt	EGY

Table A2 continued from previous page

FPU	Basin name	Country or region (IMPACT)	Country or region code (IMPACT)
SAH_LBY	Sahara basin	Libya	LBY
SAH_MLI	Sahara basin	Mali	MLI
SAH_MOR	Sahara basin	Morocco	MOR
SAH_MRT	Sahara basin	Mauritania	MRT
SAH_NER	Sahara basin	Niger	NER
SAH_SDN	Sahara basin	Sudan	SDN
SAH_TCD	Sahara basin	Chad	TCD
SAL_ARG	Salada Tierra basin	Argentina	ARG
SAN_BRA	San Francisco basin	Brazil	BRA
SAU_SAU	Saudi Arabia basin	Saudi Arabia	SAU
SAY_IND	Sahyada basin	India	IND
SEI_FRP	Seine basin	France plus	FRP
SEN_GIN	Senegal basin	Guinea	GIN
SEN_MLI	Senegal basin	Mali	MLI
SEN_MRT	Senegal basin	Mauritania	MRT
SEN_SEN	Senegal basin	Senegal	SEN
SEU_USA	Southeast US basin	United States	USA
SKP_KOR	South Korean Peninsula basin	South Korea	KOR
SLB_SLB	Solomon Islands basin	Solomon Islands	SLB
SLV_SLV	El Salvador basin	El Salvador	SLV
SON_CHM	Songhua basin	China Plus	CHM
SPP_SPP	Spain plus basin	Spain plus	SPP
SRL_LKA	Sri Lanka basin	Sri Lanka	LKA
SWE_SWE	Sweden basin	Sweden	SWE
SYD_KAZ	Syr darya basin	Kazakhstan	KAZ
SYD_KGZ	Syr darya basin	Kyrgyzstan	KGZ
SYD_TJK	Syr darya basin	Tajikistan	TJK
SYD_UZB	Syr darya basin	Uzbekistan	UZB
TIE_ARG	Tierra basin	Argentina	ARG

Table A2 continued from previous page

FPU	Basin name	Country or region (IMPACT)	Country or region code (IMPACT)
TIG_IRN	Tigris Euphrates basin	Iran	IRN
TIG_IRQ	Tigris Euphrates basin	Iraq	IRQ
TIG_SYR	Tigris Euphrates basin	Syria	SYR
TIG_TUR	Tigris Euphrates basin	Turkey	TUR
TLS_TLS	Timor-L'este basin	Timor-L'este	TLS
TMM_BGD	Thai Myan Malay basin	Bangladesh	BGD
TMM_MMR	Thai Myan Malay basin	Myanmar	MMR
TMM_MYS	Thai Myan Malay basin	Malaysia	MYS
TMM_OSA	Thai Myan Malay basin	Other Southeast Asia	OSA
TMM_THA	Thai Myan Malay basin	Thailand	THA
TOC_BRA	Toc basin	Brazil	BRA
TWN_CHM	Tawain basin	China Plus	CHM
UKP_UKP	Great Britain plus basin	Great Britain plus	UKP
UME_MEX	Upper Mexico basin	Mexico	MEX
UMO_MNG	Upper Mongolia basin	Mongolia	MNG
UMO_RUS	Upper Mongolia basin	Russia	RUS
URA_KAZ	Ural basin	Kazakhstan	KAZ
URA_RUS	Ural basin	Russia	RUS
URA_TKM	Ural basin	Turkmenistan	TKM
URU_BRA	Uruguay basin	Brazil	BRA
URU_URY	Uruguay basin	Uruguay	URY
USN_USA	US Northeast basin	United States	USA
VOG_RUS	Volga basin	Russia	RUS
VOT_BEN	Volta basin	Benin	BEN
VOT_BFA	Volta basin	Burkina Faso	BFA
VOT_CIV	Volta basin	Ivory Coast	CIV
VOT_GHA	Volta basin	Ghana	GHA
VOT_MLI	Volta basin	Mali	MLI
VOT_TGO	Volta basin	Togo	TGO

Table A2 continued from previous page

FPU	Basin name	Country or region (IMPACT)	Country or region code (IMPACT)
VUT_VUT	Vanuatu basin	Vanuatu	VUT
WAC_CIV	West African Coast basin	Ivory Coast	CIV
WAC_GIN	West African Coast basin	Guinea	GIN
WAC_GMB	West African Coast basin	Gambia	GMB
WAC_GNB	West African Coast basin	Guinea-Bissau	GNB
WAC_LBR	West African Coast basin	Liberia	LBR
WAC_SEN	West African Coast basin	Senegal	SEN
WAC_SLE	West African Coast basin	Sierra Leone	SLE
WAI_AFG	Western Asia Iran basin	Afghanistan	AFG
WAI_IRN	Western Asia Iran basin	Iran	IRN
WAI_PAK	Western Asia Iran basin	Pakistan	PAK
WAI_TKM	Western Asia Iran basin	Turkmenistan	TKM
WAU_AUS	Western Australia basin	Australia	AUS
WGM_USA	Western Gulf of Mexico basin	United States	USA
YEM_YEM	Yemen basin	Yemen	YEM
YEN_RUS	Yenisey basin	Russia	RUS
YHE_CHM	Yili He basin	China Plus	CHM
YRD_CHM	Yuan Red River basin	China Plus	CHM
YRD_VNM	Yuan Red River basin	Vietnam	VNM
YUC_MEX	Yucatan basin	Mexico	MEX
ZAM_AGO	Zambezi basin	Angola	AGO
ZAM_BWA	Zambezi basin	Botswana	BWA
ZAM_COD	Zambezi basin	Democratic Republic of Congo	COD
ZAM_MOZ	Zambezi basin	Mozambique	MOZ
ZAM_MWI	Zambezi basin	Malawi	MWI
ZAM_NAM	Zambezi basin	Namibia	NAM
ZAM_TZA	Zambezi basin	Tanzania	TZA
ZAM_ZMB	Zambezi basin	Zambia	ZMB
ZAM_ZWE	Zambezi basin	Zimbabwe	ZWE

Table A2 continued from previous page

FPU	Basin name	Country or region (IMPACT)	Country or region code (IMPACT)
ZHJ_CHM	Zhu Jiang basin	China Plus	CHM

