**Supplementary Information for:**

**Supporting sustainable expansion of livestock production in South Asia and Sub-Saharan Africa: Scenario analysis of investment options**

Technical notes on the IMPACT Model

IMPACT, the International Model for Policy Analysis of Agricultural Commodities and Trade, is an integrated modeling system of the global agriculture sector. Originally developed at the International Food Policy Research Institute (IFPRI) in the 1990s as a global, partial equilibrium, multimarket model, IMPACT has undergone a series of changes. Current versions of the model (e.g., since 2015) incorporate simultaneous accounting of biophysical systems, socioeconomic trends, technological changes, and policies in the assessments of global food and agricultural systems. Continually updated, the current versions link information from climate models, crop simulation models and water models to a core global, partial equilibrium, multimarket model; the integration of multidisciplinary modules being considered better suited to the needs of researchers and policymakers for analytical tools that support longer term scenario analysis and decision-making.

The core multimarket model in IMPACT simulates national and international markets for each of (62) distinctly defined agricultural commodities. These commodities represent the bulk of food and cash crops traded globally. Agricultural production is modelled at a sub-national level, within a unit of analysis defined as the food production unit (FPU). FPUs correspond to the intersection between countries (159) and water basins (154) in IMPACT. There are 320 FPUs in total in the IMPACT framework. Within these units, crop production is specified by models of land supply, allocation of land to irrigated and rainfed crops, and crop yields. The livestock sector is linked to crop production and the use of water and land resources through use of crop biomass as animal feeds. The livestock value chain in IMPACT simulates activities from seed grains to dressed meat and milk.

A full description of the history, uses and structure of IMPACT, including the model’s input and output data is presented in Robinson et al. (2015). The following narratives have been reproduced from that original report, appropriately contextualized to aid readers’ understanding of the model and scenario results as they have been used in the current analysis. First, livestock production as simulated in IMPACT’s multi-market model is presented. Next, the model’s representation of food demand and markets are presented. A description of IMPACT’s suite of models follows, for which we describe key indicators of food security, welfare, and environmental management that we have included in our study. The technical note on the IMPACT model is then concluded with one section on the model’s validation and the use of scenario analysis, and another highlighting key exceptions relevant to the current study.

For even more detailed discussion, readers may refer to Robinson et al. (2015).

1. Livestock production

Livestock production in IMPACT is simulated through animal numbers, with associated feed demands, and meat/dairy production based on processing the animals, e.g., milking of dairy animals and slaughter of meat animals. The choice of specifying production in this way has a long history in IMPACT and facilitates interaction with livestock experts who typically work with concepts such as herd sizes and unit feed requirements. Livestock production occurs within livestock production systems that have been defined to characterize global production of livestock based on land cover, human population density and length of (crop) growing period, amongst others (Robinson et al., 2011). In the current version of IMPACT, there is no modeling of herd dynamics—herd size over time is set exogenously. Feed demand is a function of the livestock’s own price, the prices of intermediate (feed) inputs, and a trend variable reflecting growth in livestock herds (slaughter rates are implicitly assumed to stay more or less constant over time).

The relevant equations for livestock numbers and production are shown following.

$Animals\_{j,fpu,livsys}=AnimalInt\_{j, fpu,livsys}\* AnimalInt2\_{j,fpu,livsys} \*\left(PNET0\_{j,cty}\right)^{ANe}\*\prod\_{cfeeds}^{}\left(PC\_{j,cty})\right)^{Feede}$ (Eqn A1)

*Animals* = Number of producing animals

*AnimalsInt* = Animal intercept (initial number of animals)

*AnimalInt2* = Exogenous population growth rate

*j* = Activity (livestock-derived food product)

*FPU* = Food production unit

*Livsys* = Livestock production systems

*PC* = Consumer price

*PC0* = Initial consumer price

*PNET* = Net price for the Activity at the country level mapped to *livsys*

*PNET0* = Initial net price

*ANe* = Supply elasticity with respect to changes in net price

*Feede* = Supply elasticity with respect to changes in feed prices

*Cfeeds* = Feed commodities’ demand by livestock sector

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

$AnimalYield\_{j,fpu,livsys}=AnimalYieldInt\_{j, fpu,livsys}\* AnimalYieldInt2\_{j,fpu,livsys} $ (Eqn A2)

*AnimalYield* = Livestock production per animal unit

*AnimalYieldInt* = Initial animal yield

*AnimalYieldInt2* = Exogenous yield growth rate

The subscripts *j, fpu* and *livsys* are as earlier defined (for Eqn A1)*.*

Total national production is calculated by multiplying the number of slaughtered animals by the yield per head and summing across livestock production systems.

