INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
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International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)

Model Description

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[1] See Appendix 2 for a full description of the IMPACT Development Team.
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INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

The International Food Policy Research Institute (IFPRI) was established in 1975 to identify and analyze national and international strategies and policies for meeting the food needs of the developing world on a sustainable basis, with particular emphasis on low-income countries and on the poorer groups in those countries. IFPRI is a member of the CGIAR Consortium.

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This Report has been prepared as an output of the International Model for Policy Analysis of Agricultural Commodities and trade (IMPACT). While the report has not been peer reviewed, the IMPACT model has undergone peer review. Any options stated herein are those of the author(s) and do not necessarily reflect the policies or opinions of IFPRI.

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INTRODUCTION

The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) was developed at IFPRI at the beginning of the 1990s to address a lack of long-term vision and consensus among policy-makers and researchers about the actions that are necessary to feed the world in the future, reduce poverty, and protect the natural resource base. In 1993, these same long-term global concerns launched the 2020 Vision for Food, Agriculture, and the Environment Initiative which created the opportunity for further development of the IMPACT model. 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) in which the effects of population, investment, and trade scenarios on food security and nutrition status, especially in developing countries, were analyzed.

IMPACT continues to serve as the basis for research examining the linkage between the production of key food commodities and food demand and security at the national level in the context of scenarios of future change. Studies focus on regional issues, commodity-level analyses, and cross-cutting thematic issues. IMPACT is also embedded in a variety of major global assessments to complement interdisciplinary, scenario-based work on the future of food supply and demand. The first comprehensive set of results for IMPACT were published in the book *Global Food Projections to 2020* (Rosegrant et al. 2001). These projections—which were presented in 2001 at the IFPRI-sponsored conference in Bonn entitled: *Sustainable Food Security for All by 2020*—are presented with details on the demand system and other underlying data used in the projections work, and cover both global and regionally-focused projections. A complete list of the research published using the IMPACT modeling framework is provided in Appendix 1, including reports for international organizations, such as the World Bank, the Asian Development Bank, the FAO, and national governments.

The IMPACT model has also been employed in regional studies, such as the *Asian Economic Crisis and the Long-Term Global Food Situation* (Rosegrant and Ringler 2000) and *Transforming the Rural Asian Economy: the Unfinished Revolution* (Rosegrant and Hazell 2000), which were both written in response to the Asian financial crisis of 1997 and which try to assess its impact on the regional food economy. Sulser et al. (2011) focused on an analysis of rising food security issues in the Arab region. One of the more popular discussion papers from the IMPACT team was the contribution to the 2020 Vision conference in Kampala on “Assuring Food and Nutrition Security in Africa by 2020” (Rosegrant et al. 2005).

Examples of commodity-focused studies can be found in the paper looking at the relationship between meat-intensive diets in developed nations and food security in developing countries, Alternative Futures for World Cereal and Meat Consumption (Rosegrant et al. 1999); or the article Global Projections for Root and Tuber Crops to the Year 2020 (Scott et al. 2000), which gives a detailed analysis of roots and tuber crops and their importance to the food economies of the poor. The report Livestock to 2020: The next food revolution (Delgado et al. 1999) assesses the rise in livestock demand in developing countries that was trigged by rising incomes in recent decades, and considers the current and expected future developments of this “livestock revolution”, as well as its implications for policy. IMPACT also provided the first comprehensive policy evaluation of global fishery production and projections for demand of fish products in the book *Fish to 2020: Supply and Demand in Changing Global Markets* (Delgado et al. 2003).

Ongoing research has also expanded the set of agricultural commodities to 44, which include oilseeds, such as groundnuts, soybeans, and rapeseed, as well as cotton, and major dryland grains and pulses, such as sorghum, millet, chickpeas, and pigeonpeas. Given the prominence of many of dryland crops in the semi-arid tropics and their important linkage to livestock through feed, along with other fodder crops, we felt these additions were necessary to fully understanding the drivers behind projected future growth in global oil, meat, and milk demand. The importance of many of these commodities in global water demand also warranted their full inclusion into the model.

One of the primary thematic issues that became a focus of IMPACT studies was the recognition that the long-term change in water demand and availability—and particularly the rapidly increasing demand in non-agricultural water uses—as well as the year-to-year variability in rainfall and runoff would affect future food production, demand, and trade led to an effort on the part of IFPRI and partner collaborators to make more explicit linkages between food production and water availability in an integrated modeling framework. The result of this research has led to the development of the IMPACT-WATER model, which integrates the primary IMPACT model with a water simulation module (IWSM) that balances water availability and uses within various economic sectors at the global and regional scale.

IMPACT-WATER[3]—through the combination of the IMPACT and IWSM models—incorporates water availability as a driving variable with observable flows and storage to examine the impact of water on

[3] For the sake of ease in documentation and citations and because IMPACT-WATER forms the basis for all work with this model, we will simply refer to the current model as IMPACT—not to be confused with the older model which lacks integration with IWSM.

food supply, demand, trade, and prices. This framework allows exploration of the relationship between water availability and food demand at trade at a variety of spatial scales ranging from river basins, countries, and more aggregated regions, to the global level. Water supply and demand and crop production are first assessed at the river-basin scale and crop production is then summed to the national level where food demand and trade are modeled. While the earlier IMPACT model divided the world into 36 countries and regions, the model was further disaggregated to 281 "food-producing units," (FPUs) which represent the spatial intersection of 115 economic (mostly geo-political) regions and 126 water basins out of recognition of the fact that significant climate and hydrologic variations within regions make the use of large spatial units inappropriate for water resource assessment and modeling. Of the countries represented within the IMPACT-WATER model, China, India, and the United States (which together produce about 60 percent of the world's cereals) have the highest level of sub-national disaggregation and are divided into 9, 13, and 14 major river basins, respectively, while the other countries or regions considered in IMPACT are combined into the remaining 90 basins (see Appendix 5 for further details).

Key publications with the joint water-food projections model include the IFPRI-IWMI book titled *World Water and Food to 2025: Dealing with Scarcity* (Rosegrant et al. 2002) as well as a series of journal articles (Rosegrant 2002; Cai and Rosegrant 2002). To assess the impact of climate change on food supply and demand, the IMPACT Global Hydrologic Model (IGHM) was developed in the early 2000s (Zhu et al. 2012). The IGHM hydrological model is a semi-distributed model outputting hydrological fluxes including effective rainfall (for calculating net irrigation water requirement in the IWSM), potential and actual evapotranspiration, and runoff, which are then spatially aggregated to the FPUs of IMPACT weighted by grid cell areas and then incorporated into the IWSM.

Following on the model developments specifically focused on water, representation of the growing biofuels sector and the specific impacts climate change rose as critical themes. The work on biofuels resulted in two highly-cited works by (Rosegrant 2008) and (Rosegrant et al. 2008) that provided critical, forward-thinking insight into the sudden shocks in agricultural markets happening at that time. The complexities of climate change impacts on agriculture led to the development of a system of modeling interconnections among large-scale climate models; biophysical, process-based models that represent plant-specific responses to changes in climate; and an enhanced IMPACT model set up to deal with an ever-expanding set of scenarios of plausible futures. Details on the climate side of IMPACT are thoroughly documented in (ADB and IFPRI 2009) and (Nelson et al. 2010).

The IMPACT model has also been used in various global assessment studies. The Millennium Ecosystem Assessment (MA 2005), the International Assessment of Agricultural Science and Technology for Development (IAASTD 2009), the Global Environment Outlook (UNEP 2007, 2012), the World Development Report 2008: Agriculture for Development (World Bank 2007), and the CGIAR's Strategic Results Framework (SRF 2009) that formed the basis for priority exercises embedded in the CGIAR reform process.

The next section discusses the food and water components of the IMPACT model, including a technical description that shows the equations and the sources of the data used in the model. A general overview of the countries/regions and commodities is given in Appendix 3, Appendix 4, and Appendix 6 while the definitions of the river basins are shown in Appendix 5. A schematic overview of the integrated modeling framework is given in Appendix 10.

THE MODEL

Basic Methodology on Food

The food sub-module is a system of equations offering a methodology for analyzing baseline and alternative scenarios for global food demand, supply, trade, income, and population. The food sub-module encompasses 115 geopolitical regions (see Appendix 3) and 126 hydrological basins (see Appendix 5) in the world. The intersection of these two geographical layers creates 281 food production units (FPUs) (see Appendix 11). IMPACT models 44 main agricultural commodities produced in the world (see Appendix 6). Within each region supply, demand, and prices for agricultural commodities are determined. All regions are linked through trade.

Supply and demand functions incorporate elasticities to approximate the underlying production and demand. World agricultural commodity prices are determined annually at levels that clear international markets.

<u>Food Supply</u>

Crop Production

Domestic crop production at the FPU-level is determined by area and yield response functions separately for irrigated and rainfed cultivation. Harvested area[4] is specified as a response to the crop's own price, the prices of other competing crops, the projected rate of exogenous (non-price) growth

[4] Harvested area is the total area planted and harvested within a year, which may include multi-cropping or multiple harvests and differ from total arable land or reported physical area within a region.

trends in harvested area, and water (Equation 1). The projected exogenous trend in harvested area captures changes in area resulting from factors other than direct crop price effects, such as expansion through population pressure and contraction from soil degradation or conversion of land to nonagricultural uses. Assumptions for exogenous trends are determined by a combination of historical changes in land use and expert judgment on potential future regional dynamics.

Commodity yield is a function of the commodity prices, the prices of inputs, available water, and a projected non-price exogenous trend factor. The trend factor reflects productivity growth driven by technology improvements, including crop management research, conventional plant breeding, wide-crossing and hybridization breeding, and biotechnology and transgenic breeding. Other sources of growth considered include private sector agricultural research and development, agricultural extension and education, markets, infrastructure, and irrigation, and water (Equation 2). Water usage and climate change effects are embedded into the IMPACT model, through adjustments to the generic crop area and yield functions (see Equation 4). Annual production of commodity *i* in country *n* is then estimated as the product of its area and yield (Equation 3).

Equation 1 Area response

$$AC_{tni} = \alpha_{tni} \times (PS_{tni})^{\varepsilon_{iin}} \times \prod_{j\neq i}\left(PS_{tnj}\right)^{\varepsilon_{ijn}} \times (1 + gA_{tni}) \quad (1)$$

Equation 2 Yield response

$$YC_{tni} = \beta_{tni} \times (PS_{tni})^{\gamma_{iin}} \times \prod_{k}(PF_{tnk})^{\gamma_{ikn}} \times (1 + gCY_{tni}) \quad (2)$$

Equation 3 Production

$$QS_{tni} = AC_{tni} \times YC_{tni} \quad (3)$$

where,

AC	=	crop area
YC	=	crop yield
QS	=	quantity produced
PS	=	effective producer price
PF	=	price of inputs k (e.g. labor and fertilizer)
$\prod$	=	product operator
i, j	=	commodity indices specific for crops
k	=	inputs such as labor and capital
n	=	country index
t	=	time index
gA	=	growth rate of crop area
gCY	=	growth rate of crop yield
ε	=	area price elasticity
γ	=	yield price elasticity
α	=	crop area intercept

β = crop yield intercept

Supply elasticities are broken up area, and yield elasticities. Crop area elasticities simulate the supply response to changes in own-commodity and competing commodity prices. Own-price area elasticities of supply for most products in developing countries are approximately two-thirds of those in the developed countries, reflecting the difficulties that producers in developing countries face in access to markets, information, and technology. Crop yield elasticities simulate the supply response of cropping intensity with respect to changes in crop prices, the cost of labor, and the cost of inputs. The absolute values of yield elasticities with respect to own-price, capital and labor add up to the crop price elasticity.

Incorporation of Water into Crop Production

Over time the water available for crop production varies due to changes in demographics, climate, and competing demand for water from other sectors of the economy. The effects of water stress on irrigated and rainfed crop production are handled differently in the model.

Irrigated Crop Production

Area

The effect of water stress on irrigated crop area comes from the DSSAT suite of crop models and analysis. Using location specific information on climate, soils, and nitrogen application, growth of each crop is simulated in the initial year of analysis assuming a current-but-randomly-generated climate for temperature and precipitation. The DSSAT analysis then applies the localized temperature and precipitation effects and simulates crop growth again, noting changes in yields, area, and production when compared to the initial simulation of current climate for temperature and precipitation. For irrigated area, only the negative effects from changes in temperature and precipitation are considered.

Yield

Total irrigation water supply is allocated to crops according to crop water requirements incorporating changes in the hydrological cycle, including precipitation, runoff, and crop-specific potential evapotranspiration. The effect of water stress on irrigated crop yield is calculated through shifting the intercepts of the initial irrigated crop yields by a water stress factor. This factor is calculated by using a ratio of actual evapotranspiration, ETA, and the maximum potential evapotranspiration, ETM , for the growing season. Both of these are outputs of IMPACT Water Simulation Model (IWSM) described in more detail in later sections. The calculation of the irrigated yield reduction due to water stress is found in Equation 4 and is then incorporated in the calculation of yield intercepts. Additionally, the biophysical effects of climate change modeled by DSSAT effect irrigated yields only through temperature change.

