[Preliminary Draft

The IMPACT Model: A Global Simulation Modelling System for Analysis of Water-Economy Links in Climate Change Scenarios

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Table of Contents

Introduction 1
IMPACT model 2
Crop Production 2
Demand 4
Markets, Trade, and Equilibrium Prices 4
Modularity 5
Water Models 7
IGHM 7
IWSM 8
Water Demand 8
Water Supply 9
ICWASM 10
Linking the IMPACT Water and Multimarket Models 11
Scenario Analysis 13
Climate, Economic, and Demographic Drivers 13
Scenario Results 18

Introduction

This paper describes a linked, modular, system of models called IMPACT that includes global economic and water models to explore the impact of different irrigation investment scenarios under changing conditions of water availability (e.g., climate shocks, ground water shortages).[1] The paper will describe recent advances in version 3 of the model used in this analysis. The core economic model is a global, partial-equilibrium, multimarket model that focuses on agriculture. The multi-market model is linked to a set of water models (hydrology, water basin management, and water stress) for this analysis. The modular framework combines the strengths of the component economic and water models, without having to make compromises typical of water

[1] The description of the IMPACT model in this paper draws heavily on Robinson et al. (2015).

models that incorporate simple economics or economic models that include water in a simplified manner.

We next describe the components of the IMPACT model system and then present results from a set of simulations that include a variety of climate scenarios, focusing on the role of water.

IMPACT model

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

In IMPACT, the core global multimarket economic model simulates the operation of national and international markets, solving for production, demand, international trade, and prices that equate supply and demand of agricultural products across the globe. The core model is linked to a number of "modules" that include climate models (Earth System Models, ESMs), water models (hydrology, water basin management, and water stress models), crop simulation models (e.g., Decision Support System for Agrotechnology Transfer [DSSAT]), value chain models (e.g., sugar, oils, livestock), and land use (pixel-level land use, cropping patterns by regions). The integration of separate water models and the focus on crop technology using crop simulation models is especially useful in our analysis of the impact of investment in expanding irrigated land and improving the efficiency of irrigation systems under different scenarios of climate change and water shortages.

The IMPACT model system integrates information flows among the component modules in a consistent equilibrium framework that supports longer-term scenario analysis. Some of the model communication is one way, with no feedback links (for example, climate scenarios to hydrology models to crop simulation models), while other links require capturing feedback loops (for example, water demand from the core multimarket model and water supply from the water models must be reconciled to estimate water stress impacts on crop yields).

Crop Production

Crop production in IMPACT is simulated through area[2] and yield response functions. The choice of specifying crop production in this way has a long history in IMPACT and facilitates interaction with commodity experts and land-use specialists, who work in natural units (hectares, tons per hectare). Crop production in IMPACT is specified subnationally with the area and yield functions at the level of FPUs. This regional disaggregation permits linking with water models

[2] 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.

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

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

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

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

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

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

Demand

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

Food demand is a function of the price of the commodity and the prices of other competing commodities, per capita income, and total population. Per capita income and population increase annually according to country-specific population and income growth rates. Population and gross domestic product (GDP) trends vary by scenario and are drawn from the Shared Socio-economic Pathway (SSP) database representing socioeconomic scenarios from IPCC's

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

Intermediate demand is a derived demand that is based on the demand for final processed goods, such as food oils and sugar. Input-output coefficients determine the proportions of input commodities required for each producing activity.

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

Other demand summarizes all other demands for agricultural products from sectors outside of the focus of IMPACT (for example, seeds, industrial use). It is simulated under two equations. The primary method follows the household food demand equation and is sensitive to changes in income, population, and prices.The second method is used in a few cases where other demand historically has not shown much of a response to prices and is instead a function of changes in per capita GDP from the previous year.

Markets, Trade, and Equilibrium Prices

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

National production and demand for tradable commodities are linked to world markets through trade. Commodity trade by country 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.

