Tradeoff Analysis of Agri-Food Systems for One CGIAR

John Antle and Roberto Valdivia

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EXECUTIVE SUMMARY

This report describes how Tradeoff Analysis (TOA) of agri-food systems can contribute to the One CGIAR mission of *ending hunger by 2030—through science to transform food, land and water systems in a climate crisis*. Science and industry recognize TOA as a valuable analytical tool to inform choice among management options for complex systems with uncertain, incommensurate, multi-dimensional outcomes. Alternative strategies to transform complex food, land and water systems will result in inevitable tradeoffs and potential synergies across the CGIAR impact areas: nutrition and food security; poverty reduction, livelihoods, and jobs; gender equality, youth, and social inclusion; climate adaptation and greenhouse gas reduction; environmental health and biodiversity. Through coordination of research design and evaluation at the project level with global One CGIAR goals, TOA can help One CGIAR and its stakeholders efficiently and effectively set priorities among potential innovations to balance inevitable tradeoffs and exploit synergies.

This report reviews the conceptual foundations of tradeoff analysis, describes current data and modeling tools from farm to global scales, and identifies their strengths and limitations. The first step in set-based TOA is the identification of *impact indicators* in the five impact areas. Stakeholders use these indicators to identify goals for agri-food system performance as acceptable ranges (or sets) of impacts. Analysts then use qualitative and quantitative data and modeling tools to evaluate the ranges (or sets) generated by agri-food system innovations under plausible future scenarios. These analyses can inform One CGIAR's research priority setting, and provide guidance to the design of stage-gated research project management and evaluation, to ensure that projects generate essential data for periodic re-evaluation of priorities by One CGIAR and its stakeholders.

This report also reviews the currently available modeling tools, and illustrates recent applications with case studies at scales ranging from farm to global. A key implication for use of TOA by One CGIAR is that analysis must be carried out at the temporal and spatial scales appropriate to the impacts. This insight derives from the earliest research on TOA carried out in the 1990s which showed that the spatial and temporal scales of analysis must correspond to the scales at which impact indicators can be meaningfully defined and quantified. This insight helps to explain why global-scale foresight analysis (FA) studies and global modeling studies do not adequately represent impacts in several of the One CGIAR priority impact areas – nutrition and food security; poverty reduction, livelihoods, and jobs; and, gender dimensions, youth, and social inclusion. Today, one of the frontiers of research

on TOA and related impact assessment methods is the integration of data and models across the relevant disciplines and scales to address these limitations.

This report concludes with a discussion of the opportunities and challenges for the use of TOA in One CGIAR research priority setting and management at global and project levels. Just as FA and TOA have proved valuable to increase the efficiency of industrial design, FA and TOA could yield a high rate of return to One CGIAR by providing the means to achieve more efficient design and evaluation of research projects that meet stakeholder goals.

RECOMMENDATIONS

The recommendations of this report are designed to be consistent with the new research modality recommended to the CGIAR System Council by the Systems Reference Group (SRG, November 2019). In this report, the term ”Big Lifts” refers to major One CGIAR global research thrusts to address global challenges, as defined in recent One CGIAR transition documents, and the term "Research Projects" refers to research activities carried out as part of the research portfolio implemented at regional and national levels. Of particular relevance to this report are the following elements:

- Research Projects supported by qualitative and quantitative ex-ante impact analysis
- Trade-off and delivery analysis among multiple benefits (at least do no harm)
- Positioning within a theory of change that explains expected impacts across all five Impact Areas, with projected positive impacts for multiple benefits
- Ex ante assessment and projection of impacts, including disaggregation of intended beneficiaries among small-scale producers
- A Performance and Results Management System that encompasses planning, monitoring, stage-gate decision points and reporting, and includes a dashboard open to Funders, via a Common Services information system

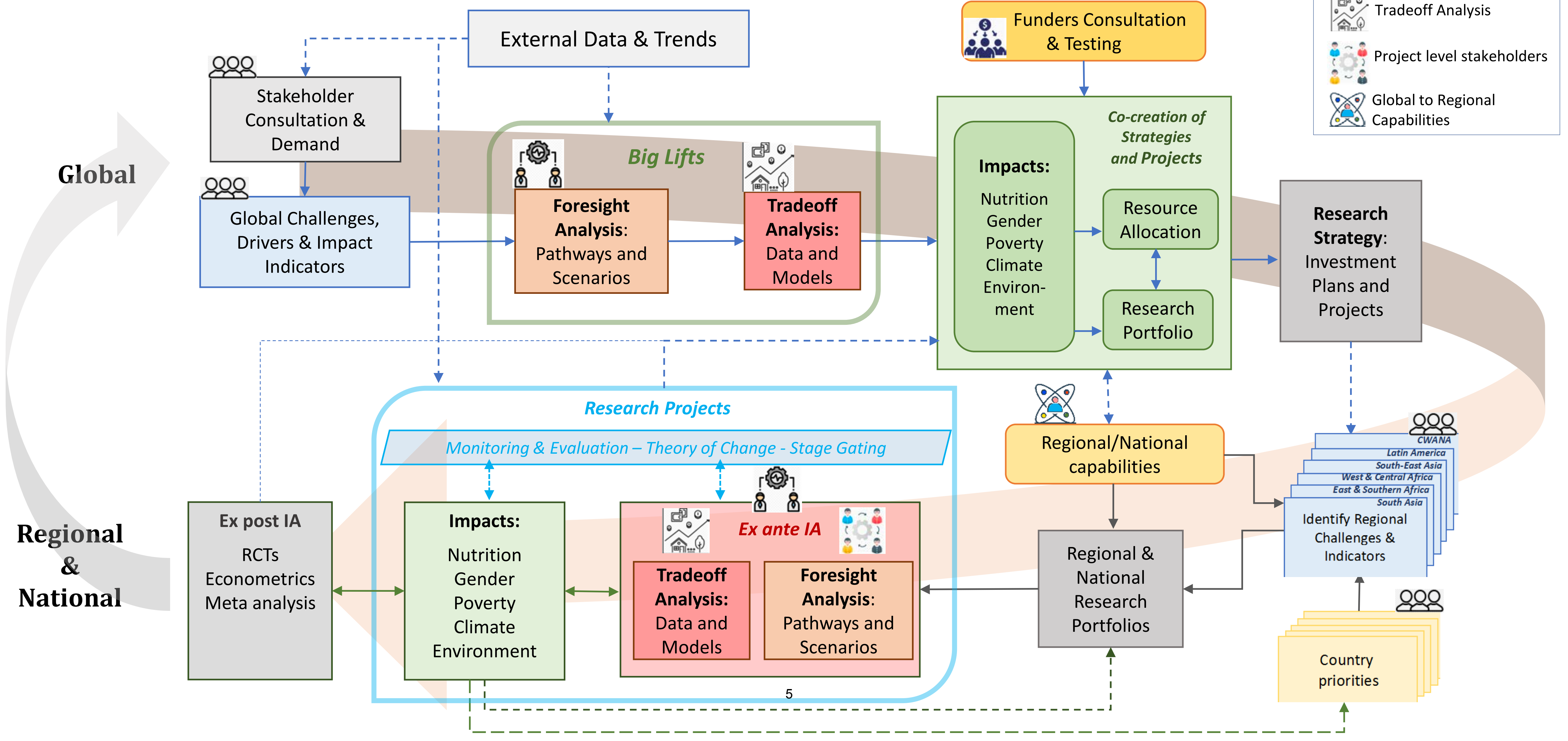
The principal recommendation of this report is to integrate two types of analytical processes – *foresight analysis* (FA) and *tradeoff analysis* (TOA) – into the ongoing One CGIAR global and regional priority setting processes (see Figure 1). These processes should be based on data and evidence created through the incorporation of FA, TOA and aligned with the Theory of Change (ToC) and monitoring and evaluation (ME) processes at the spatial and temporal scales appropriate to selected impact indicators. Impact indicators from the five One CGIAR areas should be identified through participatory processes at farm system, regional and global scales. Tradeoff analysis of technology options using selected indicators generates information needed for periodic re-evaluation of priorities. The components of Figure 1 and their roles in One CGIAR research management are discussed further in the concluding section of this report; recommendation G1 below also provides additional details.

Figure 1 portrays the use of FA and TOA in One CGIAR's ongoing research management processes. For the transition into One CGIAR, priorities should be based on the currently available evidence (see recommendation G2 below); systematic use of FA, TOA and ME over time at the project level will lead to accumulation of better data and analysis, and re-evaluation of priorities and research portfolios.

The second general recommendation of this report is that to deal with complexity and uncertainty in agri-food systems, FA and TOA implementation should respect the principle of parsimony. The main value of FA and TOA is to provide One CGIAR leaders and stakeholders with a forward-looking, systematic, evidence-based framework for priority setting and research design under uncertainty. One CGIAR should embrace the principle that information to support decisions under uncertainty should be *minimally sufficient* to identify options that are consistent with goals and balance tradeoffs across multiple impact dimensions – not to achieve "optimal" solutions in a single dimension. A key first step in TOA implementation is the selection of a minimally sufficient set of impact indicators that in turn guide data and quantitative analysis. The need for timely, minimally sufficient information argues for *parsimonious* quantitative analysis that is feasible given available resources. FA and TOA at the project level will facilitate systematic, coordinated design of data collection and analysis that will lower the cost and improve the quality of information needed for priority setting at the global and regional levels. Also see recommendation R1 below regarding resource allocation for project-level FA and TOA.

The third general recommendation is that One CGIAR build a strategy for capacity building to enable the use of FA and TOA by management and research teams. This strategy should build on the capacity within the system (such as the current CGIAR Global Futures and Foresight project), but also recognize that much of the data and expertise needed for FA and TOA will necessarily reside outside the CGIAR, particularly for analysis that goes beyond agricultural production system to the up-stream food system and economy. Capacity building should aim to facilitate essential activities such as collection of necessary data by CGIAR research projects needed for FA and TOA. Those data should be used with analytical tools developed largely outside of CGIAR either by CGIAR scientists or outside experts.

Figure 1. **Foresight** and **Tradeoff Analysis** in One CGIAR Priority Setting, Research Portfolio Design and Monitoring & Evaluation



Recommendations for Global Priority Setting

G1. Integrate FA, TOA, and ME into the research management system being developed for One CGIAR (Figure 1). To advance the research strategies for each of the "Big Lift" priority areas:

- Define future development pathways and agri-food system scenarios to be used with TOA. For the One CGIAR transition, these should be based on the existing foresight studies reviewed in Lentz, 2020; Zurek, Hebinck and Selomane, 2020.
- Engage with stakeholders to identify quantifiable impact indicators, and acceptable boundaries for each indicator, at the scales to be used in TOA. When quantitative indicators cannot be identified, qualitative indicators should be used. These indicators provide the basis for delivering measurable outcomes and impacts impacts that should be made available to stakeholders in a web-based dashboard tool.
- Use the impact indicators and boundaries to carry out set-based TOA to identify, evaluate, and update over time the technology "funnel" in the stage-gated innovation system.