Equation 4 Reduction of crop yield (mt/ha)

$$\Delta YC_j = YC_j \times ky_j \times \left(1 - \frac{ETA_j}{ETM_j}\right) \quad (4)$$

where

ET_a = actual crop evapotranspiration in the crop growth season
ET_m = potential crop evapotranspiration in the crop growth season
YC = Calibrated crop yield
Ky = crop response coefficient to water stress (FAO 1979)

Rainfed Crop Production

Area and Yield

The effect of water stress on rainfed area due to climate change is calculated using the DSSAT suite of crop models—as described above—using changes in precipitation and temperature to simulate future climate.

Incorporation of Climate Change into crop production

The biophysical effects on area and yield from climate change are incorporated into the simulations through the intrinsic productivity growth rates (gCY) and area growth rates (gA) in Equation 1 and Equation 2 and are applied at the FPU-level. The average annual rate of growth or decline of area and yield due to climate change are added to the existing exogenous area and yield growth rates (see Equation 5 and Equation 6).

Equation 5 Climate change and area

$$gA = gA_{PM} + \tau^{a}_{clim} \quad (5)$$

Equation 6 Climate change and crop yield

$$gCY = gCY_{PM} + \tau^{y}_{clim} \quad (6)$$

where

gA_{PM} = Area growth rate without the effects of climate change
gCY_{PM} = Intrinsic productivity growth rates without the effects of climate change
τ^{a}_{clim} = The effect of climate change on area growth rates
τ^{y}_{clim} = The effects of climate change on the intrinsic productivity growth rates

The positive impact of climate change on yields and rainfed area is capped at 30 percent over the 50 year time horizon. The negative impact of climate change on yields and area are limited to -2 percentage points decline of annual growth rates. Irrigated area expansion is assumed to grow only through investment. These assumptions reflect reasonable climate change extremes.

At present, the biophysical effects from climate change are modeled for five IMPACT commodities: rice, wheat, maize, soybean, and groundnut. The effects from these five commodities are mapped to other IMPACT commodities according to their common plant physiology (see Appendix 9).

Livestock Production

Livestock production is modeled similarly to crop production except that livestock yield reflects only the effects of expected developments in technology (Equation 8). Total number of livestock slaughtered is a function of the livestock's own price and the price of competing commodities, the prices of intermediate (feed) inputs, and a trend variable reflecting growth in the livestock slaughtered (Equation 7). Total production is calculated by multiplying the slaughtered number of animals by the yield per head (Equation 10). The price elasticities in the livestock supply function are derived in a similar fashion to the crop area and yield elasticities.

Equation 7 Number slaughtered

$$AL_{tni} = \alpha_{tni} \times (PS_{tni})^{\varepsilon_{iin}} \times \prod_{j \neq i} \left(PS_{tnj}\right)^{\varepsilon_{ijn}} \times \prod_{b \neq i} (PI_{tnb})^{\gamma_{ibn}} \times (1 + gSL_{tni}) \tag{7}$$

Equation 8 Yield

$$YL_{tni} = (1 + gLY_{tni}) \times YL_{t-1,ni} \tag{8}$$

Equation 9 Production

$$QS_{tni} = AL_{tni} \times YL_{tni} \tag{9}$$

where

AL	=	number of slaughtered livestock
YL	=	livestock product yield per head
PI	=	price of intermediate (feed) inputs
i, j	=	commodity indices specific for livestock
b	=	commodity index specific for feed crops
gSL	=	growth rate of number of slaughtered livestock
α	=	intercept of number of slaughtered livestock
ε	=	price elasticity of number of slaughtered livestock
γ	=	feed price elasticity

The remaining variables are defined as for crop production.

Demand

Domestic demand for a commodity is the sum of its demand for food, feed, biofuels, crush, and other uses (Equation 17). Food demand is a function of the price of the commodity and the prices of other competing commodities, per capita income, and total population (Equation 10). Per capita income and population increase annually according to region-specific population and income growth rates as shown in Equation 11 and Equation 12. Population statistics are drawn from the United Nations Population Division World Population Prospects, the 2010 Revision (UN 2011). Regional income growth is based on the World Bank EACC study (Margulis 2010) and updated for Sub-Saharan Africa and south Asian countries. Feed demand is a derived demand determined by the changes in livestock production, feed ratios, and own- and cross-price effects of feed crops (Equation 13). The equation also incorporates a technology parameter that indicates improvements in feeding efficiencies. Demand for feedstock for biofuels production (Equation 14) is derived from the implied demand that various alternatives for the development of ethanol and biodiesel. The crush demand for oilseeds for processing into oils is derived (Equation 15) from the prices of the oil and meal by-product, the oilseed commodity, and the oil- and meal- processing ratios. The demand for other uses is estimated as a proportion of food and feed demand (Equation 16).

Equation 10 Demand for food

$$QF_{tni} = \alpha_{tni} \times (PD_{tni})^{\varepsilon_{iin}} \times \prod_{j \neq i} \left(PD_{tnj}\right)^{\varepsilon_{ijn}} \times (INC_{tn})^{\eta_{in}} \times POP_{tn} \quad (10)$$

Equation 11 Income growth

$$INC_{tn} = INC_{t-1,ni} \times (1 + gI_{tn}) \quad (11)$$

Equation 12 Population growth

$$POP_{tn} = POP_{t-1,ni} \times (1 + gP_{tn}) \quad (12)$$

Equation 13 Demand for feed

$$QL_{tnb} = \beta_{tnb} \times \sum_l (QS_{tnl} \times FR_{tnbl}) \times (PI_{tnb})^{\gamma_{bn}} \times \prod_{o \neq b} (PI_{tnb})^{\gamma_{bdn}} \times (1 + FE_{tnb}) \quad (13)$$

Equation 14 Demand for biofuels

$$QB_{tni} = f(GM_{tni}, EP_{tni}, PSE_{tni}) \quad (14)$$

Equation 15 Crush demand for oilseeds

$$QC_{tnc} = \delta_{tnc} \times \left(\frac{PI_{tno} \times CO_{tnco} + PI_{tnm} \times CM_{tncm}}{PI_{tnc}}\right)^{\varepsilon_{tnc}} \quad (15)$$

Equation 16 Demand for other uses

$$QE_{tni} = QE_{t-1,ni} \times \left(\frac{QF_{tni}}{QF_{t-1,ni}} + \frac{pcGDP_{tn}}{pcGDP_{t-1,n}}\right) \quad (16)$$

Equation 17 Total demand

$$QD_{tni} = QF_{tni} + QL_{tni} + QB_{tni} + QC_{tni} + QE_{tni} \quad (17)$$

where

QD = total demand
QF = demand for food
QL = derived demand for feed
QB = demand for biofuel feedstock
QC = crush demand for oilseeds
QE = demand for other uses
PD = the effective consumer price
INC = per capita income
POP = total population

FR	=	feed ratio
FE	=	feed efficiency improvement
PI	=	the effective intermediate (feed) price
GM	=	government blending mandates
EP	=	energy price
PSE	=	producer subsidy equivalents of both subsidies and trade measures
CO	=	oil crush ratio of oilseeds
CM	=	meal crush ratio of oilseeds
i,j	=	commodity indices specific for all commodities
l	=	commodity index specific for livestock
b,d	=	commodity indices specific for feed crops
c	=	commodity index for oilseed
o	=	commodity index for oil by-product
m	=	commodity index for meal by-product
gI	=	income growth rate
gP	=	population growth rate
ε	=	price elasticity of food demand
γ	=	price elasticity of feed demand
η	=	income elasticity of food demand
α, β, δ	=	Food, Feed, and Crush demand intercepts

The rest of the variables are as defined earlier

The IMPACT demand elasticities are originally based on USDA 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 the elasticities are adjusted to accommodate the gradual shift in demand from staples to high value commodities like meat, especially in developing countries. This assumption is based on expected economic growth, increased urbanization, and continued commercialization of the agricultural sector.

Prices

Prices are endogenous in the system of equations for food, and are calibrated to year 2000 commodity prices (World Bank 2000, 2012). Prices are in constant 2000 US dollars using the World Bank's MUV-Index sheet[5] (World Bank 2000). Domestic prices are a function of world prices, adjusted by the effect of price policies and expressed in terms of the producer subsidy equivalent (PSE), the consumer subsidy equivalent (CSE), and the marketing margin (MI). PSEs and CSEs measure the implicit level of taxation or subsidy borne by producers or consumers relative to world prices and account for the wedge between domestic and world prices. PSEs and CSEs are based on OECD estimates and are adjusted by expert

[5] A proxy for the price of developing country imports of manufactures in U.S. dollar terms, used to assess cost escalation for imported goods. Updated twice a year, the index is a weighted average of export prices of manufactured goods for the G-5 economies, with local-currency based prices converted into current U.S. dollars using market exchange rates. Contains historical data from 1960 through 2007 and projections through 2020.

judgment to reflect regional trade dynamics (OECD 2000). MI reflects other factors such as transport and marketing costs of getting goods to market and is based on expert opinion on the quality and availability of transportation, communication, and market infrastructure. In the model, PSEs, CSEs, and MIs are expressed as percentages of the world price. To calculate producer prices, the world price is reduced by the MI value and increased by the PSE value (Equation 18). Consumer prices are obtained by adding the MI value to the world price and reducing it by the CSE value (Equation 19). The MI of the intermediate prices is smaller because wholesale instead of retail prices are used, but intermediate prices (reflecting feed prices) are otherwise calculated the same as consumer prices (Equation 20).

Equation 18 Producer prices

$$PS_{tni} = PW_i \times (1 - MI_{tni}) \times (1 + PSE_{tni}) \tag{18}$$

Equation 19 Consumer prices

$$PD_{tni} = PW_i \times (1 + MI_{tni}) \times (1 - CSE_{tni}) \tag{19}$$

Equation 20 Intermediate (feed) prices

$$PI_{tni} = PW_i \times (1 + 0.5MI_{tni}) \times (1 - CSE_{tni}) \tag{20}$$

Where

PW	=	the world price of the commodity
MI	=	the marketing margin
PSE	=	the producer subsidy equivalent
CSE	=	the consumer subsidy equivalent

The rest of the variables are as defined earlier.

International Linkage—Trade

Regional production and demand are linked to world markets through trade. Commodity trade by region is a function of domestic production, domestic demand, and stock change (Equation 21). Regions with positive trade are net exporters, while those with negative values are net importers. This specification does not permit a separate identification of both importing and exporting regions of a particular commodity.

Equation 21 Net trade

$$QT_{tni} = QS_{tni} - QD_{tni} + QSt_{tni} \tag{21}$$

where

QT	=	volume of trade
QS	=	domestic supply of the commodity
QD	=	domestic demand of the commodity
QSt	=	change in held stock of the commodity

i = commodity index specific for all commodities

The rest of the variables are as defined earlier.

Algorithm for Solving the Equilibrium Condition

Our systems of equations are written in the General Algebraic Modeling System (GAMS) programming language (GAMS 2012). The solution of these equations is achieved by the PathNLP solver. This procedure minimizes the sum of net trade at the international level and seeks a world market price for a commodity that satisfies Equation 22, the market-clearing condition.

Equation 22 Market clearing conditions

$$\sum_n QT_{tni} = 0 \qquad (22)$$

The world price (PW) of a commodity is the equilibrating mechanism such that when an exogenous shock is introduced in the model, PW will adjust and each adjustment is passed back to the effective producer (PS) and consumer (PD) prices via the price transmission equations (Equation 18-Equation 20). 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.

Basic Methodology on Water Demand and Supply

The IMPACT modeling suite includes two water models, the IGHM and the IWSM.

IMPACT Global Hydrologic Model (IGHM)

The IMPACT GHM hydrological model 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 over the global land surface except the Antarctic. Gridded output of hydrological fluxes, namely effective rainfall (for calculating net irrigation water requirement in the IWSM), potential and actual evapotranspiration, and runoff, are spatially aggregated to FPUs within the river basin, weighted by grid cell areas, and then incorporated into the 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 the IGHM hydrological model. The Priestley-Taylor equation is used to calculate potential evapotranspiration:

Equation 23 Potential evapotranspiration

$$PET = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G) \qquad (23)$$

In Equation 23, *PET* is potential evapotranspiration in mm per day; the value of α is 1.26 for humid climate and 1.74 in arid locations. The humid and arid conditions are defined as having relative humidity above or below 60 percent in the month with peak evapotranspiration; Δ is the slope of the vapor pressure curve in kPa °C-1; *γ* is the psychrometric constant in kPa °C-1; R_n is net radiation at the land surface in mm per day; and *G* is soil heat flux density in mm per day.