Base-year prices are calibrated in constant 2005 US dollars. Domestic prices of tradable commodities are a function of world prices, adjusted by the effect of trade policy represented by taxes and tariffs, and price policies are expressed in terms of producer support estimates (PSEs), consumer support estimates (CSEs), and the cost of moving products from one market to another represented by marketing margins (MMs). Export taxes and import tariffs are drawn from data from the Global Trade Analysis Project at Purdue University and reflect trade policies at the national level. PSEs and CSEs represent public policies to support production and consumption by creating wedges between world and domestic prices. PSEs and CSEs are based on Organisation for Economic Co-operation and Development (OECD) estimates and are adjusted by expert judgment to reflect regional trade dynamics (OECD 2014). MMs reflect other factors such as transport and marketing costs of getting goods to various markets and are based on expert opinion on the quality and availability of transportation, communication, and market infrastructure

Modularity

In the redesign of IMPACT 3, great effort was made to implement best practices in software design not only to widen the domain of applicability of the model (that is, more commodities, countries, and features) but also to create a model that is transparent and flexible, allowing for easier future model updates and improvements. A key feature in the new code is modularity, breaking up of the software into separate and addressable components that are integrated to address specific problems. Modular software design has many benefits that not only improve the quality of the software code but also facilitate future software development. Some of the key benefits of modular design include:

- It facilitates breaking down complex problems into smaller and easier-to-solve subproblems.
- It allows for parallel and distributed model development, with many modelers working on different subproblems simultaneously.
- It allows for different modules, in various combinations, to be used to solve different problems.

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

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

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

In IMPACT, the set of water models are designed as separate modules that can be run independently of the IMPACT multimarket model, but are also integrated with the multimarket model through two-way information flow. The details of the specification are discussed next.

Water Models

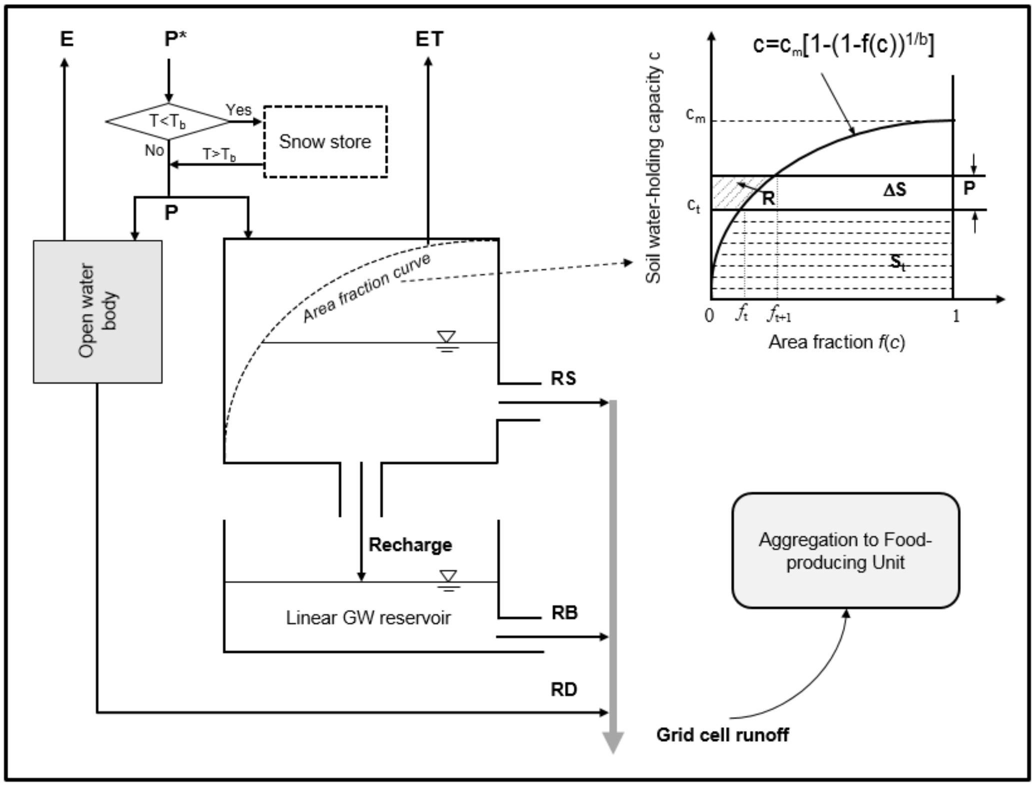
The water models in the IMPACT Modeling System include (1) the IMPACT global hydrology model (IGHM) that simulates snow accumulation and melt and rainfall-runoff processes, (2) the IMPACT water basin simulation model (IWSM) that simulates operation of aggregate surface water reservoir and water supplies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

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

IGHM

As described in the following schematic (Figure 1), IGHM is a semi-distributed parsimonious model. It simulates monthly soil moisture balance, evapotranspiration, and runoff generation on each 0.5˚ latitude by 0.5˚ longitude grid cell spanning the global land surface except the Antarctic. Gridded output of hydrological fluxes—namely, effective rainfall, evapotranspiration, and runoff—are spatially aggregated to FPUs within the river basin and weighted by grid cell areas.