G2. In the transition to One CGIAR, use available syntheses of *ex post* and *ex ante* impact assessment research in each of the five impact areas to inform FA and TOA for each "Big Lift." Update this evidence base with data generated from FA and TOA at the project level during and post-transition period.

G3. Document and make publicly available the research management system developed by One CGIAR using FA, TOA and ME. This system will be the first of its kind for provision of a public good such as agricultural research. The development and implementation of an evidence-based, forward-looking participatory management system for the provision of a public good (i.e., science for agricultural development) will constitute a major public good in its own right.

Recommendations for Regional Priority Setting

R1. Integrate FA and TOA into the design and evaluation process for the regional research portfolios, based on a set of protocols for resource allocation, indicators and data. These protocols should be designed to implement the set-based, stage-gated technology design and evaluation at scales appropriate to indicators (e.g., farming system; eco-region).

- Allocate a designated share of One CGIAR Big Lift program and project budgets to foresight analysis, TOA, and ME to ensure they are part of every project. This will avoid over-allocation of effort to research management and "mission creep." The amount allocated to each project should be based on the indicators used and the need for new data collection and analysis, but the amount for each One CGIAR Big Lift should be a policy decision of the One CGIAR management that reflects donor and stakeholder priorities.

- For each research project, identify quantifiable indicators in each impact area; if indicators are not quantifiable, then qualitative indicators should be identified. To the extent feasible, the same or similar indicators should be used for *ex ante* impact assessment using TOA as well as in *ex post* impact assessments.
- Establish standards for minimum data to support initial and ongoing TOA.
- Coordinate TOA with ME processes (stage-gating; Theory of Change) for innovation design and evaluation.

R2. Invest in periodic synthesis and meta-analysis across projects aligned with the regional stage-gate process and global priority setting process and ME.

R3. Invest in data and model improvements for use by CGIAR and the global research and development communities, including data standards to be used for impact assessment and TOA. Facilitate partnerships among CGIAR initiatives (e.g., CGIAR Big Data Initiative) and outside partners to make data Findable, Accessible, Interoperable, Ethical and Reproducible (FAIRER). Models used by One CGIAR should be publicly available and documented.

1. Introduction

Sustainability is a guiding concept and goal for our economies and societies, and for the agri-food system. The United Nations Sustainable Development Goal 2 (SDG2) is *zero hunger*, and One CGIAR's mission is *ending hunger by 2030—through science to transform food, land and water systems in a climate crisis*.

There are many calls for what humanity "must" do to achieve the SDGs. For example, the widely publicized EAT-Lancet Commission Report (EAT-Lancet Commision, 2019) argues:

> Agriculture and fisheries must not only **produce enough calories to feed a growing global population but must also produce a diversity of foods that nurture human health and support environmental sustainability...** The current global food system **requires a new agricultural revolution that is based on sustainable intensification and driven by sustainability and system innovation.** This would entail at least a 75% reduction of yield gaps on current cropland, radical improvements in fertilizer and water use efficiency, recycling of phosphorus, redistribution of global use of nitrogen and phosphorus, implementing climate mitigation options including changes in crop and feed management, and enhancing biodiversity within agricultural systems. In addition, to achieve negative emissions globally as per the Paris Agreement, the global food system must become a net carbon sink from 2040 and onward. (pp. 22-23)

Like other studies before it, the EAT-Lancet Commission Report calls for changes in agri-food systems and sets "science-based" targets for meeting these goals. What these reports do not do, and cannot do, is to say *how* the diverse agricultural systems underpinning the equally diverse local to global food systems *can* change to meet SDG2 and the mission of the CGIAR.

This is the One CGIAR challenge—to contribute to the global process of creating the science to meet critical challenges, with a priority for smallholder agriculture in developing countries. In this report, we describe TOA as an essential tool that One CGIAR needs to meet this challenge by *operationalizing the concept of sustainable agri-food system development.* Given the limited resources of the CGIAR, effective use of TOA with other modern analytical tools including FA and ME is essential to establish evidence-based priorities, assess progress towards goals, and adapt as new information becomes available and uncertainties are resolved.

Why is TOA an essential tool? The scale, scope, and complexity of agri-food systems and their linkages to natural and human systems mean that as societies strive to achieve SDGs, there will be inevitable tradeoffs among and between the One CGIAR impact areas: nutrition and food security; poverty reduction, livelihoods, and jobs; gender equality, youth, and social inclusion; climate adaptation and greenhouse gas reduction; environmental health and biodiversity. Sustainable development must meet the needs of all members of society, and the design of sustainable development pathways must involve broad stakeholder participation.

The second section of this report reviews the conceptual foundations of tradeoff analysis; the third and fourth sections describe current data and modeling tools from farm to global scales, their strengths and limitations, and capacity building to facilitate their use. The report concludes with a discussion of the opportunities and challenges for TOA to support One CGIAR research management processes at global, regional and project levels as portrayed in Figure 1.

2. Tradeoff Analysis of Agri-Food Systems

This report describes agri-food system TOA as *a participatory process using qualitative and quantitative data and modeling tools to evaluate how technological and institutional innovations can improve system performance using foresight methods and relevant metrics described as impact indicators.* This section discusses the motivations and rationale for TOA and illustrates the TOA method with the first application of TOA in CGIAR, and then discusses the conceptual foundations and key elements of TOA.

2.1 Motivations for Tradeoff Analysis

TOA addresses decision problems that arise in the management and improvement of complex, dynamic, multi-scale systems with high levels of uncertainty. A key property of complex systems, such as agri-food systems, is that the outputs and outcomes and eventual impacts of these systems are multi-dimensional and incommensurate. For example, nutritional outcomes affect people's health and can be represented with indicators such as life expectancy, infant mortality, and child stunting while economic outcomes can be represented with per capita incomes and poverty rates.

In Benefit-Cost Analysis, changes in outcomes caused by a change in the agri-food system (say, introduction of a new technology) are translated into monetary units (positive changes as benefits, negative changes as costs) and "aggregated" into a single metric (net benefits). There are two fundamental flaws with this type of procedure for decision making in the agri-food system context. First, stakeholders are heterogeneous – people are impacted in different ways and attach widely differing values regarding outcomes and impacts on themselves and others. Moreover, different societies also have different social and political processes for making private and collective decisions. Second, aggregating outcomes obscures the *distribution* of impacts across individuals and groups in society (Capalbo, Antle and Seavert, 2017).

TOA is motivated by the goal of elucidating potential impacts associated with actual or potential changes in an agri-food system so that stakeholders can make informed choices among options. A critical component of TOA implementation is therefore the selection of the relevant metrics of system performance that are described as *impact indicators*. In large, complex systems there are many potential impacts, and thus many possible impact indicators. Given that time and other resources are always limited, a key part of TOA implementation is to select a *minimally sufficient* set of impact indicators to evaluate system performance. This aspect of TOA implementation is a judgement that must be made given the problem at hand, the research objectives and the resources available.

Another motivation for TOA is the ubiquity and magnitude of tradeoffs. Often the source of tradeoffs is described in an engineering sense as a technical relationship—e.g., if there are two valued outputs of a system, and we only attempt to "optimize" one of them, we are unlikely to obtain the optimal performance of the system. But this narrow technical view ignores the critical question of *why* a system is not "optimized" or managed for all the outputs. In complex, multi-scale agri-food systems, there are many reasons why this can occur. For example, at the agricultural system level, farmers who manage to increase the income and well-being of the farm household may not take into account the "externalities" associated with their production activities, such as the impact that the use of fertilizers or pesticides have on the environment off the farm. From the farmer's perspective, for example, reducing use of agri-chemicals would be likely to reduce their productivity and their income, so they would have to bear a cost in forgone income to manage their farm to reduce the off-farm environmental externalities. It is evident that similar dis-connects between individual and group interests exist across the food system, from farms through the food system to the consumer.

2.2 Tradeoff Analysis Example: The Rockefeller Pesticide Studies

Arguably the first use of TOA in CGIAR research was done in two studies supported by the Rockefeller Foundation in the 1990s, one at IRRI and one at CIP. Besides being the first studies of their kind, they laid out the foundations and conceptual framework of TOA and served to illustrate the "mechanics" of TOA. These studies also provided important lessons about the potential unintended consequences of agricultural technology development, and the potential for forward-looking analysis to evaluate options to improve the performance of the production systems in economic, environmental and health dimensions.

Background. Two studies in the 1990s funded by the Rockefeller Foundation carried out analysis of the economic, environmental, and health impacts of pesticide use in rice production in the Philippines and potato production in Ecuador (Pingali and Roger, 1995; Crissman, Antle and Capalbo, 1998). Both studies found strong evidence of substantial acute health risks, most notably neurological impairment from exposure to highly toxic insecticides and fungicides. Both studies also showed there were tradeoffs between farm income and human health with reductions in the use of these pesticides. However, better safety procedures for handling and use, and the use of better management practices (Integrated Pest Management [IPM]), were found to produce "win-win" outcomes, thus effectively improving the terms of the economic-health tradeoffs. In the Philippine study, development of IPM, more effective labeling of pesticides for risk, and restricting use of the most harmful insecticides was a policy recommendation. In both cases, a clear implication for crop breeding was to focus attention on resistance to major disease and insect pests. Notably, in the case of potatoes, development of late blight resistant potatoes was a priority that also could potentially create win-win economic, environmental and health outcomes, and has been a focus of subsequent research led by CIP.

Tradeoff Analysis Process. Both studies used a participatory process that brought together scientists and stakeholders (researchers, farmers, local farm organizations, local to national policy and political leaders) to identify key *impact indicators*—in these studies, the indicators were economic (crop production, farm income), environmental (water contamination from pesticide leaching to ground and runoff to surface water; harm to aquatic life and other species), and human health (acute health effects on farm workers and family members, including impaired neurologic function). The indicator identification was used to identify the economic, environmental and health data needed, and the disciplinary models needed to model and simulate the systems. Stakeholders also helped to identify the impact pathways for communication of results and design of research and policy to improve the systems and impacts.

Data. A key element of both studies was to identify the data needed to quantify the selected indicators. Detailed farm production data was needed that could be combined with data on the practices and health of farm workers. As a result, a novel feature of both studies was collaboration with medical teams to collect data on pesticide use as well as the health of farm workers making the applications. These workers typically applied highly toxic "cocktails" of multiple pesticides using backpack sprayers with little protection from exposure during mixing and application.