Soil moisture balance is simulated at each grid cell using a single layer water bucket. To represent subgrid variability of soil water-holding capacity *c* we assume that it varies spatially within each grid cell following a parabolic distribution function (Equation 24)

Equation 24 Soil water-holding capacity

$$f(c) = 1 - \left(1 - \frac{c}{C_m}\right)^b \tag{24}$$

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

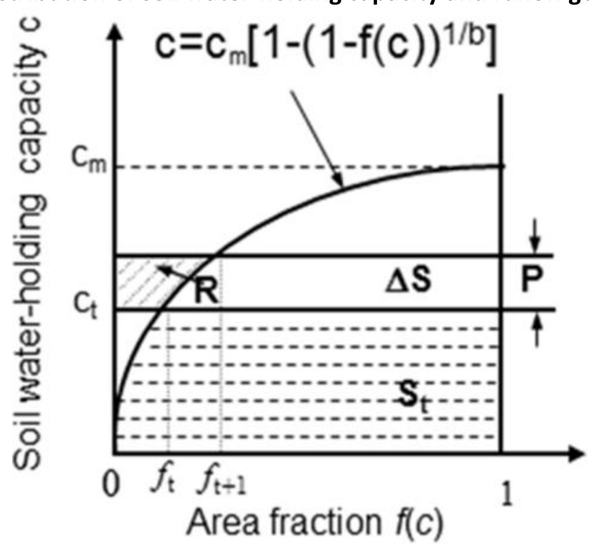
The maximum amount of water that can be held in the grid cell is

Equation 25 Maximum water-holding capacity

$$S_m = \int_0^{C_m} [1 - f(c)]\, dc = \frac{C_m}{1 + b} \tag{25}$$

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

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



Source: Modified after (Zhao 1992) and (Wood et al. 1992).
Note: *P* is precipitation, *R* is runoff and *S* is soil moisture content.

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

Equation 26 Mean areal water storage

$$S_t = S_m \cdot \left[1 - \left(1 - \frac{c_t}{C_m}\right)^{1+b}\right] \tag{26}$$

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

Equation 27 Calculating runoff

If $c_t + P_t - AET < C_m$, (27)

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

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

$$R_t = P_t - AET_t - (S_m - S_t)$$

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

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

Equation 28 Actual evapotranspiration

$$AET_t = PET_t \cdot \frac{S_t}{S_m} \tag{28}$$

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

Equation 29 Runoff partitioning

$$RS_t = \lambda \cdot R_t \tag{29}$$

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 30 Reservoir base flow

$$RB_t = \beta \cdot G_t \tag{30}$$

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

Equation 31 Change in reservoir storage

$$G_t - G_{t-1} = (1 - \lambda) \cdot R_t - RB_t \tag{31}$$

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

Equation 32 Total generated runoff

$$R_t = RS_t + RB_t \tag{32}$$

In the above equations calibration parameters include the sub-grid 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 to 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 out in our calibration experiments.

IMPACT Water Simulation Module (IWSM)

The IMPACT model estimates water demands and supply for irrigation and other water-using sectors in 281 FPUs and simulates water transport in 126 hydrological basins (see Appendix 5). An optimization approach is employed to minimize total water shortage followed by inter-sectoral allocation according to prescribed priorities of water uses. Domestic water use has the highest priority followed by industrial and livestock water uses while the priority of irrigation is the lowest. The equations that determine how much water is available to irrigation and other water-using sectors are described in detail in the following sections.

Water Demand

Equation 33 Crop water requirement

$$ETM_{i,st} = kc_{i,st} \times ETo_{st} \tag{33}$$

where

i	=	Commodity index (only for crops)
st	=	Index of crop growth stages
ETo	=	Reference evapotranspiration
kc	=	Crop coefficient

Irrigation Water Demand

Irrigation water demand is assessed as the portion of crop water requirement (Equation 33) not satisfied by precipitation or soil moisture based on hydrologic and agronomic characteristics. Net crop water demand (NCWD) in a FPU in a growing season is calculated based on an empirical crop water requirement function (Doorenbos and Pruit 1977) :

Equation 34 Net irrigation requirement per crop

$$NIRWD_i = \sum_{st}\left[ETM_{i,st} - PE_{st}\right] \quad (34)$$

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. Then total irrigation water demand (*IRWD*), with consideration of effective rainfall use and salt leaching requirement, is:

Equation 35 Total irrigation water demand

$$IRWD = \frac{\sum_i (NIRWD_i \times AI_i) \times (1 + LR)}{BE} \quad (35)$$

where

AI = Irrigated area
LR = Salt leaching factor
BE = Basin efficiency

The concept of basin efficiency was discussed and various definitions were provided by (Molden et al. 2001). 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 (2000) is calculated as the ratio of the net irrigation water demand (*NIRWD*, Equation 34) 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 a FPU depending on water infrastructure investment and water management improvement in the FPU.

The projection of irrigation water demand depends on the changes of irrigated area and cropping patterns[6], basin efficiency, and effective rainfall. Global climate change affects future irrigation water demand through changes of precipitation and temperature along with other meteorological variables that affect crop evapotranspiration.

Livestock Water Demand

Livestock water demand (*LVWD*) in the base year is estimated using livestock numbers (QS_{lv}) and water consumptive use per unit of livestock (w_{lv}), including beef, milk, pork, poultry, eggs, and sheep and goats (de Fraiture 2007). For all of the livestock products it is assumed that the projection of livestock water demand in each FPU follows the same growth rate of livestock numbers. Livestock water demand was determined to be a linear function of livestock numbers, where there is no change in consumptive water use per head of livestock as seen in Equation 36.

[6] These cropping pattern assumptions (gA) are the same as those used in the Food Model described above

Equation 36 Initial livestock water demand

$$LVWD_t = LVWD_{t-1} \times (1 + gSL_t) \quad (36)$$

Industrial Water Demand

The industrial water demand (INWD) modeled by IMPACT includes the consumptive use of water in industries such as manufacturing, energy generation, and agricultural milling. Industrial water demand is modeled as a nonlinear function of gross domestic production per capita (pcGDP) and technology change. In Equation 37, ε is income elasticity of demand and Y^t is the technology term which is determined according to our perspectives on future industrial water demand and technological improvements in industrial water use in different regions.

Equation 37 Industrial water demand

$$INWD_t = \alpha \cdot (pcGDP_t)^{\varepsilon} \cdot EXP(\gamma_t) \quad (37)$$

Domestic Water Demand

Domestic water demand (DOWD) includes municipal water demand and rural domestic water demand. Initial domestic water demand is estimated using the same sources and methods as those for the industrial water demand assessment. Future domestic water demands are based on projections of population and income growth as seen in Equation 38. 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. The annual growth rate of domestic water demand ϕ_{dwd} is a function of the growth rate of population (ϕ_{pop}) and the growth rate of income (ϕ_{GDP}) , as described in Equation 39.

Equation 38 Domestic water demand

$$DOWD_t = DOWD_{\ t-1} \times (1 + \phi_{dwd}) \quad (38)$$

Equation 39 Growth rate for domestic water demand

$$\phi_{dwd} = \phi_{pop} + (\eta \times \phi_{GDP}) \quad (39)$$

Committed Flow for Environmental, Ecological, and Navigational Uses

Committed flow is specified as a percentage of average annual runoff. When data is unavailable in a particular FPU an iterative procedure is used. The initial value for committed flows is assumed to be 10 percent with additional increments of 20–30 percent if navigation requirements are significant (for example, Yangtze River basin); 10–15 percent if environmental reservation is significant, as in most developed countries; and 5–10 percent for arid and semi-arid regions where ecological requirements, such as salt leaching, are high (for example, Central Asia).

Demand for Water Withdrawals

Off-stream water demand items described above are all expressed in water depletion/consumption terms. The demand for water withdrawal is calculated as total water depletion demand (DWP) divided by the water depletion coefficient (Equation 40).

Equation 40 Demand for water withdrawal

$$DWW = \frac{DWP}{DC} = \frac{IRWD + INWD + DOWD + LVWD}{DC} \tag{40}$$

The value of the water depletion coefficient in the context of the river basin mainly depends on the relative fraction of agricultural and nonagricultural water use (that is, larger agricultural water use corresponds to a higher value of water depletion coefficient) as well as water conveyance/distribution/recycling systems and pollution discharge and treatment facilities. In the base year DC is calculated by given water depletion (WDP) and water withdrawal (WITHD) and DC in the future is projected as a function of the fraction of non-irrigation water use (Equation 41).

Equation 41 Coefficient of water depletion

$$DC = \rho \times \left(\frac{Total\ Nonirrigation\ Depletion}{Total\ Water\ Depletion}\right)^{\psi} \tag{41}$$

This regression function is made based on historical non-irrigation water depletion and total water depletion in different basins or countries resulting in regression coefficients $\rho>0$ and $\psi<0$ for all basins and countries.

Water Supply

Assuming minimum environmental and ecological flow requirements as a predetermined hard constraint in water supply, we focus on the determination of off-stream water supply for domestic, industrial, livestock, and irrigation sectors. Two steps are undertaken to determine off-stream water supply by sectors. The first is to determine the total water supply represented as depletion/consumption (WDP) in each month of a year; and the second is to allocate the total to different sectors. Particularly, irrigation water supply is further allocated to different crops in the FPU.

To determine the total amount of water available for various off-stream uses in a FPU, hydrologic processes such as precipitation, snow accumulation and ablation, evapotranspiration, and runoff are taken into account to assess total renewable water (TRW) by a global hydrological model. Anthropogenic impacts are combined to define the fraction of the total renewable water that can be used. These impacts can be classified into (1) water demands; (2) flow regulation through storage, flow diversion, and groundwater pumping; and (3) water allocation policies, such as committed flows for environmental purposes or water transfers from agricultural to municipal and industrial uses. Therefore, water supply is calculated based on both natural hydrologic processes and anthropogenic impacts through the model, including the relationships listed above.

A simple network with a two-basin framework can be used as an example (Figure 2). Surface water availability in the downstream basin depends on the rainfall drainage in the basin and the inflow from the upstream basin(s) as defined in Equation 42.

Equation 42 Surface water balance

$$ST_t - ST_{t-1} = ROFF_t + INF_t + OS_t - SWDP_t - RL_t - EL_t \quad (42)$$

where

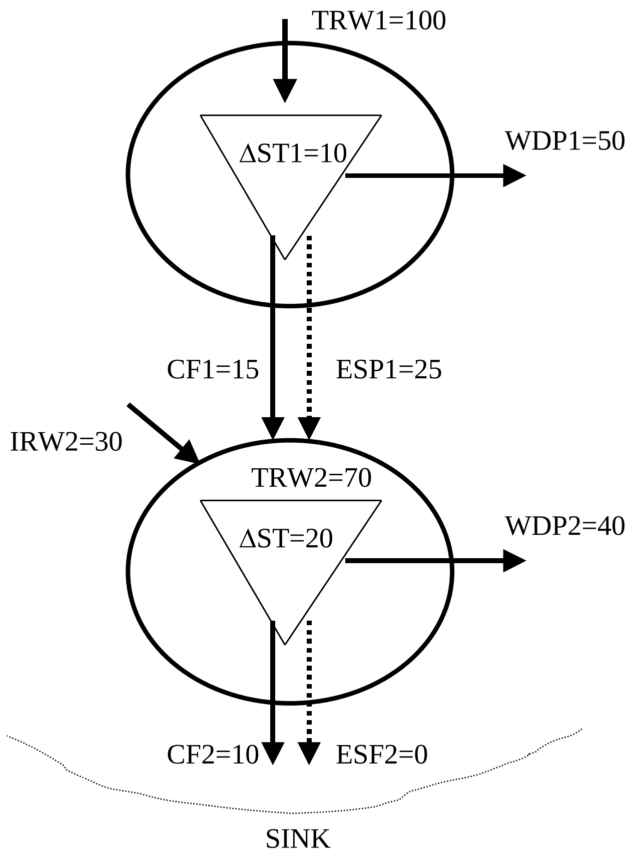
t	=	time interval
ST	=	aggregated reservoir storage
ROFF	=	internal renewable water resource
INF	=	inflow from other basins
RL	=	total release, including the committed instream flow and spill in flooding periods
EL	=	Evaporation loss, mainly from surface reservoir surface
SWDP	=	total water deletion from surface water sources

SWDP which is equal to water withdrawal minus return flow is determined from this water balance equation, with an upper bound constrained by surface maximum allowed annual water withdrawal (*SMAWW*) as:

Equation 43 Surface maximum allowed water withdrawal

$$\sum_t SWDP_t / DC \leq SMAWW \quad (43)$$

Figure 2 Connected flow within and between upstream-downstream basins



Other constraints related to the items in Equation 42 include that flow release (*RL*) must be equal or greater than the committed instream flow. Monthly reservoir evaporation is calculated based on reservoir surface area and open water evaporation potential determined using local climate data.

Depletion from groundwater (GWDP) is constrained by maximum allowed water withdrawal from groundwater (GMAWW):

Equation 44 Maximum allowed water withdrawal from groundwater

$$\sum_t GWDP_t / DC \leq GMAWW \quad (44)$$

The estimation of the *SMAWW* and *GMAWW* in the base year is based on the actual annual water withdrawal and annual groundwater withdraw around the base year. Projections of *SMAWW* and *GMAWW* are based on assumptions on future surface and ground water development in different countries and regions. In particular, the projection of *GMAWW* is based on historic pumping and potential groundwater sources (measured by groundwater recharge).

