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The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model documentation for version 4

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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 since its initial development in the early 1990s, IMPACT version 4 represents the latest iteration of the model, offering an enhanced treatment of complex issues such as climate change, food security, and economic development. IMPACT 4 modeling system 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.

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Author contributions

Abhijeet Mishra, Sherwin Gabriel, Nicola Cenacchi, and Faaiqa Hartley updated IMPACT v4 documentation based on Robinson et al. 2025.

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All authors contributed to the research design of IMPACT 4.

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IMPACT 4 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 development and improvement over time, including many of our past colleagues at IFPRI for their valuable expertise and support especially Daniel Mason-D'Croz, Tingju Zhu, Arthur Gueneau, and Gauthier Pitois. We also greatly appreciate the assistance and feedback from Claudia Ringler, Hua Xie, and Nicostratos Perez.

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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/m2	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 built around a core multimarket economic model of global agricultural production, trade, demand, and prices, with integrated representations of cropland use and water resources, climate change impacts on crops, evolving diets, and nutrition outcomes. This document updates and replaces previous technical reports and documentations that served as the basis of this documentation, in particular Rosegrant et al. 1995; Rosegrant et al. 2008; Rosegrant et al. 2012; Robinson et al. 2015b; Robinson et al. 2025.

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), and crop simulation models like Decision Support System for Agrotechnology Transfer (DSSAT)[1]. IMPACT results can be used by output modules like land use (pixel-level land use, cropping patterns by regions) as well as nutrition and health modules[2]. IMPACT also represents value chains[3] within the multi-market model (for example, sugar, oils, livestock). 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 (Islam et al. 2016). 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 the 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 provide an economy-wide representation of economic flows across multiple sectors and markets,including factor markets (for example, labor and capital markets), but with

[1] IMPACT in principle can be linked to other biophysical simulation models as well, provided that those models can provide the same inputs DSSAT provides to IMPACT.

[2] See subsection 5.3 Food security modules

[3] See subsection 4.6 Activity-commodity framework

varying degrees of detail. 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 covering 158 countries/regions[4]. 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). FPUs correspond to water basins within national boundaries of these 158 countries (see Fig. 1.1 for a geography overview and Geography for more detailed IMPACT geography). The multimarket model simulates 71 agricultural commodity markets including crops, livestock, aquatic foods and processed commodities (see 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.

[4]Some countries are aggregated into a single *region* in IMPACT. See Country and region codes and names in IMPACT along with their FAO counterparts for more details.

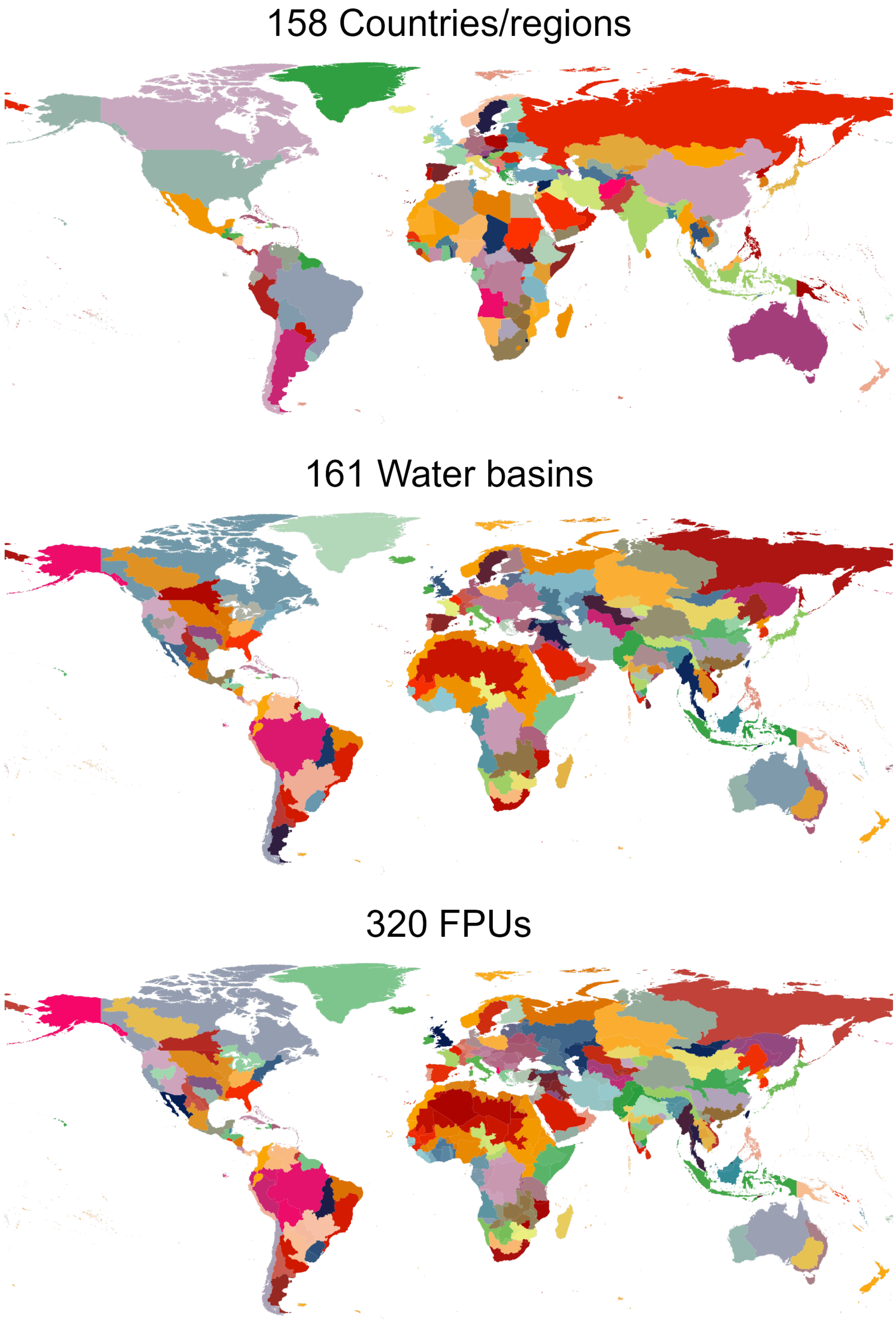

Figure 1.1: Spatial scale of IMPACT model's operation. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

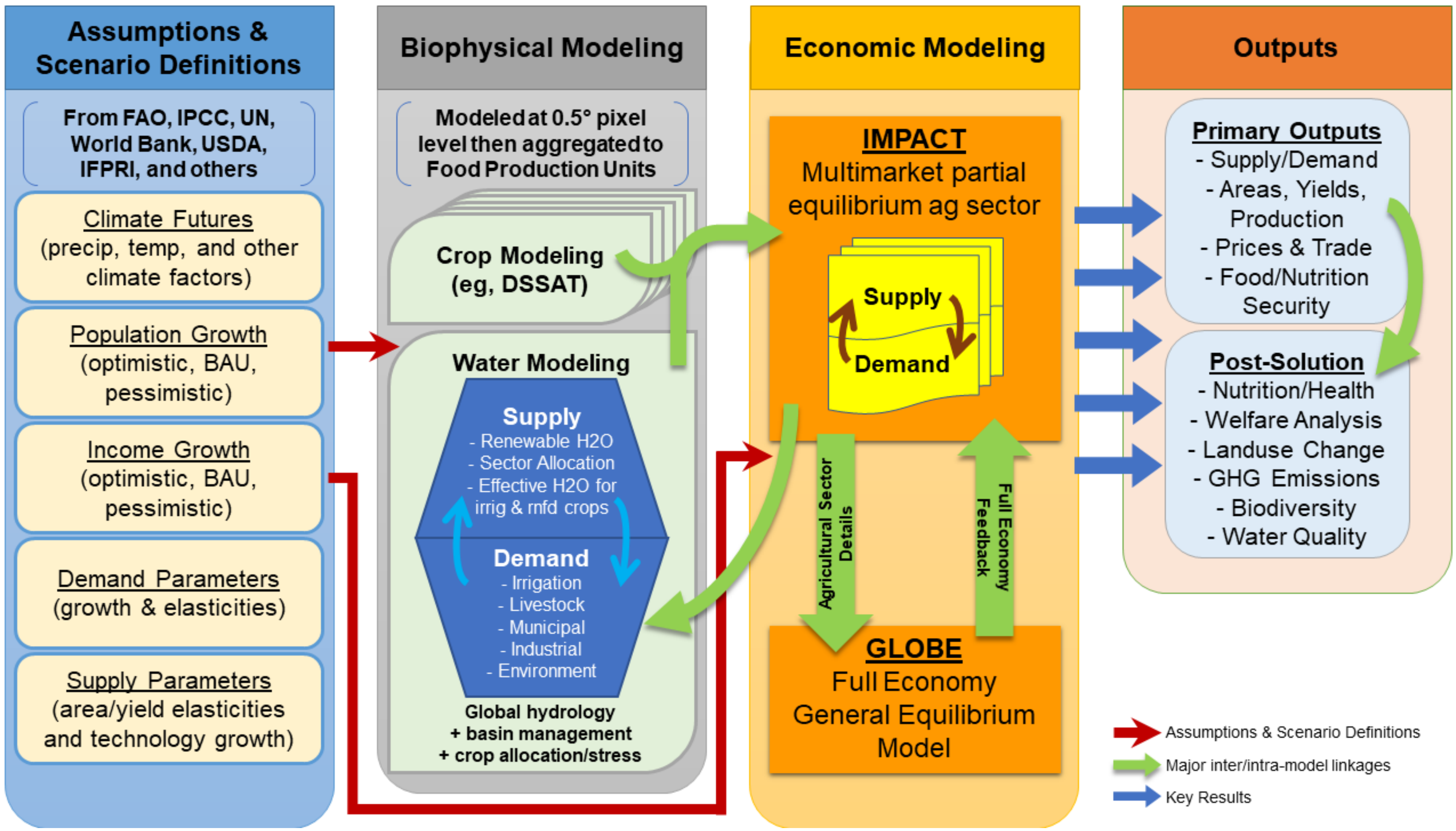

Figure 1.2: IMPACT modeling framework and interactions

2 Background

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 et al. 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. 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.

IMPACT version 4 brings forward additional capabilities to the modeling framework. These include re-introduction of aquatic foods in IMPACT modeling framework as well as an updates to Intrinsic Productivity Growth Rate (IPR) assumptions based on extensive expert discussions among CGIAR centers.

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 71 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 since version 3 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 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. 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 and above), 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 last publicly available results (IMPACT v3.4) are shown in Rosegrant et al. 2024.

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 fo**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).

Since IMPACT 4, aquatic food has been incorporated back in IMPACT, with 16 aquatic food activities and 9 aquatic food commodities. Aquatic food production and demand in IMPACT are represented in a manner similar to the treatment of processed oilseeds. Production of aquatic foods is determined by a combination of exogenous growth trends and endogenous producer prices. The model does not explicitly distinguish between capture fisheries and aquaculture. Aquatic food demand is driven by exogenous income and population growth trends, together with endogenous consumer prices. In the current version of IMPACT, only household demand for fish is modeled i.e., only for food. Non-food uses of aquatic foods are not explicitly represented in this version of IMPACT.

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 a powerful analytical tool that allows policymakers to explore plausible futures in a systematic manner by considering deep future uncertainties. It is fundamentally distinct from forecasting analysis, which primarily utilizes statistical methods to extrapolate one or two variables that describe a system. While forecasting includes confidence intervals to capture statistical uncertainty, it is generally void of qualitative components and relies on the assumption that the future will largely mirror historical experience.

In contrast, scenario analysis is the quantification of a qualitative process designed to specify "possibility spaces" for a large number of interconnected variables. Rather than aiming to predict a single, most likely outcome, it focuses on system dynamics. By generating logically consistent future pathways, it accounts for linear and nonlinear interactions and trends that may deviate significantly from the past. Because of the sheer volume of variables and the complex ways they influence the modeled system, traditional statistical forecasting becomes insufficient, making scenario analysis essential for navigating multifaceted future landscapes.

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

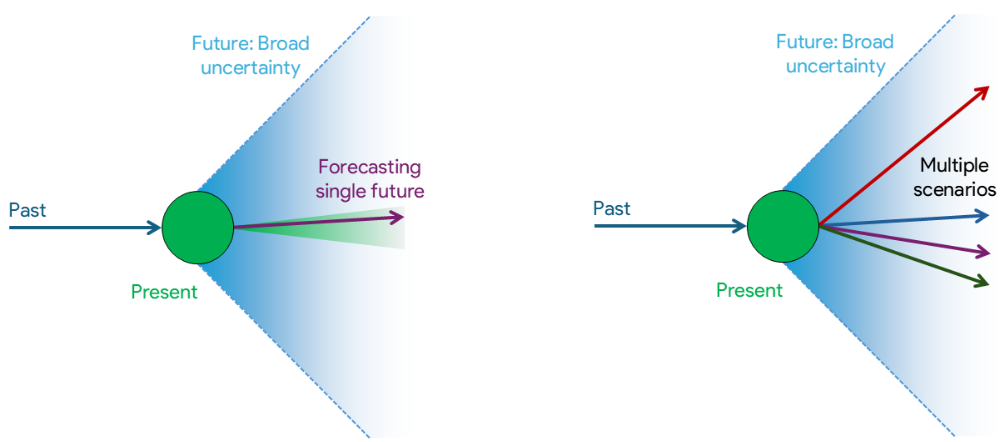

Figure 3.1: Forecasting vs. scenario analysis. Source: Authors, using Vervoort et al. 2013.

Scenario analysis with simulation models allows policymakers to explore the robustness of different policies by testing them against alternative futures focused on key uncertainties. Central to this approach is the idea of *contextual environment* where a broad set of background drivers, such as population and income growth (e.g. SSP2) or climate trajectories (e.g. RCP7.0) set the stage for a simulation. By establishing this environment, researchers can then isolate and analyze the impact of specific drivers (e.g. trade restriction, the outbreak of a disease, or the introduction of a new technology) within that broader framework. This method ensures that policy performance is evaluated not in a vacuum, but against a range of plausible and logically consistent systemic shifts. 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 relative magnitude of change with respect to a reference scenario. These scenario results can be useful for informing policy decisions as well as providing many global and regional contexts for more detailed scenario development.

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.

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 4, they are based in IPCC's sixth assessment report (AR6).

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. Structural simulation models like IMPACT and global CGE models that focus on long-run scenario analysis are inherently difficult to validate. The validation process for short-run forecasting models such as reduced-form macro-econometric models, is relatively straightforward in principle. It typically involves back-casting, where the model is simulated against recent historical data to statistically analyze the quality and accuracy of the results. This approach is inherently

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 Pests and diseases
Policy	Investment in agriculture research and development Trade policies (taxes, tariffs, consumer & producer support policies)
Infrastructure	Investment in irrigation expansion and irrigation technologies Investment in connectivity infrastructure for transportation
Technological	Change in agricultural productivity due to improved genetics and management

data-driven and grounded in statistical probability.

In contrast, scenario analysis is rooted in qualitative narratives that are subsequently quantified to serve as model inputs. Because these scenarios often explore structural shifts (e.g. socioeconomic changes in the future, climate variability etc.) rather than simple linear trends, traditional statistical validation is less applicable. Structural models like IMPACT are uniquely suited for "what-if" analysis, allowing researchers to test the impact of specific shocks rather than just long-term historical trends (e.g., Petsakos et al. 2019, Rosegrant et al. 2024, Mishra et al. 2025, Schiek et al. 2026). Unlike forecasting, which struggles to account for abrupt system deviations, these structural simulations provide a framework to explore how a system responds within a given contextual environment.

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. 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 like IMPACT, specifying the domain of applicability is a major part of the model design and provides the starting point for model specification.

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 Crop production

Crop production in IMPACT is simulated through area[5] 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 FPUs. This regional disaggregation permits linking with water models and provides the added benefit of smaller geographical units for aggregating climate change results, which can vary significantly from one location to another. Land used for crop production is divided into irrigated and rainfed systems, capturing the significant differences in yields observed across these cultivation systems and linking directly with the water models, which treat irrigated and rainfed water supplies separately.

IMPACT version 3 and above come with an implementation of a land market to manage competing demands for agricultural land from different crops, as well as providing new linkage points to land-use models that work with broader land-use changes, such as conversion of forest to grasslands and agricultural land.

It also allows us to separate total area supply (irrigated and rainfed) from individual crop area demands and allows equilibrium conditions to determine the best economic use of the available land. The total supply of land is assumed to be a function of the scarcity value or shadow price index of land, which can also be considered a summary of changes in crop prices. The shadow price (*WF* in equation 1) is indexed to 1 in the first year and changes based on changing demands from all crops for land area.

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. These are shown in equations 2a and 2b.

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

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

where:

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

IMPACT is a recursive-dynamic model. This means that the model is solved year-by-year, with the solution of one year being the starting point of the next year. Recursively solving the model involves updating key parameters that represent dynamic elements of the system, such as land availability per FPU, as shown in Equations eq. 2a and 2b. Equation 2a illustrates the land supply growth factor affected by an exogenous trend. Equation 2b shows the land supply growth factor affected by the endogenously-determined shadow price of land for the preceding three years. 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.

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

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

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	= Elasticity of land supply
fpu	= Food production unit
lnd	= Land type (irrigated or rainfed)
t	= Simulation time step

Equation 3 describes the marginal revenue product for crop activities. Broadly, the MRP gauges the income that could be earned from an additional hectare's worth of production of a particular crop. MRP is an important metric for resource allocation, as shown in equation 4, which defines the area demand for each crop.

$$MRP_{j,fpu,lnd} = Yld_{j,fpu,lnd} \times PNET_{j,cty} \qquad \forall cty \in fpu \tag{3}$$

where:

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

Equation 4 shows the demand function defining cropping area. Area demand for a crop is affected by its marginal revenue product, the shadow cost of the land, and exogenous non-market trends in cropping area (included in $AreaInt2$). Non-market factors include government programs encouraging expansion of particular crops, reductions due to soil degradation, or conversions to non-agricultural use.

$$\begin{aligned} Area_{j,fpu,lnd} = {} & AreaInt_{j,fpu,lnd} \times AreaInt2_{j,fpu,lnd} \\ & \times (WF_{fpu,lnd})^{\gamma_{j,fpu,lnd}} \times \left(\frac{MRP_{j,fpu,lnd}}{MRP0_{j,fpu,lnd}} \right)^{\alpha_{j,fpu,lnd}} \end{aligned} \tag{4}$$

where:

$Area$ = Solution for crop area
$AreaInt$ = Crop area intercept (base year crop area)
$AreaInt2$ = Exogenous crop area growth multiplier
WF = Shadow price index of land
γ = Land demand elasticity
MRP = Marginal revenue product of land
$MRP0$ = Base year marginal revenue product of land (used to index prices)
α = Area supply elasticity
j = Activity
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.

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

where:

$AreaInt2$ = Exogenous crop area growth multiplier
$Areagr$ = Exogenous area demand growth rate
j = Activity
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 determines the land allocation and ensures that all crop area demand sums up to the total land supply for each FPU, as shown in Equation 1.

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

where:

QFS = Land supply
$Area$ = Solution for crop area
j = Activity
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 et al. 1998.

These long-run trends, or intrinsic productivity growth rates (IPRs), are intended to reflect the expected increases in inputs, improved seeds, and improvements in management practices. These intrinsic productivity growth rates are exogenous to the model, and changes in them are specified as part of the definition of different scenarios. 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. 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. The SSP scenarios assume differences in socioeconomic development, technology, and resources, associated with them, which are expected to affect the capacity and effectiveness to adapt to climate change, and can amplify or diminish the IPRs. In the yield equation (Equation 7), the differences in adaptation are captured using an exogenous scaling factor. This is distinct from different climate and water stresses associated with RCPs. Incorporation of IPRs in IMPACT is described in detail in Hareau et al. 2025. The methodology described in Hareau et al. 2025 intrinsically assumes a business-as-usual (SSP2) pathway for future socioeconomic development. To incorporate other socioeconomic futures, we scale IPRs according to differences in per-capita GDP in other socioeconomic futures (i.e., SSP1, SSP3, SSP4 and SSP5) to SSP2. For example, if SSP1 GDP per capita is $1.1\times$ that of an SSP2 scenario in a given geography, we scale the IPRs in that geography by a factor of 1.1.

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 the effects of changes in temperature and precipitation due to climate change on crop yields for rainfed and irrigated crops. This climate effect is calculated from the solution of a crop simulation model (DSSAT) for different climate change scenarios. Crop simulations with DSSAT 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.[6] This mechanism is modeled through the IMPACT water models which include:

1. 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.
3. 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.

[6] Further information on the water modelling system in IMPACT is provided in section 5.5 and Appendix E.

These yields shocks are then passed to the IMPACT model, affecting year-to-year crop yields as shown in Equation 7.

$$
\begin{aligned}
Yield_{j,fpu,lnd} = {} & YieldInt_{j,fpu,lnd} \times YieldInt2_{j,fpu,lnd} \times YieldIntB2_{fpu} \\
& \times YldShk_{j,fpu,lnd} \times YldCliShk_{j,fpu,lnd} \\
& \times \prod_{pfac} (WF_{fpu,pfac})^{YE_{j,fpu,lnd,pfac}} \\
& \times \left(\frac{PNET_{j,cty}}{PNET0_{j,cty}} \right)^{Y_{j,fpu,lnd}} \qquad \forall cty \in fpu
\end{aligned} \tag{7}
$$

where:

$Yield$	= Final yield
$YieldInt$	= Yield intercept (base year yield)
$YieldInt2$	= Exogenous yield growth multiplier
$YieldIntB2$	= Scaling factor of exogenous yield growth multiplier linked to SSPs (SSP2 = 1)
$YldShk$	= Water stress shock (from water models)
$YldCliShk$	= 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)
YE	= Yield elasticity wrt to other input prices
Y	= Yield elasticity wrt land prices
WF	= Shadow price index of land by fpu and land type
$pfac$	= Non- land and livestock production factors (wages and fertilizer)
j	= Activity
fpu	= Food production unit
lnd	= Land type (irrigated or rainfed)
cty	= Country

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[7]. 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.