Tradeoff Analysis Modeling. These studies used simulation models to evaluate the economic and health outcomes associated with changes in pesticide use. Economic outcomes were quantified using econometric models that were simulated over alternative prices and management practices. Equations representing health outcomes were estimated using data collected from medical examinations of farm workers and detailed data on pesticide use (Antle and Pingali, 1994; Antle, Cole and Crissman, 1998).

Tradeoff Analysis: Graphical Representation. The simulation models were used to construct "tradeoff curves" that show graphically the relationships between two indicators that result from a change in pesticide use, while holding constant the parameters representing the production system technology and the processes generating health and environmental outcomes. For example, in Figure 2.1, the "base" or observed potato-pasture production system in Ecuador was simulated to show the relationship between farm income and health risk due to pesticides generated by varying potato prices, while holding other parameters of the model fixed. The changes in economic and health outcomes result from the simulated changes in farmers' management decisions, including their land allocation between potatoes and other crops, and their use of pesticides and fertilizers. As Figure 2.1 shows, at the time of the study, over 50 percent of the population of farm workers was observed to experience risk of substantial neurological disorders, but generating a per-hectare income of about $1500.

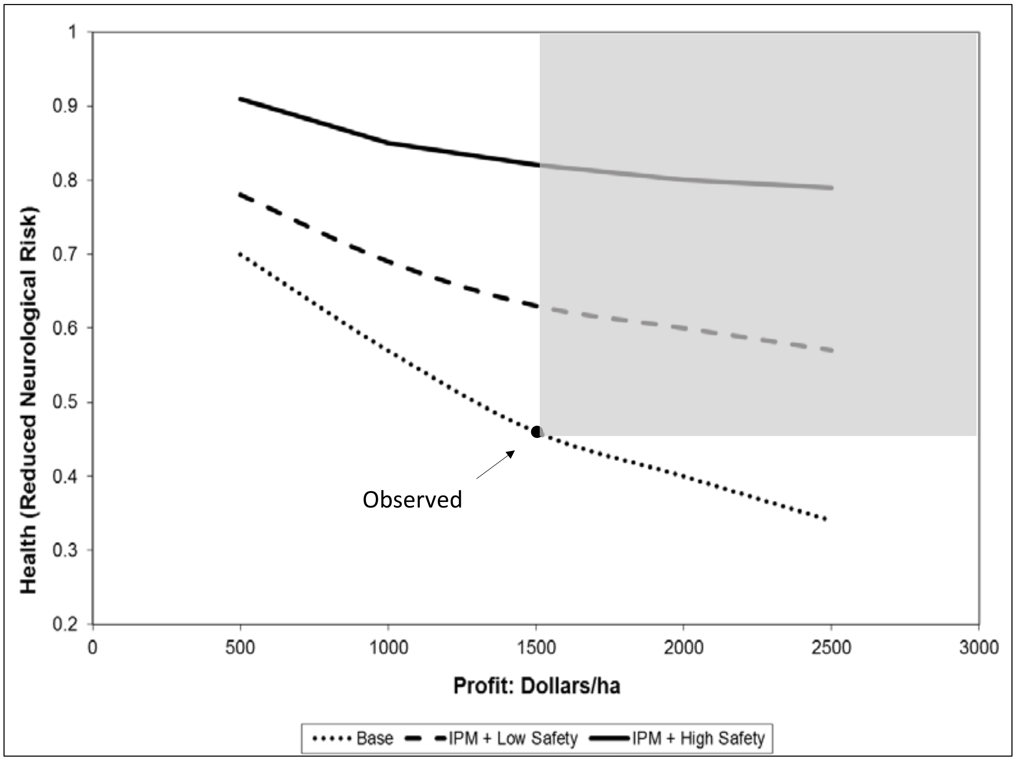


Figure 2.1. Tradeoffs between profitability of Ecuadorian potato production and farm worker health. Shaded area represents a "no-harm" set for potential impacts of IPM and safety practices. Safety practices include use of protective clothing and appropriate handling and application. *Source:* based on data from Crissman, Antle and Capalbo, 1998.

The high risk of experiencing neurological disorders was due to mixing and application of hazardous fungicides and insecticides using backpack sprayers with minimal or no person protection and generally unsafe handling practices (e.g., mixing with bare hands; application in dense foliage with ordinary clothing, as in the picture on the cover of this report). Even at low potato prices and much lower farm incomes, reductions in the use of fungicides and insecticides were not enough to improve health outcomes substantially.

Tradeoff analysis modeling is used to explore how improvements in system performance could improve outcomes. In this study, two improvements in the system were explored: one was the adoption of Integrated Pest Management that would increase the efficacy of pesticides and reduce the amounts and frequency of use (in the observed system, pesticides were routinely applied about 10 times per season); the other was the use of safe handling practices and protective gear that would reduce exposure. Figure 2.1 shows that IPM alone would allow farms to maintain their incomes while reducing health risk from about 55 percent to about 35 percent (i.e., to improve the proportion that were not at risk from about 45 percent to 65 percent). Combining IPM with safe practices was estimated to further those at risk to less than 20 percent (more than 80 percent safe). In addition, these changes substantially "flattened" the tradeoff between income and safety, meaning that higher incomes could be achieved without substantially increasing risk.

Set-Based Tradeoff Analysis: Working with stakeholders, TOA researchers can identify the pathways that are considered acceptable. For example, in Figure 2.1, the goal of "doing no harm" in either dimension would imply the goal of moving the system from its observed point into the shaded area where some improvement in both economic and health outcomes is achieved (a win-win). This type of "set-based" system design is used in industry to provide flexibility in potential development pathways. In a public policy context, it can be used to recognize that there may be a range of preferences among stakeholders and also a range of outcomes may occur as economic and other conditions vary. It is also important to note that some stakeholders might prefer a win-lose or lose-win outcome – that is, some farmers might prefer to accept higher risk in exchange for higher income, while others might prefer to give up some income in exchange for greater safety.

Impact Pathways. The set-based discussion shows that many outcomes are possible in complex systems, and will usually depend on technology and policy interventions. In part as a result of the research in Ecuador, the government instituted efforts to improve pesticide safety, for example by encouraging farmer field schools to provide training in safe use of chemicals, and in 2010 banned the most hazardous insecticides. High levels of pesticide use in the Philippines and many other countries continues with minimal regulation and remains a serious health problem. Unfortunately, the use of hazardous pesticides is now spreading into Africa as agricultural productivity improves, risking a repeat of the experiences in East Asia and Latin America (Sheahan and Barrett, 2014). Efforts are being made to improve awareness of the problem and develop solutions, for example, the Integrated Production and Pest Management Program supported by the United Nations Food and Agriculture Organization (Settle and Garba, 2011).

Lessons for Use of TOA by One CGIAR

Identifying Unintended Consequences of Technologies. New technologies inevitably have unintended consequences. The pesticide example illustrates how a focus on productivity in Green Revolution research led to production systems that provided much-needed growth in calorie availability to feed rapidly growing populations, but were not sustainable in the other dimensions now part of the One CGIAR impact areas.

Design of Innovations. The TOA process did not provide precise "predictions" of the future; rather, it demonstrated the potential to improve production system performance through research and policy interventions. These studies illustrate how TOA can help design innovations that move systems towards win-win outcomes.

Identification of Impact Indicators. These studies demonstrated the importance of quantifiable impact indicators that matter to stakeholders and that demonstrate the importance of tradeoffs and the need for improvements in system performance. Before this research, many in the agricultural establishment argued that health impacts of these technologies were not important, or that industry efforts in pesticide safety were adequate. These studies provided the evidence that a production system relying on highly toxic pesticides in these human populations and environments would lead to unacceptable human health and environmental risks, and eventually led to research and policy interventions to address the unsustainable outcomes. It is also important to note that impact indicators for some of the One CGIAR areas (e.g., gender) were not included in this study. In fact, the research did recognize the importance of gender in evaluating risk of exposure (males typically do application in the field; women and other family members were at risk of exposure in the household from washing contaminated clothing). Also the role of women in farm management was considered, but not included in the analysis based on qualitative evaluation of the farm decision making process.

Importance of data. These studies identified critical new data needed – data on farm workers' health that could be linked to their pesticide use and exposure – to provide the evidence needed on impacts. Today this remains true in several of the One CGIAR impact areas, notably nutrition and gender.

Importance of Appropriate Disciplinary Models and Analytical Methods. A multi-disciplinary, model-based approach made it possible to simulate outcomes that could not be observed in the field, and could not be obtained from classical experimental approaches. Models could predict out of sample to show potential pathways to improve system performance. Whereas disciplinary models for some environmental impacts were available (i.e., for pesticide transport in the environment), models for health impacts were not available to the research teams, so statistical models needed to be devised. This lack of disciplinary models remains a challenge for several of the impact areas of concern to One CGIAR, notably in nutrition and gender.

Methods to Communicate Impacts. The pesticide project research teams realized that even two-dimension graphs such as Figure 2.1 were not likely to be effective to communicate results of TOA, so other types of data displays and pictures were used. Since then, many innovations in data analytics and visualization, such as the ones illustrated in Section 3, are available and should be used. Particularly useful for presenting TOA results would be recently developed dashboard tools designed to compare and contrast results from multiple scenarios. These include the AgMIP Impact Explorer (http://agmip-ie.wenr.wur.nl/) and the Food Security Portal and the CGIAR's Global Foresight for Food and Agriculture Tool (http://tools.foodsecurityportal.org/impacts-alternative-agricultural-investments-version-9).

2.3 Key Elements of Tradeoff Analysis

Conceptual Framework. The early pesticide studies discussed above developed a participatory approach (Crissman, Antle and Capalbo, 1998) that involved scientists and stakeholders to identify the key impact indicators, and the corresponding disciplinary data and models that were needed to quantify those indicators in an agricultural system simulation. Since the 1990s, there have been many innovations in methods for participatory modeling, as well as many advances in data and models (see section 3 of this report).

An example of a participatory modeling approach is the one developed by the Agricultural Model Inter-comparison and Improvement Project (Rosenzweig and Hillel, 2015) in collaboration with several CGIAR centers to assess climate impact and adaptation (Figure 2.2). This figure shows the process from initial evaluation of a system using prior knowledge, stakeholder inputs and modeling results. A key feature of this approach is that scientists and stakeholders identify the key indicators to be used to evaluate the performance of the agricultural systems of interest, and co-design system adaptations to improve performance. These choices then guide the data and models needed for impact evaluation. Results of model simulations are interpreted and communicated to stakeholders using tools such as the web-based Impacts Explorer..