Figure 1—IMPACT global hydrology model schematic illustrating vertical water balance of the land and open water fraction of a grid cell



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

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

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

IWSM

Water Demand

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

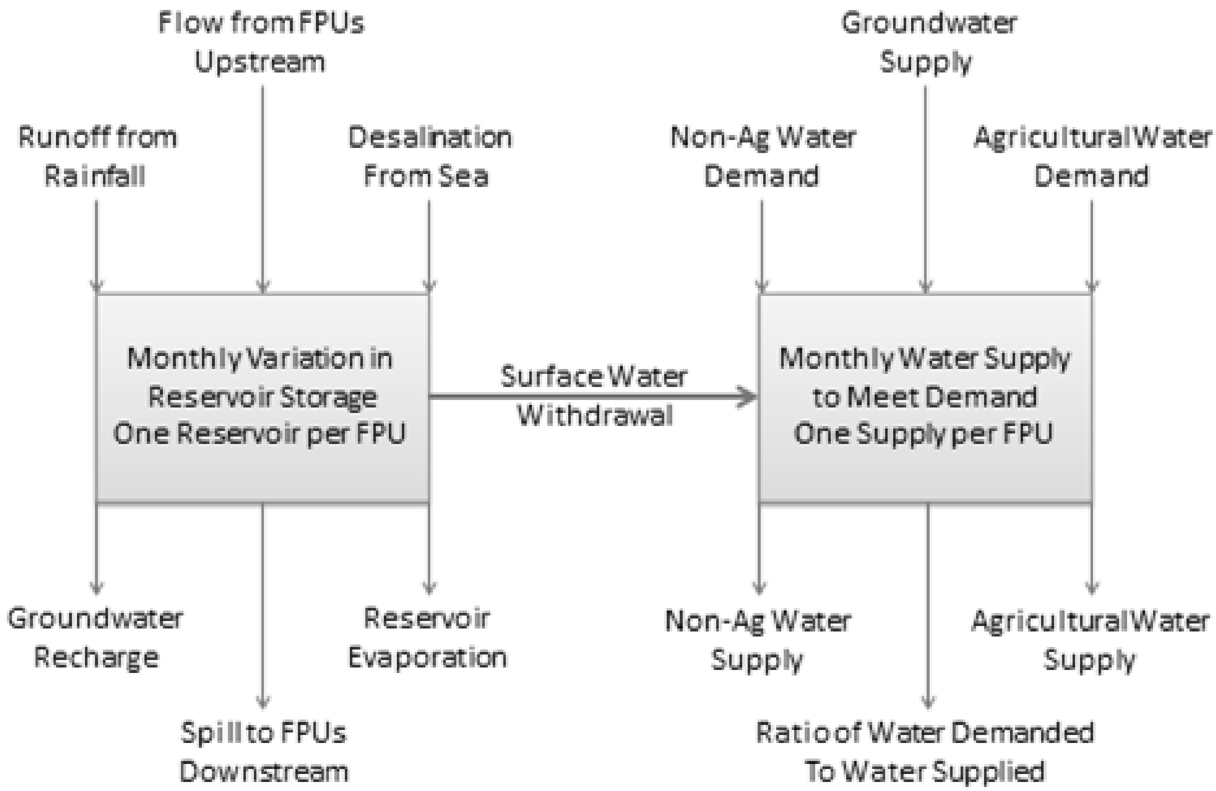
Industrial water demand is modeled for the manufacturing and energy sectors using growth rates for the value-added by sector and energy production values for the electricity sector from the Emissions Prediction and Policy Analysis Model version 6 (EPPA6) of the MIT Joint Program on the Science and Policy of Global Change (Chen et al. 2015). For countries in Africa south of the Sahara industrial water demand is modeled as a nonlinear function of gross domestic production per capita and technology change.

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

Water Supply

IWSM is a water basin management model. For FPUs where there is surface water storage capacity (for example, dams), the model specifies a single reservoir that summarizes all water storage capacity. For a given water basin that includes more than one FPU, IWSM manages storage in all those FPUs to maximize the ratio of water supply to water demand in the water basin. IWSM uses the runoff calculated by IGHM, the climatic data, and the water demands presented above to allocate available water to different uses. The schematic in Figure 2 provides an overview of the model. In each FPU, IWSM solves for a balance between the change in the amount of water stored in the reservoirs, the entering water flows (runoff from precipitation, water from nontraditional sources such as desalination, and inflows from FPUs situated upstream), the exiting water flows (groundwater recharge from the stream, evaporation from the reservoirs, outflows to the FPU downstream or the ocean), and the water withdrawn for human use (surface water depletion). The model uses a simple hedging rule to avoid leaving empty storage for the next year.