[7]Shape of this adoption function can be changed, for example to a linear adoption curve, according to assumptions made in a given scenario

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

where:

$Yield$	= Final yield
$TechShare$	= Share of crop area adopting the technology
$TechYield$	= Yield from technology
j	= Activity
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.

$$QS_{j,cty} = \sum_{fpu,lnd}(Area_{j,fpu,lnd} \times Yield_{j,fpu,lnd}) \qquad \forall fpu \in cty \tag{9}$$

where:

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

4.2 Livestock production

Livestock production is modeled at the FPU level and includes animal numbers (equation 10), 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.

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

$$\begin{aligned} AnN_{jl,fpu,lvs} = AnNInt_{jl,fpu,lvs} \times AnNInt2_{jl,fpu,lvs} \\ \times \prod_{jl} \left(\frac{PNET_{jl,cty}}{PNET0_{jl,cty}} \right)^{AN_\varepsilon} \\ \times \prod_{cfeed} \left(\frac{PC_{cfeed,cty}}{PC0_{cfeed,cty}} \right)^{Feed_\varepsilon} \qquad \forall\, cty \in fpu \end{aligned} \tag{10}$$

where:

AnN	= Animal Numbers
$AnNInt$	= Animal intercept (initial number of animals)
$AnNint2$	= Exogenous population growth for animals
AN_ε	= Animal stock supply elasticity
$Feed_\varepsilon$	= 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
$cfeed$	= Livestock feed commodities i.e., $cfeed \in c$
jl	= Activity (livestock)
fpu	= Food production unit
lvs	= Livestock production system
cty	= Country

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.

$$AnY_{jl,fpu,lvs} = AnYInt_{jl,fpu,lvs} \times AnYInt2_{jl,fpu,lvs} \times YieldIntB2_{fpu} \tag{11}$$

where:

AnY	= Animal yields
$AnYInt$	= Initial animal yields
$AnYInt2$	= Exogenous yield growth
$YieldIntB2$	= Scaling factor of exogenous yield growth multiplier linked to SSPs (SSP2 = 1)
jl	= Activity (livestock)
fpu	= Food production unit
lvs	= Livestock production system

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.

$$QS_{jl,cty} = \sum_{lvs}(AnN_{jl,fpu,lvs} \times AnY_{jl,fpu,lvs}) \qquad \forall fpu \in cty \tag{12}$$

where:

QS = Production from animals
AnN = Animal numbers
AnY = Animal yields
jl = Activity (livestock)
fpu = Food production unit
lvs = Livestock production system

4.3 Production of processed goods

Modeling of processed goods allows for a general handling of all processed goods in IMPACT through input-output matrixes and the use of net prices. The input-output matrices 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.[8]. Additionally, production of aquatic foods is modeled as a supply function that takes into account endogenous price effects and exogenous technological change.

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

where:

$PNET$ = 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
ci = Commodities that are inputs for activity j
cty = Country

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

Production of processed goods is then simulated by a supply function that incorporates both endogenous price effects and exogenous technological change. As opposed to crop and livestock production, processed goods are modeled at the country level instead of at the FPU as shown in Equation 14.

$$QS_{j,cty} = QSInt_{j,cty} \times QSInt2_{j,cty} \times \prod_{jj} \left(\frac{PNET_{jj,cty}}{PNET0_{jj,cty}} \right)^{QSE_{j,jj,cty}} \tag{14}$$

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)
QSE	= Supply price elasticities
j, jj	= Activity (processed goods)
cty	= Country

Production of aquatic foods is treated similar to processed goods and is also simulated by a supply function that includes endogenous price effects. Fish production is also modeled at the country level instead of at the FPU as shown in Equation 15.

$$QS_{jfish,cty} = QSInt_{jfish,cty} \times QSInt2_{jfish,cty} \times \prod_{jjfish} \left(\frac{PNET_{jjfish,cty}}{PNET0_{jjfish,cty}} \right)^{QSE_{jfish,jjfish,cty}} \tag{15}$$

where:

QS	= Production of aquatic foods
$QSInt$	= Aquatic food activity supply intercept
$QSInt2$	= Supply multiplier for aquatic food 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)
QSE	= Supply price elasticities
$jfish, jjfish$	= Activity (aquatic foods)
cty	= Country

4.4 Commodity supply and demand

Total supply of commodities requires mapping from output of production activities to supply of commodities. The mapping is given by Equation 16.

$$QSUP_{c,cty} = \sum_{j}(JCRatio_{j,c} \times QS_{j,cty}) \tag{16}$$

where:

$QSUP$	= Total commodity supply
$JCRatio$	= Activity to commodity mapping
QS	= Total production
c	= Commodity
j	= Activity
cty	= Country

The parameter $JCRatio$ maps from the activity output to commodities. Usually, each activity produces a matched commodity (for example, wheat-growing activity produces the commodity wheat and nothing else). The specification, however, is generic, and can be extended as needed to represent many activities as 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 17, 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).

$$\begin{aligned} QD_{c,cty} = \Big[\sum_{h}(QH_{c,h,cty}) \times (1 + WasteH_{c,cty})\Big] \\ + QInterm_{c,cty} \\ + QL_{c,cty} \\ + QBF_{c,cty} \\ + QOth_{c,cty} \end{aligned} \tag{17}$$

where:

QD	=	Total commodity demand
QH	=	Household food demand
$WasteH$	=	Waste fraction in household 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	=	Country

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 socioeconomic scenarios reflected in the Shared Socio-Economic Pathway (SSP) database.

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 are 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, currently IMPACT models a single representative household per country.

$$\begin{aligned} QH_{c,h,cty} = {} & QHDint_{c,h,cty} \times QHDInt2_{c,h,cty} \\ & \times \left(\frac{pcGDP_{h,cty}}{pcGDP0_{h,cty}}\right)^{Ie_{c,h,cty}} \times \left(\frac{popH_{h,cty}}{popH0_{h,cty}}\right) \\ & \times \prod_{cc} \left(\frac{PC_{c,cty}\,(1 - CSE_{c,cty})}{PC0_{c,cty}\,(1 - CSE0_{c,cty})}\right)^{Fe_{c,cc,h,cty}} \end{aligned} \tag{18}$$

where:

QH	= Household food demand
$QHDInt$	= Initial household food demand
$QHDInt2$	= Demand adjuster for implementing change in diets
$pcGDP$	= Per capita GDP
$pcGDP0$	= Initial per capita GDP
PC	= Consumer price
$PC0$	= Initial consumer price
Ie	= Income demand elasticity
$popH$	= Household population
$popH0$	= Initial household population
$\prod_{cc \neq c} \left(\frac{PC_{c,cty} \times (1 - CSE_{c,cty})}{PC0_{c,cty} \times (1 - CSE0_{c,cty})} \right)^{F_\varepsilon}$	= Cross price response
Fe	= Household final demand price elasticties
h	= Household type (urban or rural)
c, cc	= Commodity
cty	= Country

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 19, IMPACT also incorporates a technology parameter that indicates improvements in feeding efficiencies over time.

$$\begin{aligned} QL_{cfeed,cty} = {} & QLInt_{cfeed,cty} \times QLInt2_{cfeed,cty} \\ & \times \sum_{lvs} (QS_{lvs,cty} \times FR_{lvs,cfeed,cty}) \\ & \times \prod_{cfeed} \left(\frac{PC_{cfeed,cty}}{PC0_{cfeed,cty}} \right)^{LF_{cfeed,cc,cty}} \end{aligned} \tag{19}$$

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
LF	= Livestock feed demand elasticity
PC	= Consumer price
$PC0$	= Initial consumer price
lvs	= Livestock production systems
c, cc	= Commodity
$cfeed$	= Feed commodities
cty	= Country

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 20.

$$QInterm_{c,cty} = \sum_{j}(IOMat_{c,j,cty} \times QS_{j,cty}) \tag{20}$$

where:

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

Biofuel feedstock demand (equation 21) 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.

$$QBF_{c,cty} = QBFInt_{c,cty} \times QBFInt2_{c,cty} \times \prod_{c}\left(\frac{PC_{c,cty}}{PC0_{c,cty}}\right)^{BF_{c,cc,cty}} \tag{21}$$

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
PC = Consumer price
$PC0$ = Initial consumer price
c, cc = Commodity
cty = Country

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 22 and Equation 23. The primary method follows the household food demand equation and is sensitive to changes in income, population, and prices.

$$QOth_{c,cty} = QOthInt_{c,cty} \times QOthInt2_{c,cty} \times \left(\frac{pcGDP_{cty}}{pcGDP0_{cty}}\right)^{OIe_{c,cty}} \times \left(\frac{pop_{cty}}{pop0_{cty}}\right) \times \prod_{cc=c} \left(\frac{PC_{c,cty}}{PC0_{c,cty}}\right)^{OPe_{c,cc,cty}} \tag{22}$$

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
OIe	= Income demand elasticity for other demand
OPe	= Price demand elasticity for other demand
PC	= Consumer price
$PC0$	= Initial consumer price
c, cc	= Commodity
cty	= Country

The second method is used in a few cases where other demand historically has not shown much of a response to prices (e.g., pigeon-pea in India) and is instead a function of changes in per capita GDP from the previous year ($pcGDP1$). The conditional $\Leftarrow$ accounts the combination of c and cty for which $QHD1$ exists (or not).

$$\begin{aligned} QOth_{c,cty} = QOth1_{c,cty} \times \left(\frac{\sum_h QH_{c,h,cty}}{\sum_h QHD1_{c,h,cty}}\right) \Leftarrow \sum_h QHD1_{c,h,cty} \\ +QOth1_{c,cty} \times \left(\frac{pcGDP_{cty}}{pcGDP1_{cty}}\right) \Leftarrow \sum_h QHD1_{c,h,cty} = 0 \end{aligned} \tag{23}$$

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	= Country
h	= Type of household

4.5 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 domestic and global 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.

In IMPACT, at the end of every year the world's production must equal the world's demand. This constraint is ensured by Equation 24, where the sum of net trade over the globe must equal zero.

$$\sum_{cty} NT_{c,cty} = 0 \tag{24}$$

where:

NT = Net trade of commodities
c = Commodity
cty = Country

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 25.

$$NT_{c,cty} = QSUP_{c,cty} - QD_{c,cty} - QSt_{c,cty} \tag{25}$$

where:

NT = Net trade of commodities
$QSUP$ = Total commodity supply
QD = Total commodity demand
QSt = Total change in stocks
c = Commodity
cty = Country

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. 4.1 illustrates the pricing system in IMPACT and where the appropriate price wedges are applied. Abbreviations used in Fig. 4.1 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 **Im**ports
- MME is **M**arketing **M**argins for **E**xports
- TM is **T**ariffs on **Im**ports, and,
- TE is **T**axes on **E**xports

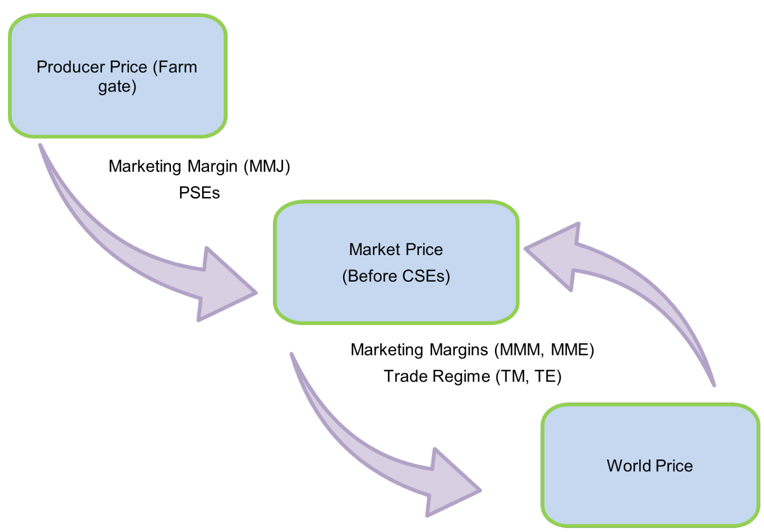

Figure 4.1: Price structure in IMPACT.

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 26.

$$PP_{j,cty} \times (1 + MMJ_{j,cty}) = (1 + PSE_{j,cty}) \times \sum_{c} (JCRatio_{j,c,cty} \times PC_{c,cty}) \tag{26}$$

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)
PC = Consumer price
j = Activity
cty = Country

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 27.

$$QSUP_{c,cty} = QD_{c,cty} \tag{27}$$

where:

$QSUP$ = Domestic supply
QD = Domestic demand
c = Commodity
cty = Country

Nontraded commodities are indirectly linked to world markets through the demand for final products (e.g., sugar), and potential substitution from tradable commodities (e.g., grass and other feeds). IMPACT 4, 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 28.

$$PM_{c,cty} = PW_c \times EXR_{cty} \times (1 + TM_{c,cty}) \times (1 + MMM_{c,cty}) \tag{28a}$$

$$PE_{c,cty} = PW_c \times EXR_{cty} \times (1 - TE_{c,cty}) \times (1 - MME_{c,cty}) \tag{28b}$$

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 = Country

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 markets[9], this inequality is not used, the domestic consumer price is set to the import price (equation 29), and the export price equation is never used.

[9]This is done for all traded commodities in IMPACT 4

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

where:

PC = Consumer price
PM = Import demand
c = Commodity
cty = Country

4.6 Activity-commodity framework

IMPACT since update to version 3 carries a full implementation of an activity-commodity framework, borrowed from the CGE literature (Lofgren et al. 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. 4.2, 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 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.

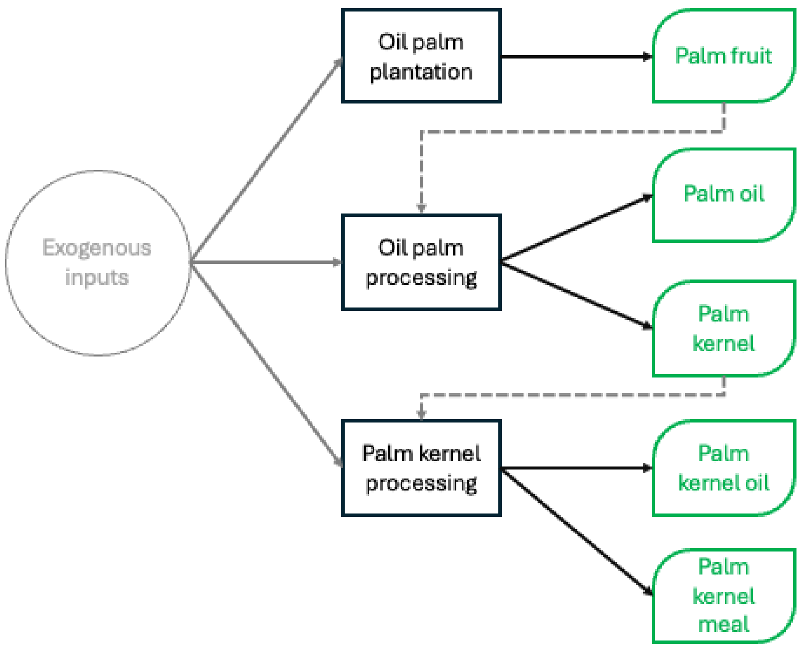

Figure 4.2: Conceptual diagram explaining the palm oil value chain in the IMPACT activity-commodity framework. Boxes in black are activities. Irregular boxes in green are commodities in IMPACT.

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.

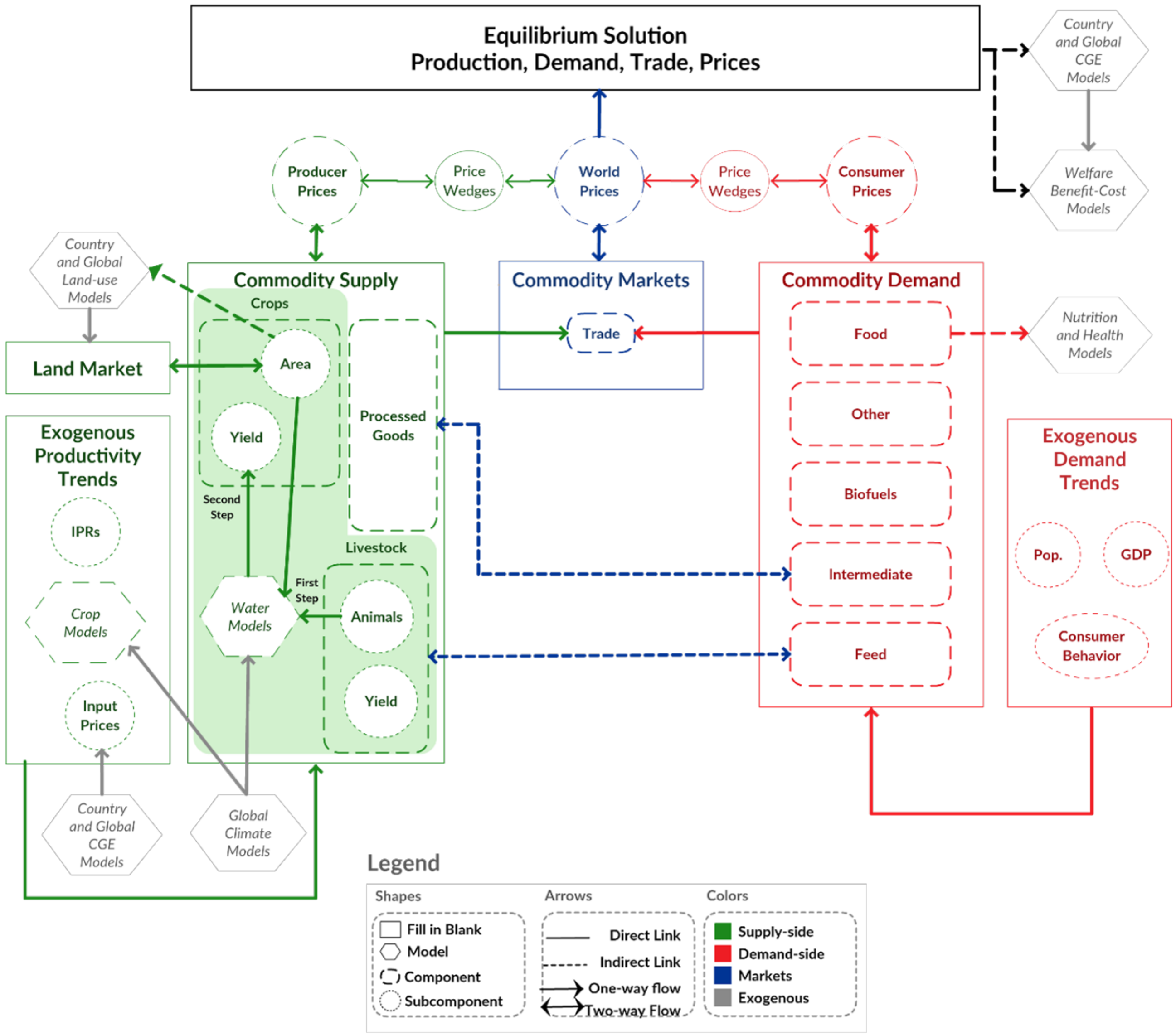

Figure 5.1: Detailed schematic of the IMPACT multimarket model. CGE = computable general equilibrium; GDP = gross domestic product; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; IPRs = intrinsic productivity growth rates.

5.1 IMPACT-GLOBE System

The IMPACT–GLOBE system is an integrated global modeling framework that combines detailed agricultural and food system modeling with broad economy-wide general equilibrium analysis to assess long-term outcomes for food security, economic development, and climate change under alternative policy and investment scenarios and assessing the macroeconomic income and welfare effects associated with the alternative pathways under different scenarios which helps feed the simulated aggregate income pathways back to IMPACT. The modeling system incorporates a link with the GLOBE global general equilibrium model, which is used to assess the economy-wide impacts of climate change and agricultural investments, including GDP, household income, and employment.

At its core, the system links IMPACT with GLOBE, a global CGE (computable general equilibrium) model that represents the entire world economy, capturing how changes in one sector (such as agriculture) propagate through markets, income, trade, and consumption across all sectors and regions (Willenbockel et al. 2018). As a CGE model, GLOBE is calibrated using a detailed Social Accounting Matrix (SAM), usually based on the GTAP data framework to ensure consistency across production, consumption, and trade flows in the global economy.

Together, the IMPACT–GLOBE system allows to capture sectoral detail and economy-wide feedback where IMPACT provides agricultural and climate sector projections while GLOBE feeds back macroeconomic effects (e.g., income changes) into the agricultural projections. This helps evaluate scenarios such as climate change, trade reforms, technological change, and policy interventions that affect food systems, natural resources, and national economies.

5.2 IMPACT data management and estimation system

The 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.
- 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.

5.3 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.

5.3.1 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.

$$\Delta UndNrsh_{t,t0} = -25.54 \times \ln \frac{kcal_t}{kcal_{t0}} - (71.76 \times \Delta LFER_{t,t0}) - (0.22 \times \Delta SCH_{t,t0}) - (0.08 \times \Delta WAT_{t,t0}) \quad (30)$$

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

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 30, with the population of children (0–5 years old) coming from the appropriate SSP scenario (IIASA 2024).