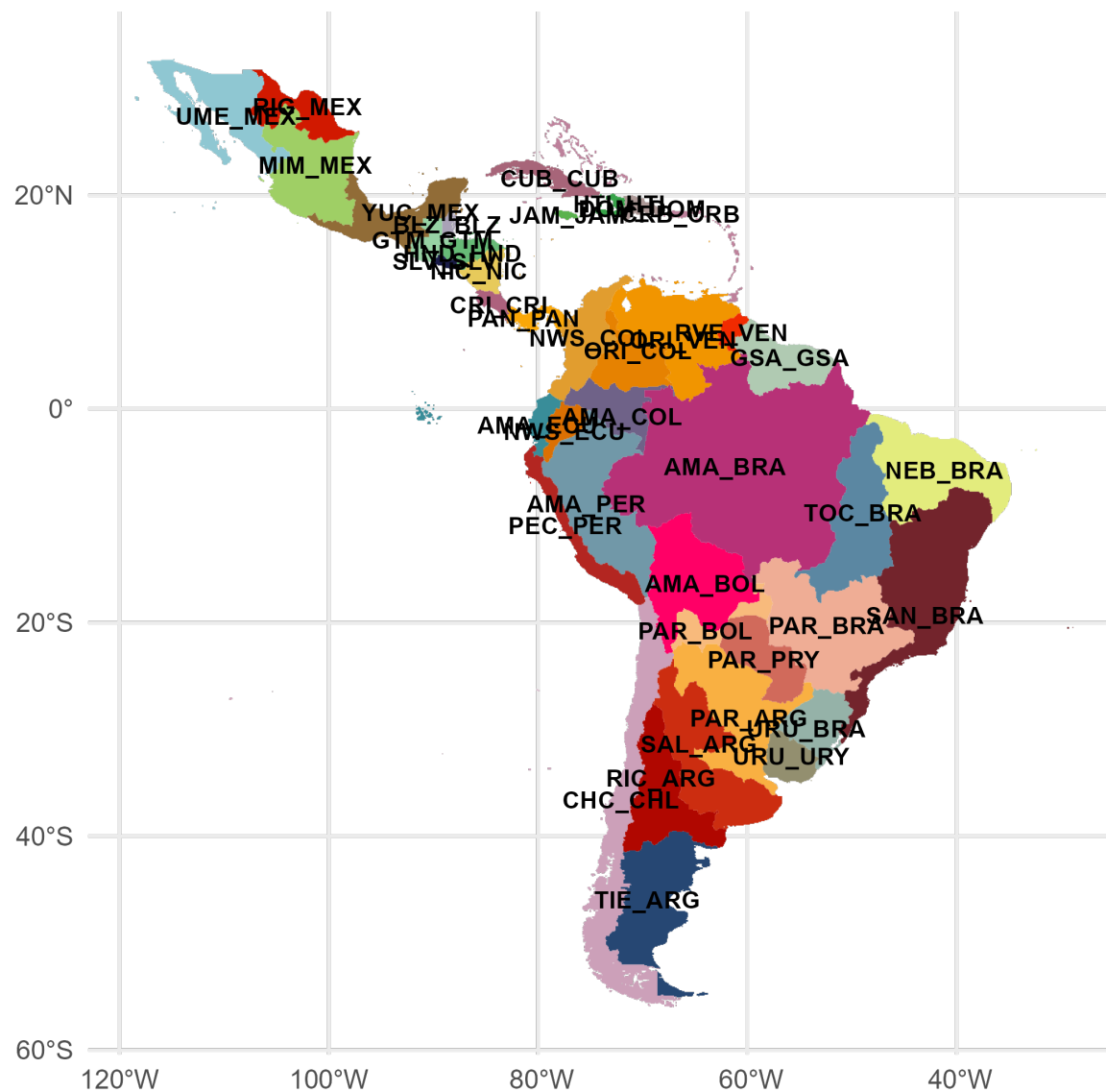


Figure A10: Map of FPU in Latin America and the Caribbean. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