Figure 2—IMPACT water basin simulation model



Source: Authors.

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

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

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

ICWASM

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

Linking the IMPACT Water and Multimarket Models

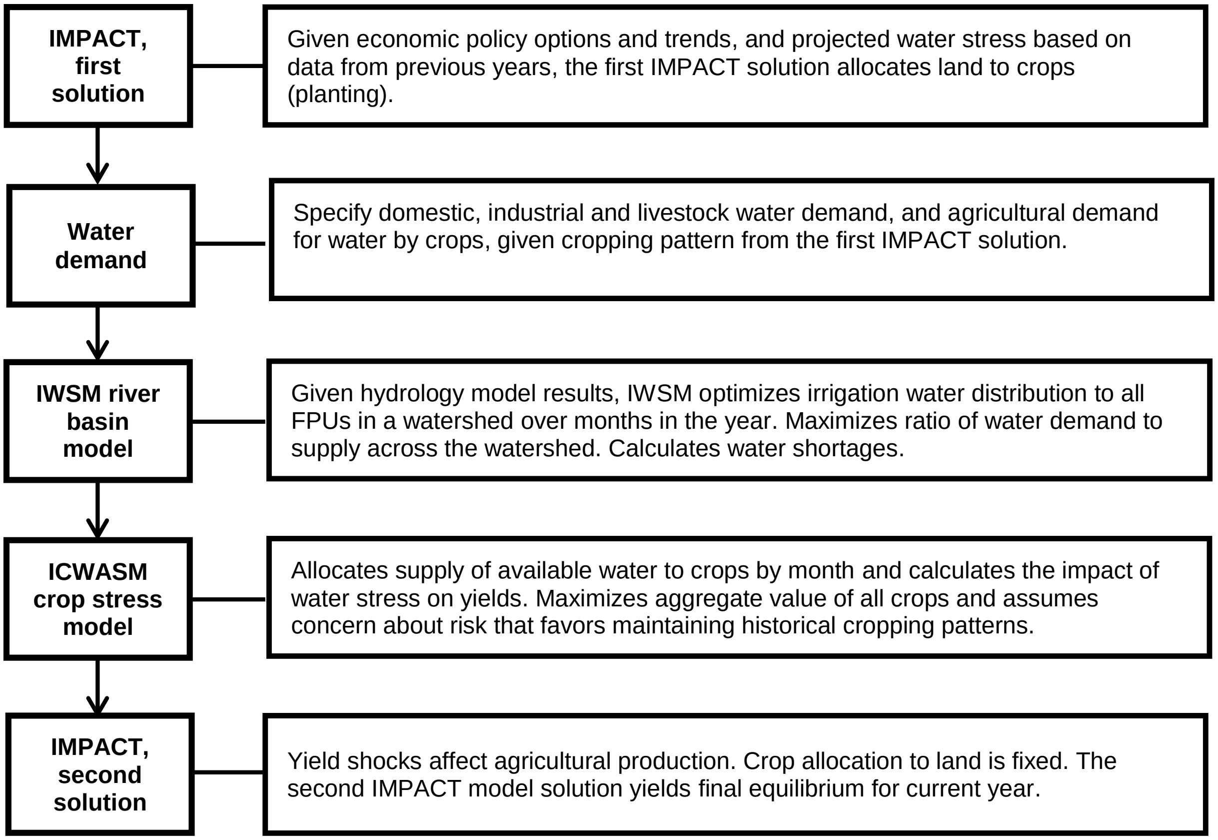
Communication between the water models and the multimarket model is shown in Figure 3. In a given year, the IMPACT multimarket model is first solved assuming exogenous trends on various parameters, yielding projected production, prices, and allocation of land to crops. For this first run, expected water stress is set to the average of the previous four years, which sets harvest expectations for the allocation of land to different crops. This solution can be seen as providing projections that farmers use to make their cropping decisions.