$QS\_{j,cty}=\sum\_{fpu,livsys}^{}\left(Animals\_{j,fpu,livsys} X AnimalYield\_{j,fpu,livsys}\right)\_{}$ (Eqn A3)

*QS* = National production of livestock activity

*Animals* and *AnimalYield* are as defined for the earlier equations.

There is work under way to improve IMPACT’s representation of livestock production to better account for inputs (including different feed types) and outputs (including secondary production) typically observed in lower-resource production systems globally. The scope of this work has been outlined in Msangi et al. (2014).

1. Demand for IMPACT crop and livestock commodities

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

$QD\_{c,cty}=\sum\_{h}^{}\left(QH\_{c,h,cty} \right)+QInterim\_{c, cty}+QL\_{c, cty}+QBF\_{c, cty}+QOth\_{c, cty}\_{}$ (Eqn A4)

*QD* = Total commodity demand

*QH* = Household food demand

*QInterim* = Intermediate demand from ag-processing sector

*QL* = Feed demand from livestock sector

*QBF* = Intermediate demand for biofuel feedstock

*QOth* = All other demand

*h* =Household type

Food demand is a function of the price of the commodity and the prices of other competing commodities, per capita income, and total population. Per capita income and population increase annually according to country-specific population and income growth rates. Population and gross domestic product (GDP) trends vary by scenario and are drawn from the Shared Socioeconomic Pathway (SSP) database representing socioeconomic scenarios from IPCC’s AR5. The IMPACT demand elasticities are originally based on United States Department of Agriculture–estimated elasticities and adjusted to represent a synthesis of average, aggregate elasticities for each region, given the income level and distribution of urban and rural population (United States Department of Agriculture 1998). Over time the elasticities are adjusted to accommodate the gradual shift in demand from staples to high-value commodities like meat, especially in developing countries. This assumption is based on expected economic growth, increased urbanization, and continued commercialization of the agricultural sector. IMPACT is designed to simulate multiple types of households (that is, rural, urban, rich, poor, and so forth); however, currently, IMPACT treats household demand with one representative consumer per country.

Feed demand is a derived intermediate demand defined by animal feed requirements and price effects. The price effects take into account potential substitution possibilities among different feeds. The equation also incorporates a technology parameter that indicates improvements in feeding efficiencies over time.

$QL\_{c,cty}=\sum\_{jlvst}^{}\left(QS\_{jlvst,cty}\*Req\_{jlvst,c, cty} \right)\* \prod\_{cfeeds}^{}\left(PC0\_{c,cty}\right)^{LFDe} \_{}$ (Eqn A5)

*QL* = Total feed demand from livestock sector

*QS* = Total production of each livestock activity

*Req* = Feed requirements for each livestock activity

*LFDe* = Price elasticity of demand for feed

*jlvst* = Set of livestock producing activities

Intermediate demand is a derived demand that is based on the demand for final processed goods, such as food oils and sugar. Exogenous biofuel feedstock demand is determined through exogenous growth rates, which represent government mandates to encourage the production of biofuels. Other demand summarizes all other demands for agricultural products from sectors outside of the focus of IMPACT (for example, seeds, industrial use).

1. Markets and trade

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

IMPACT assumes a closed world economy—at the end of every year the world’s production must equal the world’s demand. National production and demand for tradable commodities are linked to world markets through trade. Commodity trade by country (cty) is a function of domestic production, domestic demand, and stock change. Regions with positive net trade are net exporters, while those with negative values are net importers. This specification does not permit a separate identification of international trade by country of origin and destination—all countries export to and import from a single global market. Prices are endogenous in the system of equations for food and are calibrated to 2005 commodity prices. Prices are in constant 2005 US dollars.

1. The IMPACT model system

Macroeconomic trends in IMPACT reflect projections from demographic and economic growth models, while earth system models (ESMs) provide climate data, i.e., temperature and precipitation, as inputs to IMPACT’s water and crop simulation models (see Figure A1). While the other linkages are unidirectional, the flow of information between the core multimarket model and the water model is two-flow over time. Other modules such as value chains and land allocation to crops, are integrated within-period with the core multimarket model. Finally, results from the equilibrium model solution are used as inputs in calculating some extended results.

Figure A1: The IMPACT system of models



Source: Adapted from Robinson, et al., 2015.