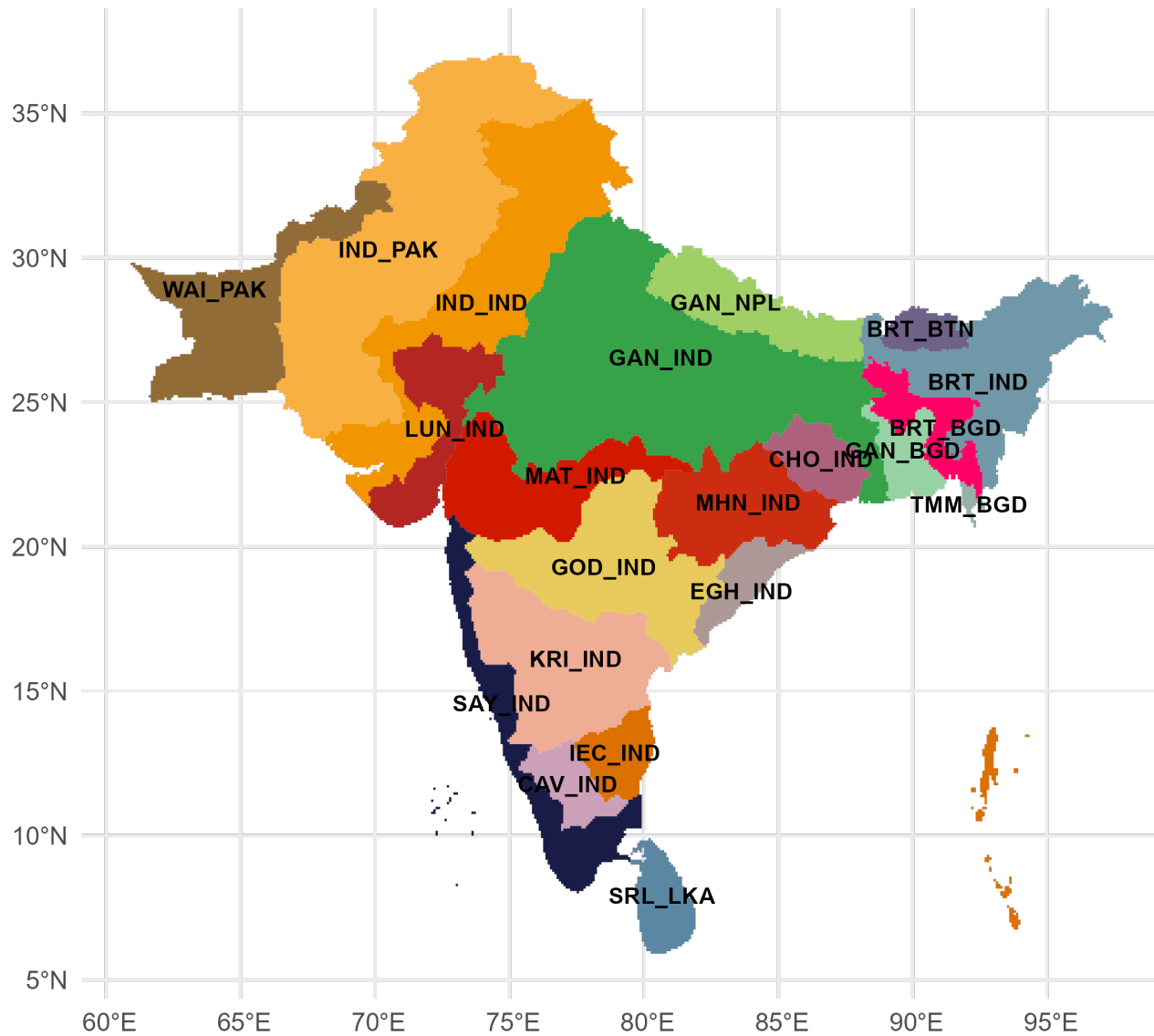


Figure A11: Map of FPUs in South Asia. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

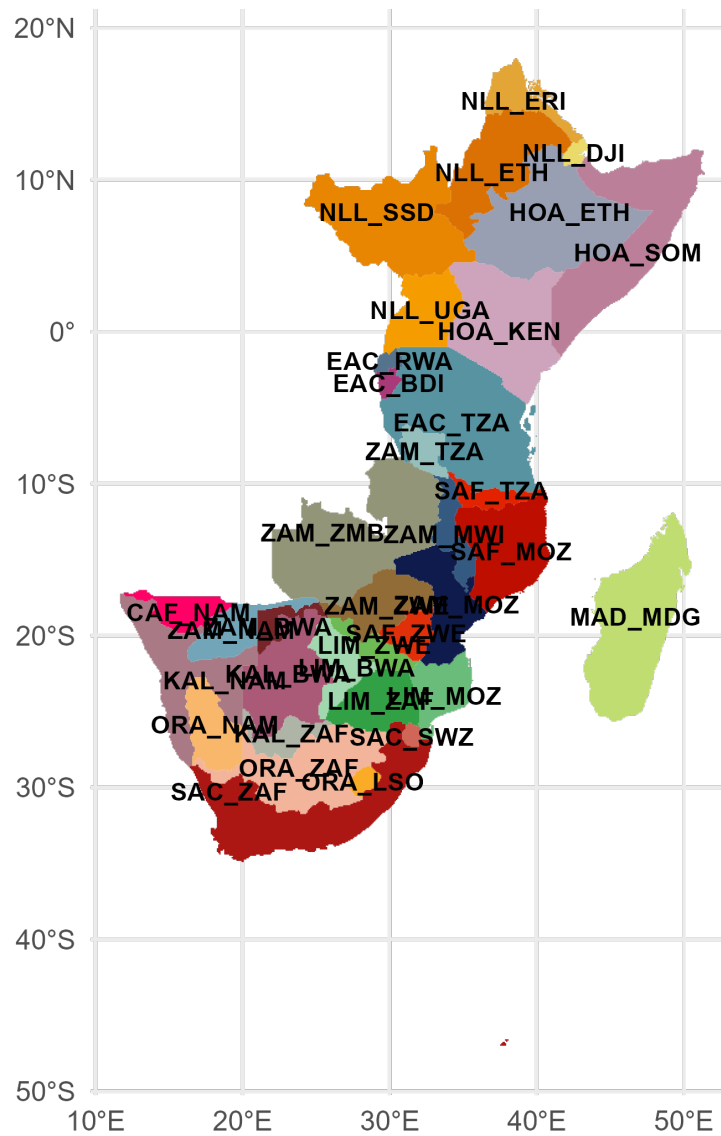
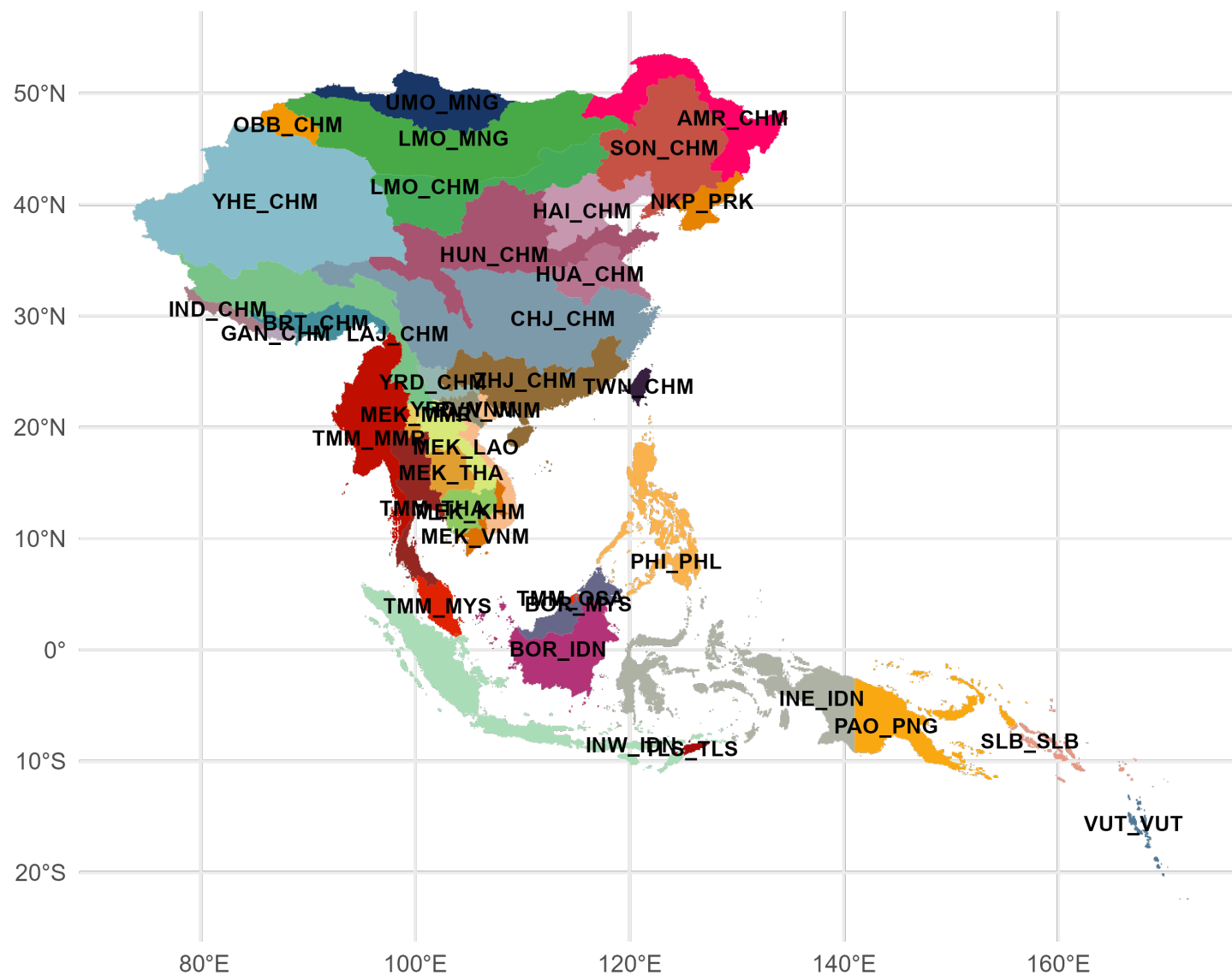