The water demand module then calculates water demand for crops, industry, households, and livestock. Agricultural and nonagricultural water demands are then calculated as outlined above. IWSM (Figure 5.6) uses these water demands, along with river flows provided by IGHM (Figure 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 3—Linking IMPACT to water models: Dynamic two-way communication year by year



Source: Authors.

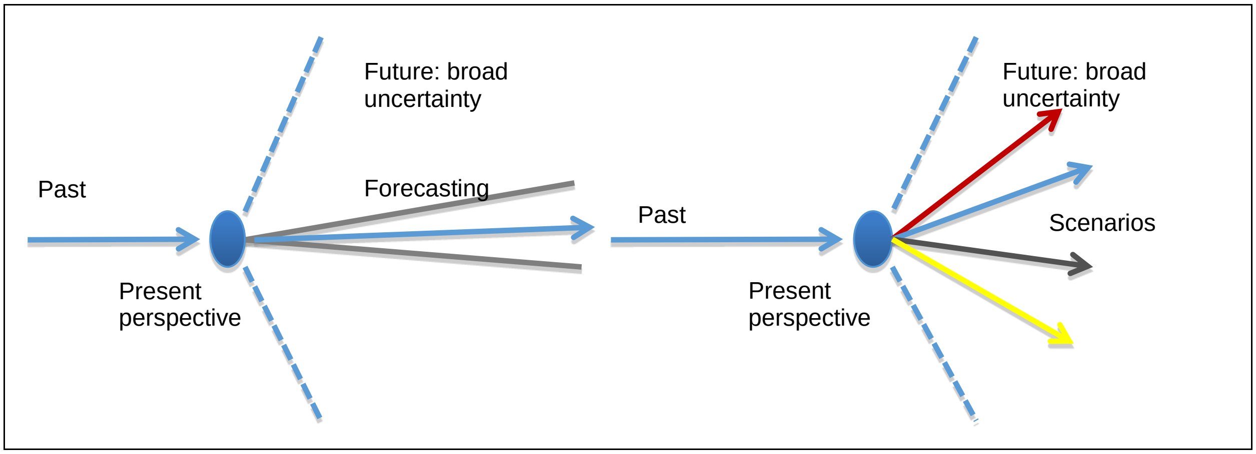
Note: FPUs = food production units; IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade; IWSM = IMPACT water basin simulation model; ICWASM = IMPACT crop water allocation and stress model.

Scenario Analysis

In this section, we present simulation results for a variety of climate scenarios, focusing on the role of water.

Ex ante analysis of global agricultural markets several decades into the future requires a flexible, scenario-based approach that involves specification of the impacts of long-run drivers (such as changes in population, income, consumer behavior, climate, and technology development) whose nature is highly uncertain. Scenario analysis is a powerful analytical tool that allows policymakers to explore plausible futures in a systematic manner, considering future uncertainties. Scenario analysis is distinct from forecasting in that the objective is not to predict the most likely outcome (usually extrapolating from historical experience). Instead, scenario analysis focuses on system dynamics, generating logically consistent future pathways that include trends and nonlinear interactions that may deviate significantly from past experience. Figure 4 illustrates the difference in the range of possibilities that are considered in scenario analysis versus traditional forecasting.

Figure 4 Forecasting versus scenario analysis

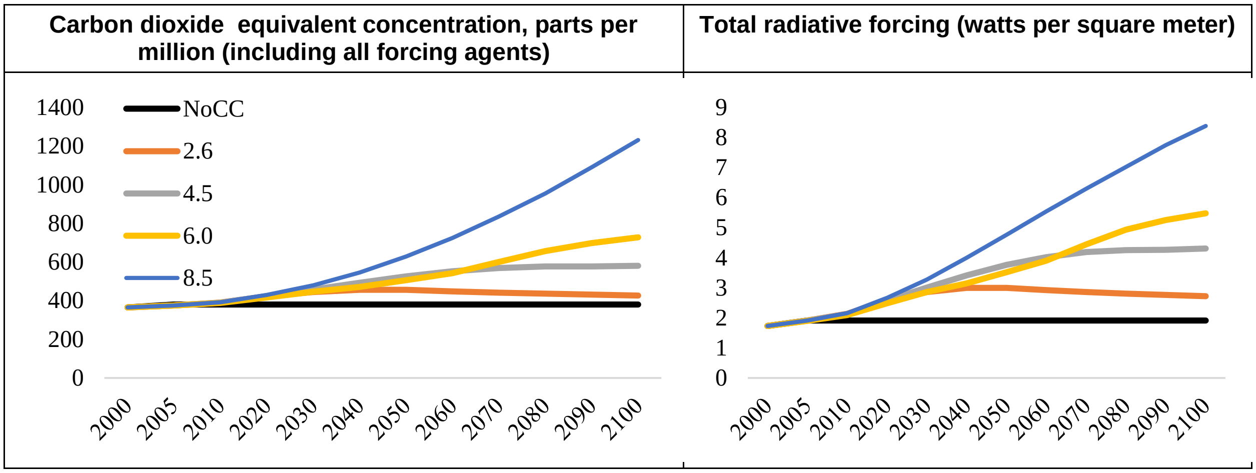


Source: Vervoort et al. (2013).