5.3.2 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. 2005 [10].

$$ShrRisk_{cty,t} = \beta_0 + (\beta_1 \times rKcal_{cty,t}) + (\beta_2 \times rKcal^2_{cty,t}) + \varepsilon \tag{31}$$

where:

$ShrRisk$ = Share of population at risk of hunger
$rKcal$ = Ratio of available kilocalories over minimum kilocalories
β_0 = Constant term (288.1)
β_1 = -319.7
β_2 = 89.7
ε = Estimation error
cty = Countries
t = 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

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

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.

5.4 Crop models[11]

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 (SPAM) 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.

[11] Crop models are further discussed in Appendix D (Crop models).

5.5 Water models[12]

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.

5.5.1 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 FPUs 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

[12] Water models are further discussed in Appendix E (Water models).

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.

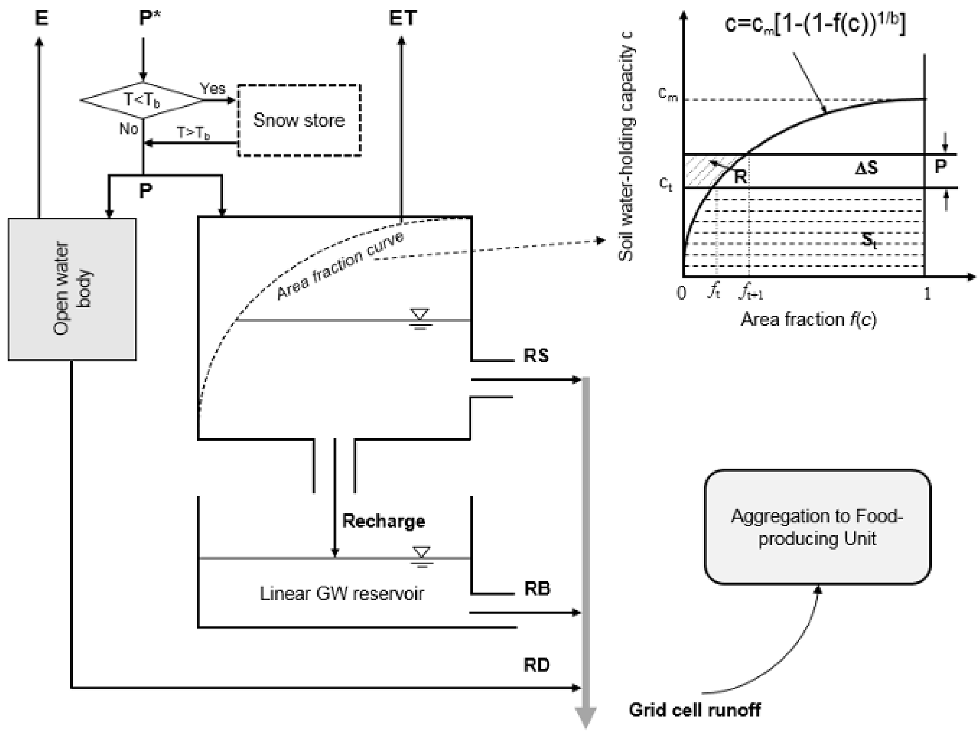

Figure 5.2: IMPACT global hydrology model schematic illustrating vertical water balance of the land and open water fraction of a grid cell. E = evaporation (millimeters per month [mm/m]); ET = evapotranspiration (mm/m); GW = groundwater; $IMPACT$ = International Model for Policy Analysis of Agricultural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

5.5.2 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 (de Fraiture 2007; Rosegrant et al. 2002). These elasticities of demand measure the propensity to consume water with respect to increases in per capita income. The elasticities also capture both direct income effects and conservation of domestic water use through technological and management change. Livestock water demand is proportional to the number of animals raised as calculated by the multimarket model.

Water supply

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

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

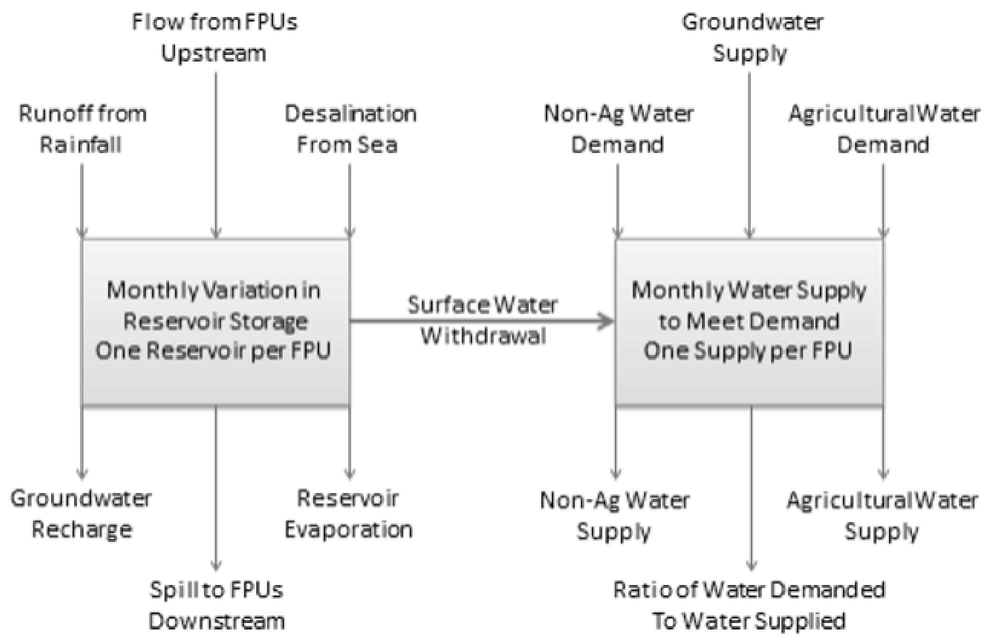

Figure 5.3: IMPACT water basin simulation model. FPU = food production unit; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; Non-Ag = nonagricultural

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.

5.5.3 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.

5.5.4 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 FPUs given the objective function described above.

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

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

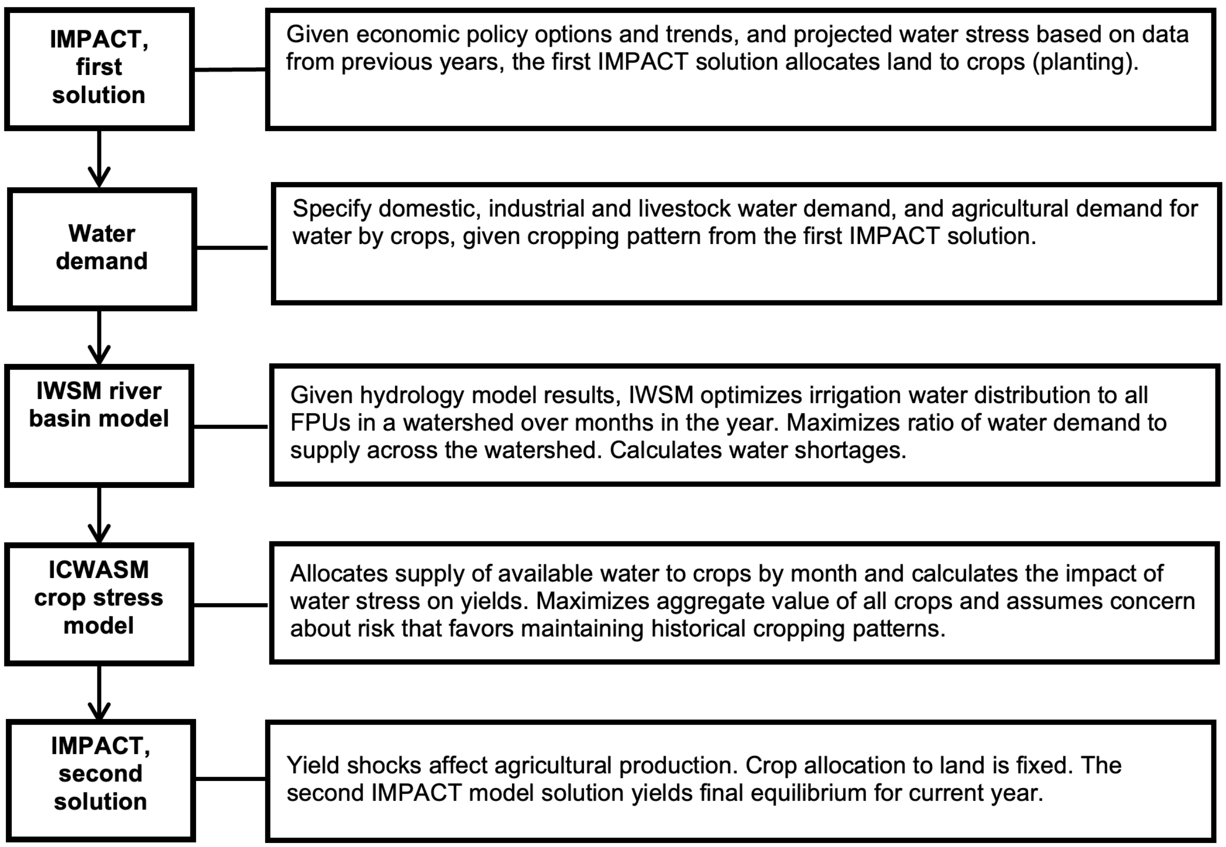

Figure 5.4: Linking IMPACT to water models: Dynamic two-way communication year by year. FPUs = food production units; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; IWSM = IMPACT water basin simulation model; ICWASM = IMPACT crop water allocation and stress model.

6 Summary

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 4 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 / Region code (IMPACT)**	**Country name (FAO)**	**Country / Region name (IMPACT)**
2	AFG	Afghanistan	Afghanistan
3	ALB	Albania	Albania
4	DZA	Algeria	Algeria
5	OPO	American Samoa	Other Pacific Ocean
7	AGO	Angola	Angola
8	CRB	Antigua and Barbuda	Other Caribbean
9	ARG	Argentina	Argentina
1	ARM	Armenia	Armenia
22	CRB	Aruba	Other Caribbean
10	AUS	Australia	Australia
11	AUT	Austria	Austria
52	AZE	Azerbaijan	Azerbaijan
12	CRB	Bahamas	Other Caribbean
13	RAP	Bahrain	Rest of Arab Peninsula
16	BGD	Bangladesh	Bangladesh
14	CRB	Barbados	Other Caribbean
57	BLR	Belarus	Belarus
255	BLX	Belgium	Belgium-Luxembourg
23	BLZ	Belize	Belize

Table A1 continued from previous page

FAO country code	Country / Region code (IMPACT)	Country name (FAO)	Country / Region name (IMPACT)
53	BEN	Benin	Benin
17	OAO	Bermuda	Other Atlantic Ocean
18	BTN	Bhutan	Bhutan
19	BOL	Bolivia	Bolivia
80	OBN	Bosnia and Herzegovina	Other Balkans
20	BWA	Botswana	Botswana
21	BRA	Brazil	Brazil
239	CRB	British Virgin Islands	Other Caribbean
26	OSA	Brunei	Other Southeast Asia
27	BGR	Bulgaria	Bulgaria
233	BFA	Burkina Faso	Burkina Faso
29	BDI	Burundi	Burundi
115	KHM	Cambodia	Cambodia
32	CMR	Cameroon	Cameroon
33	CAN	Canada	Canada
35	OAO	Cape Verde	Other Atlantic Ocean
36	CRB	Cayman Islands	Other Caribbean
37	CAF	Central African Republic	Central African Republic
39	TCD	Chad	Chad
40	CHL	Chile	Chile

Table A1 continued from previous page

FAO country code	Country / Region code (IMPACT)	Country name (FAO)	Country / Region name (IMPACT)
351	CHM	China	China, Hong Kong, Macao and Taiwan
44	COL	Colombia	Colombia
45	OIO	Comoros	Other Indian Ocean
47	OPO	Cook Islands	Other Pacific Ocean
48	CRI	Costa Rica	Costa Rica
107	CIV	Cote d'Ivoire	Ivory Coast
98	HRV	Croatia	Croatia
49	CUB	Cuba	Cuba
50	CYP	Cyprus	Cyprus
167	CZE	Czech Republic	Czech Republic
250	COD	Democratic Republic of the Congo	Democratic Republic of Congo
54	DNK	Denmark	Denmark
72	DJI	Djibouti	Djibouti
55	CRB	Dominica	Other Caribbean
56	DOM	Dominican Republic	Dominican Republic
176	TLS	East Timor	Timor-L'este
58	ECU	Ecuador	Ecuador
59	EGY	Egypt	Egypt
60	SLV	El Salvador	El Salvador
61	GNQ	Equatorial Guinea	Equatorial Guinea

Table A1 continued from previous page

FAO country code	Country / Region code (IMPACT)	Country name (FAO)	Country / Region name (IMPACT)
178	ERI	Eritrea	Eritrea
63	BLT	Estonia	Baltic States
238	ETH	Ethiopia	Ethiopia
65	OAO	Falkland Islands	Other Atlantic Ocean
64	UKP	Faroe Islands	Great Britain and nearby protectorates
66	FJI	Fiji	Fiji
67	FNP	Finland	Finland Plus
68	FRP	France	France plus
69	GSA	French Guiana	Guyanas South America
70	OPO	French Polynesia	Other Pacific Ocean
74	GAB	Gabon	Gabon
75	GMB	Gambia	Gambia
73	GEO	Georgia	Georgia
79	DEU	Germany	Germany
81	GHA	Ghana	Ghana
84	GRC	Greece	Greece
85	GRL	Greenland	Greenland
86	CRB	Grenada	Other Caribbean
87	CRB	Guadeloupe	Other Caribbean
88	OPO	Guam	Other Pacific Ocean

Table A1 continued from previous page

FAO country code	Country / Region code (IMPACT)	Country name (FAO)	Country / Region name (IMPACT)
89	GTM	Guatemala	Guatemala
90	GIN	Guinea	Guinea
175	GNB	Guinea-Bissau	Guinea-Bissau
91	GSA	Guyana	Guyanas South America
93	HTI	Haiti	Haiti
95	HND	Honduras	Honduras
97	HUN	Hungary	Hungary
99	ISL	Iceland	Iceland
100	IND	India	India
101	IDN	Indonesia	Indonesia
102	IRN	Iran	Iran
103	IRQ	Iraq	Iraq
104	IRL	Ireland	Ireland
105	ISR	Israel	Israel
106	ITP	Italy	Italy plus
109	JAM	Jamaica	Jamaica
110	JPN	Japan	Japan
112	JOR	Jordan	Jordan
108	KAZ	Kazakhstan	Kazakhstan
114	KEN	Kenya	Kenya

Table A1 continued from previous page

FAO country code	Country / Region code (IMPACT)	Country name (FAO)	Country / Region name (IMPACT)
83	OPO	Kiribati	Other Pacific Ocean
118	RAP	Kuwait	Rest of Arab Peninsula
113	KGZ	Kyrgyzstan	Kyrgyzstan
120	LAO	Lao People's Democratic Republic	Laos
119	BLT	Latvia	Baltic States
121	LBN	Lebanon	Lebanon
122	LSO	Lesotho	Lesotho
123	LBR	Liberia	Liberia
124	LBY	Libya	Libya
125	CHP	Liechtenstein	Switzerland plus
126	BLT	Lithuania	Baltic States
256	BLX	Luxembourg	Belgium-Luxembourg
129	MDG	Madagascar	Madagascar
130	MWI	Malawi	Malawi
131	MYS	Malaysia	Malaysia
132	OIO	Maldives	Other Indian Ocean
133	MLI	Mali	Mali
134	ITP	Malta	Italy plus
127	OPO	Marshall Islands	Other Pacific Ocean
135	CRB	Martinique	Other Caribbean

Table A1 continued from previous page

FAO country code	Country / Region code (IMPACT)	Country name (FAO)	Country / Region name (IMPACT)
136	MRT	Mauritania	Mauritania
137	OIO	Mauritius	Other Indian Ocean
138	MEX	Mexico	Mexico
145	OPO	Micronesia	Other Pacific Ocean
146	MDA	Moldova	Moldova
141	MNG	Mongolia	Mongolia
273	OBN	Montenegro	Other Balkans
142	CRB	Montserrat	Other Caribbean
143	MOR	Morocco	Morocco
144	MOZ	Mozambique	Mozambique
28	MMR	Myanmar	Myanmar
147	NAM	Namibia	Namibia
148	OPO	Nauru	Other Pacific Ocean
149	NPL	Nepal	Nepal
150	NLD	Netherlands	Netherlands
151	CRB	Netherlands Antilles	Other Caribbean
153	OPO	New Caledonia	Other Pacific Ocean
156	NZL	New Zealand	New Zealand
157	NIC	Nicaragua	Nicaragua
158	NER	Niger	Niger

Table A1 continued from previous page

FAO country code	Country / Region code (IMPACT)	Country name (FAO)	Country / Region name (IMPACT)
159	NGA	Nigeria	Nigeria
160	OPO	Niue	Other Pacific Ocean
161	OPO	Norfolk Island	Other Pacific Ocean
116	PRK	North Korea	North Korea
154	OBN	North Macedonia	Other Balkans
162	NOR	Norway	Norway
221	RAP	Oman	Rest of Arab Peninsula
165	PAK	Pakistan	Pakistan
299	PSE	Palestine	Occupied Palestinian Territory
166	PAN	Panama	Panama
168	PNG	Papua New Guinea	Papua New Guinea
169	PRY	Paraguay	Paraguay
170	PER	Peru	Peru
171	PHL	Philippines	Philippines
173	POL	Poland	Poland
174	PRT	Portugal	Portugal
177	CRB	Puerto Rico	Other Caribbean
179	RAP	Qatar	Rest of Arab Peninsula
46	COG	Republic of Congo	Congo
183	ROU	Romania	Romania

Table A1 continued from previous page

FAO country code	Country / Region code (IMPACT)	Country name (FAO)	Country / Region name (IMPACT)
185	RUS	Russia	Russia
184	RWA	Rwanda	Rwanda
187	OAO	Saint Helena	Other Atlantic Ocean
188	CRB	Saint Kitts and Nevis	Other Caribbean
189	CRB	Saint Lucia	Other Caribbean
190	OAO	Saint Pierre and Miquelon	Other Atlantic Ocean
244	OPO	Samoa	Other Pacific Ocean
193	OAO	Sao Tome and Principe	Other Atlantic Ocean
194	SAU	Saudi Arabia	Saudi Arabia
195	SEN	Senegal	Senegal
272	OBN	Serbia	Other Balkans
196	OIO	Seychelles	Other Indian Ocean
197	SLE	Sierra Leone	Sierra Leone
200	OSA	Singapore	Other Southeast Asia
199	SVK	Slovakia	Slovakia
198	SVN	Slovenia	Slovenia
25	SLB	Solomon Islands	Solomon Islands
201	SOM	Somalia	Somalia
202	ZAF	South Africa	South Africa
117	KOR	South Korea	South Korea

Table A1 continued from previous page

FAO country code	Country / Region code (IMPACT)	Country name (FAO)	Country / Region name (IMPACT)
203	SPP	Spain	Spain plus
38	LKA	Sri Lanka	Sri Lanka
206	SDN	Sudan	Sudan
207	GSA	Suriname	Guyanas South America
209	SWZ	Swaziland	Swaziland
210	SWE	Sweden	Sweden
211	CHP	Switzerland	Switzerland plus
212	SYR	Syria	Syria
208	TJK	Tajikistan	Tajikistan
215	TZA	Tanzania	Tanzania
216	THA	Thailand	Thailand
217	TGO	Togo	Togo
218	OPO	Tokelau	Other Pacific Ocean
219	OPO	Tonga	Other Pacific Ocean
220	CRB	Trinidad and Tobago	Other Caribbean
222	TUN	Tunisia	Tunisia
223	TUR	Turkey	Turkey
213	TKM	Turkmenistan	Turkmenistan
227	OPO	Tuvalu	Other Pacific Ocean
226	UGA	Uganda	Uganda

Table A1 continued from previous page

FAO country code	Country / Region code (IMPACT)	Country name (FAO)	Country / Region name (IMPACT)
230	UKR	Ukraine	Ukraine
225	RAP	United Arab Emirates	Rest of Arab Peninsula
229	UKP	United Kingdom	Great Britain and nearby protectorates
231	USA	United States	United States
234	URY	Uruguay	Uruguay
240	CRB	US Virgin Islands	Other Caribbean
235	UZB	Uzbekistan	Uzbekistan
155	VUT	Vanuatu	Vanuatu
236	VEN	Venezuela	Venezuela
237	VNM	Vietnam	Vietnam
205	MOR	Western Sahara	Morocco
249	YEM	Yemen	Yemen
251	ZMB	Zambia	Zambia
181	ZWE	Zimbabwe	Zimbabwe