Figure A12: Map of FPUs in East and Southern Africa. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.



74

Figure A13: Map of FPU in Southeast Asia and the Pacific. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT. Small Atlantic and Pacific islands are not plotted in this map. See Table A2 for full list of FPUs.

Appendix B: Activities and commodities

Table B1: IMPACT activity list with their FAO codes.See fao.org/faostat/en/#definitions (section "Item") for full list of FAO codes and definitions.

FAO Item Code	IMPACT activity	Activity group	Activity name
2615	jbanana	Fruits and Vegetables	Banana
2513	jbarl	Cereals	Barley
2546	jbean	Pulses	Beans
2731	jbeef	Meat	Beef
2630	jcafe	Other Crops	Coffee
2532	jcass	Root and Tubers	Cassava
2633	jcoco	Other Crops	Cacao
2661	jcott	Other Crops	Cotton
2744	jeggs	Dairy	Eggs
2591	jgdml	Oilmeals	Groundnut meal
2556	jgrnd	Traded Oilseeds	Groundnut
2572	jgdol	Processed Oils	Groundnut Oil
2732	jlamb	Meat	Lamb
2514	jmaiz	Cereals	Maize
2848	jmilk	Dairy	Dairy
2517	jmill	Cereals	Millet
2515	jocer	Cereals	Other Cereals
2516	jocer	Cereals	Other Cereals
2520	jocer	Cereals	Other Cereals
2534	jorat	Root and Tubers	Other Roots
2551	jothr	Other Crops	Other
2642	jothr	Other Crops	Other
2645	jothr	Other Crops	Other
2662	jothr	Other Crops	Other
2663	jothr	Other Crops	Other
2664	jothr	Other Crops	Other
2665	jothr	Other Crops	Other
2666	jothr	Other Crops	Other
2667	jothr	Other Crops	Other
2671	jothr	Other Crops	Other
2672	jothr	Other Crops	Other
2595	jkml	Oilmeals	Palm Kernel Meal
2576	jkol	Processed Oils	Palm Kernel Oil
2562	jkrl	Non-traded Oilseed	Palm Kernel
2616	jplnt	Fruits and Vegetables	Plantain
2577	jplol	Processed Oils	Palm Fruit Oil
2733	jpork	Meat	Pork
2531	jpota	Root and Tubers	Potato
2734	jpoul	Meat	Poultry
2805	jrice	Cereals	Rice

Table B1 continued from previous page

FAO Item Code	IMPACT activity	Activity group	Activity name
2593	jrplm	Oilmeals	Rapeseed Meal
2574	jrpol	Processed Oils	Rapeseed Oil
2558	jrpsd	Traded Oilseeds	Rapeseed
2590	jsbml	Oilmeals	Soybean Meal
2571	jsbol	Processed Oils	Soybean Oil
2592	jsfml	Oilmeals	Sunflower Meal
2573	jsfol	Processed Oils	Sunflower Oil
2557	jsnfl	Traded Oilseeds	Sunflower
2518	jsorg	Cereals	Sorghum
2555	jsoyb	Traded Oilseeds	Soybean
2611	jsubf	Fruits and Vegetables	Tropical Fruit
2612	jsubf	Fruits and Vegetables	Tropical Fruit
2613	jsubf	Fruits and Vegetables	Tropical Fruit
2614	jsubf	Fruits and Vegetables	Tropical Fruit
2618	jsubf	Fruits and Vegetables	Tropical Fruit
2619	jsubf	Fruits and Vegetables	Tropical Fruit
2537	jsugb	Sugar Crops	Sugar beet
2536	jsugc	Sugar Crops	Sugarcane
2542	jsugr	Sugar Crops	Sugar
2533	jswpt	Root and Tubers	Sweet Potato
2635	jteas	Other Crops	Tea
2617	jtemf	Fruits and Vegetables	Temperate Fruit
2620	jtemf	Fruits and Vegetables	Temperate Fruit
2560	jtols	Traded Oilseeds	Other Oilseeds
2561	jtols	Traded Oilseeds	Other Oilseeds
2563	jtols	Traded Oilseeds	Other Oilseeds
2570	jtols	Traded Oilseeds	Other Oilseeds
2594	jtoml	Oilmeals	Other meals
2596	jtoml	Oilmeals	Other meals
2597	jtoml	Oilmeals	Other meals
2598	jtoml	Oilmeals	Other meals
2575	jtool	Processed Oils	Other Oils
2578	jtool	Processed Oils	Other Oils
2580	jtool	Processed Oils	Other Oils
2586	jtool	Processed Oils	Other Oils
2579	jtool	Processed Oils	Other Oils
2601	jvege	Fruits and Vegetables	Vegetables
2602	jvege	Fruits and Vegetables	Vegetables
2605	jvege	Fruits and Vegetables	Vegetables
2640	jvege	Fruits and Vegetables	Vegetables
2641	jvege	Fruits and Vegetables	Vegetables
2511	jwhea	Cereals	Wheat