Climate, Economic, and Demographic Drivers

Our scenarios start from different assumptions about the drivers of climate change. First, Representative Concentration Pathways (RCPs) describe alternative future climates depending on the levels of greenhouse gas emissions that may be observed in the 21st century. although similar to SSPs, in IMPACT the projection period is only to 2050. We consider four RCPs, which are named according to approximate level of radiative forcing in 2100, which ranges from 2.6 watts per square meter (W/m^2) to 8.5 W/m^2. These RCPs are quantified to 2100, but we only do projections to 2050. Second, economic and population drivers are quantified in Shared Socioeconomic Pathways (SSPs). There are five SSPs defined by the IPCC—we use SSP 2, which is a “middle of the road” scenario in terms of population and GDP growth. We also include a baseline scenario with historical climate (sometimes also referred to perfect mitigation or no climate change), where historical climate conditions in 2005 are assumed to continue throughout the projection period. While this assumption is not realistic (greenhouse gas emissions have continued to increase since 2005), it is similar to the RCP 2.6 scenario and provides a useful counterfactual baseline to isolate the effects of climate change from other assumptions. Figure 5 illustrates the range of climate scenarios currently available in IMPACT.

Figure 5 Comparing carbon dioxide concentration and radiative forcing assumptions for RCPs



Source: RCP data downloaded from the RCP Database, version 2.0.5 (International Institute for Applied Systems Analysis 2015); RCP 2.6: van Vuuren et al. (2006); van Vuuren et al. (2007); RCP 4.5: Clark et al. (2007); Smith and Wigley (2006); Wise et al. (2009); RCP 6.0: Fujino et al. (2006); Hijioka et al. (2008); RCP 8.5: Riahi, Gruebler, and Nakicenovic (2007).
Note: NoCC = no climate change or perfect mitigation scenario used in International Model for Policy Analysis of Agricultural Commodities and Trade.

The consequences of this radiative forcing leads to increasing temperature, which in turn leads to greater glacier melt and rising sea levels. The projected global warming and sea level rise of the RCPs are summarized in Table 1.

Table 1 Likely range of global warming and sea level rise, by RCP

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

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

Traditionally, analysis with IMPACT has used the most extreme climate scenarios to provide an envelope of potential climate impacts on agriculture (see Nelson et al. 2010; Nelson et al. 2013; Nelson et al. 2014). This strategy has the added benefit of maintaining a larger possibility space to test policies under climate change through 2050. As the three lower RCPs do not diverge significantly by midcentury in either increases in radiative forcing (3 to 3.7 W/m^2) or temperatures (0.4–2.0°C), using the no climate change scenario and RCP 8.5 provides a broader climatic range from 1.9 W/m^2 to 4.8 W/m^2 and of temperature from 0.0 to 2.6°C.

Each RCP represents global climate change through the role of greenhouse gas emissions and radiative forcing. This is just one physical dynamic that determines climate and weather. To simulate all of these systems that determine climate and to provide weather as inputs to crop models, the RCPs must be simulated in Earth System Models (ESMs).[3] The ESMs are complex models that simulate earth's biogeochemical cycles and combine modules that simulate physical climate, atmospheric circulation, and ocean and ice dynamics. Each ESM has somewhat different assumptions about how each of these complex dynamics works and interacts, which means that each ESM's realization of the RCP will be somewhat different. This diversity of results creates model uncertainty, as it is not possible to determine which ESM realization is more likely. To better handle this uncertainty, and to expand the climate possibility space in which IMPACT scenarios can be tested, it was decided to use multiple ESM realizations of each RCP and allow the use of a multimodel ensemble to test climate uncertainty.