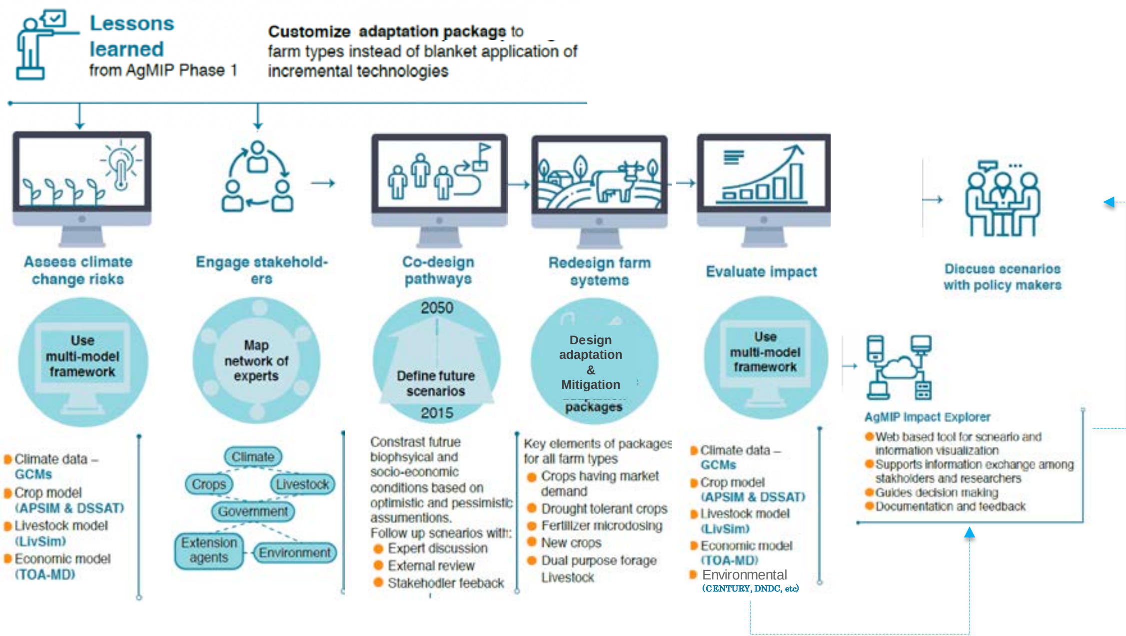


Figure 2.2. AgMIP Regional Integrated Assessment process (Source: Valdivia *et al.*, 2019)

Impact Indicators. A key part of tradeoff analysis is the identification of impact (or sustainability) indicators that can be used to set goals and to evaluate and compare the performance of systems along alternative development pathways. There is a large number of indicators across the three "pillars" of sustainable development (economic, environmental, and social) that are often used in technology impact assessments and TOA (Appendix Tables A1-A3). Many of these indicators can be associated with the One CGIAR impact areas. Identification of a relatively small number of key impact indicators is the foundation of TOA, and is critical to guide coordinated data collection and modeling tool selection for system simulation.

Data and Modeling Tools to Implement TOA. Section 3 discusses the wide range of currently available data and tools to implement TOA and related types of impact assessments, such as climate impact assessment and analysis of adaptation options as portrayed in Figure 2.2. The key elements of TOA modeling are portrayed in Figure 2.3.

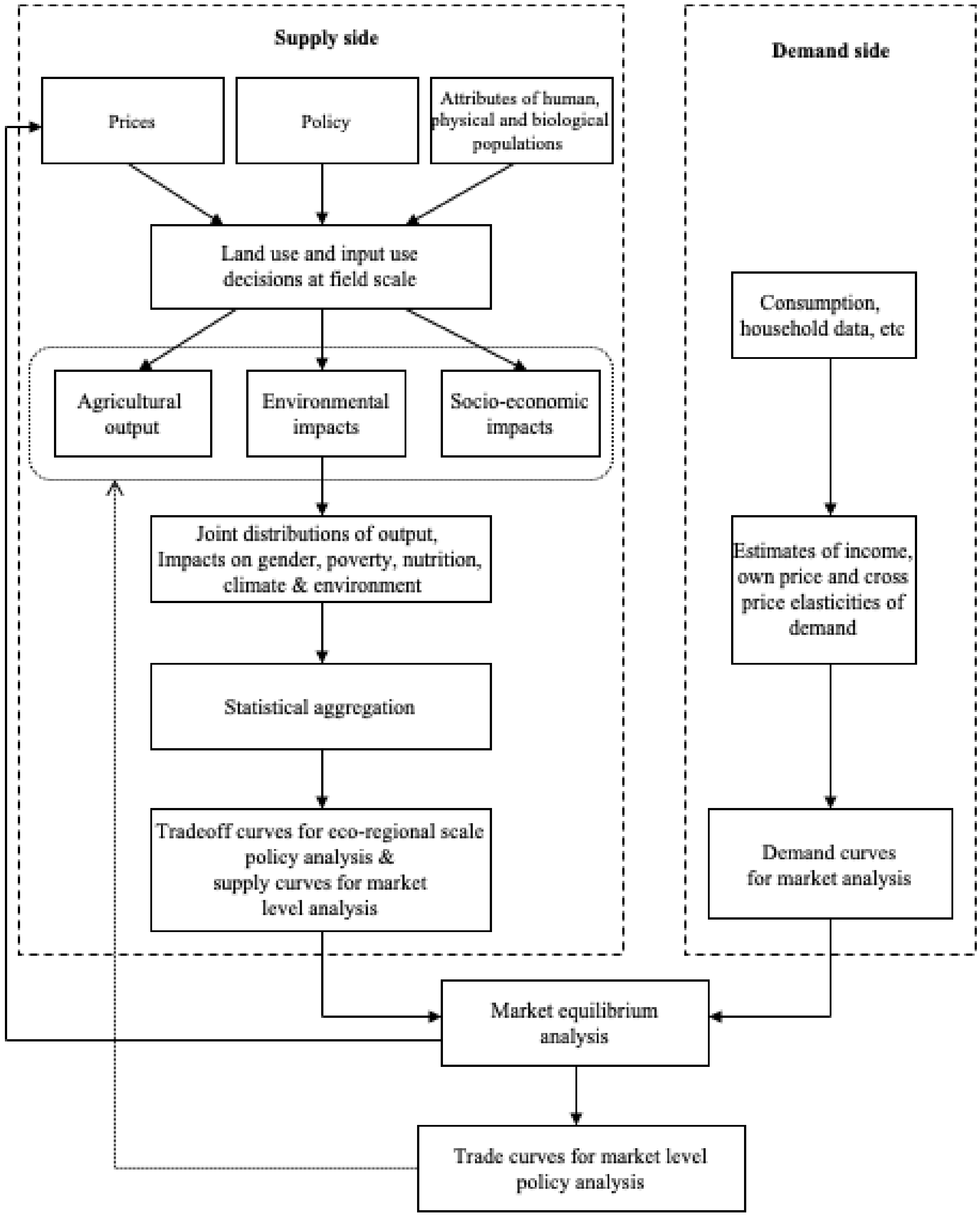


Figure 2.3. Model Components and Linkages in TOA (Valdivia, Antle and Stoorvogel, 2012).

The early TOA applications, such as the pesticide studies presented in section 2.2, corresponded to the left-hand side of Figure 2.3 labeled as "Supply Side." These studies, and many of the ones at the farm and eco-regional scale discussed in section 3, represent the farm production system, the farm household, or eco-regions comprised of a population of farms and farm households. These analyses are usually structured as what economists call "price-taking" farms, meaning that the analysis is done for prices set at a given level to represent conditions defined by the scenarios determined relevant to the analysis (i.e., in the participatory development pathway design processes of Figure 2.2). However, more recent studies have begun to link these "Supply Side" analyses to the demand-side of markets at sub-national, national or global levels, represented by the "Demand Side" in Figure 2.3. Currently, this sort of cross-scale linkage is at the frontier of TOA modeling. It provides a way to expand the scope of indicators in an analysis to the demand side, and to incorporate feedbacks from market processes and price changes to the impacts at the farm or eco-regional scale.

Disciplinary Data and Coordinated Disciplinary Research. An important insight from research on modeling human systems and their environmental impacts is the importance of the similarities and differences in spatial and temporal scales within and across the various processes involved. These systems (physical, biological, human) are each complex and operate at various scales. Understanding these systems, modeling them, and devising ways to link them through their inputs and outputs, or integrate them into larger, ever more complex systems, is a daunting scientific challenge. Most research to date has linked disciplinary models through input and output protocols. The need to combine models gives rise to the need for coordination across disciplines to identify and obtain the data needed. For example, agronomists doing on-farm trials of new crop varieties need to know what data are needed for economic analysis of the adoption and impact of the technology. These insights are the basis for the recommendation in this report that data standards should be established for ongoing efficient data collection efforts by projects and programs, linked to the impact indicators that are identified in collaboration with stakeholders.

3. Data and Models for TOA

This section reviews the application of modeling tools at multiple scales and their features to conduct tradeoff analysis of agricultural systems. We emphasize models that have been or can be applied to the five One CGIAR impact areas.

3.1 Major Modeling Approaches

A range of tools and approaches have been developed to evaluate impacts of agricultural technologies and their potential tradeoffs, and have been used by the CGIAR and other research organizations since the early years of the CGIAR and the Green Revolution. In this section we briefly discuss the major modeling approaches. The following section reviews a number of modeling studies that have used these approaches.

Cost-benefit analysis (CBA) was applied in the 1970s to evaluate financial margins of new agricultural technologies (Herdt, 1991; Alston *et al.*, 1995). As sustainability began to be accepted as a valid concept to guide economic development, interest in agricultural sustainability led to new analytical approaches that coupled bio-physical and economic data and models to assess the sustainability of agricultural systems. As discussed in Section 2, early TOA coupled economic, environmental and health models to evaluate agricultural sustainability. Analytical methods used for quantitative impact assessment and TOA are described below; opportunities and challenges for their use in TOA are described in table 3.1.

Simulation Modelling: This approach is used to explore options that are not observed or can be difficult to test in reality. These models have been applied to assess agricultural production at various levels of research, including crop, livestock and farming system. Simulation models are typically complex and are data intensive (e.g. spatially explicit models). Reduced-form or parsimonious simulation models have been developed as alternative to provide with timely information and at low cost.

Mathematical Programming and Optimization Methods: These models are based on linear or quadratic programming to achieve an objective such as input minimization or output maximization, subject to suitable constraints, at the farm or household level. Multi-criteria analysis has been used to assess tradeoffs of new.

Econometric Models: Econometric models involve statistical methods using historical datasets on system responses (e.g. crop yields, dairy production, output and input prices).

Early applications focused at single crop production functions, usually estimated from experimental data. As econometric methods evolved, multi-crop production analysis was possible using farm survey data. Econometric models have been used with bio-physical simulation models to assess tradeoffs of production systems.