Table B1 continued from previous page

FAO Item Code	IMPACT activity	Activity group	Activity name
2535	jyams	Root and Tubers	Yams

Table B2: Mapping of activities to commodities in IMPACT

Group	Activity	Description	Commodity	Description
Animal products	jbeef	Cattle ranch	cbeef	Cattle
Animal products	jeggs	Egg production	ceggs	Eggs
Animal products	jlamb	Sheep, lamb, goat production	clamb	Sheep and goats
Animal products	jmilk	Dairy production	cmilk	Dairy
Animal products	jpork	Pigs	cpork	Pigs
Animal products	jpoul	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	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	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	Groundnut farm	cgdnt	Groundnuts for oil
Oilseeds (nontraded)	jpalm	Oil palm plantation	cpalm	Oil palm fruit
Oilseeds (nontraded)	jrpnf	Rapeseed farm	crpnf	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	jgdol	Groundnut processing	cgdol	Groundnut oil
	jgdolnt		cgdml	Groundnut meal

Table B2 continued from previous page

Group	Activity	Description	Commodity	Description
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
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	Cotton plantation	ccott	Cotton
Other	jfodr	Fodder production	cfodr	Fodders
Other	jother	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

Table B2 continued from previous page

Group	Activity	Description	Commodity	Description
Sugar	jsugc	Sugarcane plantation	csugc	Sugarcane
Sugar	jsugr	Sugar processing	csugr	Refined sugar

Appendix C: Data inputs and outputs

Table C1: IMPACT data requirements in the model base year

Data source	Geographic scope	IMPACT parameter	Commodity requirement	Unit
OECD Agricultural Market Access Database	Global	World prices	All commodities	US dollars per mt
SSP database	National	Population GDP	— —	Million Billion US dollars
FAOSTAT commodity balances	National	Total supply	All commodities	000 mt
		- Animal numbers	Livestock only	000 producing animals
		- Harvested 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	kilograms/capita/year
		Food supply	Food commodities	kcal/commodity/person/day
FAO AquaStat and OECD	National	Total irrigated area		000 ha
		Irrigated crop area	Crops only	000 ha
IFPRI SPAM	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

Table C2: 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.
Population growth rates	SSP database	IMPACT is calibrated to the IIASA SSP 2 (version 3, see KC et al. 2024) population scenario.
GDP growth rates	SSP database	IMPACT is calibrated to the OECD SSP 2 (version 3, see KC et al. 2024) GDP scenario.

Table C3: 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

Appendix D: Crop models

Crop models

As a decision-support tool, crop systems models have potential at various levels of decision making, 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. 2019; Hoogenboom et al. 2021; 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 (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.

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 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) x (2 water sources) x ([1 baseline] + [2 CO₂ assumptions]) = 42 individual yield realizations that are used to calculate climate change impacts across the appropriate domains of the IMPACT model.

Table D1: Mapping DSSAT crop model results to IMPACT

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

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

- Climate data are derived from ESM outputs (IPSL, GFDL-ESM4, MPIESM1-2HR, MRI-ESM2-0, and UKESM1-o-LL). In particular, the Inter-sectoral Impact Model Intercomparison Project (ISIMIP) initiative provides gridded versions of ESM outputs relevant to agricultural modeling (Hempel et al. 2013; Piani, Haerter, and Coppola 2010; Weedon et al. 2011). As of this writing, the ISIMIP3b datasets are used to build the future climates (Lange and Büchner 2021). This is accomplished by taking patterns of change from the ISIMIP maps and applying them to a common and trusted set of baseline/historic climate data to allow for consistent comparisons and realistic baseline results. The Princeton Global Forcing dataset (Sheffield, Goteti, and Wood 2006) is used as the common baseline. The historical period of interest

is defined as the average of the years 1995-2015. The change to the future climates is determined by extracting similar averages over the years 1995-2015 (i.e., centered on 2005) and 2040-2060 (centered on 2050) and applying those to the Princeton Global Forcing averages centered on 2005.

- Soils were handled using a generic soil profile approach. The Harmonized World Soil Database (HWSD) 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)
- 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.

Appendix E: Non-exhaustive list of publications using IMPACT 3.x to 3.6

- Beach et al. [2019](#)
- Chan et al. [2021](#)
- Chan et al. [2019](#)
- Delzeit et al. [2020](#)
- Enahoro et al. [2023](#)
- Fuglie et al. [2022](#)
- Gustafson et al. [2021](#)
- Hasegawa et al. [2018](#)
- Hinz et al. [2020](#)
- Islam et al. [2016](#)
- Komarek et al. [2021](#)
- Mason-D’Croz et al. [2020](#)
- Mason-D’Croz et al. [2019a](#)
- Mason-D’Croz et al. [2019b](#)
- Nelson et al. [2009](#)
- Nelson et al. [2010](#)
- Nelson et al. [2018](#)
- Pandey et al. [2010](#)
- Petsakos et al. [2018](#)
- Petsakos et al. [2019](#)
- Petsakos et al. [2023](#)
- Rosegrant et al. [2024](#)
- Rosegrant, Sulser, and Wiebe [2022](#)
- Rosegrant et al. [2023](#)
- Smith et al. [2022](#)
- Springmann et al. [2018](#)
- Sulser et al. [2021b](#)
- Sulser et al. [2011](#)
- Sulser et al. [2010](#)
- Sulser et al. [2021a](#)
- Van Zeist et al. [2020](#)
- Wiebe et al. [2021](#)
- Zhu et al. [2013](#)