A traditional reservoir operation model is incorporated including all of the above relationships of natural water availability, storage regulation, withdrawal capacity, and committed flow requirements. The model is formulated as an optimization model and run for individual years with month as the time period. The objective is to maximize the reliability of water supply (that is, ratio of water supply over demand, less or equal to 1.0), as

Equation 45 Maximizing the reliability of water supply

$$\max\left[\frac{\sum_t(SWDP_t+GWDP_t)}{\sum_t(DOWD_t+INWD_t+LVWD_t+IRWD_t)}+\omega\min_t\left(\frac{SWDP_t+GWDP_t}{DOWD_t+INWD_t+LVWD_t+IRWD_t}\right)\right] \quad (45)$$

and, as can be seen, the objective function also drives the water application according to the water demand in crop growth stages (months) by maximizing the minimum ratio among time periods (12 months). The weight item ω is determined by trial-and-error until water supply is distributed to months approximately proportional to monthly water demand.

Once the model solves for total water that could be depleted in each month ($SWDP_t$ and $GWDP_t$) for various off-stream uses under the constraints described above, the next step is to determine the water supply available for different sectors. Assuming domestic water demand is satisfied first, priority is then given to industrial and livestock water demand while irrigation water supply is the residual claimant. Monthly non-irrigation water demands are calculated based on their annual value multiplied by monthly distribution coefficients. Water supply represented as depletion for different sectors is calculated as:

Equation 46 Domestic water depletion

$$WDPDO_t = \min(DOWD_t, DWDP_t + GWDP_t) \quad (46)$$

Equation 47 Industrial water depletion

$$WDPIN_t = \min(INWD_t, SWDP_t + GWDP_t - WDPDO_t) \quad (47)$$

Equation 48 Livestock water depletion

$$WDPLV_t = \min(LVWD_t, SWDP_t + GWDP_t - WDPDO_t - WDPIN_t) \quad (48)$$

Equation 49 Irrigation water depletion

$$WDIR_t = \min(IRWD_t, SWDP_t + GWDP_t - WDPDO_t - WDPIN_t - WDPLV_t) \tag{49}$$

Finally, total water available for crop evapotranspiration (TNIW) is calculated by introducing the basin efficiency (*BE*) for irrigation systems and discounting the salinity leaching requirements, as

Equation 50 Total water available for crop evapotranspiration

$$TNIW_t = BE \times \frac{WDIR_t}{1+LR} \tag{50}$$

This can be further allocated to crops according to crop irrigation water demand, yield response to water stress (*ky*), and average crop price (P_i) for each of the irrigated crops.

The allocation fraction is defined as:

Equation 51 Allocation fraction

$$\pi_{i,t} = ALLO_{i,t} / \sum_i ALLO_{i,t} \tag{51}$$

Equation 52 Crop water allocation

$$ALLO_i = AI_i \times ky_i \times \left[1 - PE_{i,t}/ETM_{i,t}\right] \times PC_i \tag{52}$$

in which $ETM_{i,t} = ET0_{i,t} \times kc_{i,t}$, is the maximum crop evapotranspiration; π is a scaled number in the range of (0,1) and the sum of π overall crops is set to equal 1. The effective water supply allocated to each crop is then calculated by

Equation 53 Effective water supply

$$NIW_{i,t} = TNIW_t \times \pi_{i,t} \tag{53}$$

Thus, irrigation water is allocated based on profitability of the crop, sensitivity to water stress, and irrigation water demand (total demand minus effective rainfall) of the crop. Higher priority is given to the crops with higher profitability, which are more drought sensitive, and/or that require more irrigation water.

Effective Rainfall

Effective rainfall (*PE*) depends on total rainfall (*PT*), previous soil moisture content (*SM*0), maximum crop evapotranspiration (*ETM*), and soil characteristics (hydraulic conductivity *K*, moisture content at field capacity Z_s, and others). *PE* is calculated by an SCS method (USDA-SCS 1992), given *PT*, *ETM*, and effective soil water storage:

Equation 54 Effective rainfall

$$PE = SF \times (0.70917 PT^{0.82416} - 0.11556) \times 10^{0.02426 \times ETM} \tag{54}$$

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

Equation 55 Soil water storage

$$SF = 0.531747 + (0.295167 \times D) - (0.057697 \times D^2) + (0.003804 \times D^3) \quad (55)$$

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).

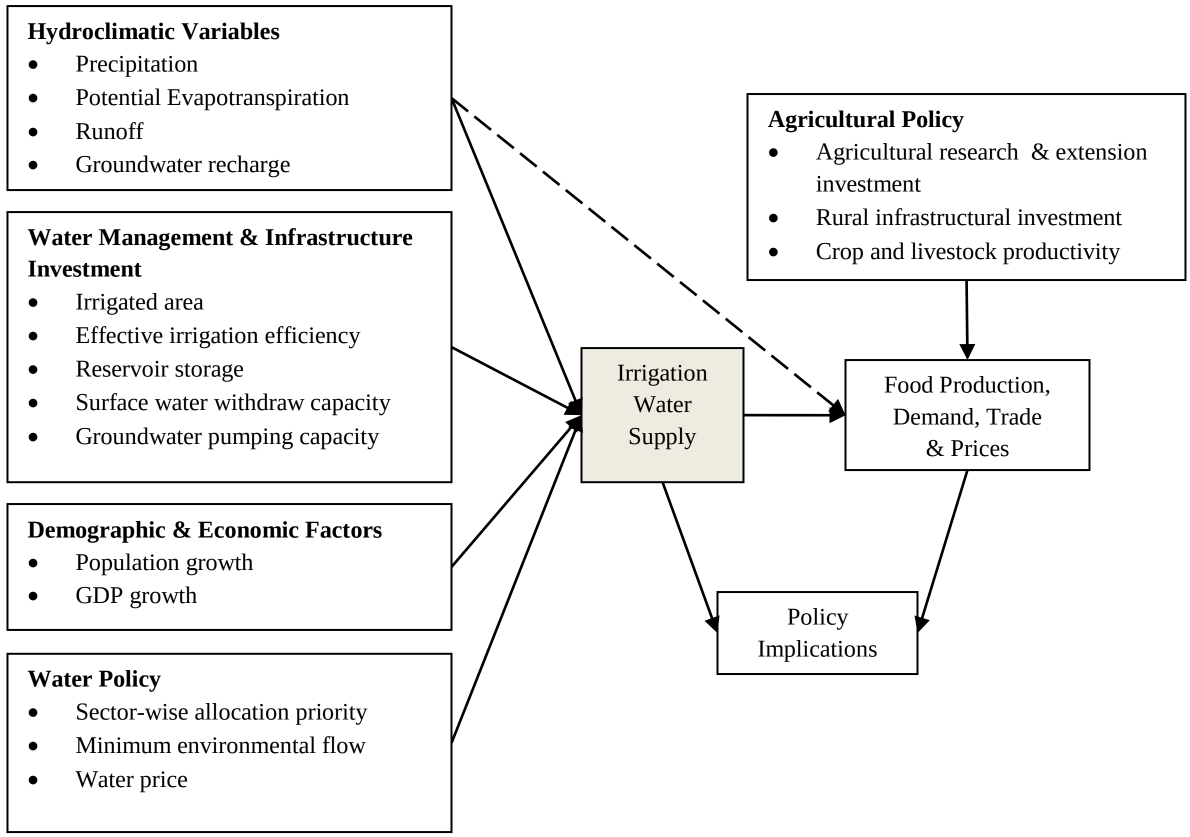
Global gridded monthly climatology for the period 1951-2000 comes from the CRU TS 2.1 database (Mitchell and Jones 2005; CRU 2000), and is used to extract the monthly rainfall on the cropland in the FPUs. Reference crop evapotranspiration is calculated using the Priestley and Taylor method (Priestley and Taylor 1972) and the CRU TS 2.1 climate dataset in grid cells.

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 semi-arid 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 can also increase the share of rainfall that goes to infiltration and evapotranspiration. Contour plowing, which is typically a soil-preserving technique, should also act to detain and infiltrate a higher share of the precipitation. Precision leveling can also lead to greater relative infiltration, and therefore a higher percentage of effective rainfall.

Model Implementation

The IWSM simulates water demand, supply, reservoir storage regulation, and surface and ground water withdraw at monthly time period, using FPUs, usually a basin or sub-basin, as the fundamental unit of depletion accounting. Using the lumped unit avoids tracking detailed water use process as river basin management models do. When the scale of analysis goes from basin down to irrigation system and then to field scale water flow pathways become increasingly complex and consequently water balance calculation for depletion accounting quickly becomes not tractable if the geographic domain of analysis is not compromised. In addition, sophisticated water accounting relies on extensive flow measurement which is almost impossible for a global water model like the IWSM.

Figure 3 Primary Drivers in IWSM and links with IMPACT Agriculture Trade Model



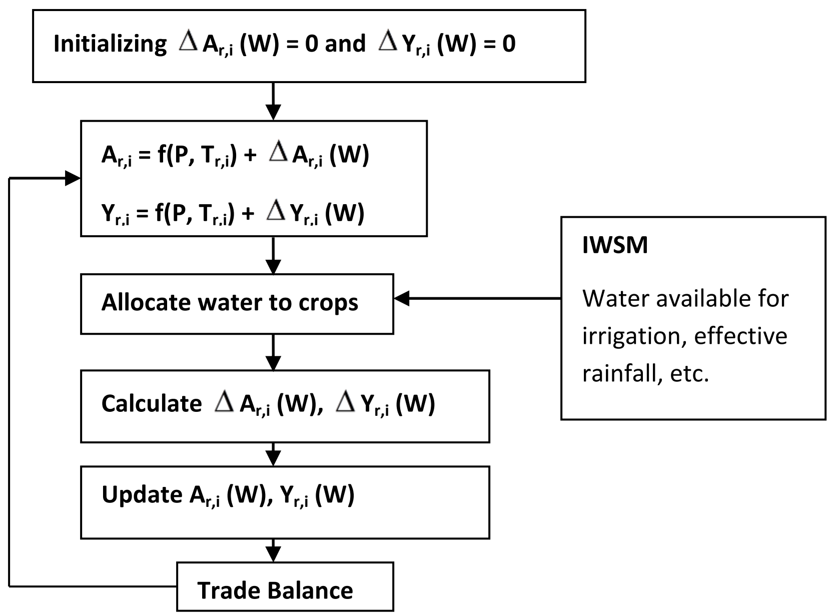
Source: (Zhu 2012)

The IWSM optimizes water supply according to demand, driven by several kinds of factors, as shown in Figure 3 The hydro-climatic factors include long-term monthly precipitation, potential evapotranspiration, and internal renewable water resources; the demographic and economic factors are population and GDP growth rates that drive the growth of domestic and industrial water demand; the water management and infrastructure investment factors include projected irrigated area growth, changing rate of effective irrigation efficiency at the FPU level, reservoir storage increase, the changes in surface and ground water withdraw capacities; and policy and institutional parameters including water allocation priorities.

The model is run for individual basins, but with simulation of trans-boundary basins. The outflow (*RL*) from one basin can be the source of downstream basins, which is important for many international river basins such as the Nile (Sudan, Ethiopia, Egypt, Uganda, Burundi, Tanzania, Kenya, Zaire, and Rwanda);

the Mekong (China, Laos, Burma, Thailand, Cambodia, and Viet Nam); the Indus (Pakistan, India, Afghanistan, and China); the Ganges-Brahmaputra (China, India, Bangladesh, Bhutan, and Nepal); the Amazon (Brazil, Peru, Bolivia, Colombia, Ecuador, Venezuela, and Guyana); the Danube (Romania, Yugoslavia, Hungry, Albania, Italy, Austria, Czechoslovakia, Germany, Russia, Poland, Bulgaria, and Switzerland); the Niger (Mali, Nigeria, Niger, Algeria, Guinea, Chad, Cameroon, Burkina Faso, Benin, Cote D'Ivoire); the Tigris-Euphrates (Iraq, Iran, Turkey, and Syria); and the Rio Grande (United States and Mexico). The river basins used in the model are described in more detail in Appendix 5.

Figure 4 Flow chart of the IMPACT-WATER program



Source: (Rosegrant 2002) and (Zhu 2012)

Connecting the Food and Water Components

The water component calculates effective irrigation water supply in each basin by crop and by period ($NIW_{i,t}$), over a 50-year time horizon. The results are then incorporated in simulating food production, demand, and trade.

Figure 4 shows the flow chart of the combined food and water system. For each year initially, it is assumed that there is no water shortage, ΔAC(W) and ΔYC(W) are zero, and crop area harvested and crop yields are determined based on price, labor, fertilizer and other inputs, and technological change. Then water availability for crops is computed, ΔAC(W) and ΔYC(W) are calculated, and crop area (*A*) and yield (*Y*) are updated. Next, crop production and stock are updated and net food trade and the global trade balance calculated (global net trade should equal zero). If the trade balance is violated then crop prices are adjusted and the model undertakes a new iteration. The loop stops when net trade equals zero. Thus, crop area and yield are determined endogenously based on water availability, price, and other agricultural inputs.