Table A2: List of FPUs in IMPACT

FPU	IMPACT country code	Basin name	IMPACT country or region
AMD_AFG	AFG	Amu	Afghanistan
WAI_AFG	AFG	Western	Afghanistan
ALB_ALB	ALB	Albania	Albania
NAC_DZA	DZA	North	Algeria
SAH_DZA	DZA	Sahara	Algeria
CAF_AGO	AGO	Central	Angola
CON_AGO	AGO	Congo	Angola
ZAM_AGO	AGO	Zambezi	Angola
PAR_ARG	ARG	Parana	Argentina
RIC_ARG	ARG	Rio	Argentina
SAL_ARG	ARG	Salada	Argentina
TIE_ARG	ARG	Tierra	Argentina
ARM_ARM	ARM	Armenia	Armenia
CAU_AUS	AUS	Central	Australia
EAU_AUS	AUS	Eastern	Australia
MAU_AUS	AUS	Murray	Australia
WAU_AUS	AUS	Western	Australia
DAN_AUT	AUT	Danube	Austria
AZE_AZE	AZE	Azerbiajan	Azerbaijan
BAL_BLT	BLT	Baltic	Baltic States
BRT_BGD	BGD	Brahmaputra	Bangladesh
GAN_BGD	BGD	Ganges	Bangladesh
TMM_BGD	BGD	Thai	Bangladesh
DNI_BLR	BLR	Dnieper	Belarus
RHI_BLX	BLX	Rhine	Belgium-Luxembourg
BLZ_BLZ	BLZ	Belize	Belize
NIG_BEN	BEN	Niger	Benin
VOT_BEN	BEN	Volta	Benin
BRT_BTN	BTN	Brahmaputra	Bhutan
AMA_BOL	BOL	Amazon	Bolivia

Table A2 continued from previous page

FPU	IMPACT country code	Basin name	IMPACT country or region
PAR_BOL	BOL	Parana	Bolivia
KAL_BWA	BWA	Kalahari	Botswana
LIM_BWA	BWA	Limpopo	Botswana
ZAM_BWA	BWA	Zambezi	Botswana
AMA_BRA	BRA	Amazon	Brazil
NEB_BRA	BRA	Northeast	Brazil
PAR_BRA	BRA	Parana	Brazil
SAN_BRA	BRA	San	Brazil
TOC_BRA	BRA	Toc	Brazil
URU_BRA	BRA	Uruguay	Brazil
DAN_BGR	BGR	Danube	Bulgaria
NIG_BFA	BFA	Niger	Burkina Faso
VOT_BFA	BFA	Volta	Burkina Faso
EAC_BDI	BDI	East	Burundi
MEK_KHM	KHM	Mekong	Cambodia
CAF_CMR	CMR	Central	Cameroon
LCB_CMR	CMR	Lake	Cameroon
NIG_CMR	CMR	Niger	Cameroon
CAN_CAN	CAN	Canadian	Canada
COB_CAN	CAN	Columbia	Canada
GLA_CAN	CAN	Great	Canada
MCK_CAN	CAN	Mackenzie	Canada
RWI_CAN	CAN	Red	Canada
CAF_CAF	CAF	Central	Central African Republic
CON_CAF	CAF	Congo	Central African Republic
LCB_CAF	CAF	Lake	Central African Republic
LCB_TCD	TCD	Lake	Chad
NIG_TCD	TCD	Niger	Chad
SAH_TCD	TCD	Sahara	Chad
CHC_CHL	CHL	Chilean	Chile

Table A2 continued from previous page

FPU	IMPACT country code	Basin name	IMPACT country or region
AMR_CHM	CHM	Amur	China Plus
BRT_CHM	CHM	Brahmaputra	China Plus
CHJ_CHM	CHM	Chang	China Plus
GAN_CHM	CHM	Ganges	China Plus
HAI_CHM	CHM	Hail	China Plus
HUA_CHM	CHM	Hual	China Plus
HUN_CHM	CHM	Huang	China Plus
IND_CHM	CHM	Indus	China Plus
LAJ_CHM	CHM	Langcang	China Plus
LMO_CHM	CHM	Lower	China Plus
OBB_CHM	CHM	Ob	China Plus
SON_CHM	CHM	Songhua	China Plus
TWN_CHM	CHM	Tawain	China Plus
YHE_CHM	CHM	Yili	China Plus
YRD_CHM	CHM	Yuan	China Plus
ZHJ_CHM	CHM	Zhu	China Plus
AMA_COL	COL	Amazon	Colombia
NWS_COL	COL	Northwest	Colombia
ORI_COL	COL	Orinoco	Colombia
CAF_COG	COG	Central	Congo
CON_COG	COG	Congo	Congo
CRI_CRI	CRI	Costa	Costa Rica
DAN_HRV	HRV	Danube	Croatia
CUB_CUB	CUB	Cuba	Cuba
EME_CYP	CYP	Eastern	Cyprus
DAN_CZE	CZE	Danube	Czech Republic
CON_COD	COD	Congo	Democratic Republic of Congo
EAC_COD	COD	East	Democratic Republic of Congo
ZAM_COD	COD	Zambezi	Democratic Republic of Congo
ELB_DNK	DNK	Elbe	Denmark

Table A2 continued from previous page

FPU	IMPACT country code	Basin name	IMPACT country or region
NLL_DJI	DJI	Nile	Djibouti
DOM_DOM	DOM	Dominican	Dominican Republic
AMA_ECU	ECU	Amazon	Ecuador
NWS_ECU	ECU	Northwest	Ecuador
EME_EGY	EGY	Eastern	Egypt
NAC_EGY	EGY	North	Egypt
NLL_EGY	EGY	Nile	Egypt
SAH_EGY	EGY	Sahara	Egypt
SLV_SLV	SLV	El	El Salvador
CAF_GNQ	GNQ	Central	Equatorial Guinea
NLL_ERI	ERI	Nile	Eritrea
HOA_ETH	ETH	Horn	Ethiopia
NLL_ETH	ETH	Nile	Ethiopia
FJI_FJI	FJI	Fiji	Fiji
FNP_FNP	FNP	Finland	Finland Plus
LBO_FRP	FRP	Loire	France plus
RHI_FRP	FRP	Rhine	France plus
RHO_FRP	FRP	Rhone	France plus
SEI_FRP	FRP	Seine	France plus
CAF_GAB	GAB	Central	Gabon
WAC_GMB	GMB	West	Gambia
GEO_GEO	GEO	Georgia	Georgia
DAN_DEU	DEU	Danube	Germany
ELB_DEU	DEU	Elbe	Germany
ODE_DEU	DEU	Oder	Germany
RHI_DEU	DEU	Rhine	Germany
VOT_GHA	GHA	Volta	Ghana
UKP_UKP	UKP	Great	Great Britain plus
GRC_GRC	GRC	Greece	Greece
GRL_GRL	GRL	Greenland	Greenland

Table A2 continued from previous page

FPU	IMPACT country code	Basin name	IMPACT country or region
GTM_GTM	GTM	Guatemala	Guatemala
NIG_GIN	GIN	Niger	Guinea
SEN_GIN	GIN	Senegal	Guinea
WAC_GIN	GIN	West	Guinea
WAC_GNB	GNB	West	Guinea-Bissau
GSA_GSA	GSA	Guyanas	Guyanas South America
HTI_HTI	HTI	Haiti	Haiti
HND_HND	HND	Honduras	Honduras
DAN_HUN	HUN	Danube	Hungary
ISL_ISL	ISL	Israel	Iceland
BRT_IND	IND	Brahmaputra	India
CAV_IND	IND	Cauvery	India
CHO_IND	IND	Chota	India
EGH_IND	IND	Easten	India
GAN_IND	IND	Ganges	India
GOD_IND	IND	Godavari	India
IEC_IND	IND	India	India
IND_IND	IND	Indus	India
KRI_IND	IND	Krishna	India
LUN_IND	IND	Luni	India
MAT_IND	IND	Mahi	India
MHN_IND	IND	Mahanadi	India
SAY_IND	IND	Sahyada	India
BOR_IDN	IDN	Borneo	Indonesia
INE_IDN	IDN	Indonesia	Indonesia
INW_IDN	IDN	Indonesia	Indonesia
TIG_IRN	IRN	Tigris	Iran
WAI_IRN	IRN	Western	Iran
ARA_IRQ	IRQ	Arabian	Iraq
TIG_IRQ	IRQ	Tigris	Iraq

Table A2 continued from previous page

FPU	IMPACT country code	Basin name	IMPACT country or region
IRL_IRL	IRL	Ireland	Ireland
EME_ISR	ISR	Eastern	Israel
ITA_ITP	ITP	Italy	Italy plus
NIG_CIV	CIV	Niger	Ivory Coast
VOT_CIV	CIV	Volta	Ivory Coast
WAC_CIV	CIV	West	Ivory Coast
JAM_JAM	JAM	Jamaica	Jamaica
JAP_JPN	JPN	Japan	Japan
EME_JOR	JOR	Eastern	Jordan
CHU_KAZ	KAZ	Chu	Kazakhstan
LBA_KAZ	KAZ	Lake	Kazakhstan
LTZ_KAZ	KAZ	Lake	Kazakhstan
OBB_KAZ	KAZ	Ob	Kazakhstan
SYD_KAZ	KAZ	Syr	Kazakhstan
URA_KAZ	KAZ	Ural	Kazakhstan
HOA_KEN	KEN	Horn	Kenya
CHU_KGZ	KGZ	Chu	Kyrgyzstan
SYD_KGZ	KGZ	Syr	Kyrgyzstan
MEK_LAO	LAO	Mekong	Laos
EME_LBN	LBN	Eastern	Lebanon
ORA_LSO	LSO	Orange	Lesotho
WAC_LBR	LBR	West	Liberia
NAC_LBY	LBY	North	Libya
SAH_LBY	LBY	Sahara	Libya
MAD_MDG	MDG	Madagascar	Madagascar
ZAM_MWI	MWI	Zambezi	Malawi
BOR_MYS	MYS	Borneo	Malaysia
TMM_MYS	MYS	Thai	Malaysia
NIG_MLI	MLI	Niger	Mali
SAH_MLI	MLI	Sahara	Mali

Table A2 continued from previous page

FPU	IMPACT country code	Basin name	IMPACT country or region
SEN_MLI	MLI	Senegal	Mali
VOT_MLI	MLI	Volta	Mali
NWA_MRT	MRT	Northwest	Mauritania
SAH_MRT	MRT	Sahara	Mauritania
SEN_MRT	MRT	Senegal	Mauritania
MIM_MEX	MEX	Middle	Mexico
RIG_MEX	MEX	Rio	Mexico
UME_MEX	MEX	Upper	Mexico
YUC_MEX	MEX	Yucatan	Mexico
DAN_MDA	MDA	Danube	Moldova
LMO_MNG	MNG	Lower	Mongolia
UMO_MNG	MNG	Upper	Mongolia
NWA_MOR	MOR	Northwest	Morocco
SAH_MOR	MOR	Sahara	Morocco
LIM_MOZ	MOZ	Limpopo	Mozambique
SAF_MOZ	MOZ	Southeast	Mozambique
ZAM_MOZ	MOZ	Zambezi	Mozambique
MEK_MMR	MMR	Mekong	Myanmar
TMM_MMR	MMR	Thai	Myanmar
CAF_NAM	NAM	Central	Namibia
KAL_NAM	NAM	Kalahari	Namibia
ORA_NAM	NAM	Orange	Namibia
ZAM_NAM	NAM	Zambezi	Namibia
GAN_NPL	NPL	Ganges	Nepal
RHI_NLD	NLD	Rhine	Netherlands
NZE_NZL	NZL	New	New Zealand
NIC_NIC	NIC	Nicaruagua	Nicaragua
LCB_NER	NER	Lake	Niger
NIG_NER	NER	Niger	Niger
SAH_NER	NER	Sahara	Niger

Table A2 continued from previous page

FPU	IMPACT country code	Basin name	IMPACT country or region
LCB_NGA	NGA	Lake	Nigeria
NIG_NGA	NGA	Niger	Nigeria
NKP_PRK	PRK	North	North Korea
NOR_NOR	NOR	Norway	Norway
EME_PSE	PSE	Eastern	Occupied Palestinian Territory
OAO_OAO	OAO	Other	Other Atlantic Ocean
DAN_OBN	OBN	Danube	Other Balkans
CRB_CRB	CRB	Other	Other Caribbean
OIO_OIO	OIO	Other	Other Indian Ocean
OPO_OPO	OPO	Other	Other Pacific Ocean
TMM_OSA	OSA	Thai	Other Southeast Asia
IND_PAK	PAK	Indus	Pakistan
WAI_PAK	PAK	Western	Pakistan
PAN_PAN	PAN	Panama	Panama
PAO_PNG	PNG	Papau	Papua New Guinea
PAR_PRY	PRY	Parana	Paraguay
AMA_PER	PER	Amazon	Peru
PEC_PER	PER	Peru	Peru
PHI_PHL	PHL	Philippines	Philippines
ODE_POL	POL	Oder	Poland
PRT_PRT	PRT	Portugal	Portugal
RAP_RAP	RAP	Rest	Rest of Arab Peninsula
DAN_ROU	ROU	Danube	Romania
AMR_RUS	RUS	Amur	Russia
BAL_RUS	RUS	Baltic	Russia
BLA_RUS	RUS	Black	Russia
DNI_RUS	RUS	Dnieper	Russia
NER_RUS	RUS	North	Russia
OBB_RUS	RUS	Ob	Russia
ODE_RUS	RUS	Oder	Russia

Table A2 continued from previous page

FPU	IMPACT country code	Basin name	IMPACT country or region
RRS_RUS	RUS	Rest	Russia
UMO_RUS	RUS	Upper	Russia
URA_RUS	RUS	Ural	Russia
VOG_RUS	RUS	Volga	Russia
YEN_RUS	RUS	Yenisey	Russia
EAC_RWA	RWA	East	Rwanda
SAU_SAU	SAU	Saudi	Saudi Arabia
SEN_SEN	SEN	Senegal	Senegal
WAC_SEN	SEN	West	Senegal
WAC_SLE	SLE	West	Sierra Leone
DAN_SVK	SVK	Danube	Slovakia
DAN_SVN	SVN	Danube	Slovenia
SLB_SLB	SLB	Solomon	Solomon Islands
HOA_SOM	SOM	Horn	Somalia
KAL_ZAF	ZAF	Kalahari	South Africa
LIM_ZAF	ZAF	Limpopo	South Africa
ORA_ZAF	ZAF	Orange	South Africa
SAC_ZAF	ZAF	South	South Africa
SKP_KOR	KOR	South	South Korea
NLL_SSD	SSD	Nile	South Sudan
SPP_SPP	SPP	Spain	Spain plus
SRL_LKA	LKA	Sri	Sri Lanka
NLL_SDN	SDN	Nile	Sudan
SAH_SDN	SDN	Sahara	Sudan
SAC_SWZ	SWZ	South	Swaziland
SWE_SWE	SWE	Sweden	Sweden
RHI_CHP	CHP	Rhine	Switzerland plus
EME_SYR	SYR	Eastern	Syria
TIG_SYR	SYR	Tigris	Syria
AMD_TJK	TJK	Amu	Tajikistan

Table A2 continued from previous page

FPU	IMPACT country code	Basin name	IMPACT country or region
SYD_TJK	TJK	Syr	Tajikistan
EAC_TZA	TZA	East	Tanzania
SAF_TZA	TZA	Southeast	Tanzania
ZAM_TZA	TZA	Zambezi	Tanzania
MEK_THA	THA	Mekong	Thailand
TMM_THA	THA	Thai	Thailand
TLS_TLS	TLS	Timor	Timor-L'este
VOT_TGO	TGO	Volta	Togo
NAC_TUN	TUN	North	Tunisia
BLA_TUR	TUR	Black	Turkey
DAN_TUR	TUR	Danube	Turkey
EME_TUR	TUR	Eastern	Turkey
TIG_TUR	TUR	Tigris	Turkey
AMD_TKM	TKM	Amu	Turkmenistan
URA_TKM	TKM	Ural	Turkmenistan
WAI_TKM	TKM	Western	Turkmenistan
NLL_UGA	UGA	Nile	Uganda
BLA_UKR	UKR	Black	Ukraine
DAN_UKR	UKR	Danube	Ukraine
DNI_UKR	UKR	Dnieper	Ukraine
ALK_USA	USA	Alaska	United States
ARK_USA	USA	Arkansas	United States
CAL_USA	USA	California	United States
COB_USA	USA	Columbia	United States
COL_USA	USA	Colorado	United States
GBA_USA	USA	Great	United States
GLA_USA	USA	Great	United States
HWI_USA	USA	Hawaii	United States
MIS_USA	USA	Mississippi	United States
MOU_USA	USA	Missouri	United States

Table A2 continued from previous page

FPU	IMPACT country code	Basin name	IMPACT country or region
OHI_USA	USA	Ohio	United States
RIG_USA	USA	Rio	United States
RWI_USA	USA	Red	United States
SEU_USA	USA	Southeast	United States
USN_USA	USA	US	United States
WGM_USA	USA	Western	United States
URU_URY	URY	Uruguay	Uruguay
AMD_UZB	UZB	Amu	Uzbekistan
SYD_UZB	UZB	Syr	Uzbekistan
VUT_VUT	VUT	Vanuatu	Vanuatu
ORI_VEN	VEN	Orinoco	Venezuela
RVE_VEN	VEN	Rest	Venezuela
MEK_VNM	VNM	Mekong	Vietnam
RVN_VNM	VNM	Rest	Vietnam
YRD_VNM	VNM	Yuan	Vietnam
YEM_YEM	YEM	Yemen	Yemen
ZAM_ZMB	ZMB	Zambezi	Zambia
LIM_ZWE	ZWE	Limpopo	Zimbabwe
SAF_ZWE	ZWE	Southeast	Zimbabwe
ZAM_ZWE	ZWE	Zambezi	Zimbabwe

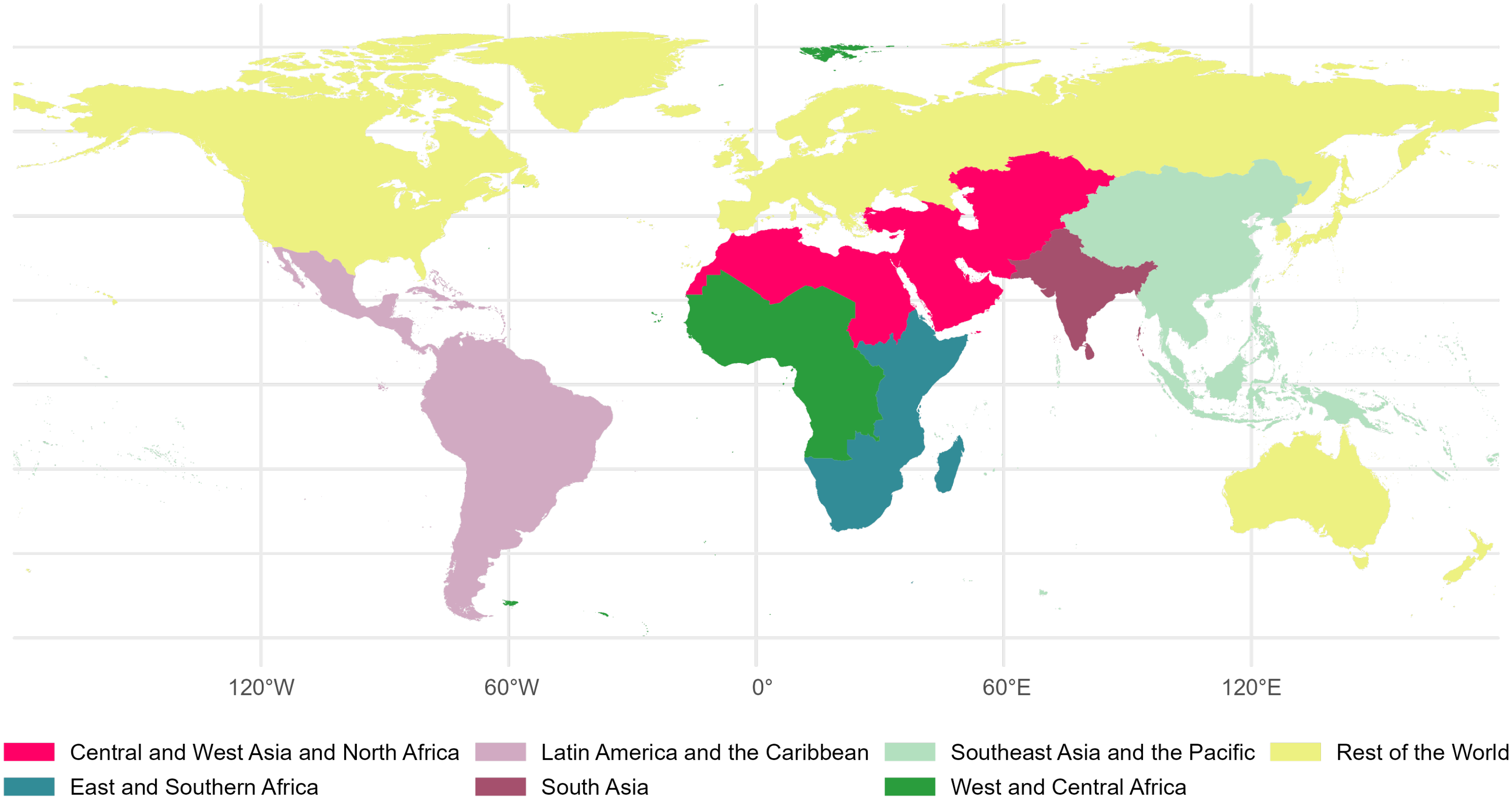

Figure A1: Map of CGIAR regions. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in CGIAR regional definitions. See cgiar.org/research/cgiar-regions for more details and description of CGIAR regions.