Bibliography

- Allen, Richard G, Luis S Pereira, Dirk Raes, Martin Smith, et al. (1998). "Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56". In: *FAO, Rome* 300.9, p. D05109.
- Beach, Robert H, Timothy B Sulser, Allison Crimmins, Nicola Cenacchi, Jefferson Cole, Naomi K Fukagawa, Daniel Mason-D'Croz, Samuel Myers, Marcus C Sarofim, Matthew Smith, et al. (2019). "Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: a modelling study". In: *The Lancet Planetary Health* 3.7, e307–e317.
- Chan, Chin Yee, Nhuong Tran, Kai Ching Cheong, Timothy B Sulser, Philippa J Cohen, Keith Wiebe, and Ahmed Mohamed Nasr-Allah (2021). "The future of fish in Africa: Employment and investment opportunities". In: *PLoS one* 16.12, e0261615.
- Chan, Chin Yee, Nhuong Tran, Shanali Pethiyagoda, Charles C Crissman, Timothy B Sulser, and Michael J Phillips (2019). "Prospects and challenges of fish for food security in Africa". In: *Global food security* 20, pp. 17–25.
- Chen, Y-HH, Sergey Paltsev, John Matthew Reilly, Jennifer F Morris, and Mustafa H Babiker (2015). *The MIT EPPA6 model: Economic growth, energy use, and food consumption*. Tech. rep. MIT Joint Program on the Science and Policy of Global Change.
- Delzeit, Ruth, Roberto Beach, Ruben Bibas, Wolfgang Britz, Jean Chateau, Florian Freund, Julien Lefevre, Franziska Schuenemann, Timothy Sulser, Hugo Valin, et al. (2020). "Linking global CGE models with sectoral models to generate baseline scenarios: Approaches, opportunities and pitfalls". In: *Journal of Global Economic Analysis* 5.1, pp. 162–195.
- Doorenbos, J and AH Kassam (1979). "Yield response to water". In: *Irrigation and drainage paper* 33, p. 257.
- Enahoro, Dolapo, Marta Kozicka, Catherine Pfeifer, Sarah K Jones, Nhuong Tran, Chin Yee Chan, Timothy B Sulser, Elisabetta Gotor, and Karl M Rich (2023). "Linking ecosystem services provisioning with demand for animal-sourced food: an integrated modeling study for Tanzania". In: *Regional Environmental Change* 23.1, p. 48.
- Evenson, Robert E and Mark W Rosegrant (1995). "Productivity projections for commodity market modeling". In: *final workshop of the international cooperative research project on Projections and Policy Implications of Medium and Long-Term Rice Supply and Demand, Beijing*.
- Evenson, Robert Eugene, Carl Pray, and Mark W Rosegrant (1998). *Agricultural research and productivity growth in India*. Vol. 109. International Food Policy Research Institute.
- Fischer, Günther, Mahendra Shah, Francesco N. Tubiello, and Harrij Van Velhuizen (2005). "Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080". In: *Philosophical Transactions of the Royal Society B: Biological Sciences* 360.1463, pp. 2067–2083.
- Fraiture, Charlotte de (2007). "Integrated water and food analysis at the global and basin level. An application of WATERSIM". In: *Water Resources Management* 21, pp. 185–198.
- Fuglie, Keith, Keith Wiebe, Timothy B Sulser, Nicola Cenacchi, and Dirk Willenbockel (2022). "Multidimensional impacts from international agricultural research: Implications for research priorities". In: *Frontiers in sustainable food systems* 6, p. 1031562.
- Gustafson, David, Senthold Asseng, John Kruse, Greg Thoma, Kaiyu Guan, Gerrit Hoogenboom, Marty Matlock, Morven McLean, Ranjan Parajuli, Kirti Rajagopalan, et al. (2021). "Supply chains for processed potato and tomato products in the United States will have enhanced resilience with planting adaptation strategies". In: *Nature Food* 2.11, pp. 862–872.
- Hasegawa, Tomoko, Shinichiro Fujimori, Petr Havlík, Hugo Valin, Benjamin Leon Bodirsky, Jonathan C Doelman, Thomas Fellmann, Page Kyle, Jason FL Koopman, Hermann Lotze-Campen, et al. (2018). "Risk of increased food insecurity under stringent global climate change mitigation policy". In: *Nature climate change* 8.8, pp. 699–703.
- Hempel, Sabrina, Katja Frieler, Lila Warszawski, Jacob Schewe, and Franziska Piontek (2013). "A trend-preserving bias correction—the ISI-MIP approach". In: *Earth System Dynamics* 4.2, pp. 219–236.
- Hinz, Roman, Timothy B Sulser, Rebekka Hüfner, Daniel Mason-D'Croz, Shahnaila Dunston, Sunil Nautiyal, Claudia Ringler, Jan Schüngel, Pavan Tikhile, Florian Wimmer, et al. (2020). "Agricultural development and land use change in India: A scenario analysis of trade-offs between UN Sustainable Development Goals (SDGs)". In: *Earth's Future* 8.2, e2019EF001287.