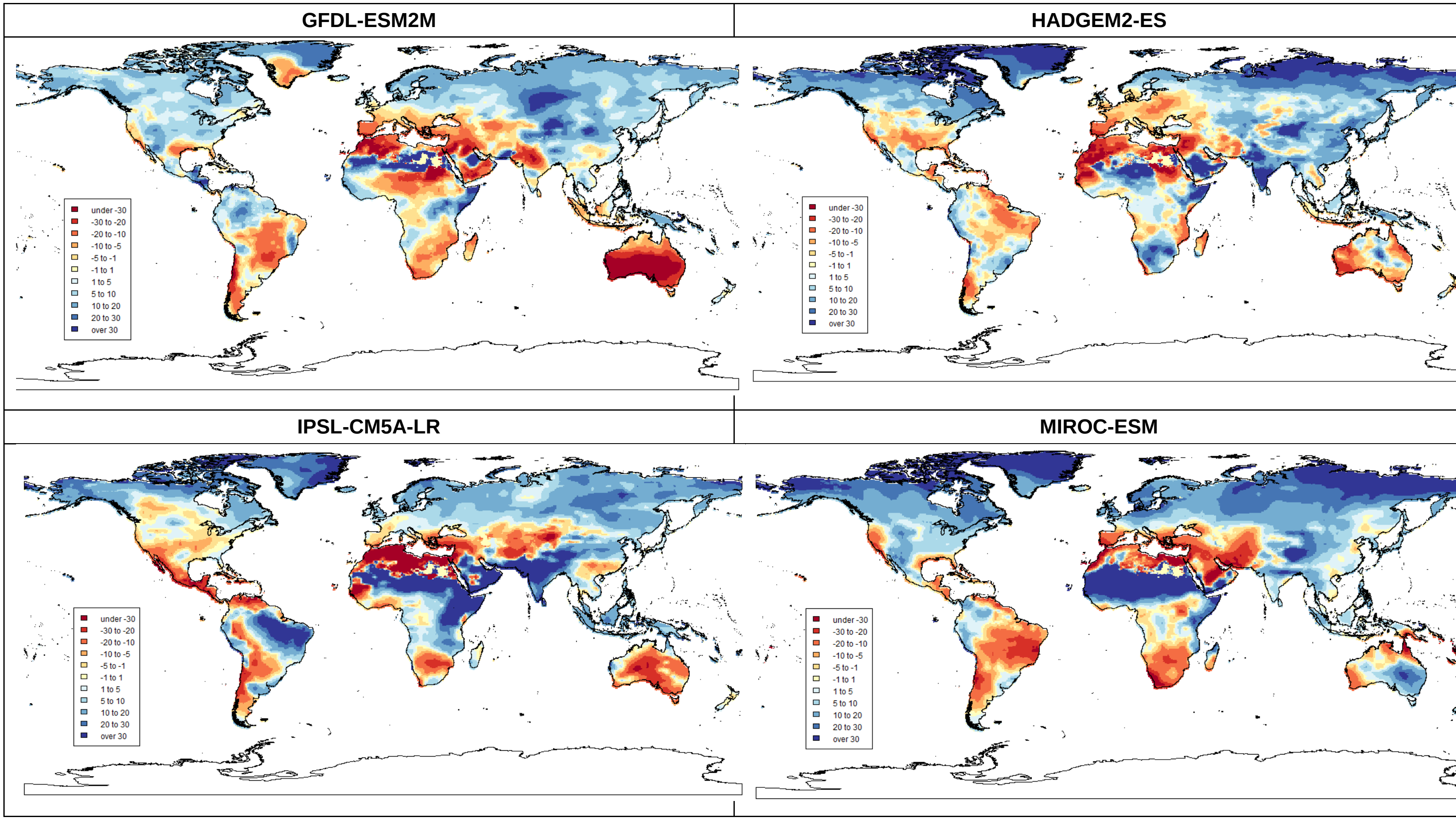
The ESMs, which are currently used to provide climatic data to the Decision Support System for Agrotechnology Transfer crop models are the following:

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

These four ESMs were selected because these modeling teams had participated in several major modeling projects as part of Coupled Model Intercomparison Project (Taylor et al. 2012) for the IPCC's fifth assessment report, the Inter-sectoral Impact Model Intercomparison Project (ISI-MIP), and the Agriculture Model Intercomparison and Improvement Project (AgMIP). This participation has meant that all of the results are processed and shared in the same format, allowing for better standardization of data processing and handling for use in crop models. Agriculture is dependent on weather, which is local. Using these four ESMs allows us to test regional uncertainties with respect to climate change as different assumptions across models provide us with different projections of key climatic data such as precipitation and temperature. Figures 6 and 7 illustrates how these four ESMs can project different 2050 weather conditions for different regions.