Welfare Indicators

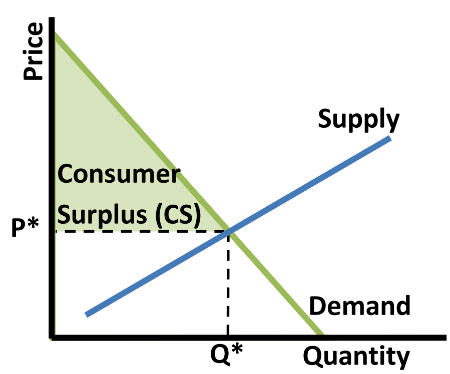
One of the strengths of IMPACT is that it offers a framework for scenario analysis. Scenario analysis provides policy makers the ability to test different assumptions of how agricultural markets will evolve. It allows analysis on the effects of differing assumptions on the supply, demand, prices, and trade of agricultural goods. IMPACT additionally offers a suite of welfare metrics that provide insight on the effects of changes in the agricultural sector on society as a whole. The suite of welfare analysis tools includes traditional welfare analysis, and estimates of malnourished children, and the share of the population at risk of hunger.

Welfare Analysis

The welfare module in IMPACT follows a traditional economic welfare analysis approach to estimate the benefits to society on the consumer- and producer-side. It allows policy makers to disentangle some of the effects of alternative plausible futures in changes to agricultural commodity prices, and quantities produced and consumed.

On the demand-side a consumer surplus is calculated to estimate changes faced by consumers from changes in agricultural markets. Calculating the consumer surplus in IMPACT is straightforward, as we measure the area below the demand curve (defined in Equation 10) and above the market price for each agricultural commodity, and region (see Figure 5).

Figure 5 Traditional Consumer Surplus



P*, Q* are market price and quantity

These consumer surpluses can be aggregated to give a measure of national and global consumer surplus (Equation 56 and Equation 57).

Equation 56 National consumer surplus

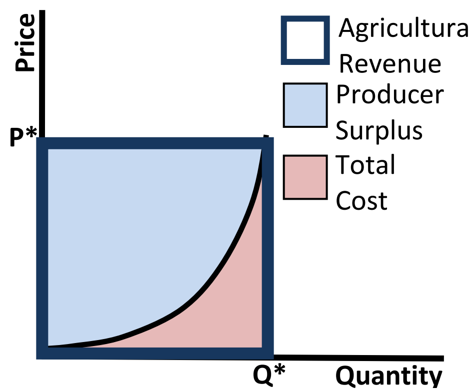
$$CS_n = \sum_j CS_j \tag{56}$$

Equation 57 Global consumer surplus

$$CS = \sum_n CS_n \tag{57}$$

The producer surplus is the area above the supply curve and under the equilibrium price. Calculating this area directly is relatively complicated. Thus, in IMPACT the producer surplus is calculated by calculating agricultural revenue (P* x Q*) minus total cost of production, which is the area under the supply curve (see Figure 6).

Figure 6 Graphical Representation of Producer Surplus



Similar to the consumer surplus, the producer surplus is aggregated to national and global levels.

Total welfare is the combination of the supply- and demand- side effects, which is calculated by summing the consumer and the producer surplus (Equation 58).

Equation 58 Total welfare calculation

$$Welfare = CS + PS \tag{58}$$

The welfare metrics were designed to be used in a comparative context to give policy makers insight into different welfare effects of alternative futures. Thus, total welfare, consumer and producer surplus are expressed as changes from one scenario to another in the following way (Equation 59).

Equation 59 Calculating changes in welfare

$$\begin{aligned} \Delta CS &= CS_{scenario1} - CS_{scenario2} \\ \Delta PS &= PS_{scenario1} - PS_{scenario2} \\ \Delta Welfare &= Welfare_{scenario1} - Welfare_{scenario2} \end{aligned} \tag{59}$$

Malnourished Children

The percentage of malnourished children under the age of five is estimated from the average per capita calorie consumption, female access to secondary education, the quality of maternal and child care, and health and sanitation (Rosegrant 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 malnourished children to be derived from data describing the average per capita calorie consumption, female access to secondary education, the quality of maternal and child care, and health and sanitation. The precise relationship used to project the percentage of malnourished children is based on a cross-country regression relationship of Smith and Haddad (Smith and Haddad 2000).

Equation 60 Percent of children aged 0 to 5 malnourished:

$$\Delta MAL_{t,t2000} = -25.24 \times \ln\frac{KCAL_t}{KCAL_{2000}} - \left(71.76 \times \Delta LFEXPRAT_{t,t2000}\right) - \left(0.22 \times \Delta SCH_{t,t2000}\right) - \left(0.08 \cdot \Delta \mathrm{WATER}_{t,t2000}\right) \qquad (60)$$

where

MAL	=	percentage of malnourished children
KCAL	=	per capita kilocalorie availability
LFEXPRAT	=	ratio of female to male life expectancy at birth
SCH	=	the gross female secondary school enrollment rate[7]
WATER	=	percentage of population with access to safe water
$\Delta_{t,t2000}$	=	the difference between the variable values at time t and the base year t2000

The data used in this calculation comes from a variety of sources. The base values for malnourished children originally comes from the World Health Organization's Global Database on Child Growth Malnutrition (WHO 1997) and have been adjusted to reflect changes reported in the World Bank's World Development Indicators (WDI) (World Bank 2010). The base values for female-male life expectancy ratio, female secondary school enrollment, and access to safe water come from the WDI (World Bank 2010, 1998, 1997). The projections of changes in female-male life expectancy come from the United Nations Populations Prospects medium variant (UN 2006). The projections of changes in female secondary school enrollment and access to clean water come from the Technogarden Baseline Scenario (MA 2005).

The per capita kilocalorie availability is derived from two sources: (1) the amount of calories obtained from commodities included in the IMPACT-Food model and (2) the calories from commodities outside the model (FAO 2011).

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[7] Total female enrollment in secondary education (any age group) as a percentage of the female age-group corresponding to national regulations for secondary education

After calculating the percentage of malnourished children, the total number of malnourished children is calculated using the following equation, with the child (0-5 year old) population coming from the medium variant of UN population projections (UN 2011).

Equation 61 Number of children malnourished:

$$NMAL_t = MAL_t \times POP_t \quad (61)$$

where

MAL	=	Percent of malnourished children
POP	=	number of children 0–60 months old in the population

Share at Risk of Hunger

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

Equation 62 Share at risk of hunger

$$ShareAtRisk = \alpha RelativeKCal^2 + \beta RelativeKCal + int + \varepsilon \quad (62)$$

where

RelativeKCal	=	the ratio of average food supply to minimum food requirement
int[8]	=	the share at risk of hunger intercept, estimated to be 314.84
A	=	the x^2 parameter, estimated at 106.97
B	=	the x parameter, estimated at -364.54
ε	=	the estimation error

It should be noted that the due to the quadratic nature of this equation it is necessary to bound the share at risk. The lower bound is defined as zero, and the upper bound is 100. Developed countries unsurprisingly have low share at risk, to save time we treat all countries below four percent share at risk of hunger as if they had zero percent share of hunger.

The relative availability of food has been bounded to ensure realistic results, and is calculated in Equation 63. 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 below four percent.

Equation 63 Relative food availability

$$RelativeKCal = \frac{KCal}{MinKCal} \quad (63)$$

where

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

Kcal	=	the per capita kilocalorie consumption calculated by the IMPACT model
MinKCal	=	the minimum calories from food requirement, adjusted by the rate of change estimated by FAO(FAO 2010)

References

ADB and IFPRI 2009. *Building Climate Resilience in the Agriculture Sector*, Asian Development Bank, Manila, Philippines.

AMAD 2010. "Agricultural market Access Data Base." Retrieved from http://www.amad.org

CRU 2000. "TS2.1 Global Cimate Data. CDROM." University of East Anglia, East Anglia, UK.

Cai X and MW Rosegrant 2002. "Global water demand and supply projections. Part 1: A modeling approach." *Water International*, vol. 27, no. 3, pp. 159-169.

Chow VT, DR Maidment and LW Mays 1988. *Applied Hydrology*, McGraw-Hill.

Delgado CL, MW Rosegrant, H Steinfeld, S Ehui and C Courbois 1999. "Livestock to 2020: The next food revolution." Washington, D.C. Retrieved February 20, 2012, from http://www.ifpri.org/publication/livestock-2020

Delgado CL, N Wada, MW Rosegrant, S Meijer and M Ahmed 2003. "Fish to 2020: Supply and Demand in Changing Global Markets." Washington, D.C. Retrieved from www.ifpri.org/pubs/books/fish2020/oc44.pdf

Doorenbos J and WO Pruit 1977. *Crop water requirements*, Rome.

FAO 1979. "Crop yield vs. water." Rome.

--- 2010. "Food Security Statistics: Rates of Change." Retrieved from http://www.fao.org/economic/ess/ess-fs/fs-data/ess-fadata/en/Rates_of_change_en.xls

--- 2011. "FAOSTAT Database." Retrieved from http://faostat.fao.org

Fischer G, M Shah, FN Tubiello and H van Velhuizen 2005. "Socio-economic and climate change impacts on agriculture: an integrated assessment." *Phil. Trans. R. Soc B*, vol. 360, pp. 2067-2083. Retrieved from http://rstb.royalsocietypublishing.org/content/360/1463/2067.full

de Fraiture C 2007. "Integrated water and food analysis at the global and basin level. An application of WATERSIM." *Water Resource Management*, vol. 21, pp. 185-198.

GAMS 2012. "General Algabraic Modeling System (GAMS)." GAMS, Washington, D.C. Retrieved from www.gams.com

IAASTD 2009. *Agriculture at a Crossroads* BDM et Al. (ed), Island Press, Washington D.C. Retrieved from http://www.agassessment.org/reports/IAASTD/EN/Agriculture at a Crossroads_Global Report (English).pdf

MA 2005. *Millennium Ecosystem Assessment - Ecosystems and Human Well-being: Synthesis*, Island Press, Washington, D.C. Retrieved from http://www.millenniumassessment.org/documents/document.356.aspx.pdf

Margulis S 2010. *Economics of Adaptation to Climate Change: Synthesis Report*, Washington, DC.

Mitchell TD and PD Jones 2005. “An improved method of constructing a database of monthly climate observations and associated high-resolution grids.” *International Journal of Climatology*, vol. 25, pp. 693-712.

Molden D, R Sakthivadivel and Zaigham 2001. *Basin-level use and productivity of water: Examples from South Asia*, Colombo, Sri Lanka.

Nelson GC, MW Rosegrant, A Palazzo, I Gray, C Ingersoll, R Robertson, S Tokgoz, T Zhu, TB Sulser, C Ringler, S Msangi and L You 2010. *Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options*, International Food Policy Research Institute, Washington D.C. Retrieved July 16, 2012, from http://www.ifpri.org/publication/food-security-farming-and-climate-change-2050

OECD 2000. “Producer and Consumer Support Estimates database.” Retrieved from www.oecd.org/agriculture/pse

Priestley CHB and RJ Taylor 1972. “On the assessment of surface heat flux and evaporation using large scale parameters.” *Monthly Weather Review*, vol. 100, pp. 81-92.

Rosegrant MW 2008. “Biofuels and Grain Prices: Impacts and Policy Responses.” Testimony to U.S. Senate Committee on Homeland Security and Governmental Affairs, Washington D.C.

Rosegrant MW, MC Agcaoili-Sombilla and N Perez 1995. “Global Food Projections to 2020: Implications Investment.” Washington, D.C.

Rosegrant MW, X Cai and SA Cline 2002. *World Water and Food to 2025*, Washington, D.C.

Rosegrant MW, SA Cline, W Li, TB Sulser and RA Valmonte-Santos 2005. “Looking Ahead Long-term prospects for Africa’s Agricultural Development and Food Security.” Washington D.C. Retrieved from http://www.ifpri.org/sites/default/files/publications/vp41.pdf

Rosegrant MW and PBR Hazell 2000. *Transforming the Rural Asian Economy: The Unfinished Revolution*, Oxford University Press, Hong Kong.

Rosegrant MW, N Leach and RV Gerpacio 1999. “Alternative futures for world cereal and meat consumption.” *Nutrition Society*, vol. 58, no. 2, pp. 219-234.

Rosegrant MW, MS Paisne, S Meijer and J Witcover 2001. *Global Food Projections to 2020: Emerging Trends and Alternative Futures*, Washington, D.C.

Rosegrant MW and C Ringler 2000. "Asian Economic Crisis and the Long-Term Global Food Situation." *Food Policy*, vol. 25, no. 3, pp. 243-254.

Rosegrant MW, T Zhu, S Msangi and T Sulser 2008. "Global Scenarios for Biofuels: Impacts and Implications." *Review of Agricultural Economics*, vol. 30, no. 3, pp. 495-505.

SRF 2009. "A Strategy and Results Framework for the CGIAR." Montpellier, France. Retrieved from http://www.cgiar.org/changemanagement/pdf/cgiar_srf_june7_2010.pdf

Scott G, MW Rosegrant and C Ringler 2000. "Roots and Tubers for the 21st Century: Trends, Projections, and Policy Options." Washington, D.C.

Shiklomanov I 1999. "World Water Resources and Their Uses." *SHI/UNESCO*.