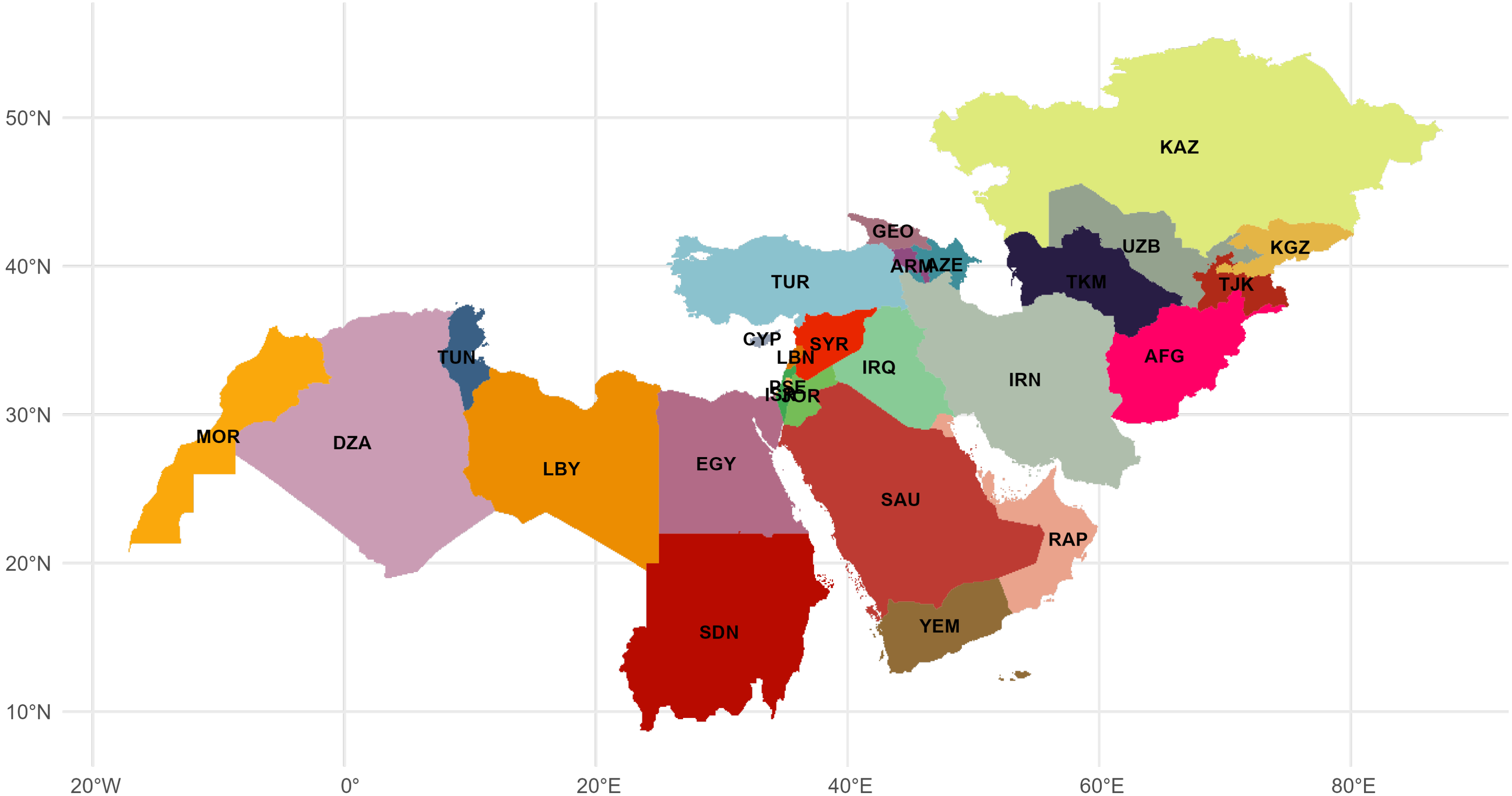

Figure A2: Map of countries/regions in Central and West Asia and North Africa. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

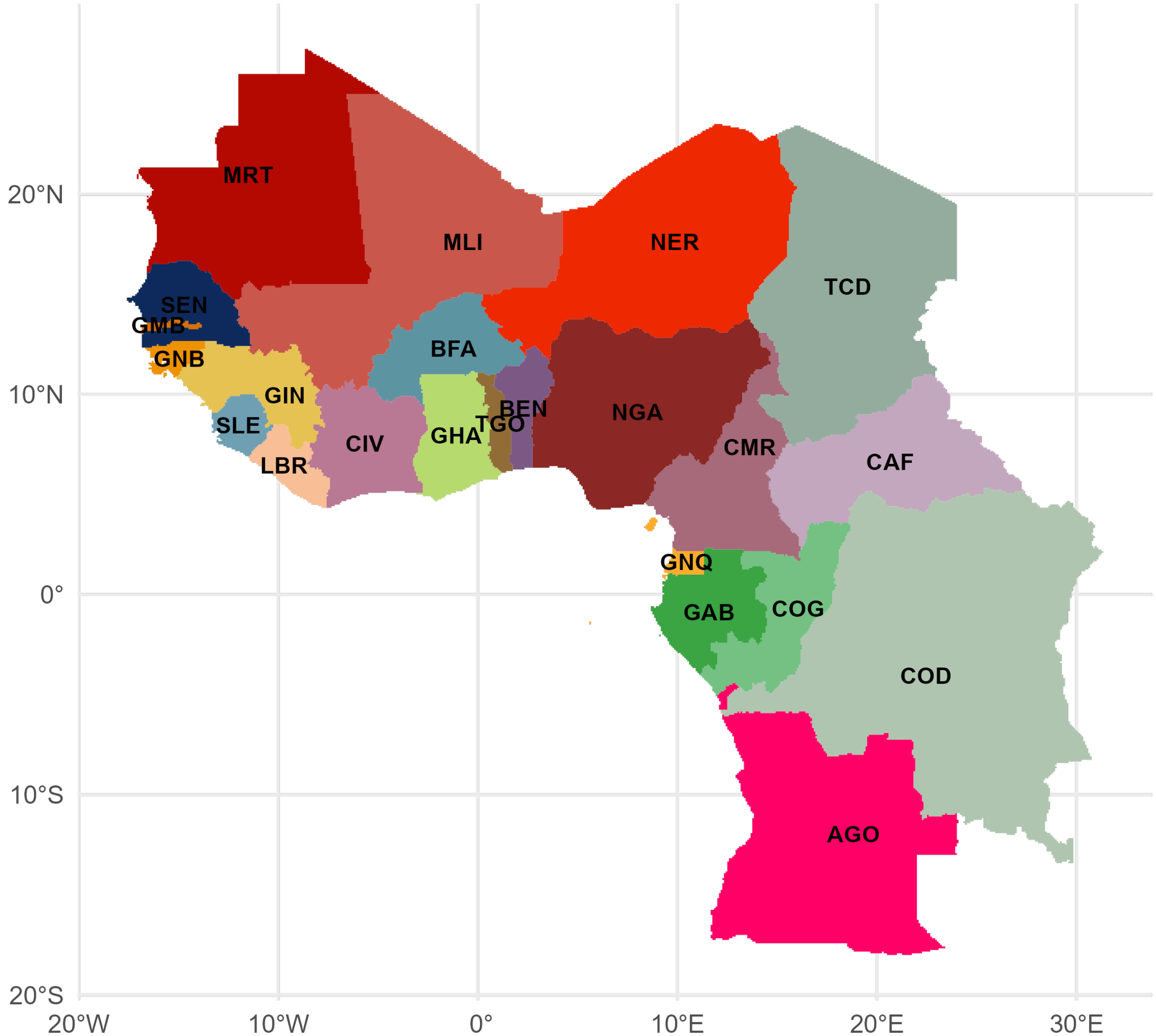

Figure A3: Map of countries/regions in West and Central Africa. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

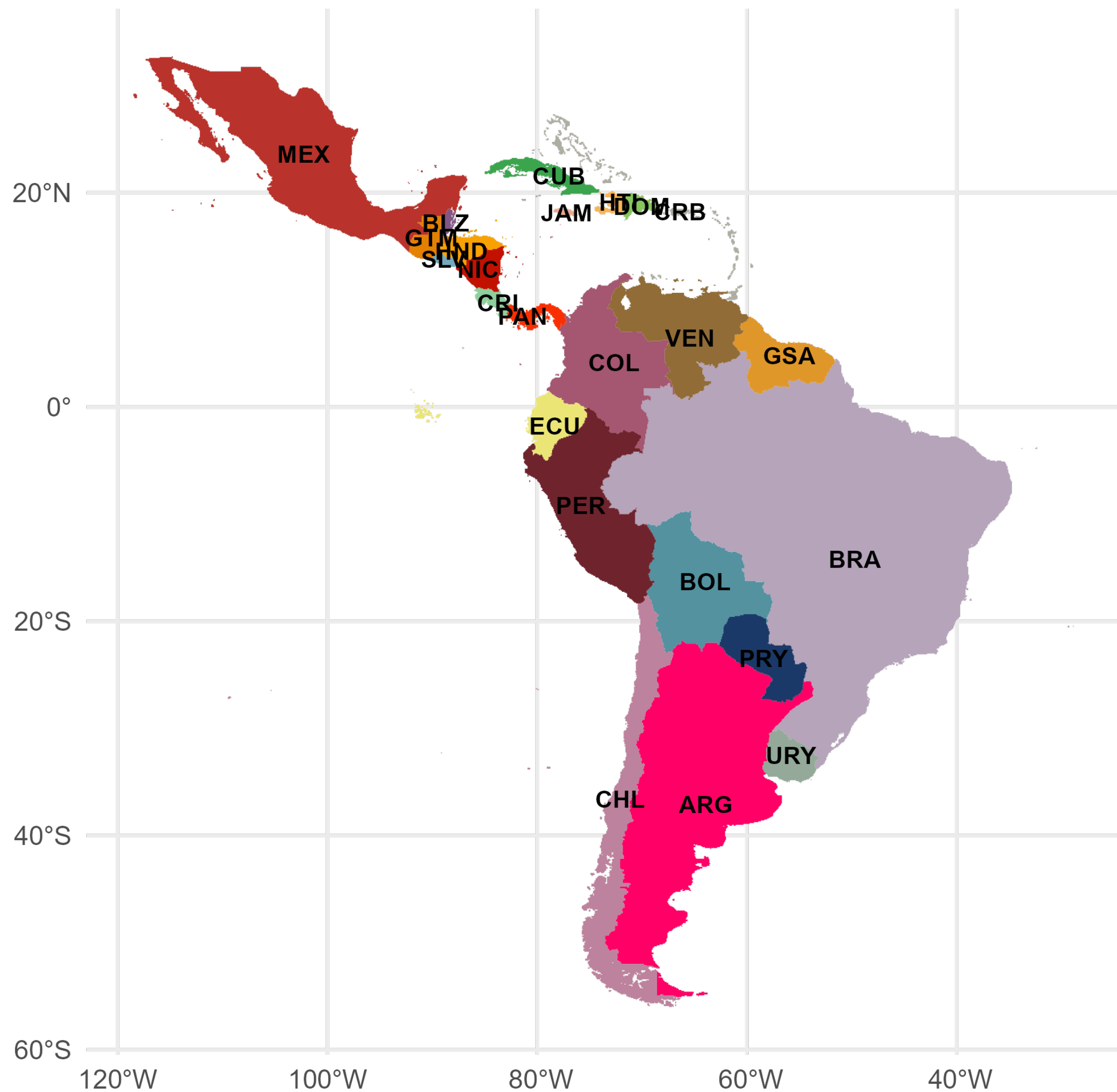

Figure A4: Map of countries/regions in Latin America and the Caribbean. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

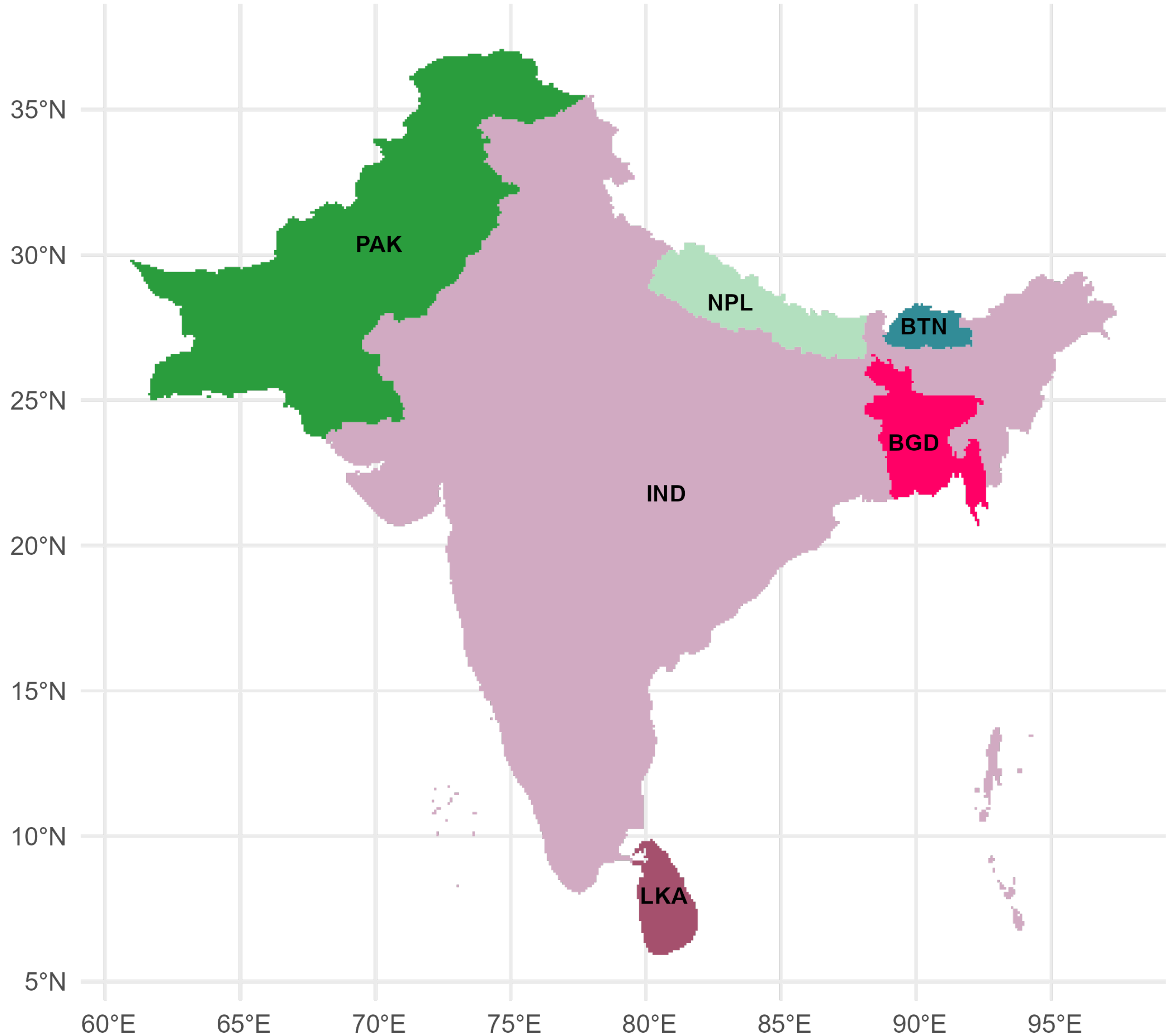

Figure A5: Map of countries/regions in South Asia. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

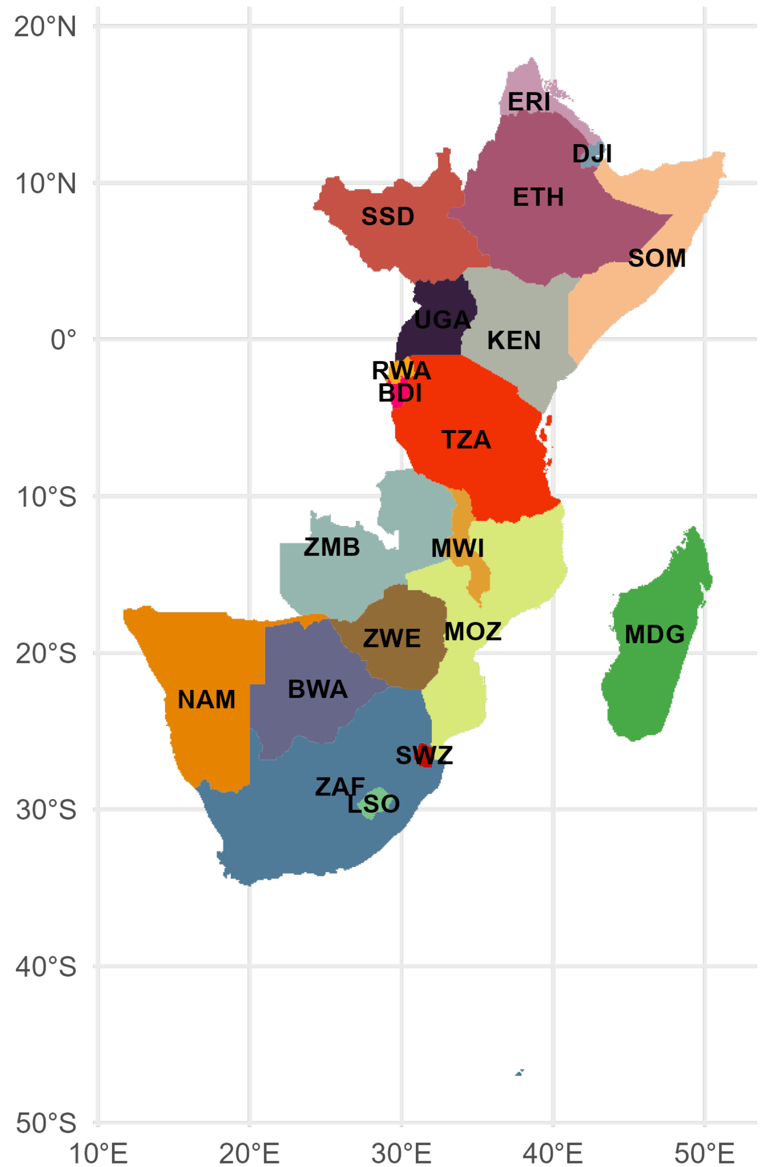

Figure A6: Map of countries/regions in East and Southern Africa.Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

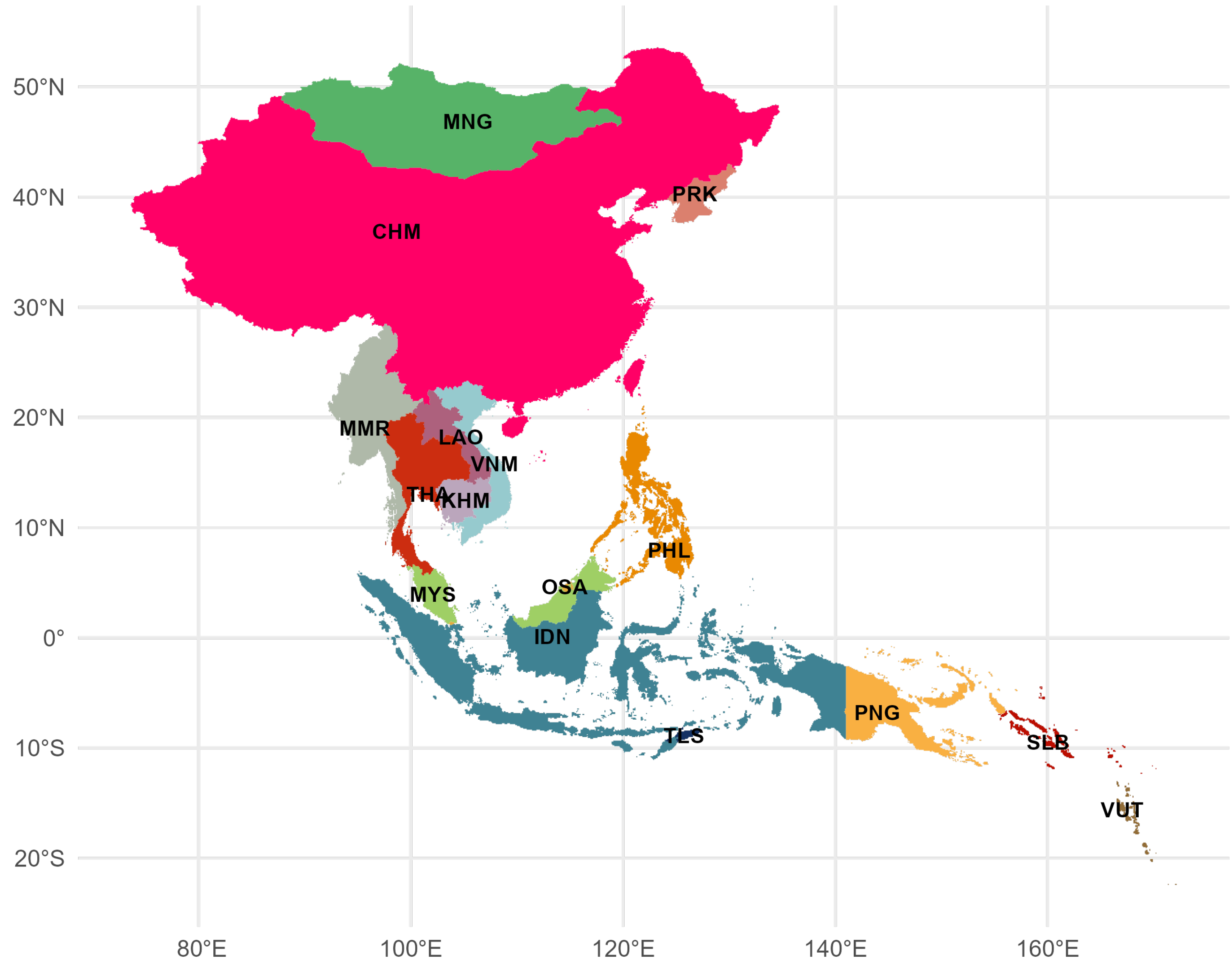

Figure A7: Map of countries/regions in Southeast Asia and the Pacific. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT. Small Atlantic and Pacific islands are not plotted in this map. See Table A1 for full list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