Understanding the interplay of commodity production, trade, and demand is valuable, but understanding some of the potential implications of these changes is also important. The following post-solution are/can be coupled to IMPACT’s primary results:

* 1. Underweight among children under five

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

$∆UndNrsh\_{t,t0}=-25.24\*ln{KCal\_{t}}/{KCal\_{t0}}- \left(71.76\* ∆LFER\_{t,t0}\right)-\left(0.22\* ∆Sch\_{t,t0}\right)- \left(0.08\*∆WAT\_{t,t0} \right)\_{}$ (Eqn A6)

*UndNrsh* = Percent change in number of undernourished children

*KCAL* = Per capita kilocalorie availability

*LFER* = Ratio of female-male life expectancy at birth

*Sch* = Gross female secondary school enrollment rate

*WAT* = Percent of population with access to safe water

* 1. Share of population at risk of hunger

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

$ShareatRisk=(89.63\*RelativeKCal^{2}) - (319.69\*RelativeKCal)+288.16+ ε\_{}$ (Eqn 7)

$ε$= Estimation error

$RelativeKCal$ = $\left(MinKCal\right)$

$KCal$= Food supply

$MinKCal$= Minimum food requirement

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

* 1. Consumer and Producer welfare

The welfare module in IMPACT follows a traditional economic welfare analysis approach to estimate the benefits to society on the consumer and producer side. It allows policymakers to disentangle some of the effects of alternative plausible futures in changes to agricultural commodity prices as well as quantities produced and consumed. The welfare analysis module is a one-way postprocessing module, taking in the results from the multimarket model as inputs for welfare calculations. On the demand side a consumer surplus is calculated to estimate changes faced by consumers from changes in agricultural markets. These consumer surpluses can be aggregated to give a measure of national and global consumer surplus. The producer surplus is the area above the supply curve and under the equilibrium price. In IMPACT, calculating this area directly is relatively complicated; thus, the producer surplus is calculated using agricultural revenue (market price multiplied by quantity) minus total cost of production, which is the area under the supply curve. 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. For this specific analysis, we used changes to producer incomes, assuming no specific change to production costs from the different interventions.

* 1. Water Use

The water demand module calculates water demand for crops, industry, households, and livestock at the FPU/livsys level. The IMPACT multimarket model solves endogenously for the allocation of land to different crops while IWSM requires information about the cropping pattern to calculate irrigation water demand and hence water stress that is then an input into the multimarket model, which requires two-way communication between the models (as mentioned earlier). Industrial water demand is modeled for the manufacturing and energy sectors. Future domestic water demands are based on projections of population and income growth. In each region or water basin, income elasticities of demand for domestic water use are synthesized based on the literature and available estimates. These elasticities of demand measure the propensity to consume water with respect to increases in per capita income. The elasticities also capture both direct income effects and conservation of domestic water use through technological and management change. Livestock water demand is proportional to the number of animals raised as calculated by the multimarket model.

* 1. Greenhouse gas emissions

The analysis of greenhouse gas emissions focused on quantifying GHG emissions derived from productivity changes in crop and livestock production systems projected under all 12 scenarios for IMPACT model runs. Simple empirical approaches were employed (e.g., IPCC Tier 1 and/or 2) instead of more sophisticated approaches (e.g., Tier 3, such as process-based simulation modeling), mainly because of the difficulties in implementing socioeconomic components of the IMPACT scenarios into agronomic information required to run process-based simulation models. Among 11 agricultural subcategories of the AFOLU sector, we estimated GHG emissions from three subcategories: i) synthetic fertilizers [nitrous oxide (N2O)] ii) rice cultivation [methane (CH4)] iii) enteric fermentation (CH4).

Livestock production is responsible for CH4 emissions from enteric fermentation and CH4 and N2O emissions from livestock manure management systems. Among several species of livestock, ruminants (e.g., cows, buffaloes, camels, and goats) are important sources of CH4 in many countries. Thus, CH4 emissions were calculated based on ruminant animal numbers projected in IMPACT (both slaughtered cattle and dairy animals) and emission numbers from the enteric fermentation section of FAOSTAT.

1. Model validation, sensitivity analyses and scenario analysis

Like global Computable General Equilibrium (CGE) models that focus on long-run scenario analysis, structural simulation models like IMPACT are inherently difficult to validate. In particular, the types of validation that are possible for short-run forecasting models (e.g., by simulating the model for recent years for which data are available and doing statistical analysis of the quality of the results) or for econometric models (e.g., estimating the model parameters to maximize a measure of goodness of fit to the data used in estimation) are typically not feasible for structural models. These simulation models have many parameters and functional forms that are hard to estimate econometrically, while the models are designed for use in the analyses of scenarios outside of the domain of historical data. In addition, sensitivity testing, at least in a stochastic sense is not possible to conduct in IMPACT. This is the case as there is no way to fully test all of the relevant parameters in isolation, and in combination. Scenario analysis instead have been used to analyze ranges of potential futures, assessing whether the model results (e.g., outcomes on a specific indicator such as food security) remain robust under alternatives of system drivers and interventions such as policies.