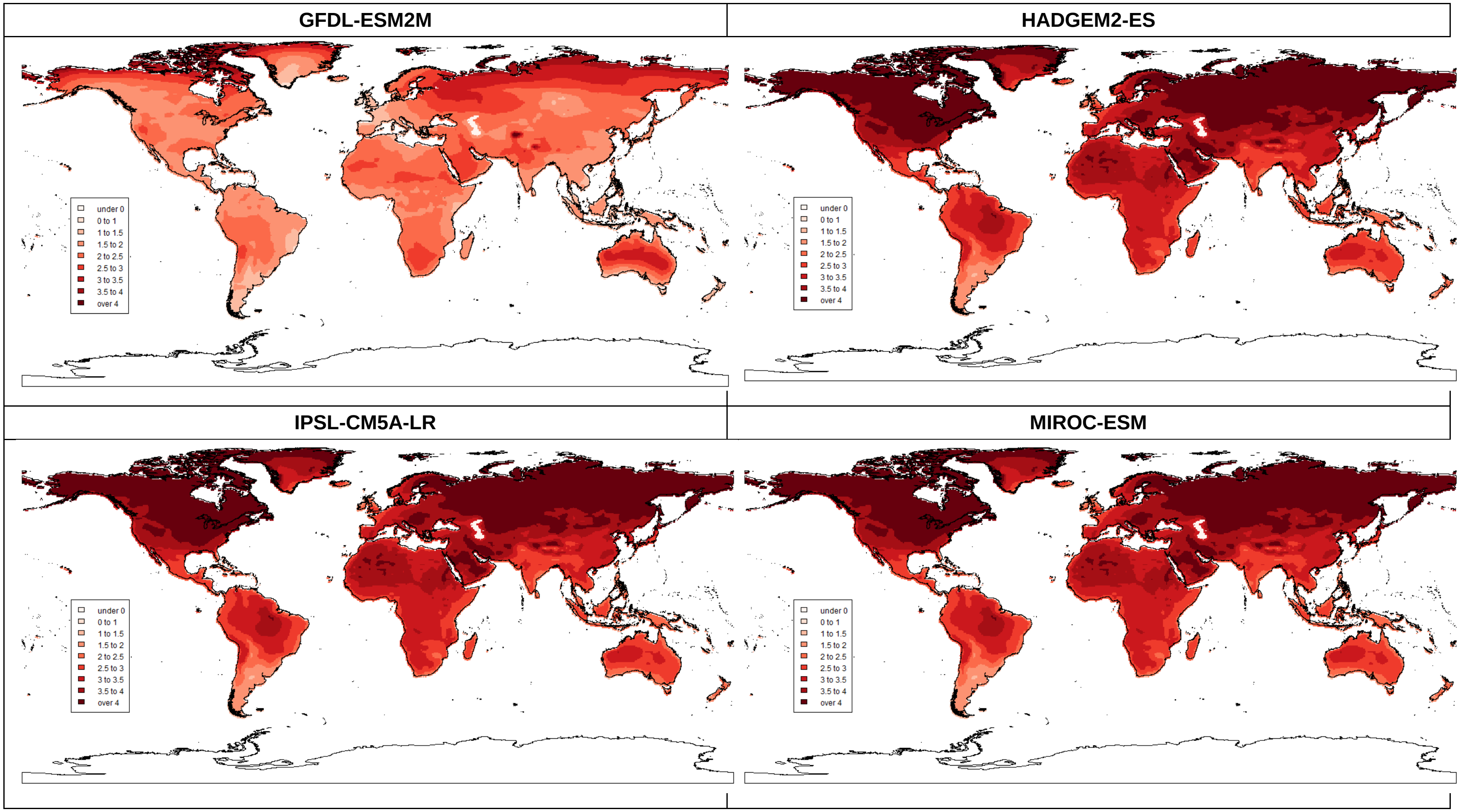
[3] ESMs were formerly called *General Circulation Models.*

Figure 6 Changes in annual precipitation in 2050 compared to 2000 (millimeters) according to four Earth System Models using RCP 8.5



Source: Compiled by authors.

Figure 7 Changes in maximum temperature in 2050 compared to 2000 (°C) according to four Earth System Models using RCP 8.5



Source: Compiled by authors.

Scenario Results

[To be added]