Smith L and L Haddad 2000. "Explaining Child Malnutrition in Developing Countries: A Cross-Country Analysis." Washington, D.C.

Sulser TB, B Nestorova, M Rosegrant and T van Rheenen 2011. "The future role of agriculture in the Arab region's food security." *Food Security*, vol. 3, no. S1, p. S23-S48.

UN 2006. "World Population Prospects, 2005 revision."

--- 2011. *World population prospects: The 2010 Revision*, United Nations, New York. Retrieved from http://esa.un.org/wpp/Documentation/publications.htm

UNEP 2007. "GEO-4." Retrieved from http://www.unep.org/geo/geo4.asp

--- 2012. "GEO-5." Retrieved from http://www.unep.org/geo/GEO5_Products.asp

USDA 1998. "Commodity and Food Elasticities." Retrieved from http://www.ers.usda.gov/Data/Elasticities/

--- 2010a. "Agricultural Price Summary Database." Retrieved from http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1003

--- 2010b. "Poultry Yearbook." Retrieved from http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1367

--- 2010c. "Sugar and Sweeteners Yearbook." Retrieved from http://www.ers.usda.gov/Briefing/Sugar/Data.htm

USDA-SCS 1992. "Irrigation Water requirements," in *National engineering handbook, Part 623 - Irrigation national engineering handbook*, Washington, DC.

WHO 1997. *WHO Global Database on Child Growth and Malnutrition*, Geneva. Retrieved from http://www.who.int/nutgrowthdb/en/

Wood EF, DP Lettenmaier and VG Zartarian 1992. "A Land-Surface Hydrology Parameterization With Subgrid Variability for General Circulation Models." *Journal of Geophysical Research*, vol. 97, no. D3, p. 2717.

World Bank 1997. "World Development Indicators." World Bank, Washington, D.C.

--- 1998. "World Development Indicators." World Bank, Washington, D.C.

--- 2000. "Manufactures Unit Value Index." Retrieved from http://data.worldbank.org/data-catalog/MUV-index

--- 2007. *World Development Report 2008 - Agriculture for Development*, Washington D.C.

--- 2010. "World Development Indicators." World Bank. *World DataBank*. Retrieved from http://databank.worldbank.org/data/home.aspx

--- 2012. "Prospects Commodity Markets." Retrieved from http://go.worldbank.org/4ROCCIEQ50

Zhao R-J 1992. "The Xinanjiang model applied in China." *Journal of Hydrology*, vol. 135, no. 1-4, pp. 371-381.

Zhu T, C Ringler and MW Rosegrant 2012. *Development and Testing of a Global Hydrological Model for Integrated Assessment Modeling*, International Food Policy Research Institute, Washington, DC.

APPENDIX 1 CITED WORKS WITH IMPACT

Agcaoili-Sombilla, M. and M.W. Rosegrant. 1994. World Supply and Demand Projections for Cereals, 2020. 2020 Brief No. 2. Washington, D.C.: International Food Policy Research Institute.

Bradford, E., R. Lee Baldwin, H. Blackburn, K.G. Cassman, P.R. Crosson, C.L. Delgado, J.G. Fadel, H.A. Fitzhugh, M. Gill, J.W. Oltjen, M.W. Rosegrant, M. Vavra, R.O. Wilson. 1999. Animal Agriculture and Global Food Supply. Task Force Report No. 135. Iowa, USA: Council for Agricultural Science and Technology.

Carruthers, I., M.W. Rosegrant, and D. Seckler. 1997. Irrigation and Food Security in the 21st Century. *Irrigation and Drainage Systems* 11(2)(May): 83-101.

Delgado, C. L., M.W. Rosegrant, and S. Meijer. 2001. Livestock to 2020: The Revolution Continues. Paper presented at the annual meetings of the International Agricultural Trade Research Consortium (IATRC), Auckland, New Zealand, January 18-19, 2001.

Delgado, C., M.W. Rosegrant, H. Steinfeld, S. Ehui, and C. Courbois. 2000. Livestock to 2020: The next food revolution. International Meat Secretariat Newsletter, No. 24, January 2000.

Delgado, C. L., M.W. Rosegrant, H. Steinfeld, S. Ehui, and C. Courbois. 1999. Livestock to 2020. The Next Food REvolution. 2020 Vision for Food, Agriculture, and the Environment. Discussion Paper No. 28. Washington, D.C.: International Food Policy Research Institute.

Delgado C., M.W. Rosegrant, H. Steinfeld, S. Ehui, and C. Courbois. 1999. The Coming Livestock Revolution. Special millennium issue of *Choices* (fourth quarter 1999).

Evenson, R. E., C. Pray, and M.W. Rosegrant. 1999. *Agricultural Research and Productivity Growth in India*. IFPRI Research Report No. 109. Washington, D.C.: International Food Policy Research Institute.

Evenson, R. E., and M.W. Rosegrant. 1995. Productivity Projections for Commodity Marketing Modeling. Paper presented at the final workshop of the International Cooperative Research Project on "Projections and Policy Implications of Medium and Long-Term Rice Supply and Demand", organized by IFPRI, IRRI, and CCER, Beijing, China, April 23-26, 1995.

Huang, J., S. Rozelle, and M.W. Rosegrant. 1999. China's Food Economy to the 21st Century. *Economic Development and Cultural Change* 47(4): 737-766.

Huang, J., S. Rozelle, and M.W. Rosegrant. 1997. *China's food economy to the twenty-first century: Supply, demand, and trade*. IFPRI 2020 Vision for Food, Agriculture, and the Environment Discussion Paper No. 19 (January). Washington, D.C.: International Food Policy Research Institute.

McKinney, D.C., X. Cai, M. Rosegrant, C. Ringler, C.A. Scott. 2000. Integrated Basin-Scale Water Resources Management Modeling: Review and Future Directions. *Agricultural Economics* 24(1): 33-46.

Pandya-Lorch, R., P. Pinstrup-Andersen, and M.W. Rosegrant. 2001. Prospects for food demand and supply towards 2020. Paper presented to the International Fertilizer Society at a Symposium in Lisbon, March 4.

Pandya-Lorch, R. and M.W. Rosegrant. 2000. Prospects for Food Demand and Supply in Central Asia. *Food Policy* 25(6): 637-646.

Pandya-Lorch, R. and M.W. Rosegrant. 1999. World Food in the Twenty-First Century. Special millennium issue of *CHOICES* (fourth quarter 1999).

Pinstrup-Andersen, P., R, Pandya-Lorch, and M.W. Rosegrant. 2000. World Food Prospects. *Agrarwirtschaft* 49(9/10). September special issue "Meeting the Food Challenge of the Twenty-First Century".

Pinstrup-Andersen, P., R. Pandya-Lorch, and M.W. Rosegrant. 1999. *World Food Prospects: Critical Issues for the Early Twenty-first Century*. Food Policy Report No. 29. Washington, D.C.: International Food Policy Research Institute.

Pinstrup-Andersen,P.;R. Pandya-Lorch,Rajul, M.W. Rosegrant, and F. Peterson. 1999. *World Food Prospects: Critical Issues for the Early Twenty-First Century*. Food Policy Report. Washington, D.C.: International Food Policy Research Institute.

Pinstrup-Andersen, P., R. Pandya-Lorch, and M.W. Rosegrant. 1997. The World Food Situation: Recent Developments, Emerging Issues, and Long-Term Prospects. Food Policy Report. Washington, D.C: International Food Policy Research Institute.

Rosegrant M. W., M. S. Paisner, S. Meijer, and J.Witcover. 2001. *Global Food Projections to 2020: Emerging Trends and Alternative Futures*. Washington D.C.: International Food Policy Research Institute.

Rosegrant M. W., M. S. Paisner, S. Meijer, and J. Witcover. 2001. 2020 *Global Food Outlook: Trends and Alternative Futures*. IFPRI Food Policy Report. Washington D.C.: International Food Policy Research Institute.

Rosegrant, M.W., M.S. Paisner, and C. Ringler. 2001. Global and Southeast Asian trends in food supply, demand, and food security. Paper presented at the World Food Program conference, "The role of Food Aid in Cambodia," February 8-9, Phnom Penh.

Rosegrant, M.W., M.S. Paisner, and S. Meijer. 2001. Long-term perspectives on the change of major agricultural and resource base variables. Background Paper prepared for the World Bank's "Vision to Action".

Rosegrant, M.W. and X. Cai. 2001. Water Scarcity and Food Security: Alternative Futures for the 21st Century. *Journal of Water Science and Technology* 43(4): 61-70.

Rosegrant, M.W. and C. Ringler. 2000. Asian Economic Crisis and the Long-Term Global Food Situation. *Food Policy* 25(3): 243-254.

Rosegrant, M.W., C. Ringler, D. C. McKinney, X. Cai, A. Keller, and G. Donoso. 2000. Integrated Economic-hydrologic Water Modeling at the Basin Scale: The Maipo River Basin. *Agricultural Economics* 24(1): 33-46.

Rosegrant, M.W., M. S. Paisner, and C. Ringler. 2000. Agricultural research, technology and world food markets. Paper presented at the 2000 IAAE Conference, August 11-17, Berlin.

Rosegrant, M.W. and P. B. R. Hazell. 2000. *Transforming the Rural Asian Economy: The Unfinished Revolution*. Hong Kong: Oxford University Press.

Rosegrant, M.W. and C. Ringler. 1999. World Water Vision Scenarios: Consequences for food supply, demand, trade, and food security: Results from the IMPACT implementation of the World Water Vision Scenarios, Paper prepared for the Scenario Development Panel of the World Commission on Water for the 21st Century, Forthcoming, Second World Water Forum, Scenario Vision Proceedings.

Rosegrant, M.W., N. Leach, and R.V. Gerpacio. 1999. Alternative futures for world cereal and meat consumption. *Proceedings for the Nutrition Society* 58(2): 219-234.

Rosegrant, M.W., and C. Ringler. 1998. Impact on Food Security and Rural Development of Transferring Water out of Agriculture. *Water Policy* 1(6): 567-586.

Rosegrant, M.W. and C. Ringler. 1997. World Food Markets into the 21st Century: Environmental and Resource Constraints and Policies. The *Australian Journal of Agricultural and Resource Economics*. 41(3): 401-428.

Rosegrant, M.W., C. Ringler, and R. Gerpacio. 1999. Water and Land Resources and Global Supply. In *Food Security, Diversification and Resource Management: Refocusing the Role of Agriculture*, ed. G.H. Peters and J. von Braun. Proceedings of the 23rd International conference of Agricultural Economics held at Sacramento, California 10-16 August 1997. England: University of Oxford.

Rosegrant, M.W. and M.C. Agcaoili-Sombilla. 1996. South Asia and the Global Food Situation: Challenges for Strengthening Food Security. *Journal of Asian Economics* 7(2): 265-292.

Rosegrant, M.W. 1996. *Global Food Supply and Demand: the Impact on People, Politics and Prices*. Canberra: Crawford Fund for International Agricultural Research.

Rosegrant, M.W., M. Agcaoili-Sombilla, and N.D. Perez. 1995. *Global Food Projections to 2020: Implications for Investment*. 2020 Discussion Paper No. 5. Washington, D.C.: International Food Policy Research Institute.

Rozelle, S. and M.W. Rosegrant. 1997. China's Past, Present, and Future Food Economy: Can China Continue to Meet the Challenges? *Food Policy* 22(3)(June): 191-200.

San, N.N. and M.W. Rosegrant. 1998. Indonesian agriculture in transition: Projections of alternative futures. *Journal of Asian Economics* 9(3): 445-65.

Scott, G., M.W. Rosegrant, and C. Ringler 2000. *Roots and Tubers for the 21st Century: Trends, Projections, and Policy Options*. 2020 Vision Discussion Paper 31. Washington, D.C.: International Food Policy Research Institute.

Scott, G.J., M.W. Rosegrant, and C. Ringler. 2000. *Roots and Tubers for the 21st Century*. 2020 Discussion Paper No. 31. Washington, D.C.: International Food Policy Research Institute.

Scott, G. J., M.W. Rosegrant, and C. Ringler. 2000. Global Projections for Root and Tuber Crops to the Year 2000. *Food Policy* 25(5): 561-597.

Appendix 2 The IMPACT Development Team

The IMPACT model has had many contributors over the years and remains in active development today.