- Hoogenboom, G, CH Porter, V Shelia, KJ Boote, U Singh, JW White, W Pavan, FAA Oliveira, LP Moreno-Cadena, JI Lizaso, et al. (2021). "Decision support system for agrotechnology transfer (DSSAT) version 4.7 (www.DSSAT.net)". In: *DSSAT Foundation, Gainesville, Florida, USA*.
- Hoogenboom, Gerrit, Cheryl H Porter, Kenneth J Boote, Vakhtang Shelia, Paul W Wilkens, Upendra Singh, Jeffrey W White, Senthold Asseng, Jon I Lizaso, L Patricia Moreno, et al. (2019). "The DSSAT crop modeling ecosystem". In: *Advances in crop modelling for a sustainable agriculture*. Burleigh Dodds Science Publishing, pp. 173–216.
- Islam, Shahnila, Nicola Cenacchi, Timothy B Sulser, Sika Gbegbelegbe, Guy Hareau, Ulrich Kleinwechter, Daniel Mason-D'Croz, Swamikannu Nedumaran, Richard Robertson, Sherman Robinson, et al. (2016). "Structural approaches to modeling the impact of climate change and adaptation technologies on crop yields and food security". In: *Global Food Security* 10, pp. 63–70.
- Jones, James W, Gerrit Hoogenboom, Cheryl H Porter, Ken J Boote, William D Batchelor, LA Hunt, Paul W Wilkens, Upendra Singh, Arjan J Gijsman, and Joe T Ritchie (2003). "The DSSAT cropping system model". In: *European journal of agronomy* 18.3-4, pp. 235–265.
- KC, S, M Dhakad, M Potančoková, S Adhikari, D Yildiz, M Mamolo, T Sobotka, K Zeman, G Abel, W Lutz, et al. (2024). "Updating the Shared Socioeconomic Pathways (SSPs) Global Population and Human Capital Projections". In.
- Komarek, Adam M, Shahnila Dunston, Dolapo Enahoro, H Charles J Godfray, Mario Herrero, Daniel Mason-D'Croz, Karl M Rich, Peter Scarborough, Marco Springmann, Timothy B Sulser, et al. (2021). "Income, consumer preferences, and the future of livestock-derived food demand". In: *Global Environmental Change* 70, p. 102343.
- Lange, Stefan and Matthias Büchner (2021). "ISIMIP3b bias-adjusted atmospheric climate input data (v1.1)". In.
- Lofgren, Hans, Rebecca Lee Harris, and Sherman Robinson (2002). *A standard computable general equilibrium (CGE) model in GAMS*. Vol. 5. International Food Policy Research Institute.
- Maack, J (2001). "Scenario Analysis: A Tool for Task Managers. in "Social Analysis: Selected Tools and Techniques."" In: *Social Development Paper* 36.
- Mason-D'Croz, Daniel, Jessica R Bogard, Timothy B Sulser, Nicola Cenacchi, Shahnila Dunston, Mario Herrero, and Keith Wiebe (2019a). "Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study". In: *The Lancet Planetary Health* 3.7, e318–e329.
- Mason-D'Croz, Daniel, Timothy B Sulser, Keith Wiebe, Mark W Rosegrant, Sarah K Lowder, Alejandro Nin-Pratt, Dirk Willenbockel, Sherman Robinson, Tingju Zhu, Nicola Cenacchi, et al. (2019b). "Agricultural investments and hunger in Africa modeling potential contributions to SDG2–Zero Hunger". In: *World development* 116, pp. 38–53.
- Mason-D'Croz, D, S Robinson, and S Islam (2015). *International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Data Management Technical Description*. Tech. rep. IFPRI Technical Report. Unpublished, International Food Policy Research ...
- Mason-D'Croz, Daniel, Jessica R Bogard, Mario Herrero, Sherman Robinson, Timothy B Sulser, Keith Wiebe, Dirk Willenbockel, and H Charles J Godfray (2020). "Modelling the global economic consequences of a major African swine fever outbreak in China". In: *Nature Food* 1.4, pp. 221–228.
- MEA (2005). *Ecosystems and human well-being: synthesis*.
- Mishra, Abhijeet (2024). *App for IMPACT (App for ImpAct)*. Version 2.5.0. <https://github.com/IFPRI/ARIA>.
- Müller, Christoph and Richard D Robertson (2014). "Projecting future crop productivity for global economic modeling". In: *Agricultural Economics* 45.1, pp. 37–50.
- Nelson, Gerald, Jessica Bogard, Keith Lividini, Joanne Arsenault, Malcolm Riley, Timothy B Sulser, Daniel Mason-D'Croz, Brendan Power, David Gustafson, Mario Herrero, et al. (2018). "Income growth and climate change effects on global nutrition security to mid-century". In: *Nature Sustainability* 1.12, pp. 773–781.
- Nelson, Gerald C, Mark W Rosegrant, Jawoo Koo, Richard Robertson, Timothy Sulser, Tingju Zhu, Claudia Ringler, Siwa Msangi, Amanda Palazzo, Miroslav Batka, et al. (2009). *Climate change: Impact on agriculture and costs of adaptation*. Vol. 21. International Food Policy Research Institute.
- Nelson, Gerald C, Mark W Rosegrant, Amanda Palazzo, Ian Gray, Christina Ingersoll, Richard Robertson, Simla Tokgoz, Tingju Zhu, Timothy B Sulser, Claudia Ringler, et al. (2010). *Food security, farming, and climate change to 2050: scenarios, results, policy options*. Vol. 172. International Food Policy Research Institute.
- Pandey, Sushil, Timothy Sulser, Mark W Rosegrant, and Humnath Bhandari (2010). "Rice price crisis: Causes, impacts, and solutions". In: *Asian Journal of Agriculture and Development* 7.2, pp. 1–15.
- Petsakos, Athanasios, Guy Hareau, Ulrich Kleinwechter, Keith Wiebe, and Timothy B Sulser (2018). "Comparing modeling approaches for assessing priorities in international agricultural research". In: *Research Evaluation* 27.2, pp. 145–156.
- Petsakos, Athanasios, Marta Kozicka, Guy Blomme, Juliet N Nakakawa, Walter Ocimati, and Elisabetta Gotor (2023). "The potential impact of banana Xanthomonas wilt on food systems in Africa: modeling scenarios of policy