Qualitative Approaches: Strategic design using scenarios and expert judgement have become widely used tools in foresight analysis by the military, business, government and research. Observational and modeled data can be combined with qualitative judgement to formulate "fuzzy" estimates of future outcomes and tradeoffs. A combination of qualitative and quantitative methods is now used in most foresight analysis, such as the development of the Shared Socio-economic Pathways used in climate impact assessments.

Integrated Assessment Models (IAMs): These models are used to assess current and future agricultural systems under different socioeconomic development pathways, technological change and climate conditions. IAMs couple disciplinary models (e.g. biophysical and economic models) with the aim of supporting policy-decision making. Although most of the IAMs are global (e.g., IFPRI's IMPACT), recent modeling developments have linked models across spatial scales.

Meta-analysis and Systematic Reviews: Meta-analysis involves a systematic review of published studies, and can include statistical analysis of results to obtain general conclusions. Some recent meta-analyses include Challinor *et al.*, 2014, using 1700 studies to assess the impacts of climate change on maize, wheat and rice yields. Corbeels *et al.*, 2014 and Rusinamhodzi *et al.*, 2011 have conducted meta-analysis of conservation agriculture studies.

Table 3.1. Opportunities and Challenges of modeling approaches for TOA. (Adapted from Thornton et al., 2018)

Approach	Opportunities	Challenges
Simulation modelling (spatially explicit)	Efficiently assessing spatio-temporal variability.	Complexity and uncertainty can be high, precluding decisions
	Allows comparison across different contexts	Calibration and validation are challenging
	Allows exploration of a wide range of scenarios	High data intensity
Simulation modelling (Parsimonious)	Generic and can be applied to any production system	Static analysis
	Produces timely and accurate information to support decision-making	
	Flexible to include multiple indicators	
Mathematical Programming / Optimization methods	Consideration of multiple system objectives	Data intensive, time consuming, difficulty of eliciting household objectives and representing them appropriately (Thornton et al., 2003)
	Flexibility in defining system's objectives	Difficult to address hypothetical situations, other contexts or scenarios.
Cost-benefit analysis / Economic Surplus	Applicable in different contexts	Difficult to capture all benefits and costs (e.g. bank account or insurance aspect of cattle)
	Low data intensity	Difficult to include multiple criteria or system's objectives (e.g. poverty, nutritional outcomes)
	Requires less information than other (i.e. econometric, optimization) models.	Required information on price responsiveness of consumers and producers often not available.
	Widely used to estimate impact of agricultural technologies	Difficult to include non-economic outcomes (e.g. poverty, nutrition).
Econometrics	Allows estimating direct impacts at multiple levels (farmer, county or state)	Limited ability to extrapolate responses outside estimation sample (Antle and Capalbo, 2001)
	Allows statistical testing of economic theory	Restrictive assumptions associated with choice of functional form (work on flexible technology representations, Carter, 1984)
		Data intensive: requires detailed survey data

Qualitative approaches	Incorporates expert and stakeholder views, often reflective of realities in the field	Difficult to compare across different groups of experts or contexts
	Flexibility to incorporate multiple variables and systems' objectives	Difficulty in relating expert-based scores to measurable variables
	Various existing examples in CSA research	There can be considerable variation across experts or communities
	Many methods exist, with varying degrees of complexity and ease of implementation	Subject to bias if groups are dominated by certain individuals (e.g. women left out) or if stakeholders deliberately mislead organizers (i.e. tell organizers 'what they want to hear')
	Linkable to other approaches (e.g. modelling)	
Meta-analysis/systematic review	Can include multiple sources of potentially disparate (e.g. experimental, model-based) evidence, seeking consensus among these	Difficult to draw generalized conclusions or reach consensus when context-specificity is high or evidence is limited
	Can combine multiple indicators into aggregated dimensions, hence useful for CSA	Time consuming if the systematic review is too long and complex (many variables, many studies)
	Systematic review can include adoption rates of practices and factor this into analysis	Difficult to draw conclusions on underlying processes
Spatial analysis/GIS/Remote sensing	Allows delineation of target zones or recommendation domains	Dependent on good spatial datasets
	Simplicity	Often difficult to include socio-economic aspects at high resolution
		Difficult to incorporate systems dynamics, or to assess mixed systems
Integrated assessment modelling	Allows integration of a suite of different models to evaluate synergies and trade-offs	Complex and skill- and time-consuming to carry out
	* Can provide outputs in several dimensions relating to land-use, commodity prices, and environmental and health impacts, for example	Conceptual difficulty of model validation and calibration
		Uncertainty bounds on model outputs are often unknown; when known (e.g. Nelson et al., 2014) they may be very large

Table 3.2 Selected Case Studies: Scale, Models, Impact Areas and Indicators

			Areas of Impact							
Case study	**Scale**	**Model(s)**	**Poverty**	**Nutrition**	**Gender**	**Environment**	**Climate**	**Indicators**	**Approach**	**CGIAR Center**
Herrero, M. et al., (2014). Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models. Global Environmental Change, 24, 165-182.	Cross-scale	Logit, CLUE-S, IMPACT-Household, LP, DSSAT				X		Land use, yields,	**Integrated assessment modelling**	CCAFS, ILRI
Schlenker et al., 2006. The impact of global warming on US agriculture: an econometric analysis of optimal growing conditions. Review of Economics and statistics, 88(1), pp.113-125.	Farming System	Hedonic, Ricardian						Farm value, yield	**Econometrics**	N
Guijt, I., 1998. Participatory monitoring and impact assessment of sustainable agriculture initiatives: an introduction to the key elements (No. 1). IIED.	Farming System	Qualitative methods, M&E				X		Soil erosion, income	**Qualitative approaches**	N
Sain, G., et al., 2017. Costs and benefits of climate-smart agriculture: The case of the Dry Corridor in Guatemala. Agricultural Systems, 151, pp.163-173.	Farming System	Cost Benefit Analysis, Qualitative methods, @RISK				X		profits, Co2 sequestration, labor	**Cost-benefit/Surplus**	CIAT, CCAFS
Lamanna, C., et al., 2016. Evidence-based opportunities for out-scaling climate-smart agriculture in East Africa. CCAFS Working Paper No 172.	Farming system	Risk-Household-Option (RHO)		X		X		food security, risk of extreme events, crop productivity	**Qualitative-quantitative approach**	CCAFS
Giller, Ken E., et al. "Communicating complexity: integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development." Agricultural systems 104.2 (2011): 191-203.	Farming System	NUANCES, FARMSIM, HEAPSIM, FIELD				x		Soil fertility, crop yield	**Simulation modeling**	CIAT, ILRI, AFRICARICE

Notenbaert, A., et al., 2017. Targeting, out-scaling and prioritising climate-smart interventions in agricultural systems: Lessons from applying a generic framework to the livestock sector in sub-Saharan Africa. Agricultural systems, 151, pp.153-162.	Farming system, Global	GIS, GLEAM, Farm-scale model			X	X	GHG emissions, Soil quality, crop and dairy productivity, land use	**Integrated assessment modelling**	CIAT, ILRI
Rosegrant, et al., 2014. Food security in a world of natural resource scarcity: The role of agricultural technologies. Intl Food Policy Res Inst.	Global	IMPACT, DSSAT		X	X	X	Yields, N losses, water productivity, trade, risk of hunger, malnutrition, income	**Integrated assessment modelling**	IFPRI
Borgomeo, E., et al., 2016. Trading-off tolerable risk with climate change adaptation costs in water supply systems. Water Resources Research, 52(2), pp.622-643.	Global	MOMP, CATCHMOD			X	X	Water resources, financial costs	**Mathematical Programming/Optimization methods**	N
Herrero, M., et al., 1999. Bio-economic evaluation of dairy farm management scenarios using integrated simulation and multiple-criteria models. Agricultural systems, 62(3), pp.169-188.	Global	MCDM			X		Gross margin, dairy production	**Mathematical Programming/Optimization methods**	N
Hareau, G., et al., 2014. Strategic assessment of research priorities for potato. RTB Working Paper No. 8	Global	Economic surplus	X		X		Poverty, production	**Cost-benefit/Surplus**	CIP
Challinor, A. et al., 2014.. "A meta-analysis of crop yield under climate change and adaptation." Nature Climate Change 4, no. 4 (2014): 287-291.	Global	Meta-analysis				X	crop yields, income, emissions	**Meta-analysis/systematic review**	CCAFS
Havlík, P., et al., 2014. Climate change mitigation through livestock system transitions. Proceedings of the National Academy of Sciences, 111(10), pp.3709-3714.	Global	GLOBIOM, GFM, EPIC, CENTURY,		X	X	X	GHG emissions, food security, calorie sources, feed, livestock and crop productivity	**Integrated assessment modelling**	ILRI, CIFOR, CCAFS, CIAT
Havlík, P., et al., 2011. Global land-use implications of first and second generation biofuel targets. Energy policy, 39(10), pp.5690-5702.	Global	GLOBIOM, EPIC,			X	X	GHG emissions, Land use, Energy,	**Integrated assessment modelling**	N

Weindl, I., et al., 2015. Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. Environmental Research Letters, 10(9), p.094021.	Global	LPJmL, MAGPie				X	X	Crop yields, rangeland use	**integrated assessment modelling**	N
Rosegrant, M., et al., 2017. Quantitative foresight modeling to inform the CGIAR research portfolio. Intl Food Policy Res Inst.	Global	IMPACT		X		X	X	Hunger, calories, food security, crop yields, GHGs	**Integrated assessment modelling**	IFPRI
Kristjanson, P.M., et al., 1999. Measuring the costs of African animal trypanosomosis, the potential benefits of control and returns to research. Agricultural systems, 59(1), pp.79-98.	Multi-Country	GIS- Economic surplus				X		Income	**Cost-benefit/Surplus**	ILRI
Nedumaran, S., et al, 2014. Potential Welfare Benefit of Millets Improvement Research at ICRISAT: Multi country-Economic Surplus model approach, Socioeconomics Discussion Paper Series Number 15.	Multi-Country	Economic surplus				X		Yields	**Cost-benefit/Surplus**	ICRISAT
Twyman, J., 2018. RICE Gender research in Latin America at CIAT.	Multi-country	Qualitative methods			X			Women's participation a in farm activities and decision making	**Qualitative approaches**	CIAT
Claessens, L., et al., 2012. A method for evaluating climate change adaptation strategies for small-scale farmers using survey, experimental and modeled data. Agricultural Systems, 111, pp.85-95.	Farming system and national	TOA-MD	X				X	Crop and dairy yields, income	**Simulation modelling (Parsimonious)**	CIP
Shirsath, P.B., Aggarwal, P.K., Thornton, P.K. and Dunnett, A., 2017. Prioritizing climate-smart agricultural land use options at a regional scale. Agricultural Systems, 151, pp.174-183.	Farming system and national	InfoCrop, Cost-Benefit				X		Crop yields, income, emissions	**Cost-benefit/Surplus**	CCAFS
Valdivia, R., et al., 2017. Designing and evaluating sustainable development pathways for semi-subsistence crop–livestock systems: lessons from Kenya. Agricultural Economics, 48(S1), pp.11-26.	Farming system and national	TOA-ME, DSSAT	X			X	X	yields, income,	**Simulation Modelling (spatially explicit)**	N
Shikuku, K., et al., 2017. Prioritizing climate-smart livestock technologies in rural Tanzania: A minimum data approach. Agricultural systems, 151, pp.204-216.	Farming system and national	TOA-MD	X	X		X	X	Income, Poverty, Adoption rate, Food security, GHG Emissions, yields	**Simulation modelling (Parsimonious)**	CIAT