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APPENDIX 3 IMPACT REGIONS

1	Adriatic Europe	41	Germany	81	Pakistan
2	Afghanistan	42	Ghana	82	Papua New Guinea
3	Algeria	43	Guinea	83	Peru
4	Alpine Europe	44	Guinea Bissau	84	Philippines
5	Angola	45	Gulf	85	Poland
6	Argentina	46	Iberia	86	Russia
7	Australia	47	India	87	Rwanda
8	Baltic	48	Indonesia	88	Scandinavia
9	Bangladesh	49	Iran	89	Senegal
10	Belgium Luxembourg	50	Iraq	90	Sierra Leone
11	Benin	51	Israel	91	Singapore
12	Bhutan	52	Italy	92	Somalia
13	Botswana	53	Ivory Coast	93	South Africa
14	Brazil	54	Japan	94	South Korea
15	British Isles	55	Jordan	95	Southeast Asia
16	Burkina Faso	56	Kazakhstan	96	Sri Lanka
17	Burundi	57	Kenya	97	Sudan
18	Cameroon	58	Kyrgyzstan	98	Swaziland
19	Canada	59	Lebanon	99	Syria
20	Caribbean and Central America	60	Lesotho	100	Tajikistan
21	Caucus	61	Liberia	101	Tanzania
22	Central African Republic	62	Libya	102	Thailand
23	Central Europe	63	Madagascar	103	Togo
24	Central South America	64	Malawi	104	Tunisia
25	Chad	65	Malaysia	105	Turkey
26	Chile	66	Mali	106	Turkmenistan
27	China	67	Mauritania	107	Uganda
28	Colombia	68	Mexico	108	Ukraine
29	Congo	69	Mongolia	109	United States
30	Cyprus	70	Morocco	110	Uruguay
31	Djibouti	71	Mozambique	111	Uzbekistan
32	DRC	72	Myanmar	112	Vietnam
33	Ecuador	73	Namibia	113	Zambia
34	Egypt	74	Nepal	114	Zimbabwe
35	Equatorial Guinea	75	Netherlands	115	Rest of the World
36	Eritrea	76	New Zealand		
37	Ethiopia	77	Niger		
38	France	78	Nigeria		
39	Gabon	79	North Korea		
40	Gambia	80	Northern South America		

APPENDIX 4 DEFINITION OF COMPOSITE IMPACT REGIONS

Composite Region	Description
Adriatic Europe	Albania, Bosnia-Herzegovina, Croatia, Greece, Kosovo, Macedonia, Montenegro, Serbia, Slovenia
Alpine Europe	Austria, Liechtenstein, Switzerland
Baltic States	Belarus, Estonia, Latvia, Lithuania
Belgium-Luxembourg	Belgium, Luxembourg
British Isles	Ireland, United Kingdom
Caribbean and Central America	Belize, Costa Rica, Cuba, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Nicaragua, Panama
The Caucuses	Armenia, Azerbaijan, Georgia
Central Europe	Czech Republic, Hungary, Moldova, Romania, Slovakia
Central South America	Bolivia, Paraguay
China	China, Hong Kong, Macau
Gulf States	Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates, Yemen
Iberia	Andorra, Portugal, Spain
Morocco	Morocco, Western Sahara
Northern South America	Guyana, Surinam, Venezuela
Scandinavia	Denmark, Finland, Iceland, Norway, Sweden
Southeast Asia	Cambodia, Laos

APPENDIX 5 DEFINITIONS OF WATER BASINS

1	Amazon	43	Iberia West Atlantic	85	Philippines
2	Amudarja	44	India East Coast	86	Red-Winnipeg
3	Amur	45	Indonesia East	87	Rhine
4	Arabian Peninsula	46	Indonesia West	88	Rhone
5	Arkansas	47	Indus	89	Rio Colorado
6	Baltic	48	Ireland	90	Rio Grande
7	Black Sea	49	Italy	91	Rest-of-World
8	Borneo	50	Japan	92	Sahara
9	Brahmaputra	51	Kalahari	93	Sahyada
10	Brahmari	52	Krishna	94	Salada Tierra
11	Britain	53	Lake Balkhash	95	San Francisco
12	California	54	Lake Chad Basin	96	Scandinavia
13	Canada-Arctic-Atlantic	55	Langcang Jiang	97	Southeast Asia Coast
14	Caribbean	56	Limpopo	98	Seine
15	Cauvery	57	Loire-Bourdeaux	99	Senegal
16	Central African West Coast	58	Lower Mongolia	100	Songhua
17	Central America	59	Luni	101	South African Coast
18	Central Australia	60	Madagascar	102	South Korean Peninsula
19	Central Canada Slave Basin	61	Mahi Tapti	103	Southeast African Coast
20	Chang Jiang	62	Mekong	104	Southeast US
21	Chotanagpul	63	Middle Mexico	105	Sri Lanka
22	Colorado	64	Mississippi	106	Syrdarja
23	Columbia	65	Missouri	107	Thai-Myan-Malay
24	Columbia Ecuador	66	Murray Australia	108	Tierra
25	Congo	67	New Zealand	109	Tigris-Euphrates
26	Cuba	68	Niger	110	Toc
27	Danube	69	Nile	111	Upper Mexico
28	Dnieper	70	North African Coast	112	Upper Mongolia
29	East African Coast	71	North Euro Russia	113	Ural
30	Eastern Ghats	72	North Korea Peninsula	114	Uruguay
31	Eastern Australia Tasmania	73	North South America	115	US Northeast
32	Eastern Mediterranean	74	Northeast Brazil	116	Volga
33	Elbe	75	Northwest Africa	117	Volta
34	Ganges	76	Northwest South America	118	West African Coastal
35	Godavari	77	Ob	119	Western Asia-Iran
36	Great Basin	78	Oder	120	Western Australia
37	Great Lakes	79	Ohio	121	Western Gulf Mexico
38	Hai He	80	Orange	122	Yenisey
39	Horn of Africa	81	Orinoco	123	Yili He
40	Hua He	82	Papua Oceania	124	Yucatan
41	Huang He	83	Parana	125	Zambezi
42	Iberia East Mediterranean	84	Peru Coastal	126	Zhu Jiang

APPENDIX 6 IMPACT COMMODITIES

1	Beef	24	Rice
2	Cassava et al.	25	Sheep and Goats
3	Chickpeas	26	Sorghum
4	Cotton	27	Soybean Meal
5	Eggs	28	Soybean Oils
6	Groundnut Meal	29	Soybeans
7	Groundnut Oils	30	Sugar
8	Groundnuts	31	Sugar beets
9	Maize	32	Sugarcane
10	Milk	33	Sunflower
11	Millet	34	Sunflower Meal
12	Other Grains	35	Sunflower Oil
13	Palm	36	Sweet Potatoes and Yams
14	Palm Kernel	37	Sweeteners
15	Palm Kernel Meal	38	Temperate Fruits
16	Palm Kernel Oil	39	Total Other Meals
17	Pigeonpeas	40	Total Other Oils
18	Pork	41	Total Other Oilseeds
19	Potato	42	Tropical and Sub-Tropical Fruits
20	Poultry	43	Vegetables
21	Rapeseed	44	Wheat
22	Rapeseed Meal	45	Other Crops
23	Rapeseed Oil		

Appendix 7 Definitions of IMPACT Commodities

LIVESTOCK

Meat

1. Beef: beef and veal (Meat of bovine animals, fresh, chilled or frozen, with bone in) and buffalo meat (Fresh, chilled or frozen, with bone in or boneless).
2. Pork: pig meat (Meat, with the bone in, of domestic or wild pigs, whether fresh, chilled or frozen).
3. Poultry: Chicken meat (Fresh, chilled or frozen). Includes all types of poultry meat like duck, goose and turkey
4. Sheep and goat: Meat of sheep and lamb, or goat and kids (whether fresh, chilled or frozen, with bone in or boneless)

Other Livestock Products

5. Eggs: Eggs from any type of fowl (weight in shell)
6. Milk: Cow, sheep, goat, buffalo and camel milk (Production data refer to raw milk containing all its constituents. Trade data normally cover milk from any animal, and refer to milk that is not concentrated, pasteurized, sterilized or otherwise preserved, homogenized or peptonized.).

CROPS

Grains

7. Maize: Maize (used for human consumption, animal feed and commercial starch production)
8. Millet: Finger and Pearl Millet (used locally, both as a food and as a livestock feed)
9. Other coarse grains: Includes Barley (with and without husk, for human consumption and livestock feed), Oats (for both human and animal consumption), and Rye (used in making bread, whisky and beer. When fed to livestock, it is generally mixed with other grains). Does not include other minor grains (i.e. quinoa, teff, etc.)
10. Rice: Rice milled equivalent (White rice milled from locally grown paddy. Includes semi-milled, whole-milled and parboiled rice).
11. Sorghum: Sorghum (a cereal that has both food and feed uses)
12. Wheat: Wheat (Used mainly for human food).

Roots and Tubers

13. Cassava et al.: Cassava and other starchy tubers, roots or rhizomes. This is predominantly cassava, cocoyams and taro (both are staple foods in many tropical countries, and are not extensively traded internationally in its fresh state because the tubers deteriorate very rapidly).

This group does not include the following roots, tubers rhizomes which are treated as vegetables: Beets, Carrots, Cassava Leaves, Chicory/Endives, Ginger, Radishes, Turnips

14. Potatoes: Potatoes (Mainly used for human food).
15. Sweet potatoes and yams: Sweet potatoes (Used mainly for human food. Trade data cover fresh and dried tubers, whether or not sliced or in the form or pellets) and Yams (A starchy staple foodstuff, normally eaten as a vegetable, boiled, baked or fried).

Vegetables

16. Vegetables: Onions, Tomatoes, miscellaneous vegetables. Does not include pulses like beans and peas

Fruits

17. Temperate Fruits: Temperate Fruits such as Apples, Berries (strawberries, blackberries, raspberries, blueberries, etc.), Drupes (cherries, peaches, plums, apricots, etc.), other pommes fruits (pears, quinces, etc.), and other Miscellaneous Temperate Fruits. Mediterranean Fruits such as Grapes are included in this group
18. Tropical and Sub-tropical Fruits: Bananas, Cantaloupes & Other Melons, Citrus Fruits, Dates, Pineapples, Plantains, Watermelons, and other Miscellaneous Tropical and Sub-Tropical Fruits

Dryland Pulses

19. Chickpeas
20. Pigeonpeas

Oil Crops

21. Soybeans: The most important oil crop, but also widely consumed as a bean and in the form of various derived products because of its high protein content, e.g. soya milk, meat, etc.
22. Soybean Meal: The ground up solid residue left over from the production of soybean oil
23. Soybean Oil: Vegetable oil produced from soybeans, it is the most widely consumed cooking oil
24. Groundnuts: The underground seeds of plants in the Faboideae subfamily of the legumes, which include the commercially important peanut, and locally important bambara, and hausa nuts
25. Groundnut Meal: The ground up solid residue left over from the production of groundnut oil
26. Groundnut Oil: Vegetable oil produced from groundnuts
27. Rapeseed: Rape and mustard seed production
28. Rapeseed Meal: The ground up solid residue left over from the production of rapeseed (canola) and mustard seed oil
29. Rapeseed Oil: Vegetable oil produced from rape and mustard seeds
30. Sunflower: Sunflower seed production

31. Sunflower meal: The ground up solid residue left over from the production of sunflower oil
32. Sunflower Oil: Vegetable oil produced from sunflower seeds. Used as a cooking oil and in cosmetics
33. Palm Kernel: The production of kernel of the oil palm
34. Palm Kernel Meal: The ground up solid residue left over from the production of palm kernel oil
35. Palm Kernel Oil: Vegetable oil produced from the palm kernel
36. Palm: Palm Oil Fruit
37. Total Other Oilseeds: Coconut, cotton seed, olives, sesame seed, tung nut, tallow tree seed, castor oil seed, hempseed, kapok fruit, karite nut, linseed, melon seed, "oilseed, nes", poppy seed, and safflower seed
38. Total Other Meals: The residue from oil extraction of the above oil seeds, mainly used for feed
39. Total Other Oils: Vegetable oils and products (obtained by pressure or solvent extraction. Used mainly for food).