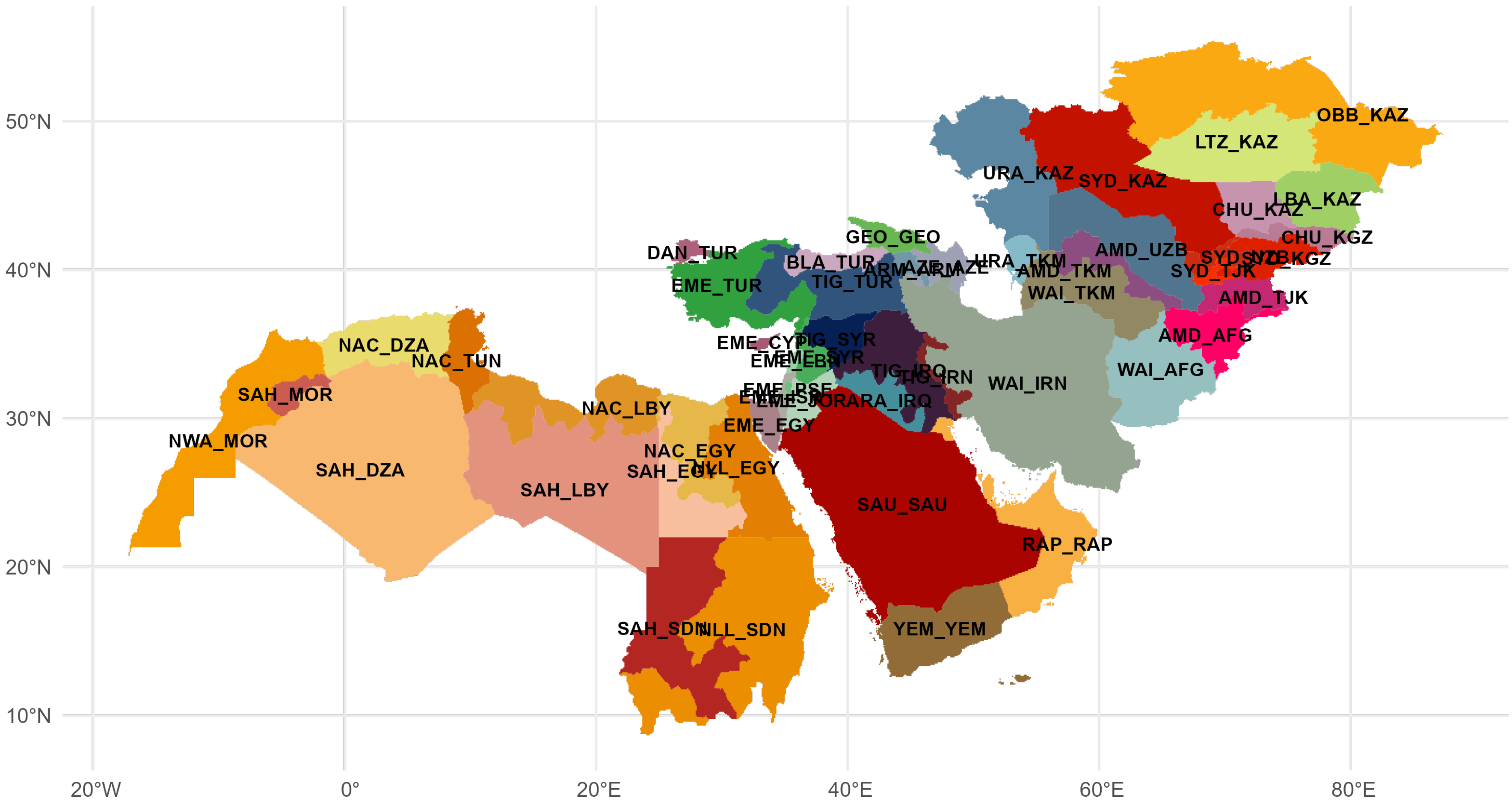

Figure A8: Map of FPUs in Central and West Asia and North Africa. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

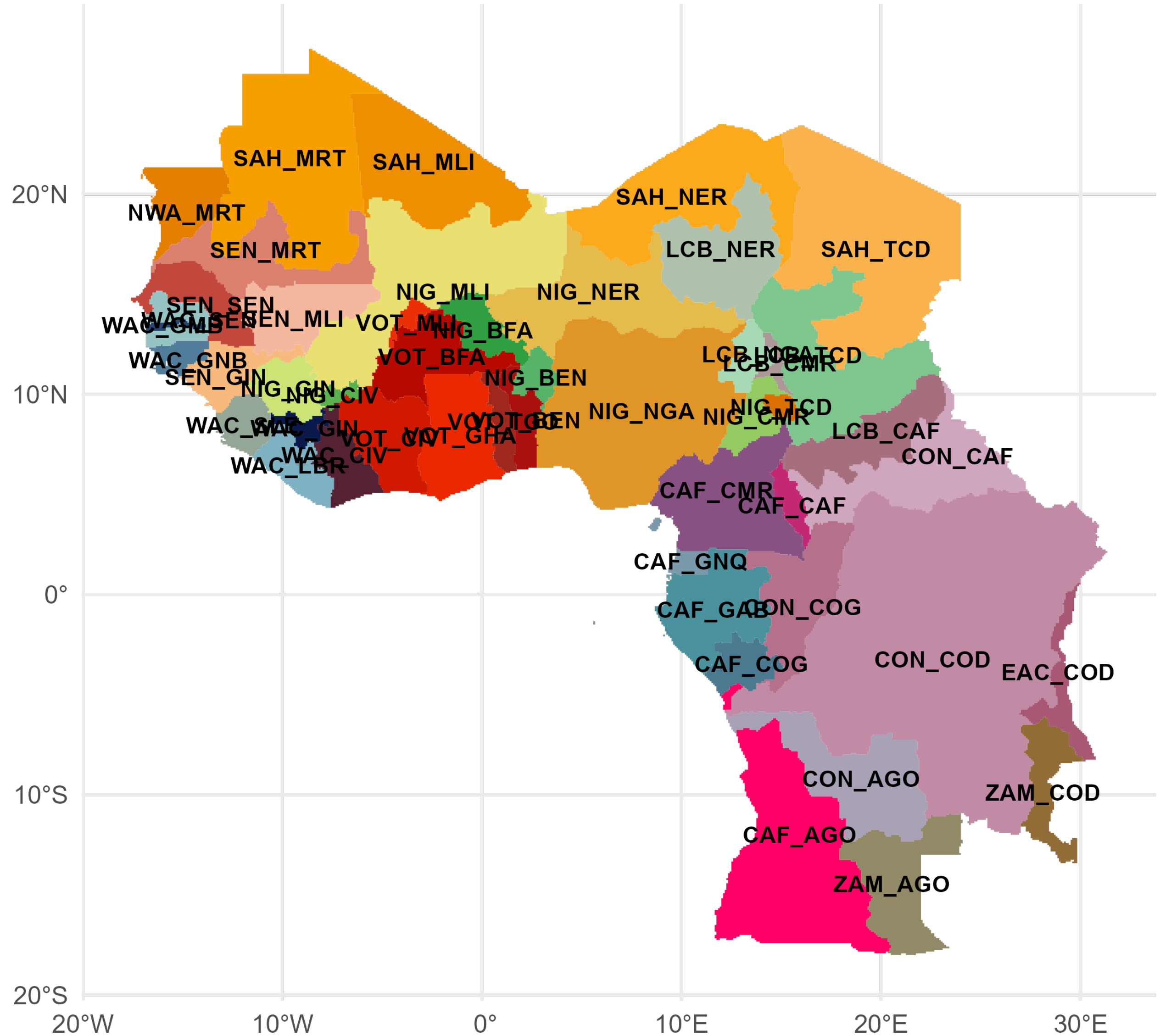

Figure A9: Map of FPUs in West and Central Africa. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

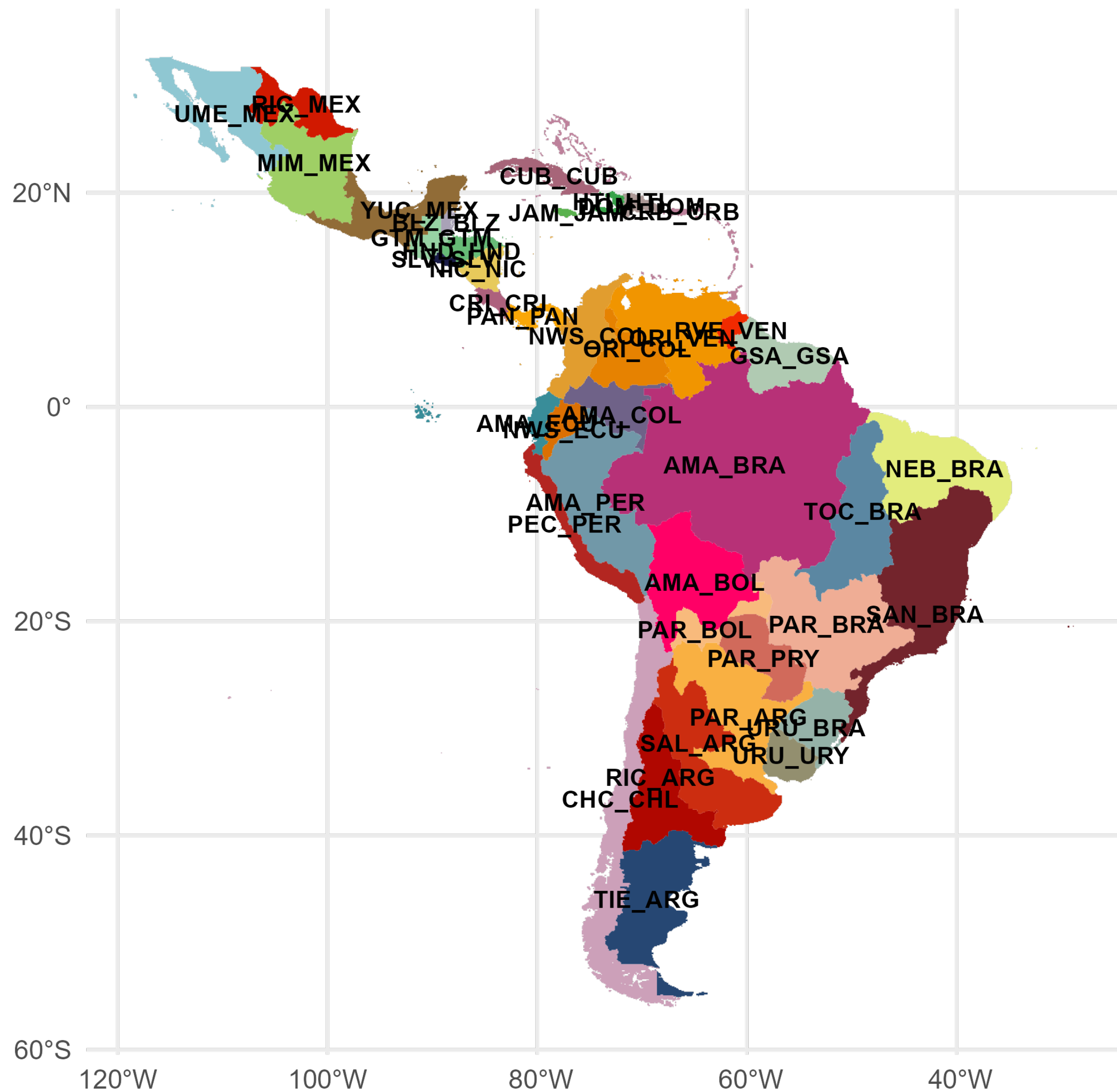

Figure A10: Map of FPUs in Latin America and the Caribbean. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

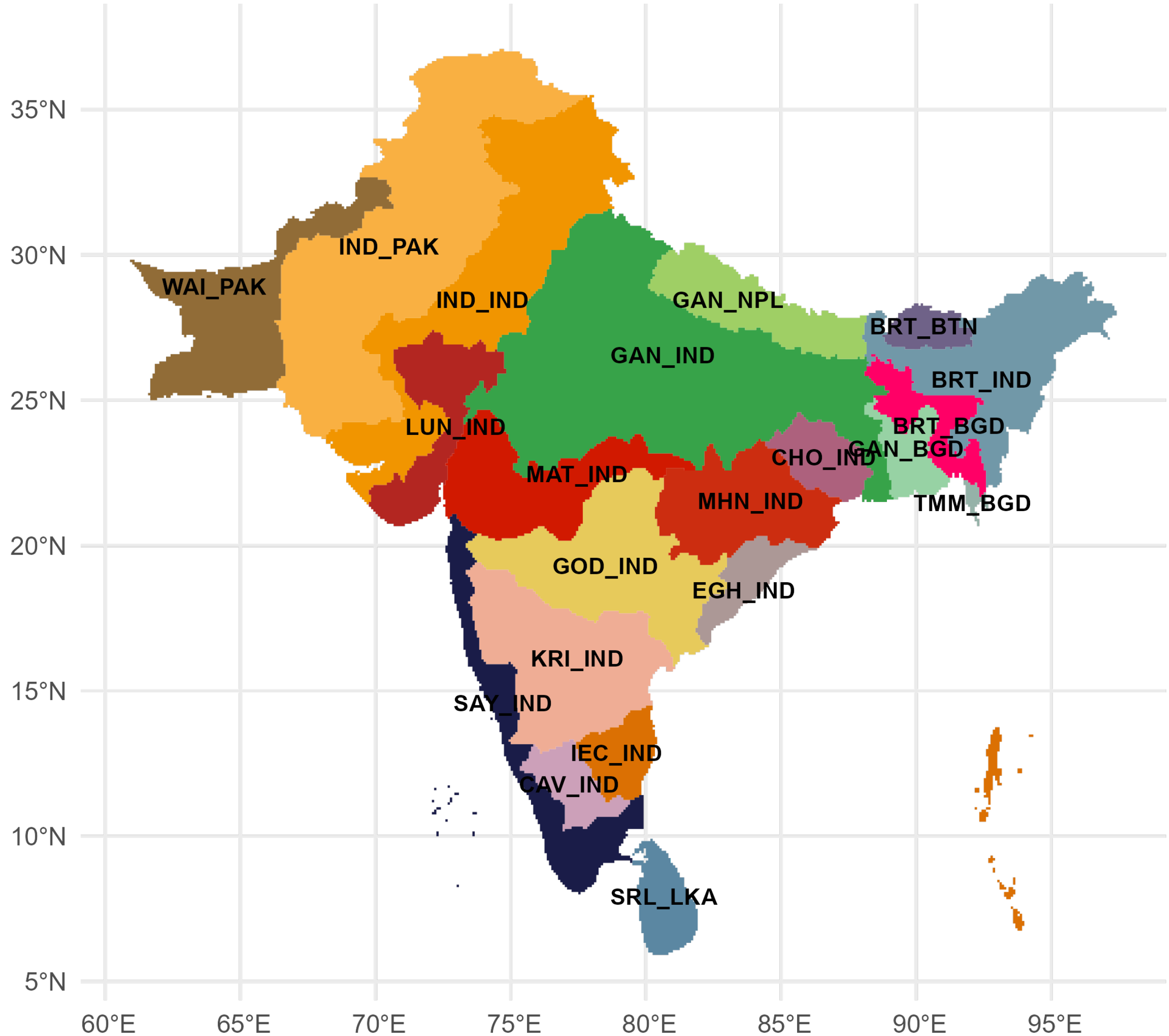

Figure A11: Map of FPUs in South Asia. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

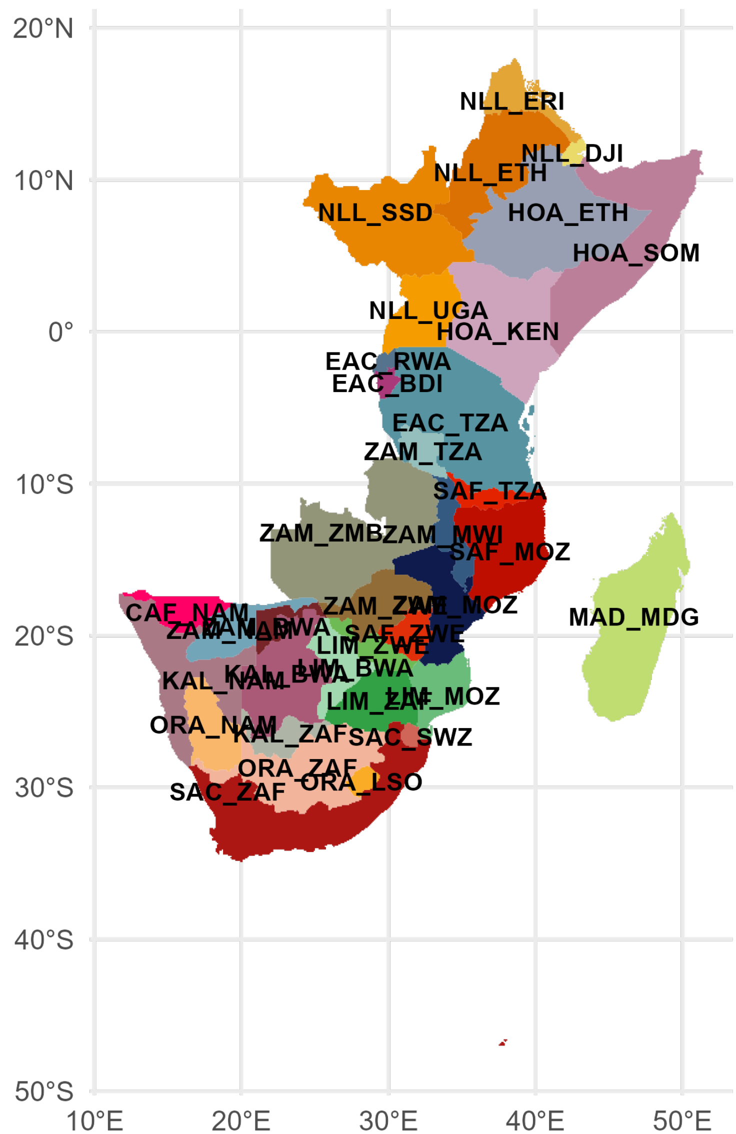

Figure A12: Map of FPUs in East and Southern Africa. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT.

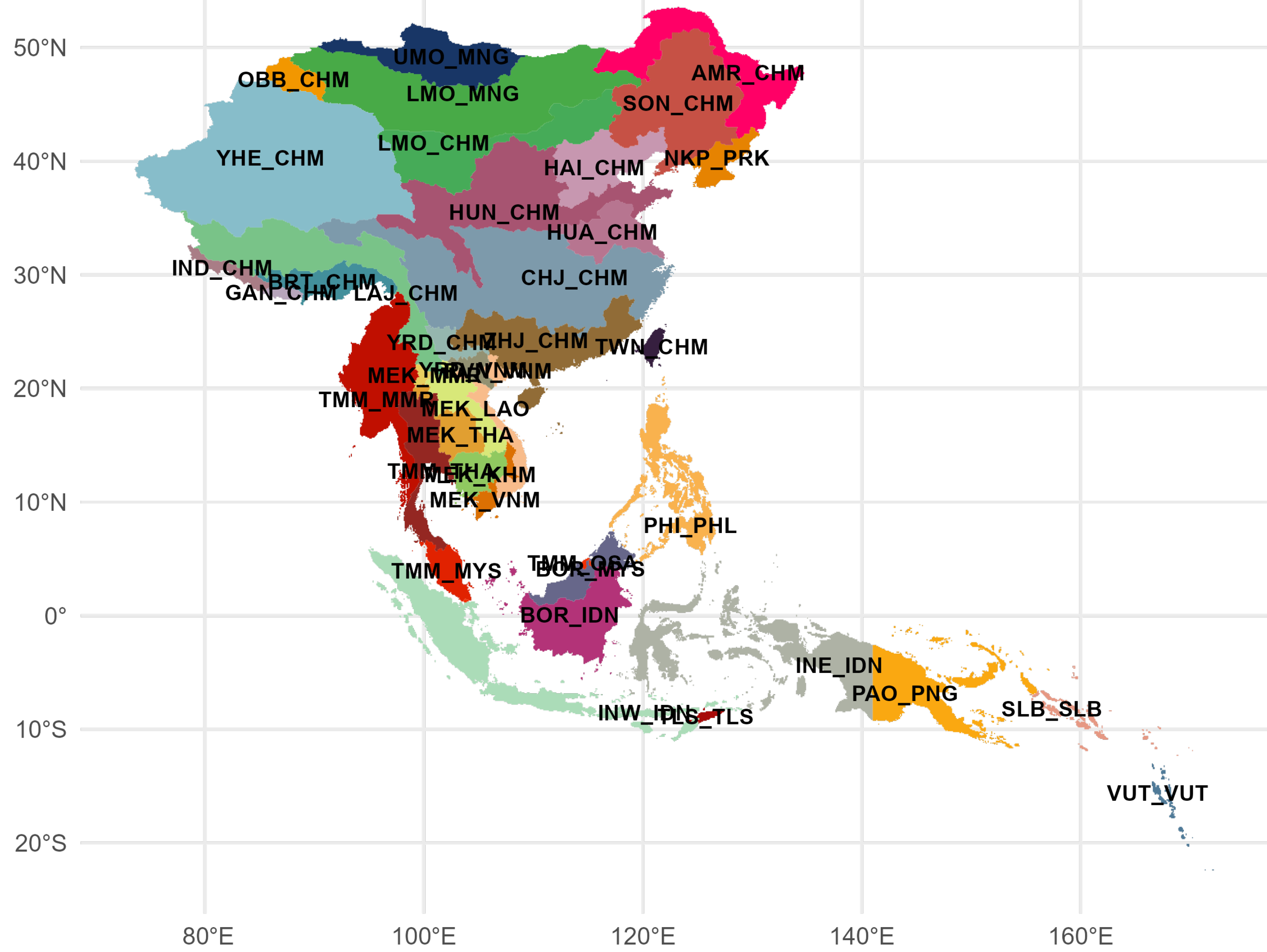

Figure A13: Map of FPUs in Southeast Asia and the Pacific. Note: Illustrative map only. National boundaries not shown. Colors and boundaries only denote geographical coverage as it exists in IMPACT. Small Atlantic and Pacific islands are not plotted in this map. See Table A2 for full list of FPUs.