Antle, J., et al., 2015. Simulation based Ex Ante Assessment of Sustainable Agricultural Technologies: An Application to Integrated Aquaculture-Agriculture in Bangladesh. A report submitted to the Standing Panel on Impact Assessment (SPIA), CGIAR Independent Science and Partnership Council (ISPC). 57 pp.	Farming system and national	TOA-MD	X	X		X		Income, Food and protein consumption, yields	**Simulation modelling (Parsimonious)**	WorldFish
Groot, J.C., et al., 2012. Multi-objective optimization and design of farming systems. Agricultural Systems, 110, pp.63-77.	Farming system and national	FARMDesign				X		Profits, yields, Soil N losses	**Mathematical Programming/Optimization methods**	N
Wossen, T. and Berger, T., 2015. Climate variability, food security and poverty: Agent-based assessment of policy options for farm households in Northern Ghana. Environmental Science & Policy 47: 95-107.	Farming system and national	MPMAS	X	X		X	X	Yield, income, poverty, food consumption	**Mathematical Programming/Optimization methods**	CIAT
Holzkämper, A., et al., 2015. Assessing the propagation of uncertainties in multi-objective optimization for agro-ecosystem adaptation to climate change. Environmental Modelling & Software, 66, pp.27-35.	Farming system and national	CROPSYST, MOMP				X	X	Yields, leaching	**Mathematical Programming/Optimization methods**	N
Van den Bergh, J.C., 2004. Optimal climate policy is a utopia: from quantitative to qualitative cost-benefit analysis. Ecological economics, 48(4), pp.385-393.	Farming system and national	Cost Benefit Analysis				X	X	Yields, GHG emissions	**Cost-benefit/Surplus**	N
Leary, N.A., 1999. A framework for benefit-cost analysis of adaptation to climate change and climate variability. Mitigation and adaptation strategies for global change, 4(3-4), pp.307-318.	Farming system and national	Cost Benefit Analysis					X	N/a	**Cost-benefit/Surplus**	N
Kumar, S., et al., 2018. Towards climate-smart agricultural policies and investments in Telangana.	Farming system and national	Cost Benefit Analysis					X	Income	**Cost-benefit/Surplus**	CCAFS-ICRISAT
Shiferaw, et al., 2008. Technology adoption under seed access constraints and the economic impacts of improved pigeonpea varieties in Tanzania. Agricultural Economics, 39(3), pp.309-323.	Farming system and national	DREAM		X		X		Income,	**Cost-benefit/Surplus**	ICRISAT, IFPRI

Wander, A.E., et al., 2004. Using the economic surplus method to assess economic impacts of new technologies: case studies of Embrapa. In Embrapa Caprinos e Ovinos-Artigo em anais de congresso (ALICE). Berlin: International Research on Food Security, Natural Resource Management and Rural Development, 2004. 10 f.	Farming system and national	Economic surplus			X		NPV, BCR	**Cost-benefit/Surplus**	N
Mendelsohn, R., et al., 1994. The impact of global warming on agriculture: a Ricardian analysis. The American economic review, pp.753-771.	Farming system and national	Ricardian, DSSAT			X	X	Land value	**Econometrics**	
Antle, J.M. and Capalbo, S.M., 2001. Econometric-process models for integrated assessment of agricultural production systems. American Journal of Agricultural Economics, 83(2), pp.389-401.	Farming system and national	Econometric process Model, Crop models					Net returns, prices and production (supply curves)	**Integrated assessment modelling**	N
Khatri-Chhetri, A., et al., 2017. Farmers' prioritization of climate-smart agriculture (CSA) technologies. Agricultural systems, 151, pp.184-191.	Farming system and national	Multinomial Probit		X	X		Income, gender,	**Econometrics**	CCAFS, IFPRI, CIMMYT
Mwongera, C., et al., 2017. Climate smart agriculture rapid appraisal (CSA-RA): A tool for prioritizing context-specific climate smart agriculture technologies. Agricultural Systems, 151, pp.192-203.	Farming system and national	CSA-Rapid Appraisal		X			Men/Women participation, income, Wellbeing-index, assets index	**Qualitative approaches**	CIAT, IITA
Agricultural Model Intercomparison and Improvement Project (AgMIP): Implemented in several countries in SSA and SA, in collaboration with ICRISAT, CIAT, CIMMYT, ICRAF (https://agmip.org)	Farming system and national	APSIM, DSSAT, TOA-MD	X		X	X	Income, poverty, adoption rates, vulnerability, gains and losses	**integrated assessment modelling**	ICRISAT, CIAT, CIMMYT

3.2. Modeling Studies: Scales, Impact Areas, and Indicators

Table 3.2 presents examples of case studies using the approaches and models discussed in the previous sections and identifies the impact areas and types of indicators used. The case studies presented illustrate how they can inform priority setting at each scale. This is not a comprehensive review; rather, the goal is to illustrate studies across the types of methods described in the previous section, the scale they have been implemented, how they map to the five One CGIAR impact areas and the indicators they have evaluated.

Field Level. Bio-physical process-based models that simulate crop or livestock yields are widely used. Among the most important ones are: the multiple crop simulation models embedded in the Decision Support System for Agrotechnology Transfer (DSSAT, Hoogenboom *et al.*, 2019), the Agricultural Production Systems sIMulator (APSIM, Keating *et al.*, 2003), Cropping Systems Simulation model (CROPSYST, Stöckle, Donatelli and Nelson, 2003), Environmental Policy Integrated Climate (EPIC, Williams and Singh, 1995), RUMINANT (Herrero *et al.*, 2013), LIVESIM (Rufino *et al.*, 2009) and LIFE-SIM (León Velarde *et al.*, 2006).

Farm Level. Economic models are used to estimate farmers' livelihoods as well as farm profitability. Often these models are linked to biophysical models to transfer field level data (e.g., crop yields) and to environmental models (e.g., pesticide leaching). van Wijk *et al.*, 2014 reviewed household and farm-level models and evaluated and compared their attributes and approaches. At the landscape scale, bio-physical models can simulate processes over large areas (e.g., watershed). The Soil Water Assessment Tool (SWAT, Arnold *et al.*, 1998) for example, simulates impacts of land use on water quantity and quality and sedimentation. The Integrated Valuation of Ecosystem Services and Trade-offs Tool (InVEST, Tallis and Polasky, 2009) estimates carbon sequestration and other ecosystem services in mixed-use landscapes using a suite of different models.

Some economic models at this scale can be used to simulate potential adoption of agricultural technology or policy interventions. The Tradeoff Analysis for Multi-Dimensional Impact Assessment Model (TOA-MD, Antle and Valdivia, 2020; Antle, Stoorvogel and Valdivia, 2014) can simulate adoption rates of alternative technologies in heterogeneous populations of farms and the associated social, economic and environmental impacts.

National Scale. Partial equilibrium economic models of the agricultural sector, and General Computable Equilibrium (CGE) models of the entire economy, are being used at the national level. For example, IFPRI's IMPACT (partial equilibrium) has been adapted for national-level analysis of policy interventions for Senegal and South Africa, and IIASA's GLOBIOM model (partial equilibrium) has been adapted for national analysis for Brazil and Ethiopia. Another national level model that has been applied to multiple countries in the context of climate change and adaptation assessments is the FAO Modelling System for Agricultural Impacts of Climate Change to Support Decision-Making in Adaptation (FAO-MOSAICC, Kuik *et al.*, 2011). The FABLE consortium has developed a generic national model that is being used by national modeling teams to assess sustainable development pathways with climate change Obersteiner, 2019.

Global Level. More than 10 major economic modeling systems have been used for global analysis of prices, trade and policy, and are also used for climate impact assessment (Nelson *et al.*, 2014). CGE models that capture interactions between agriculture and other sectors that affect supply, demand and crop price formation as well as partial equilibrium models that calculate direct and indirect effects of agricultural productivity change under different economic, climatic and demographic scenarios have been widely used by CGIAR researchers. The IMPACT model (Rosegrant *et al.*, 2008) developed by IFPRI has been used to assess agricultural policy impacts and to conduct long-term assessments of climate change on food, agriculture and natural resources at global and regional scales. Similarly, the Global Biosphere Management Model (GLOBIOM, Havlík *et al.*, 2011) developed by the International Institute of Applied Systems Analysis (IIASA) is frequently used to simulate competition for land use between agriculture, forestry and bioenergy at the global level. Other global economic models include the Computable General Equilibrium model developed by the Global Trade Analysis Project (GTAP, Hertel, McDougall and Itakura, 2001), the Model of Agricultural Production and its Impact on Environment (MAgPIE, Dietrich *et al.*, 2019), and the Environmental Impact and Sustainability Applied General Equilibrium model (ENVISAGE van Mensbrugghe, 2006).

Although there has been much progress developing and linking existing disciplinary models to assess impacts on various biological, physical, and economic outcomes (e.g., DSSAT and CENTURY have been linked to integrate soil carbon and nitrogen processes to simulate crop yields and soil carbon dynamics) large gaps remain between models at various scales, e.g., farm system and landscape scales, and national scale for economic analysis of commodity and related markets, that prevent truly integrated assessments across scales. For example, most farm system models assume farms are price takers with no formal linkage to a market equilibrium model. A few exceptions include Laborte, Van Ittersum and Van den Berg, 2007, van Ruijven, O'Neill and Chateau, 2015 and Valdivia, Antle and Stoorvogel, 2012; however further research is needed to address key aggregation and dis-aggregation issues (Antle, Stoorvogel and Valdivia, 2014).

3.3 Case Studies from Farm to Global Scales

This section presents a set of case studies that illustrate the types of analyses that are currently being done at various scales. These studies reflect the fact that stakeholder objectives vary according to the spatial and temporal scale, from local to national to global, and from growing season to the decadal progression of climate change and other global drivers. These scales in turn determine relevant indicators and the tradeoffs that need to be evaluated. These case studies illustrate how FA and TOA can be used to guide project-level research design and data collection to support ongoing ME and periodic re-evaluation of research priorities (e.g. updating ToC).