The results from Rosegrant et al., 2017, i.e., the sets of IMPACT model scenarios and results assessed in this paper, were designed in such a way as to explore initially in isolation, the response of model outcomes to assumptions of changes in system drivers and interventions, and then their interaction effects. In particular, the robustness of the results was tested under assumptions of climate change and of technologically-induced changes in agricultural productivity. All scenario assumptions were applied individually both with and without climate change, and then in combination. Within the set of agricultural productivity scenarios, a range of plausible alternative futures was further explored to assess the effects of different levels (e.g., medium to high) and pathways (e.g., global versus national research focus) of investment and productivity changes. The goal of these types of analyses is to define a broad possibility space, even if it is not possible to predict the full range of outcomes. The full list of IMPACT model scenarios included in Rosegrant et al. (2017) is presented in Appendix Table 1, along with brief descriptions of the scenarios. Only a subset of these scenario results is included in the current analysis, with careful thought to identify scenarios of most relevance to the livestock research and macro policy questions of the selected study regions.

1. Important Caveats

A number of issues arise from use of the IMPACT methodology. Highlighted below are major critiques specific to the current study.

* 1. IMPACT works on the average consumer, and as such will inevitably miss the potential variation among producers and consumers within countries. The choice of geographical unit in our analysis further leads to loss of country-specific contexts. While some results highlighting key differences between countries have been included, this does not fully address the fact that important spatial and other variability have been aggregated out.
	2. IMPACT works on average climate change over long periods of time, so it isn’t designed to capture extreme events. As such, we have not assessed potential impacts of climate-induced shocks to the livestock sector.
	3. Agricultural commodities and production practices are simulated as being homogeneous within the scale of analysis. For commodities this is at the global level (e.g., Milk in Kenya is equivalent to Milk in Mexico), assuming perfect substitutability. For production, the range of variation of production practices within the unit of analysis are not considered.
	4. IMPACT calculates global net trade so that it does not account for bi-lateral trade between any two countries. In the current context, it means there is no accounting for observed or potential intra-regional trade in livestock and livestock products that will ordinarily be important features of trade in livestock-derived foods in both Sub-Saharan Africa and South Asia.
	5. The feed databases of both the IMPACT model and the national statistics from which IMPACT takes its starting parameters do not appropriately account for use of livestock feed biomass from crop residues, grasses, and other sources relevant to smallholder and extensive systems (Msangi et al, 2014), limiting the capacity to fully assess livestock production expansion in the context of feed resources needed or available.

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Appendix Table 1: Summary of Investment Scenarios

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| --- | --- | --- | --- |
| Scenario Grouping | Scenario name in Rosegrant et al (2017) | Scenario name in this Study (blank if not included) | Description\* |
| Reference | REF\_HGEM | REFERENCE | Reference scenario with RCP 8.5 future climate using HadGEM GCM |
|  | REF\_IPSL |  | Alternative reference with RCP 8.5 future climate using IPSL GCM |
|  | REF\_NoCC |  | Alternate reference with no climate change (constant 2005 climate) Medium |
| Productivity Enhancement  | MED |  | Medium increase in R&D investment across the CGIAR portfolio |
| HIGH | HIGHYLD | High increase in R&D investment across the CGIAR portfolio |
| HIGH+NARS |  | High increase in R&D investment across the CGIAR portfolio plus complementary NARS investments |
| HIGH+RE |  | High increase in R&D investment across the CGIAR portfolio plus increased research efficiency |
| REGION | REGIONYLD | Regionally-focused high increase in CGIAR R&D investments Targets the highest increases to South Asia and Sub-Saharan Africa with medium levels of increase in Latin America and East AsiaInvestments |
| Improved Water Resource Management | IX |  | Investments to expand irrigation in the developing world |
| IX+WUE |  | Irrigation expansion plus increased water use efficiency Investments |
| ISW |  | Investments to Increase soil water holding capacity |
| Improved Infrastructure | RMM | MARKETS | Infrastructure improvements to improve market efficiency through the reduction of transportation costs and marketing margins |
| Comprehensive Investment | COMP |  | This comprehensive scenario is a combination of 4 scenarios: HIGH+RE; IX+WUE; ISW; and RMM |

Source: Rosegrant et al., 2017. The costs and implications of these investments scenarios for attaining hunger reduction in Africa has further been assessed in Mason-D’Croz et al., accepted).

\*RCP= Representative Concentration Pathway; HadGEM = Hadley Center’s Global Environment Model, version 2 (HADGEM2-ES or HGEM); GCM = Global Circulation Model; IPSL = Institut Pierre Simon Laplace’s Earth System Model (IPSL-CM5A-LR or IPSL); R&D = Research and Development; NARS = National Agricultural Research Systems.