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.

IMPACT activity name	IMPACT activity	FAO Item Code	FAO activity name
jbeef	Cattle	2731	Bovine Meat
jpork	Pigs	2733	Pigmeat
jlamb	Sheep and Goats	2732	Mutton & Goat Meat
jpoul	Poultry	2734	Poultry Meat
jeggs	Eggs	2744	Eggs
jmilk	Dairy	2848	Milk - Excluding Butter
jbarl	Barley	2513	Barley
jmaiz	Maize	2514	Maize
jmill	Millet	2517	Millet
jrice	Rice	2805	Rice (Milled Equivalent)
jsorg	Sorghum	2518	Sorghum
jwhea	Wheat	2511	Wheat
jocer	Other Cereals	2515	Rye
jcass	Cassava and Other R&T	2532	Cassava
jpota	Potato	2531	Potatoes
jswpt	Sweet Potatoes	2533	Sweet Potatoes
jyams	Yams	2535	Yams
jorat	Other Roots & Tubers	2534	Roots, Other
jbean	Beans	2546	Beans
jchkp	Chickpeas	2549	Chick peas
jcowp	Cowpeas	2549	Cow peas
jlent	Lentils	2549	Lentils
jpigp	Pigeonpeas	2549	Pigeon peas
jopul	Other Pulses	2549	Other Pulses
jbana	Bananas	2615	Bananas
jplnt	Plantains	2616	Plantains
jsubf	(Sub)-Tropical Fruits	2611	Oranges, Mandarines

Table B1 continued from previous page

IMPACT activity name	IMPACT activity	FAO Item Code	FAO activity name
jtemf	Temperate Fruits	2617	Apples
jvege	Vegetables	2601	Tomatoes
jsugc	Sugarcane	2536	Sugar Cane
jsugb	Sugarbeet	2537	Sugar Beet
jsugr	Sugar	2542	Sugar (Raw Equivalent)
jsugrc	Cane Sugar		Processed
jsugrb	Beet Sugar		Processed
jgrnd	Groundnuts	2556	Groundnuts (Shelled Eq)
jgdnt	Groundnuts for Oil		For processing
jgdol	Groundnut oil	2572	Groundnut Oil
jrpsd	Rapeseed	2558	Rape and Mustardseed
jrpnt	Rapeseed for Oil		For processing
jrpol	Rapeseed oil	2574	Rape and Mustard Oil
jsoyb	Soybeans	2555	Soyabeans
jsbnt	Soybeans for Oil		For processing
jsbol	Soybean oil	2571	Soyabean Oil
jsnfl	Sunflower Seeds	2557	Sunflowerseed
jsfnt	Sunflower seeds for Oil		For processing
jsfol	Sunflower oil	2573	Sunflowerseed Oil
jpalm	Oil Palm Fruit		For processing
jplol	Palm Oil	2577	Palm Oil
jpkol	Palm Kernal Oil	2576	Palmkernel Oil
jtols	Total Other Oilseeds	2560	Coconuts - Incl Copra
jtont	Total Other Oilseeds for Oil		For processing
jtool	Total Other Oils	2575	Cottonseed Oil
jgdoln	Groundnut oil from gdnt		Processed
jrpoln	Rapeseed oil from rpnt		Processed
jsboln	Soybean Oil from sbnt		Processed

Table B1 continued from previous page

IMPACT activity name	IMPACT activity	FAO Item Code	FAO activity name
jsfoln	Sunflower Oil from sfnt		Processed
jtooln	Total Other oils from tont		Processed
jgdolt	Groundnut oil from grnd		Processed
jrpolt	Rapeseed oil from rpsd		Processed
jsbolt	Soybean Oil from soyb		Processed
jsfolt	Sunflower Oil from snfl		Processed
jtoolt	Total other oils from tols		Processed
jcoco	Cocoa	2633	Cocoa Beans
jcafe	Coffee	2630	Coffee
jcott	Cotton	2661	Cotton Lint
jteas	Tea	2635	Tea
jothr	Other Crops	2551	Nuts
Shrimp	Shrimp		Aquatic foods from FishStatJ
Crust	Other crustaceans		Aquatic foods from FishStatJ
Mllscs	Molluscs and other invertebrates		Aquatic foods from FishStatJ
Salmon	Salmon		Aquatic foods from FishStatJ
ODmrsl	Demersals		Aquatic foods from FishStatJ
Tuna	Tuna		Aquatic foods from FishStatJ
Cobswf	Cobia and swordfish		Aquatic foods from FishStatJ
Eelstg	Eels and sturgeon		Aquatic foods from FishStatJ
Tilapia	Tilapia		Aquatic foods from FishStatJ
Pangas	Pangasius		Aquatic foods from FishStatJ
Carp	Carp		Aquatic foods from FishStatJ
Mullet	Mullet		Aquatic foods from FishStatJ
OFrshD	Other fresh and diadromous		Aquatic foods from FishStatJ
OCarp	Silver and grass carp		Aquatic foods from FishStatJ
OPelag	Other pelagic		Aquatic foods from FishStatJ
OMarn	Other marine		Aquatic foods from FishStatJ

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

Table B2 continued from previous page

Group	Activity	Description	Commodity	Description
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)	jrpnt	Rapeseed farm	crpnt	Rapeseed for oil
Oilseeds (nontraded)	jsbnt	Soybean farm	csbnt	Soybeans for oil
Oilseeds (nontraded)	jsfnt	Sunflower farm	csfnt	Sunflower seeds for oil
Oilseeds (nontraded)	jtont	Total other oilseed production	ctont	Total other oilseeds for oil
Oilseed processing	jgdol jgdolnt	Groundnut processing	cgdol cgdml	Groundnut oil Groundnut meal
Oilseed processing	jplol	Palm fruit processing	cplol cpkrl	Palm oil Palm kernel
Oilseed processing	jpkol	Palm kernel processing	cpkol cpkml	Palm kernel oil Palm kernel meal
Oilseed processing	jrpol jrpolnt	Rapeseed processing	crpol crpml	Rapeseed oil Rapeseed meal
Oilseed processing	jsbol jsbolnt	Soybean processing	csbol csbml	Soybean oil Soybean meal
Oilseed processing	jsfol jsfolnt	Sunflower oil processing	csfol csfml	Sunflower oil Sunflower meal
Oilseed processing	jtool jtoolnt	Total other oilseed processing	ctool ctoml	Total other oils Total other oilseed meal
Other	jcafe	Coffee plantation	ccafe	Coffee

Table B2 continued from previous page

Group	Activity	Description	Commodity	Description
Other	jcoco	Cocoa plantation	ccoco	Cocoa
Other	jcott	Cotton plantation	ccott	Cotton
Other	jfodr	Fodder production	cfodr	Fodders
Other	jothr	Other crop production	cothr	Other crops
Other	jpstr	Pasture and meadows	cgrss	Grass
Other	jteas	Tea plantation	cteas	Tea
Pulses	jbean	Bean farm	cbean	Beans
Pulses	jchkp	Chickpea farm	cchkp	Chickpeas
Pulses	jcowp	Cowpea farm	ccowp	Cowpeas
Pulses	jlent	Lentil farm	clent	Lentils
Pulses	jopul	Other pulse farm	copul	Other pulses
Pulses	jpigp	Pigeonpea farm	cpigp	Pigeonpeas
Roots and tubers	jcass	Cassava Farm	ccass	Cassava and other roots and tubers
Roots and tubers	jorat	Other roots and tuber production	corat	Other roots and tubers
Roots and tubers	jpota	Potato farm	cpota	Potato
Roots and tubers	jswpt	Sweet potato farm	cswpt	Sweet potatoes
Roots and tubers	jyams	Yam farm	cyams	Yams
Sugar	jsugb	Sugarbeet farm	csugb	Sugarbeet
Sugar	jsugc	Sugarcane plantation	csugc	Sugarcane
Sugar	jsugr	Sugar processing	csugr	Refined sugar
Aquatic foods	Shrimp	Shrimp	c-Shrimp	Shrimp

Table B2 continued from previous page

Group	Activity	Description	Commodity	Description
Aquatic foods	Crust	Other crustaceans	c-Crust	Other crustaceans
Aquatic foods	Mllscs	Molluscs and other invertebrates	c-Mllsc	Molluscs and other invertebrates
Aquatic foods	Salmon	Salmon	c-Salmon	Salmon
Aquatic foods	ODmrsl	Demersals	c-ODmrsl	Demersals
Aquatic foods	Tuna	Tuna	c-Tuna	Tuna
Aquatic foods	Cobswf	Cobia and swordfish	c-OPelag	Other pelagic
Aquatic foods	Eelstg	Eels and sturgeon	c-FrshD	Other fresh and diadromous
Aquatic foods	Tilapia	Tilapia	c-FrshD	Other fresh and diadromous
Aquatic foods	Pangas	Pangasius	c-FrshD	Other fresh and diadromous
Aquatic foods	Carp	Carp	c-FrshD	Other fresh and diadromous
Aquatic foods	Mullet	Mullet	c-ODmrsl	Demersals
Aquatic foods	OFrshD	Other fresh and diadromous	c-FrshD	Other fresh and diadromous
Aquatic foods	OCarp	Silver and grass carp	c-FrshD	Other fresh and diadromous
Aquatic foods	OPelag	Other pelagic	c-OPelag	Other pelagic
Aquatic foods	OMarn	Other marine	c-OMarn	Other marine

Appendix C

Data inputs and outputs

Note: IMPACT model drivers are shared publicly via
https://doi.org/10.5281/zenodo.19207793

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	—	Million
		GDP	—	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 Engel'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 3.2, see IIASA 2024) population scenario.
GDP growth rates	SSP database	IMPACT is calibrated to the OECD SSP 2 (version 3.2, see IIASA 2024) GDP scenario.

Table C3: Standard IMPACT multimarket model outputs

IMPACT result	Unit	Geographic scope	Time scope
Prices			
World prices	US$/mt	Global	Annual
Consumer prices	US$/mt	National	Annual
Producer prices	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

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.

D1 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.

D2 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 CO_2 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[a]	Barley, other cereals
	Dryland pulses[b]	Chickpeas, pigeon peas, beans, cowpeas, lentils, other pulses
	C3 average[c]	Cotton, sugar beets, tropical fruits, temperate fruits, vegetables, bananas, plantains, cocoa, coffee, tea, rapeseed, sunflower, oil palm, other oilseeds
	C3 tolerant[d]	Cassava, sweet potato, yams, other roots and tubers, other
C4 crops	CERES maize	Maize
	CERES sorghum	Sorghum, millet
	C4 tolerant[e]	Sugarcane

[a] Dryland cereals are represented by one-half the negative effects (full positive) of climate change from CERES wheat results.
[b] Dryland pulses are represented by one-half the negative effects (full positive) of the area-weighted average of the CROPGRO soybeans and CROPGRO groundnut results.
[c] C3 average is represented as the area-weighted average of all five C3 DSSAT crop models used.
[d] C3 tolerant is represented by one-half the negative effects (full positive) of the C3 average.
[e] C4 tolerant is represented by one-half the negative effects (full positive) of climate change from CERES maize results.

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

- Climate data are derived from ESM outputs (IPSL, GFDL-ESM4, MPIESM1-2HR, MRI-ESM2-0, and UKESM1-0-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 et al. 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 et al. 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

Water models

E1 IMPACT Global Hydrology Model (IGHM)

IGHM is a semi-distributed parsimonious model. It simulates snow accumulation and melt, soil moisture balance, evapotranspiration, and runoff generation at monthly intervals and on each 0.5°x 0.5°grid cell spanning the global land surface except the Antarctic.

Gridded output of hydrological fluxes, namely, effective rainfall, for calculating net irrigation water requirement in IMPACT water basin simulation model (IWSM), potential and actual evapotranspiration, and runoff are spatially aggregated to food production units (FPUs) within the river basin, weighted by grid cell areas, and then incorporated into IWSM.

The most dominant climatic drivers for water availability are precipitation and evaporative demand determined by net radiation at ground level, atmospheric humidity, wind speed, and temperature. In IGHM, the Priestley-Taylor equation is used to calculate potential evapotranspiration (Equation E.1).[1]

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

where:

PET = Potential evapotranspiration (mm day^{-1})
α = Scalar, 1.26 in humid climates, 1.74 in arid locations
Δ = Slope of the vapor pressure curve (kPa C$^{\circ-1}$)
γ = psychrometric constant (kPa C$^{\circ-1}$)
R_n = Net radiation at the land surface (mm day^{-1})
G = Soil heat flux density (mm day^{-1})

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

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

where:

$f(c)$ = Fraction of area in a grid cell that has soil water-holding capacity values lower than c
C_m = Maximum soil water-holding capacity value across all points within the grid cell
b = shape parameter defining the degree of spatial variability of soil moisture-holding capacity c

[1] For α, the humid and arid conditions are defined as having relative humidity greater or less than 60% in the month with peak evapotranspiration.

The maximum amount of water that can be held in the grid cell is defined in Equation E.3.

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

Refer to Fig. 5.2, where S_m equals the area between the parabolic curve and the x-axis with area fraction values of the x-axis ranging from 0 to 1.

Assuming that at any time t each point in the grid cell is either at C_m or at a constant moisture state c (Ren-Jun 1992), the mean areal water storage S associated with soil water-holding capacity c at time t is given by equation E.4

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

With precipitation P_t and actual evapotranspiration AET_t in time period t, runoff R_t is determined by equation E.5.

If $c_t + P_t - AET \leq C_m$, then

$$R_t = P_t - AET_t - \Delta S \tag{E.5a}$$

Where

$$\Delta S = S_m \times \left[\left(1 - \frac{c_t}{c_m}\right)^{1+b} - \left(1 - \frac{c_t + P_t - AET_t}{c_m}\right)^{1+b}\right] \tag{E.5b}$$

Otherwise, If $c_t + P_t - AET \geq C_m$, then

$$R_t = P_t - AET_t - (S_m - S_t) \tag{E.5c}$$

where

$$S_t = S_m \times \left[\left(1 - \frac{c_t}{c_m}\right)^{1+b} - \left(1 - \frac{c_t + P_t - AET_t}{c_m}\right)^{1+b}\right] \tag{E.5d}$$

The AET is determined jointly by the PET and relative soil moisture state in a grid cell at time period t (Equation E.6).

$$AET_t = PET_t \times \frac{S_t}{S_m} \tag{E.6}$$

Runoff generated in time period t is divided into a surface runoff component RS and a deep percolation component using partitioning factor λ (Equation E.7).

$$RS_t = \lambda \times R_t \tag{E.7}$$

A linear reservoir is assumed to model base flow RB. The storage of the linear reservoir is linearly related to output, namely, base flow by a storage constant β (Chow et al. 1988, Equation E.8).

$$RB_t = \beta \times G_t \tag{E.8}$$

where:

G_t = Storage value in time period t

The change of reservoir storage ΔG during time period t equals the difference between deep percolation and base flow RB occurred in this period (Equation E.9)

$$\Delta G = G_t - G_{t-1} = [(1 - \lambda) \times R_t] - RB_t \tag{E.9}$$

Total runoff generated R in time period t is the sum of surface runoff RS and base flow RB (Equation E.10).

$$R_t = RS_t + RB_t \tag{E.10}$$

In the above equations (E.1 - E.10), calibration parameters include the subgrid variability shape parameter b, the total runoff partitioning parameter λ, the storage constant β, and the average soil water-holding capacity S_m.

Conceptually, S_m should equal available water - namely, field capacity less wilting point in a soil moisture–accounting perspective. However, because of the monthly time step adopted, using measured available water rather than calibrating S_m can significantly overestimate runoff and underestimate actual evapotranspiration as found in our calibration experiments.

E2 IMPACT Water basin Simulation Model (IWSM)

IWSM includes three components:

1. Water demand projections for domestic, industrial, livestock, and irrigation sectors;
2. Water supply optimization; and
3. Water allocation across sectors

IWSM can also simulate water use impacts of technological and socioeconomic changes as well as climate change.

Water demand projection

Crop water requirement is defined by equation E.11 for every fpu, activity j, year yrs and month m.

$$ETM_{fpu,j,yrs,m} = Kc_{fpu,j,m} \times ET0_{fpu,yrs,m} \tag{E.11}$$

where:

ETM = Monthly Crop Specific Evapotranspiration (mm)
$ET0$ = reference evapotranspiration (mm)
Kc = crop coefficient

Domestic water demand

Domestic water demand includes municipal water demand and rural domestic water demand. Annual per capita domestic water consumption is based on previous work with the International Water Management Institute (de Fraiture 2007; Rosegrant et al. 2002), with necessary adjustments to ensure that per capita consumption in rural and urban households is not less than 15 liters per day and 25 liters per day, respectively. Total domestic water consumption $DoWD$ at the FPU level equals population POP multiplied by annual per capita consumption $pcDoWD$ (derived from daily per capita demand $pcDoWDpd$), as seen in IWSM equation E.12. The growth of domestic per capita consumption is based on projections of per capita gross domestic product ($pcGDP$) as seen in IWSM equation E.12c. In each region or basin, income elasticities η of demand for domestic water use are synthesized based on the literature and available estimates (de Fraiture 2007). These elasticities of demand measure the propensity to consume water with respect to increases in per capita income. The elasticities also capture both direct income effects and conservation of domestic water use through technological and management change. In higher-income countries where per capita domestic consumption is high, the elasticities of demand imply that water demand will decline with increased income growth, whereas in developing countries the elasticities imply an increase in water consumption with increased income growth.

$$DoWD_{fpu,t} = \sum_{h} (POP_{h,fpu,t} \times pcDoWD_{h,fpu,t}) \tag{E.12a}$$

where, $\forall$ t = 1

$$pcDoWD_{h,fpu,t} = pcDoWDpd_{h,fpu,t} \times 365.25 \times 1e^{-3} \tag{E.12b}$$

and, for $\forall$ t $\geq$ 1

$$pcDoWD_{h,fpu,t} = pcDoWDpd_{h,fpu,t-1} \times (1 + (\eta \times \Delta pcGDP_{h,fpu,t})) \tag{E.12c}$$

Industrial water demand

Industrial water demand is modeled for the manufacturing and energy sectors using growth rates for the value-added by sector and energy production values for the electricity sector from the EPPA6 Model of the MIT Joint Program on the Science and Policy of Global Change (Chen et al. 2015). For many countries in Africa south of the Sahara, the projected industrial water demands are substantially lower than those in IMPACT 2, suggesting an underestimation.

Therefore, for countries in Africa south of the Sahara we retained the projection method of IMPACT 2—namely, the industrial water demand is modeled as a nonlinear function of gross domestic production per capita and technology change. In IWSM equation E.13, ϵ is income elasticity of demand, and γ^t is the technology term, which is determined according to our perspectives on future industrial water demand and technological improvements in industrial water use in different regions.

$$InWD_{fpu,t} = \alpha \times \Delta pcGDP_t^{\epsilon} \times EXP(\gamma^t) \tag{E.13}$$

Livestock water demand

Livestock water demand is estimated using livestock numbers and water consumptive use per unit of livestock (w_{lv}), including beef, milk, pork, poultry, eggs, and sheep and goats (de Fraiture 2007; Steinfeld et al. 2006). The total number of live animals during a year includes slaughtered animals, the followers herd, and other categories (for example, milk-producing animals). The total number of animals is calculated based on the number of slaughtered animals (QS_{lv}) and a ratio of the number of slaughtered animals to the total number of animals (r_{lv}) (eq. E.14).

$$LvWD_{fpu,t} = QS_{lv} \times r_{lv} \times w_{lv} \tag{E.14}$$

Irrigation water demand

Irrigation water demand is assessed as the portion of crop water requirement (eq. E.15) not satisfied by precipitation or soil moisture based on hydrologic and agronomic characteristics. Net irrigation water demand ($NIWD$) in an FPU is calculated based on an empirical crop water requirement function (Doorenbos and Kassam 1979; Doorenbos et al. 1977) and irrigated area of the crop.

$$NIWD_{fpu,j} = \sum_m \max(0, ETM_{fpu,j,m} - PE_{fpu,m}) \times AI_{fpu,j} \tag{E.15}$$

where

ETM = Maximum evapotranspiration in month m for crop j
PE = Effective rainfall in month m
AI = Irrigated area from crop j

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

Effective rainfall

Effective rainfall depends on total rainfall (PT), previous soil moisture content ($SM0$), maximum crop evapotranspiration (ETM), and soil characteristics (hydraulic conductivity K, moisture content at field capacity Zs, and others). PE is calculated by a SCS (Soil Conservation Service) method (USDA-SCS 1992), given PT, ETM, and effective soil water storage.

$$PE = SF \times (0.70917 \times PT^{0.82416} - 0.11556) \times 10^{0.02426 \times ETM} \tag{E.16a}$$

in which, SF is the soil water storage factor and is calculated with

$$SF = 0.531747 + (0.295167 \times D) - (0.057697 \times D^2) + (0.003804 \times D^3) \tag{E.16b}$$

where D represents the usable soil water storage in inches and is generally calculated as 40 to 60 percent of available soil water capacity in the crop root zone, depending on the irrigation management practices in use (USDA-SCS 1992).