Other Crops

40. Sugarcane: Sucarcane
41. Sugar Beets: Sugar Beets (red beets are treated as a vegetable)
42. Sugar: Refined Sugar (consumed)
43. Sweeteners: Sweeteners that are not derived from Sugar Cane or Sugar Beets such as Honey, Stevia, and Syrups (i.e. maple, and agave)
44. Cotton: Cotton lint
45. Other Crops: Other agricultural crops not specifically modeled in IMPACT

Source: (FAO 2011; Delgado 2003)

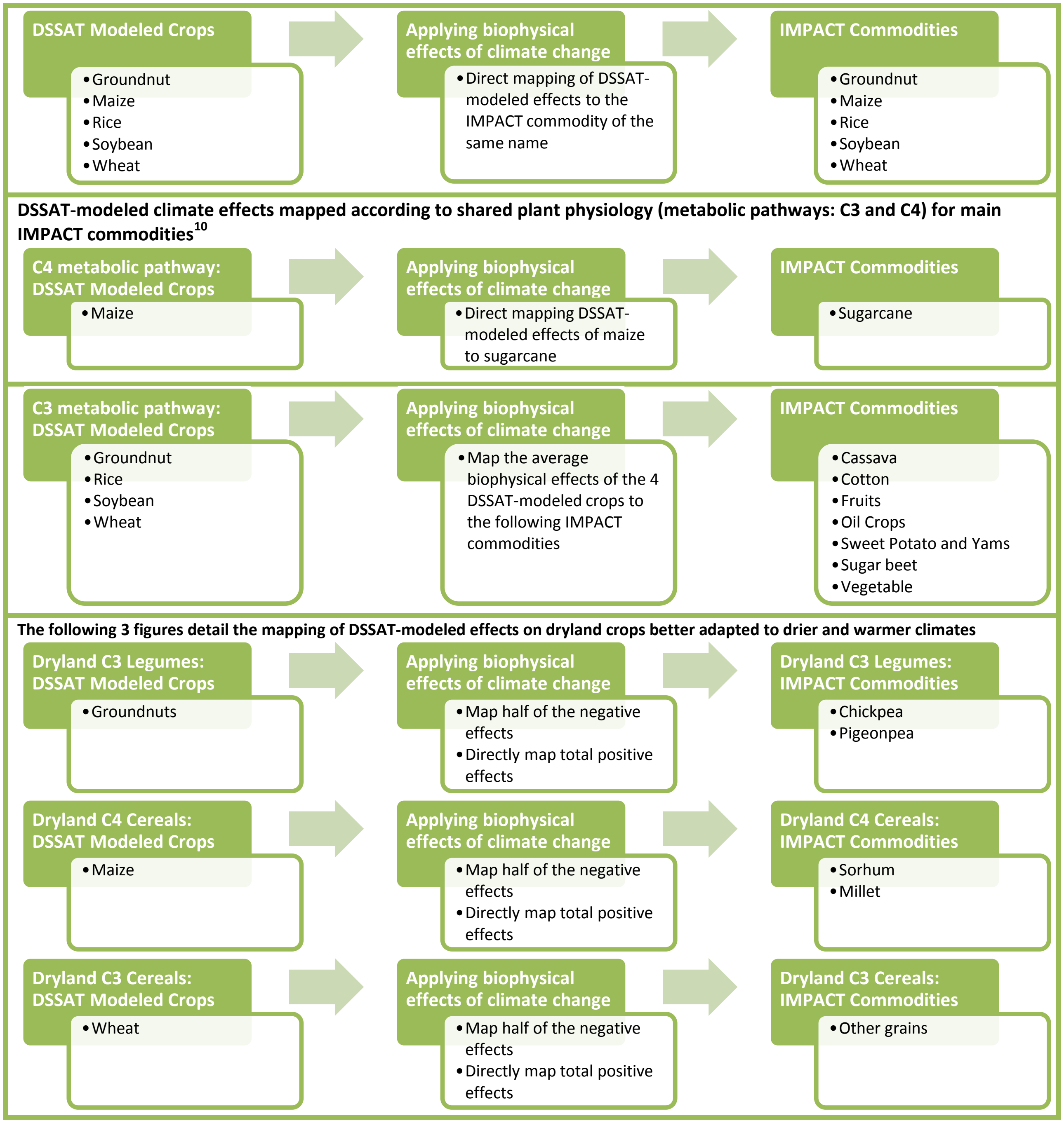
APPENDIX 8 SOURCE OF BASE 2000 COMMODITY PRICES

IMPACT Commodity	Source of 2000 Commodity Prices
Beef	Pink Sheets (World Bank 2012)
Cassava et al.	World Unit Value Database (AMAD 2010)
Chickpeas*	World Unit Value Database (AMAD 2010)
Cotton	Pink Sheets (World Bank 2012)
Eggs	World Unit Value Database (AMAD 2010)
Groundnut Meal	estimated based on related commodities
Groundnut Oil	Pink Sheets (World Bank 2012)
Groundnuts	Pink Sheets (World Bank 2012)
Maize	Pink Sheets (World Bank 2012)
Meals	Pink Sheets (World Bank 2012)
Milk	Agricultural Prices Summary (USDA 2010a)
Millet*	World Unit Value Database (AMAD 2010)
Oils	Pink Sheets (World Bank 2012)
Other Coarse Grains	World Unit Value Database (AMAD 2010)
Palm Fruit	Pink Sheets (World Bank 2012)
Palm Kernel	Pink Sheets (World Bank 2012)
Palm Meal	estimated based on related commodities
Palm Oil	Pink Sheets (World Bank 2012)
Pigeonpeas	estimated based on related commodities
Pork*	World Unit Value Database (AMAD 2010)
Potatoes	World Unit Value Database (AMAD 2010)
Poultry*	Poultry Yearbook and Agricultural Prices Summary (USDA 2010b, 2010a)
Rapeseed	Pink Sheets (World Bank 2012)
Rapeseed Meal	estimated based on related commodities
Rapeseed Oil	Pink Sheets (World Bank 2012)
Rice	Pink Sheets (World Bank 2012)
Sheep and Goats	Pink Sheets (World Bank 2012)
Sorghum	Pink Sheets (World Bank 2012)
Soybean Meal	estimated based on related commodities
Soybean Oil	Pink Sheets (World Bank 2012)
Soybeans	Pink Sheets (World Bank 2012)
Sub-tropical Fruits	Pink Sheets (World Bank 2012)
Sugar (refined)	Sugar and Sweeteners Yearbook (USDA 2010c)
Sunflower	Pink Sheets (World Bank 2012)
Sunflower Meal	estimated based on related commodities
Sunflower Oil	Pink Sheets (World Bank 2012)
Sweet Potatoes & Yams	World Unit Value Database (AMAD 2010)
Sweeteners*	World Unit Value Database (AMAD 2010)

Temperate Fruits	World Unit Value Database (AMAD 2010)
Total Other Meals	estimated based on related commodities
Total Other Oils	estimated based on related commodities
Total Other Oilseeds	estimated based on related commodities
Vegetables	estimated based on related commodities
Wheat	Pink Sheets (World Bank 2012)
Other	estimated based on related commodities

*Prices were adjusted by expert opinion

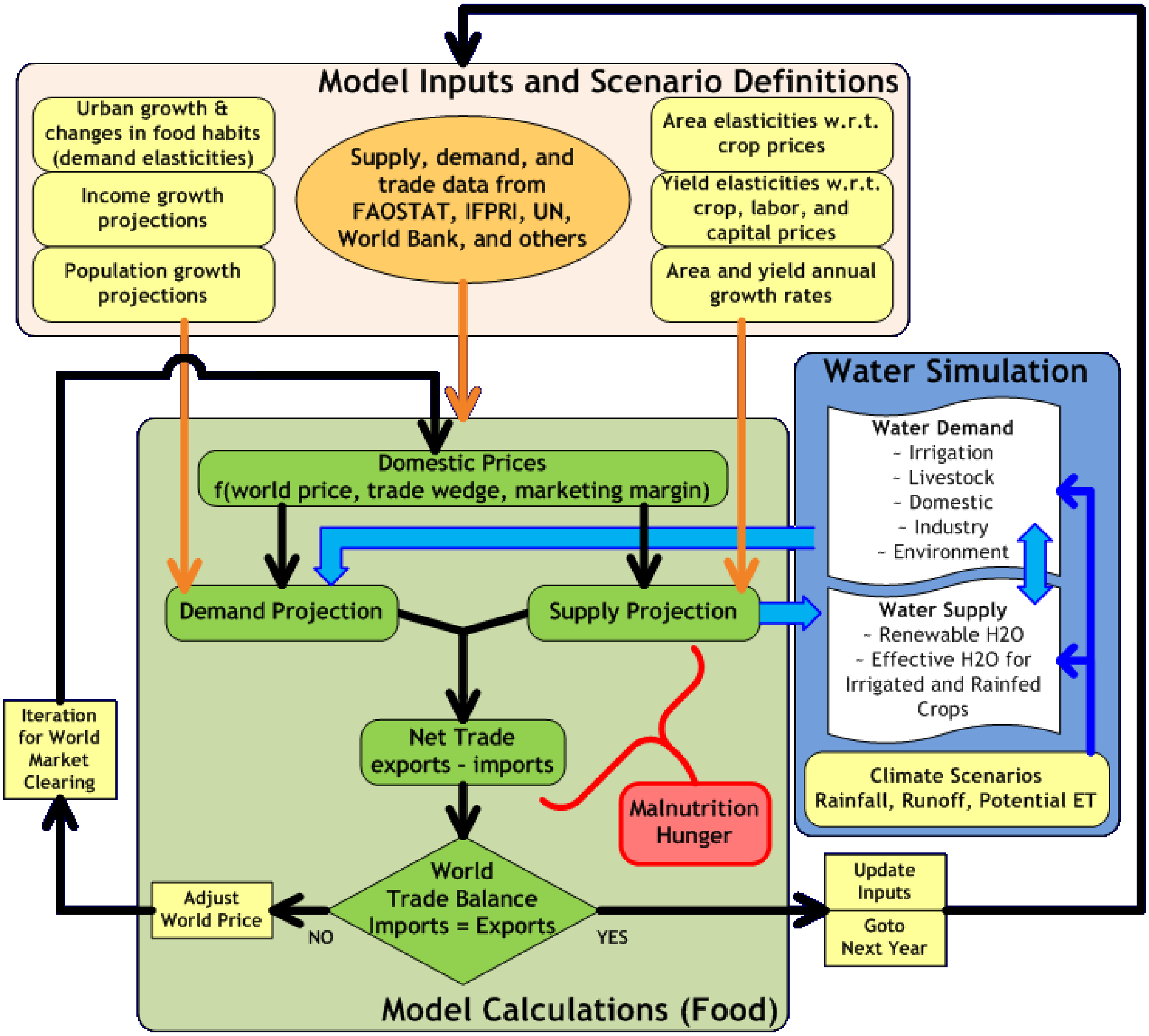
APPENDIX 9 APPLYING DSSAT-MODELED BIOPHYSICAL EFFECTS OF CLIMATE CHANGE[9]



[9] DSSAT-modeled effects are applied only on yields (both irrigated and rainfed) and on rainfed area. Expansion of irrigated area is modeled through scenarios with increased investment

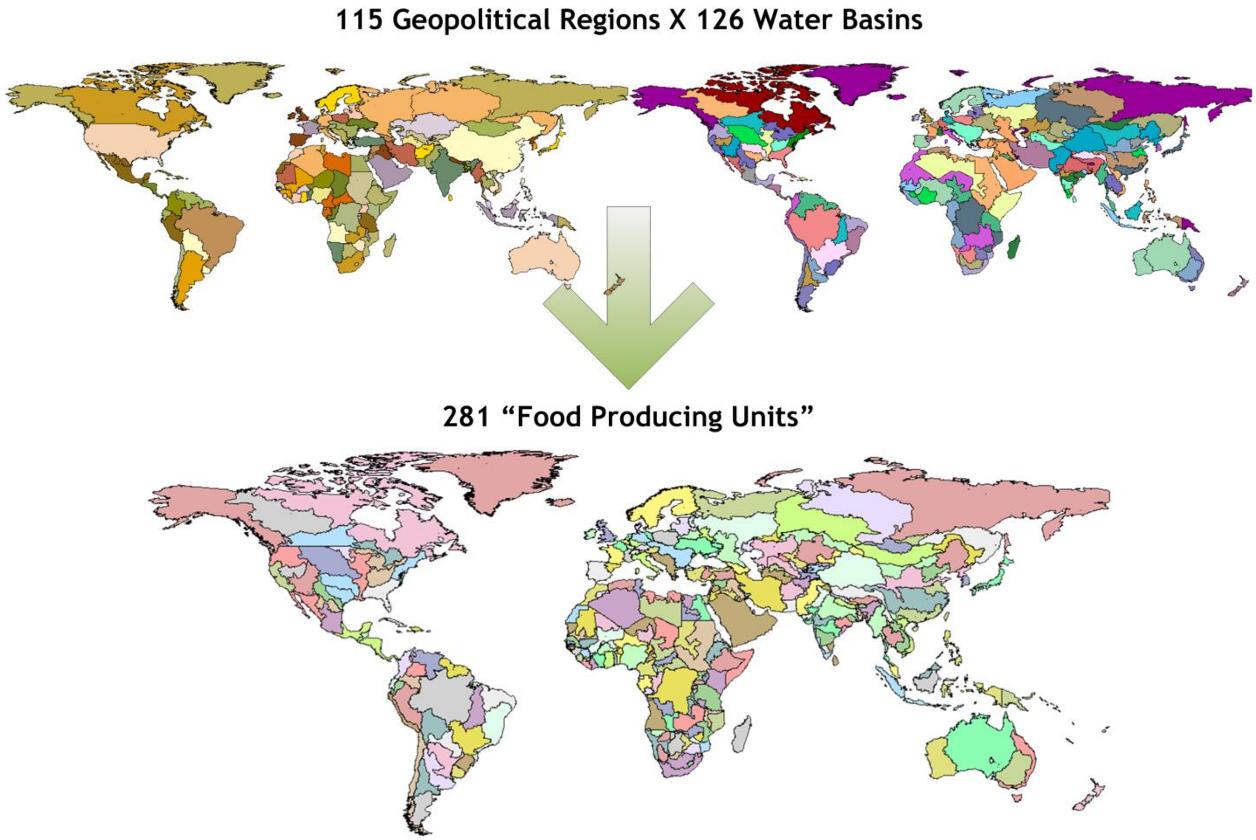
[10] Fruits include subtropical and temperate fruits; Oil Crops include rapeseed, sunflower, palm kernel, palm fruit, and total other oilseeds

APPENDIX 10 SCHEMATIC PRESENTATION OF IMPACT



Source: Authors

APPENDIX 11 IMPACT SPATIAL RESOLUTION



Source: Authors