At the farm level, the EADD study shows that while farm income increases and poverty decreases, and total assets owned by both male and women increase, the share of assets controlled by women declines, and water use and greenhouse gas emissions increase. These results indicate that there are likely to be tradeoffs between the economic benefits of livestock intensification and key social and environmental impacts that could be addressed in the research design for improvements in livestock management to reduce water use and greenhouse gas emissions. Inclusive technology dissemination could be designed to mitigate possible adverse gender effects of the new technology.

The AgMIP case study in Zimbabwe shows how FA and TOA can be used to inform multi-level stakeholders (from farming system to national level) about the likely consequences of following different development pathways. It also demonstrates that the process of co-designing pathways and adaptation strategies with stakeholders increased the demand for science-based information to support decision making. The analysis also showed that diversification of food, cash and feed crops, like legumes and small grains, can improve income and nutrition and empower youth and women in the fragile drylands. The CGIAR Research Program on Grain Legumes and Dryland Cereals Agri-food Systems (CRP GLDC), managed by ICRISAT can play a key role on the transformation of the crop-livestock system of this region. The AgMIP regional integrated assessments help researchers and stakeholders explore and quantify the potential for farming systems to be better adapted to climate change. The result is a portfolio of investment options in climate-smart agriculture.

The income and food security study in Ethiopia is an example of how an existing partial equilibrium global model (GLOBIOM) can be adapted and used for a national scale analysis.

The study analyzes long-term consequences of the agricultural sector under different agricultural policy scenarios. The range of indicators analyzed capture tradeoffs at different scales, from population growth and GDP (national) to dietary changes, food, feed production and consumption, income and food security (agro-ecological zone).

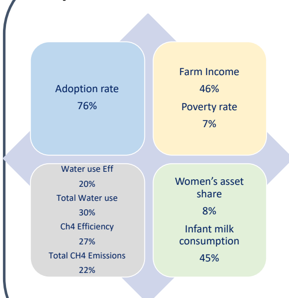
The Fertilizing Hidden Hunger study demonstrates how TOA can be used to explore tradeoffs and synergies among traditional and 'non-traditional' nutritional indicators and environmental indicators. In addition, the multi-model ensemble used in this study can be used quantify uncertainty and inform policy decision making. This study estimates iron, zinc, protein content and calories from rice, wheat and soy and how these changes due to different levels of CO2 fertilization and climate change scenarios. These results could be used by crop breeding programs to address nutritional deficiencies in diets.

Farming System Scale: Economic, Environmental and Social Impact Assessment of the East Africa Dairy Development Project in Kenya.

Objective:

The goal of this study was to conduct an impact assessment of the practices promoted by the East Africa Dairy Development Project (EADD), using baseline data collected by the International Livestock Research Institute (ILRI). This analysis was designed as a proof-of-concept for use of the Environmental Matrix, developed by the Bill and Melinda Gates Foundation (BMGF), with the Tradeoff Analysis Model for Multi-Dimensional Impact Assessment (TOA-MD). The analysis highlighted some of the complex economic, environmental and social tradeoffs and synergies that are likely to be associated with dissemination of the EADD practices at farm, sub-regional and regional scales.

Key Results:



Tradeoffs and Synergies

The analysis shows that different EADD implementation scenarios result in different potential adoption rates and important tradeoffs and synergies across the outcome indicators. Increasing income reduces poverty and increases infant milk consumption as well as efficiency in the use of water and methane emissions. However, as farm income increases, the share of assets controlled is predicted to decline. Total water use and methane emissions also increase.(See figure)

Reference

Antle, John and Valdivia, Roberto 2011. Economic, Environmental and Social Impact Assessment of the East Africa Dairy Development Project in Kenya using the Tradeoff Analysis Model. Report prepared for the Bill & Melinda Gates Foundation. Available at: https://tradeoffs.oregonstate.edu/

Indicators:

Economic

- Poverty
- farm household income

Environmental

- water consumption by livestock
- livestock methane emissions

Nutrition and social

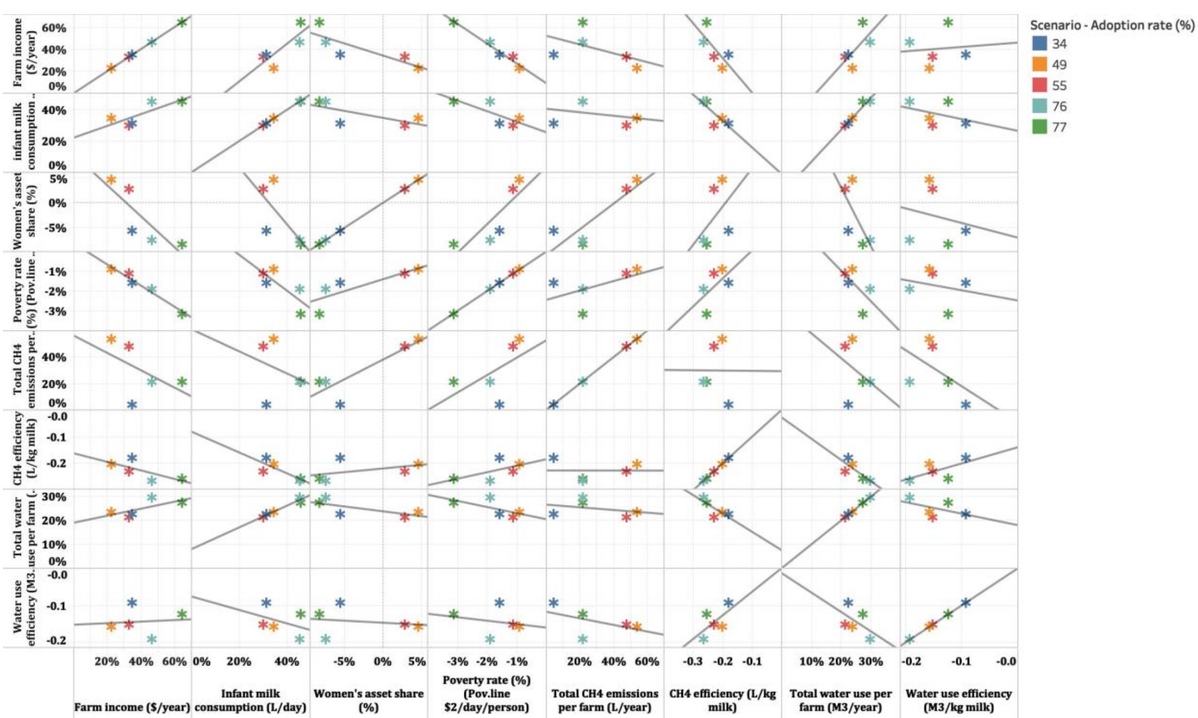
- milk consumption
- men's and women's asset ownership.

Models/Approaches:

TOA-MD – Impact Assessment
LifeSim – Livestock Model (CIP)

Data:

EAAD Baseline household survey data
Secondary data (previous studies, literature)



Tradeoffs between farm income, infant milk consumption, women's asset share, poverty rate, CH4 emissions, CH4 efficiency, water use and water efficiency

Cross-Scale Integrated Assessment: The Agricultural model Inter-comparison and Improvement Project: The Crop-Livestock Intensification Project (CLIP)-ICRISAT

Objective:

This study contributes to new science-based approaches (www.agmip.org) to generate actionable information for policy decision making.

Bottom up multi-modeling approach, point based assessments for smallholder farming systems in Zimbabwe Drylands to inform adaptation strategies for common farming systems, under current and future conditions with climate variability and change and socio-economic changes:

- Initiate change in the configuration of farms through diversification, intensification and integration
- Investment priorities to support gender sensitive, socially inclusive pathways to sustainability
- Implications for social protection and resilience building mechanism, in areas where risk and vulnerability are high

Reference

Homann-Kee Tui Sabine, Descheemaeker Katrien, Masikati Patricia, Sisito Gevious, Crespo Oliver, Elisha Moyo, Roberto Valdivia. 2020. Transforming farming systems in the face of changing climate and socio-economic conditions: a case from semi-arid Zimbabwe. *Submitted to Climatic Change.*

Indicators:

Economic

- Adoption rates
- Poverty
- farm net returns
- Vulnerability to climate change
- Gains and losses

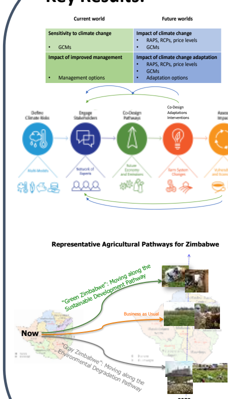
Bio-physical

- Crop Yield changes
- Livestock and dairy yields

***Social** (qualitative)*

- Youth and Gender
- Food security & nutrition

Key Results:



Tradeoffs and Synergies

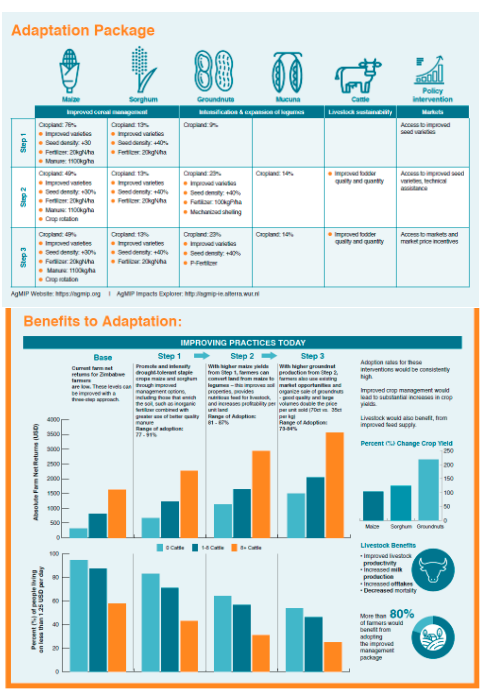
- Long term, low and stable organic soil fertility applications in poor quality depleted soils - vs high risk soil fertility using inorganic fertilizer
- Diversification of profitable food & feed crops: multiple benefits from legumes – vs artificial dependence (e.g. subsidies) on large-scale maize farming at low nutrition and income values
- Investment in livestock feed supply vs income and nutrition outcomes
- Inclusive market oriented tailored to farm types vs silver bullet production oriented approaches
- Youth, gender and nutrition empowerment approaches driving climate change adaptation planning vs information dissemination that is age and gender blind, and fails to address nutrition as critical climate change adaptation component