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

Gross irrigation water demand $GIWD$ for all crops is shown in equation E.17, with consideration of effective rainfall use and salt leaching requirement.

$$GIWD_{fpu,j} = \frac{\sum_j (NIWD_{fpu,j} \times AI_{fpu,j}) \times (1 + LR)}{BE} \tag{E.17}$$

where

LR = Salt-leaching factor
BE = Basin efficiency

The concept of basin efficiency was discussed and various definitions were provided by Keller et al. 1996. Basin efficiency is defined as the ratio of beneficial water depletion (crop evapotranspiration and salt leaching) to total irrigation water depletion at the FPU scale. Basin efficiency in the base year is calculated as the ratio of the net irrigation water demand ($NIWD$, equation E.15) to the total irrigation water depletion estimated from records (Shiklomanov 1999). Basin efficiency in future years is assumed to increase at a prescribed rate in an FPU depending on water infrastructure investment and water management improvement in the FPU.

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

Water supply optimization

IWSM is an optimization-driven simulation model with operating rules implicitly given by the objective function and constraints in the following quadratic programming model, coded in

GAMS. The model runs at monthly time step and is solved for individual years using the CPLEX solver. Adjacent years are linked through reservoir storage. Although the model is solved for all the 320 FPUs in the world simultaneously each year, it is the same as solving the 154 aggregated river basins individually because only FPUs within the same basin are connected through upstream-to-downstream water transport.

The objective function (equation E.18) minimizes the sum of a set of objectives summed across all FPUs, including the annual sum of squared deviations from 1 of monthly ratios of irrigation water supply to demand, squared deviation from 1 of the minimum irrigation water supply to demand ratio across all months, squared deviation from 1 of the ratio of end of year storage to reservoir storage capacity, and penalty terms. $STCAP_{fpu}$ is reservoir storage capacity. $WFPU_{fpu}$, WRA_{fpu}, $MINRA_{fpu}$, $WSTRG_{fpu}$, $WEVSLK$, and $WNIRST$ are weighting factors. High values are assigned to the weighting factors of the slack variables to force the solution of the slack variables to zero, through the minimization.

$$\begin{aligned}\min OBJSQV = \sum_{fpu} WFPU_{fpu} \\ \times \Bigg[WRA_{fpu} \sum_{m} (RAV_{fpu,m} - 1)^2 + MINRA_{fpu}(MINRAV_{fpu} - 1)^2 \\ + WSTRG_{fpu} \left(\frac{STRGV_{fpu,m}}{STCAP_{fpu}} - 1 \right)^2 + WEVSLK \sum_{m} EVAPSLACKV_{fpu,m} \\ + WNIRST \sum_{m} NIRSHORTV_{fpu,m} \Bigg]\end{aligned} \tag{E.18}$$

where

$OBJSQV$	= Objective function
RAV	= Monthly ratio of water supply to water demand
$MINRAV$	= The minimum ratio of monthly water supply to water demand
$STRGV$	= Reservoir storage at the end of month m
$EVAPSLACKV$	= Slack variable for reservoir evapotranspiration (?)
$NIRSHORTV$	= Slack variable for the shortage of nonirrigation water

The minimum value of monthly ratio values in a year is controlled as $MINRAV_{fpu} \leq RAV_{fpu,m} \forall m$.

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

$$
\begin{aligned}
STRGV_{fpu,m} = STRGPV_{fpu,m} \\
&+ (IRW_{fpu,m} - GWX_{fpu,m} + INFLOWV_{fpu,m}) \\
&- (EVAPV_{fpu,m} + SPV_{fpu,m} + SWDPV_{fpu,m})
\end{aligned}
\tag{E.19}
$$

where

$STRGV$	= Reservoir storage at the end of month m
$STRGPV$	= Initial or Beginning-of-period storage in the First Month
IRW	= Irrigation water
$INFLOWV$	= Monthly inflows from upstream food production units
$EVAPV$	= Monthly reservoir evaporation
SPV	= Monthly reservoir spill
$SWDPV$	= Monthly surface water depletion

For Beginning-of-period Storage in the First Month (equation E.20), in the base year, as beginning storage is unknown, beginning storage is set as equivalent to the end-of-period storage of the last month. This is equivalent to the $IWSM$ running an infinite number of times using base year data such that the ending storage converges to a certain value. In case it is not the base year, beginning storage of the first month is set at the ending storage of the last month of the previous year ($ISTRG_{fpu}$). For all other months, beginning storage of a month equals ending storage of the previous month.

$$
STRGPV_{fpu,m} = \begin{cases} STRGV_{fpu,12} & m = 1 \text{ and Base Year} \\ ISTRG_{fpu,m} & m = 1 \text{ and NOT Base Year} \\ STRGV_{fpu,m-1} & m > 1 \end{cases} \tag{E.20}
$$

where

$STRGPV$	= Initial or Beginning-of-period storage in the First Month
$STRGV$	= Reservoir storage at the end of month m
$ISTRG$	= Ending storage of the last month of the previous year

The inflow from FPUs upstream within the basin is given by equation E.21.

$$
INFLOWV_{fpu,m} = \sum_{fpub \in \mathcal{N}(fpu)} SPV_{fpub,m} \tag{E.21a}
$$

where

$$\mathcal{N}(fpu) = \{fpub \mid neigb(fpu, fpub) = 1\} \tag{E.21b}$$

$INFLOWV$	= Monthly inflows from upstream food production units
SPV	= Monthly reservoir spill
$fpub$	= Alias of FPUs
$neigb$	= Mapping of neighboring FPUs

Reservoir evaporation (equation E.22) equals potential evaporation multiplied by reservoir surface area. Considering storage capacity growth over time, reservoir surface area equals the area of reservoir when storage is at its capacity in the base year multiplied by a coefficient that is a power function of the ratio of average storage of the current month to base-year storage capacity. The power $\frac{2}{3}$ is applied for converting the change in three-dimensional reservoir storage to that of two-dimensional reservoir surface area. $STRGC^{00}_{fpu}$, $RESA^{00}_{fpu,m}$, and $PET_{fpu,m}$ are, respectively, reservoir storage capacity in the base year, reservoir surface area at full storage in the base year, and potential evaporation in month m of the current year. Reservoir storage capacity and reservoir surface area values in the base year are based on the GRanD database (Lehner et al. 2011).

$$\begin{aligned} EVAPV_{fpu,m} = &-EVAPSLACKV_{fpu,m} \\ &+ PRET1_{fpu,m} \\ &\times \frac{1}{2}\begin{bmatrix} STRGV_{fpu,m} \\ + ISTRG1_{fpu} \mid m = 1 \wedge t \neq 1 \\ + STRGV_{fpu,m\ominus 1} \mid m = 1 \wedge t = 1 \\ + STRGV_{fpu,m-1} \mid m \neq 1 \end{bmatrix} \\ &\times STRGC1^{-1}_{fpu} \end{aligned} \tag{E.22}$$

where

$EVAPV$	= Monthly reservoir evaporation
$EVAPSLACKV$	= Slack variable for reservoir evapotranspiration
$PRET1$	= Evaporation when reservoir is full
$STRGV$	= Reservoir storage at the end of month m
$ISTRG1$	= Initial storage (in m=1 i.e., january equals m=12 i.e., December)
$STRGC1$	= basin storage capacity

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

$$SWDPV_{fpu,m} + GWDPV_{fpu,m} + WDSL_{fpu,m} = IRRWUV_{fpu,m} + WDNI_{fpu,m} - NIRSHORTV_{fpu,m} \tag{E.23}$$

where

$SWDPV$	= Monthly surface water depletion
$GWDPV$	= Monthly groundwater depletion
$WDSL$	= Desalinated water amount
$IRRWUV$	= Monthly irrigation water use
$WDNI$	= Water depletion in non-irrigation sectors
$NIRSHORTV$	= Slack variable for the shortage of non-irrigation water

The ratio of irrigation water supply to gross irrigation water requirement, $GIWD_{fpu,m}$, which considers effective basin efficiency, is given by equation E.24.

$$RAV_{fpu,m} = \frac{IRRWUV_{fpu,m}}{GIWD_{fpu,m}} \tag{E.24}$$

where

RAV	= Monthly ratio of water supply to water demand
$IRRWUV$	= Monthly irrigation water use
$GIWD$	= Irrigation water demand

The total surface water withdrawal in a given year cannot exceed surface water withdrawal capacity i.e., $\sum_m SWDPV_{fpu,m} \leq SWDCAP_{fpu}$. The capacity has been converted into a consumptive use term, using estimated depletion coefficients of domestic, industrial, and agricultural sectors. Water withdrawal data by source around year 2005 from FAO's AQUASTAT global databasewere used to estimate surface and groundwater withdrawal capacity values (FAO 2014), considering inter-annual variability of water demand at the FPU level.

The total groundwater water withdrawal in a given year cannot exceed groundwater withdrawal capacity of that year i.e., $\sum_m GWDPV_{fpu,m} \leq GWDCAP_{fpu}$. The capacity has been converted into a consumptive use term, using estimated depletion coefficients of domestic, industrial, and agricultural sectors.

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

$$SPV_{fpu,m} \geq \frac{1}{24} \times CFY_{fpu} \times \sum_{m} \Big[IRW_{fpu,m} - GSEXG_{fpu} \times GRCHGfpu, m2 + INFLOWV_{fpu,m2} - EVAPV_{fpu,m2} \Big] \tag{E.25}$$

wehre

SPV	$=$ Monthly spill
CFY	$=$ annual committed flow in percentage of total
IRW	$=$ Monthly runoff
$GSEXG$	$=$ Percentage of groundwater recharge from surface water
$GRCHG$	$=$ Groundwater recharge
$INFLOWV$	$=$ Monthly inflows from upstream food production units
$EVAPV$	$=$ Reservoir evaporation

The reservoir storage in any month should be greater than its dead storage, and, less than its storage capacity i.e. $STCAPMN_{fpu} \leq STRGV_{fpu,m} \leq STCAP_{fpu}$.

Intersector water allocation

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

E3 IMPACT Crop Water Allocation and Stress Model (ICWASM)

ICWASM allocates irrigation water among crops in an area. We use FAO's K_y/K_c approach[2] (Doorenbos et al. 1977; Doorenbos and Kassam 1979) to measure water stress using a monthly time step to include seasonality of water stress. The model maximizes the total value of production given fixed prices and also includes a measure of risk aversion for farmers in the objective function, which preserves a diversified production structure even in case of a drought.

The monthly (m) irrigation water delivered to FPU has to be less than or equal to total water available for that FPU. This constraint on water availability is expressed by the following inequality (Equation E.26):

$$\sum_j CWDLV_{fpu,j,m} \times AREAC_{j,fpu} \leq WDAG_{fpu,m} \tag{E.26}$$

where:

$CWDLV$ = Crop water delivered per hectare (millimeters)
$AREAC$ = area for crop j in the fpu
$WDAG$ = Available water, which comes from $IWSM$

The water supplied to each crop has to be less than or equal to the crop irrigation water demand (IWD) requirement, which does not include basin efficiency as shown in Equation E.27.

$$CWDLV_{fpu,j,m} \leq IWD_{fpu,j,m} \tag{E.27}$$

Additionally, water delivery ratio by crop ($RatioCWDLV$), and mean of water delivery ratio across crops ($MeanRatioV$) are calculated using Equation E.28 where N_j is the total number of crops.

$$RatioCWDLV_{fpu,j,m} = \frac{CWDLV_{fpu,j,m}}{IWD_{fpu,j,m}} \tag{E.28a}$$

$$MeanRatioV_{fpu,m} = \frac{\sum_j RatioCWDLV_{fpu,j,m}}{N_j} \tag{E.28b}$$

[2] K_y is the Yield response factor, K_c is the crop coefficient

The monthly irrigation yield reduction rate ($IYRMV$[3], equation E.29) is equal to the yield coefficient times the fraction of the water requirement unmet by supply for that month, given the cropping calendar. We ensure that yield reduction is less than 1, such that a yield reduction cannot lead to a negative yield. Ky is the yield coefficient, $precip$ is monthly precipitation, and $etcrop$ is the monthly crop-specific evapotranspiration (millimeters). Here, $IYRMSLKV$ is a slack variable to ensure $IYRMV \leq 1$.

$$IYRMV_{fpu,j,m} + IYRMSLKV_{fpu,j,m} = Ky_{fpu,j,m} \times \left[1 - \frac{MIN(precip_{fpu,m}, etcrop_{fpu,j,m})}{etcrop_{fpu,j,m}}\right] \tag{E.29}$$

Equations E.30a and E.30b provide alternative approaches to aggregating the monthly yield shocks to produce the annual shock. Both approaches are based on Rao et al. 1988. Equation E.30a shows a multiplicative representation of monthly yield shocks, where the annual yield reduction shock equals the product during the months of 1 minus the monthly irrigated yield reductions. It is a nonlinear equation that requires that the model be solved with a nonlinear programming (NLP) solver. Equation E.30b shows an additive representation of monthly yield shocks where the annual yield reduction shock equals 1 minus the sum of the monthly irrigated yield reduction terms. The equation is linear, and the model can be solved as a quadratic programming (QCP) problem.

$$IYRYV_{fpu,j} = \prod_{m|Ky_{fpu,j,m}} (1 - IYRMV_{fpu,j,m}) \tag{E.30a}$$

$$IYRYV_{fpu,j} = \begin{cases} 1 - \frac{\sum_m \left(KyMod_j \times Ky_{fpu,j,m} \times IYRMV_{fpu,j,m}\right)}{\sum_m \left(KyMod_j \times Ky_{fpu,j,m}\right)} & \text{if } \sum_m Ky_{fpu,j,m} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{E.30b}$$

$$IYRYV_{fpu,j} = \prod_{m|Ky_{fpu,j,m}} (1 - IYRMV_{fpu,j,m})^{wKy_{fpu,j,m}} \tag{E.30c}$$

where

$IYRYV$ = Annual irrigated yield multiplier
$IYRMV$ = Monthly irrigated yield reduction rate
Ky = Monthly crop yield coefficient
$KyMod$ = Technology-Specific Yield Sensitivity Mapping

As $IYRMV$ is the rate of reduction in yield by month, so a value of 1 means total crop loss.

[3] As $IYRMV$ is the rate of reduction in yield by month, so a value of 1 means total crop loss.

$IYRYV$ is the annual yield multiplier, so the new yield equals old yield times IYRY, and 1 means no crop loss (see equation E.32).

Crop production is reduced by the value of the yield shock in ICWASM as defined in equation E.31.

$$CProdV_{fpu,j} = IYRYV_{fpu,j} \times YldIrr_{fpu,j} \times AREAC_{j,fpu} \tag{E.31}$$

The objective function of the ICWASM module includes total revenue and a risk-aversion term to dampen changes in allocation of water to crops from the previous year and is represented mathematically by equation E.32. The first term allocates available water to crops to maximize the expected value of output, given water shortages and yield shocks. The second term minimizes the slack variables. Slack variable $IYRMSLKV$ is chosen to ensure $IYRMV \leq 1$.

$$\begin{aligned} OBJV2 = &\sum_{fpu,j} (1 - IYRYV_{fpu,j})^2 \times YldIrr_{fpu,j} \times PP_{fpu,j} \\ &+ 10^4 \times \sum_{j,fpu,m} IYRMSLKV_{fpu,j,m} \end{aligned} \tag{E.32}$$

where

$YldIrr$	=	Irrigated yield
PP	=	Producer prices at the FPU level for the previous year
$IYRMSLKV$	=	Slack variable to ensure $IYRMV \leq 1$

Appendix F

Changelog

IMPACT Changelog

v4.1.4 - Berlin

Description:

Maize price bugfix to maintain maize-wheat price ratio

Updates

- Update to maize IPR (increase by 0.5 percentage points) to fix unrealistic global maize price increase.

v4.1.3 - Bursa

Description:

Bugfix

- `QS00` for `jsbol` in `HND` given half the value of `jsbnt` without which the preloader works but the model doesnt solve
- This version fixes unrealistic calorie values (e.g. in `CRI` from groundnuts)

Updates

- `InputFiles\IMPACT3\IMPACT3_BaseProductionTrade.gdx` updated due to fix in Entropy code which resulted in negative priors.
- `InputFiles\IMPACT3\IMPACT3_IPRsAgrs.gdx` updated to have maize `YLDGR` fix from the IPROverwriting process. The change in `InputFiles\IMPACT3\IMPACT3_BaseProductionTrade.gdx` was causing weird dips in `EGY`.

v4.1.2 - Tunis

Description:

Bugfix

- `PerCapGDP` reporting bugfix (not used in the model but fixed for consistency)

---

v4.1.1 - Guayaquil

Description:

Updates

- `ReportGen` to account for aquatic foods reporting (commodities and activities)

Bugfix

- Bugfix for GLOBE model interation (`hexpdev`)
- Spelling fix in `ReportGen` for one instance of `Sierra Leone` incorrectly written as `Sierra Leon`

---

v4.1.0 - Lima

Description:

2025 Intrinsic Productivity Growth Rate (IPR) update

Updates

- **2025 IPR Updates** [FH+NC]

---

v4.0 - Penang

Description:

IMPACT-FISH

Updates

- Added **aquatic foods** to IMPACT main model

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v3.9 - Valparaíso

Description:

Updated base year from 2020 to 2021

Updates or Bug-Fixes

- Updated `IMPACT3_CCData.gdx` (Fix for spongy climate impact data due to legacy code).
- Update of base year data in IMPACT **(2020 to 2021)**

---

v3.9.0-dev - Georgetown

Description:

Updated base year from 2020 to 2021 [dev]

Updates or Bug-Fixes

- Update of base year data in IMPACT **(2020 to 2021)**

Notes

- Dev flag in this release until bugfix for CCDelta file is committed

---

v3.8.2 - Kyoto

Description:

Hotfix v2 for growth rates in MENA

Updates or Bug-Fixes

- Additional bugfix for 3.8.1 implementation for growth rates in MENA.

---

v3.8.1 - Valencia

Description:

Hotfix for MENA growth rates

Updates or Bug-Fixes

- Bugfix for 3.8.0 implementation for growth rates in MENA. Some activities (dairy, potatoes, other, vegetables and tropical fruits) are excluded for additional shocks in MENA.

---

v3.8.0 - Kavrelis

Description:

MENA-Fix

Updates or Bug-Fixes

- Area and yield growth rates for Middle-East and North Africa

---

v3.7.1 - Sarnora

Description:

hotfix_ 3.7.0

Added

- `wcdc_new`: CAGR to calcualte `wcdc` numbers from 2005 data

Updates or Bug-Fixes

- Hotfix for caluclating `wcdc` in 2020 based in 2005 data using CAGR
- Correct reporting of `wcd_s_fpu` numbers because `wcdc` calcualtion was corrected

---

v3.7.0 - Thornbridge

Description:

Water Fix

Added

- `outflow_coef_version`: Setting to decide if there is a one-to-one relationship for river basin outlows. Setting of `old` preseves one-to-one mapping and restores previous/old behavior in IMPACT. Setting of `new` allows one-to-many mapping. `new` is the current default.
- `outflow_coef` fraction of outflow to downstream FPUs

Updates or Bug-Fixes

- Neighboring cells in `neigb` set

- Updated `INFLWEQ2` equation to account for `outflow_coef` parameter
- Updated `irw` parameter to account for `outflow_coef` parameter

---

v3.6.2 - Reykjavík

Description:

2025 EAT-Lancet

Added

- Planetary health diets (EAT-Lancet 2.0)

Updates or Bug-Fixes

- Fix for waste calculation (moved to overall demand calculation equation)
- Fix for Ozone and Animal productivity shocks (.\InputFiles\Scenarios\SimulationsSetUp.xlsm)

Citation

Mishra, A., Sulser, T.B., Gabriel, S., Cenacchi, N., Dunston, S., Headey, D., Herrero, M., Mason-D'Croz, D. and Wiebe, K., 2025. Affordability and nutritional challenges for the future of EAT diets: an economic modelling analysis. The Lancet Planetary Health, 9(10).

DOI: https://doi.org/10.1016/j.lanplh.2025.101325

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v3.6.1 - Saint Cloud

Citation

Rosegrant, M.W., Wiebe, K., Sulser, T.B, Mishra, A., Cenacchi, N., Willenbockel, D., Dunston, S., Kimura, S and Yao, X. The Future of Food and Agriculture: Scenarios of Increased Public Investments and Policy Reforms for Asia and the Pacific. Asian Development Bank Briefs No. 364.

DOI: https://dx.doi.org/10.22617/BRF250480-2

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v3.4 - Leyton

Description:

Global Food Securty paper

Citation

Rosegrant, M.W., Sulser, T.B., Dunston, S., Mishra, A., Cenacchi, N., Gebretsadik, Y., Robertson, R., Thomas, T. and Wiebe, K., 2024. Food and nutrition security under changing climate and socioeconomic conditions. Global Food Security, 41, p.100755.

DOI: https://doi.org/10.1016/j.gfs.2024.100755

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