- response and disease control measures". In: *Frontiers in Sustainable Food Systems* 7, p. 1207913.
- Petsakos, Athanasios, Steven D Prager, Carlos Eduardo Gonzalez, Arthur Chibwana Gama, Timothy B Sulser, Sika Gbegbelegbe, Enoch M Kikulwe, and Guy Hareau (2019). "Understanding the consequences of changes in the production frontiers for roots, tubers and bananas". In: *Global food security* 20, pp. 180–188.
- Piani, Claudio, JO Haerter, and E Coppola (2010). "Statistical bias correction for daily precipitation in regional climate models over Europe". In: *Theoretical and applied climatology* 99, pp. 187–192.
- Priestley, Charles Henry Brian and Robert Joseph Taylor (1972). "On the assessment of surface heat flux and evaporation using large-scale parameters". In: *Monthly weather review* 100.2, pp. 81–92.
- Robinson, S, D Mason-D’Croz, S Islam, N Cenacchi, B Creamer, A Gueneau, G Hareau, U Kleinwechter, K Mottaleb, S Nedumaran, et al. (2015a). *New Crop Varieties and Climate Change Adaptation: Ex-Ante Analysis of Promising and Alternative Technologies*. Tech. rep. IFPRI Discussion Paper Series, Washington, DC: International Food Policy ...
- Robinson, Sherman, Daniel Mason-D’Croz, Timothy Sulser, Shahnila Islam, Ricky Robertson, Tingju Zhu, Arthur Gueneau, Gauthier Pitois, and Mark W Rosegrant (2015b). "The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): model description for version 3". In: IFPRI Discussion Paper 1483.
- Rosegrant, Mark W, Mercedita Castro Agcaoili-Sombilla, and Nicostrato D Perez (1995). *Global food projections to 2020: Implications for investment*. Vol. 5. Diane Publishing.
- Rosegrant, Mark W, Ximing Cai, and Sarah A Cline (2002). *World water and food to 2025: dealing with scarcity*. International Food Policy Research Institute.
- Rosegrant, Mark W, Michael S Paisner, Siet Meijer, Julie Witcover, et al. (2001). *Global food projections to 2020: Emerging trends and alternative futures*. International Food Policy Research Institute.
- Rosegrant, Mark W, Timothy B Sulser, Shahnila Dunston, Abhijeet Mishra, Nicola Cenacchi, Yohannes Gebretsadik, Richard Robertson, Timothy Thomas, and Keith Wiebe (2024). "Food and nutrition security under changing climate and socioeconomic conditions". In: *Global Food Security* 41, p. 100755.
- Rosegrant, Mark W, Timothy B Sulser, and Keith Wiebe (2022). "Global investment gap in agricultural research and innovation to meet Sustainable Development Goals for hunger and Paris Agreement climate change mitigation". In: *Frontiers in Sustainable Food Systems* 6, p. 965767.
- Rosegrant, Mark W, Brad Wong, Timothy B Sulser, Nancy Dubosse, and Travis J Lybbert (2023). "Benefit–cost analysis of increased funding for agricultural research and development in the global south". In: *Journal of Benefit-Cost Analysis* 14.S1, pp. 181–205.
- Sarukhān, José, Anne Whyte, R Hassan, R Scholes, N Ash, ST Carpenter, PL Pingali, EM Bennett, MB Zurek, K Chopra, et al. (2005). "Millenium ecosystem assessment: Ecosystems and human well-being". In: ...
- Sheffield, Justin, Gopi Goteti, and Eric F Wood (2006). "Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling". In: *Journal of climate* 19.13, pp. 3088–3111.
- Smith, Lisa C and Lawrence James Haddad (2000). *Explaining child malnutrition in developing countries: A cross-country analysis*. Vol. 111. International Food Policy Research Institute.
- Smith, Matthew R, Nathaniel D Mueller, Marco Springmann, Timothy B Sulser, Lucas A Garibaldi, James Gerber, Keith Wiebe, and Samuel S Myers (2022). "Pollinator deficits, food consumption, and consequences for human health: a modeling study". In: *Environmental Health Perspectives* 130.12, p. 127003.
- Springmann, Marco, Keith Wiebe, Daniel Mason-D’Croz, Timothy B Sulser, Mike Rayner, and Peter Scarborough (2018). "Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail". In: *The Lancet Planetary Health* 2.10, e451–e461.
- Sulser, Timothy, Keith D Wiebe, Shahnila Dunston, Nicola Cenacchi, Alejandro Nin-Pratt, Daniel Mason-D’Croz, Richard D Robertson, Dirk Willenbockel, and Mark W Rosegrant (2021a). *Climate change and hunger: Estimating costs of adaptation in the agrifood system*. International Food Policy Research Institute.
- Sulser, Timothy B, Robert H Beach, Keith D Wiebe, Shahnila Dunston, and Naomi K Fukagawa (2021b). "Disability-adjusted life years due to chronic and hidden hunger under food system evolution with climate change and adaptation to 2050". In: *The American Journal of Clinical Nutrition* 114.2, pp. 550–563.
- Sulser, Timothy B, Bella Nestorova, Mark W Rosegrant, and Teunis van Rheenen (2011). "The future role of agriculture in the Arab region’s food security". In: *Food Security* 3, pp. 23–48.
- Sulser, Timothy B, Claudia Ringler, Tingju Zhu, Siwa Msangi, Elizabeth Bryan, and Mark W Rosegrant (2010). "Green and blue water accounting in the Ganges and Nile basins: Implications for food and agricultural policy". In: *Journal of Hydrology* 384.3–4, pp. 276–291.
- USDA (1998). *Commodity and food elasticities*.

- Van Zeist, Willem-Jan, Elke Stehfest, Jonathan C Doelman, Hugo Valin, Katherine Calvin, Shinichiro Fujimori, Tomoko Hasegawa, Petr Havlik, Florian Humpenöder, Page Kyle, et al. (2020). "Are scenario projections overly optimistic about future yield progress?" In: *Global Environmental Change* 64, p. 102120.
- Vervoort, Joost M, Amanda Palazzo, Daniel Mason-D'Croz, Polly J Ericksen, Philip K Thornton, Patricia M Kristjanson, Wiebke Förch, Mario T Herrero, Petr Havlík, Christine Jost, et al. (2013). "The future of food security, environments and livelihoods in Eastern Africa: four socio-economic scenarios". In: *CCAFS Working Paper*.
- Weedon, GP, S Gomes, P Viterbo, WJ Shuttleworth, E Blyth, H Österle, JC Adam, Nicolas Bellouin, O Boucher, and M Best (2011). "Creation of the WATCH forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century". In: *Journal of Hydrometeorology* 12.5, pp. 823–848.
- White, Jeffrey W, LA Hunt, Kenneth J Boote, James W Jones, Jawoo Koo, Soonho Kim, Cheryl H Porter, Paul W Wilkens, and Gerrit Hoogenboom (2013). "Integrated description of agricultural field experiments and production: The ICASA Version 2.0 data standards". In: *Computers and electronics in agriculture* 96, pp. 1–12.
- Wiebe, Keith, Timothy B Sulser, Shahnila Dunston, Mark W Rosegrant, Keith Fuglie, Dirk Willenbockel, and Gerald C Nelson (2021). "Modeling impacts of faster productivity growth to inform the CGIAR initiative on Crops to End Hunger". In: *PLoS One* 16.4, e0249994.
- Wilson, Ian (1998). "Mental maps of the future: an intuitive logics approach to scenarios". In: *Learning from the future: Competitive foresight scenarios*, pp. 81–108.
- You, Liangzhi, Ulrike Wood-Sichra, Steffen Fritz, Zhe Guo, Linda See, Jawoo Koo, et al. (2014). "Spatial production allocation model (SPAM) 2005 v2. 0". In: *Available at mapspam.info*. Accessed June 29, p. 2015.
- Zhu, Tingju, Claudia Ringler, M Mohsin Iqbal, Timothy B Sulser, and M Arif Goheer (2013). "Climate change impacts and adaptation options for water and food in Pakistan: scenario analysis using an integrated global water and food projections model". In: *Water International* 38.5, pp. 651–669.