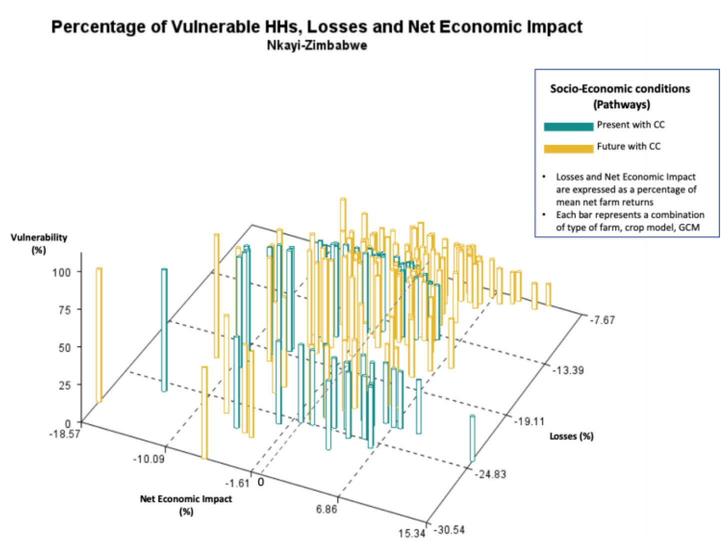
Models/Approaches:

RCP 4.5/SSP 1, RCP 8.5/SSP 3, 25 GCMs – Climate models
DSSAT / APSIM – Crop models LIVSIM – Livestock model
TOA-MD – Impact Assessment
IMPACT – Global Economic Model
Foresight: RAPS at local, district and national levels
Multi-level stakeholder engagement process – co-design of scenarios and modeling parameters

Data:

SLP/ICRISAT household survey data (n=168)
Climate, crops, livestock, economic outputs
Pathway and scenario narratives and parameters





National Scale: Improving Ethiopian smallholders' income and food security: a farm-type analysis

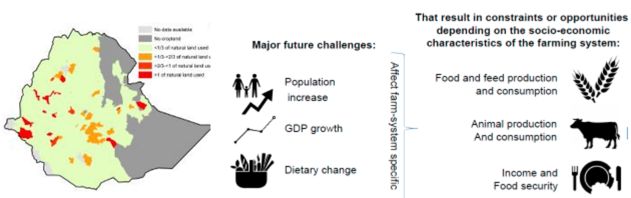
Objective:

Analyze long-term changes to the agricultural sector and its consequences for the evolution of Ethiopian smallholder farmers under various policy scenarios. A farming typology based on the agro-ecological zone, the dominant activities, and the degree of market integration is established for this purpose.
The spatially differentiated typology is integrated in an Ethiopia-version of Global Biosphere Management Model (GLOBIOM)

Smallholder farmers: Dominate food production: produce 90% of grain
Experience food insecurity: on average farm size < 1ha
In transition: poverty line decreased from 45.5% to 27.8% over past decade.
Agricultural sector: Backbone of Ethiopia's long-term plans for economic growth

Key Results:

Tradeoffs and Synergies



Total increase in cropland necessary in order for smallholder farmers in 2030 to produce food for self-consumption under the same practices, specified by the uptake of other natural land. In some areas (orange and red) productivity increase will be crucial to improve food security.

Reference

Bocqueho, G., Boere, E., Mosnier, A. and Havlik, P., 2015. Improving Ethiopian Smallholders' Income and Food Security: An Assessment of Alternative Policy Options. IIASA-IFAD

Indicators:

Economic

- GDP
- Population consumption
- Income
- Crop yields
- Livestock yields

Social

- Food security
- Dietary change

Climate

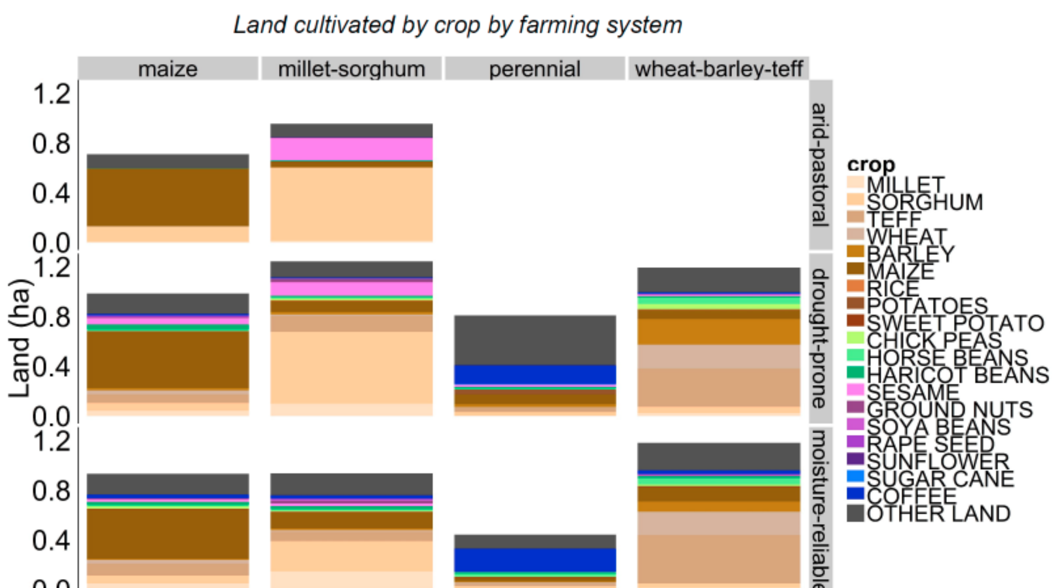
- GCM scenarios

Models/Approaches:

EPIC – Crop model
GLOBIOM – Global model

Data:

LSMS/ISA-ERSS Survey ~3000 households
National statistics



Very large proportion of maize

Millet-sorghum combination zone dependent. Oilseeds (sesame) important

Coffee and other perennials. Not in pastoral zone

Mostly wheat and teff. Not in pastoral zone.

Global Scale: Fertilizing Hidden Hunger

Objective:

This study assesses the effects of climate change and CO_2 fertilization on crop yields and nutritional value of food.
In a Letter published in *Nature*, Myers *et al.*3 present compelling evidence, based on a large meta-analysis of published studies, that CO2 fertilization will have negative effects on the nutritional value of many key food crops by reducing the concentrations of essential minerals and protein. This could have serious implications for hunger and health in many parts of the world where the quality of food is just as important as its quantity. Even if CO2 fertilization has the potential to compensate much of the negative climate change effects on agricultural yield, nutritional value may nevertheless be compromised

Reference

Müller, C., Elliott, J. and Levermann, A., 2014. Food security: Fertilizing hidden hunger. *Nature Climate Change*, *4*(7), pp.540-541.

Indicators:

Nutrition
- Calories
- Iron content
- Zinc content
- Protein content.

Economic
- Crop yields
- Livestock and dairy yields

Environmental
- CO2 fertilization

Climate change
- climate change projections

Key Results:

Increased atmospheric CO2 leads to a substantially lower supply of all three nutrients compared with a world implementing strong climate change mitigation, even though food quantities are comparable if farmers are able to fully exploit the effects of CO2 fertilization (see figure)

Tradeoffs and Synergies

- Nutritional content:
  - Iron content
  - Zinc content
  - Protein content
  - Calories

Crop yields (rice, wheat, soy)
Co2 fertilization and climate change

Models/Approaches:

EPIC – Global Crop model
GEPIC – Global crop model
LPJ-GUESS: -Global crop model
PEGASUS – Global Crop Model
pDSSAT – Global crop Model

Data:
ISI-MIP Projections

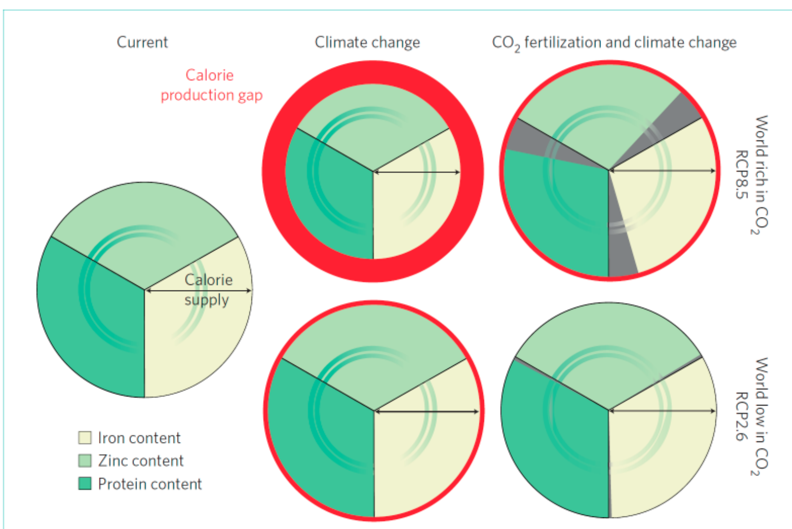


Figure 1 | Currently, the C_3-crops wheat, rice and soy provide almost 40% of the world's food calorie supply (left) as well as significant shares of iron, zinc and proteins (current levels represented as thirds of the plate area). Under climate change (middle), production quantities are projected to decline[1], especially in warm worlds rich in CO_2, leaving a calorie production gap (represented by the reduction in plate radius; red) to be filled by intensification, cropland expansion and trade[8]. Two potential CO_2 scenarios are considered: RCP8.5 (top right) and RCP2.6 (bottom right). CO_2 fertilization can reduce the negative climate change effects considerably so that they are comparable to climate change impacts in a cooler world low in CO_2 (bottom right). Assuming a linear decline of the minerals iron and zinc, as well as protein, with rising atmospheric CO_2 concentrations[3], production compensation leads to significant decreases in nutritional values (grey wedges). All data are based on median ISI-MIP projections for the end of the twenty-first century of EPIC, GEPIC, LPJ-GUESS, LPJmL, PEGASUS and pDSSAT[1].

3.4. Representation of One CGIAR 5 Impact areas in TOA Modeling Approaches

The preceding sections show the diverse use of tools at different scales and provide an insight about the features of different approaches to TOA. However, most of the studies focus on few indicators that correspond to one or two impact areas of One CGIAR. Only the East African Dairy Development study covers all five impact areas with multiple indicators. One explanation for this gap is the disciplinary orientation of the researchers carrying out projects. For example, projects led by agronomists or economists may lack the disciplinary knowledge needed to recognize the importance of impacts in environmental or social dimensions, as well as the expertise to identify appropriate indicators and design efficient data collection for those indicators.

In this section we discuss the capabilities of current modeling approaches to represent or include the five impact areas of One CGIAR, and identify needed improvements.

Nutrition and Food Security: Most current models use simple indicators such as per-capita food consumption to represent nutrition and food security, but do not incorporate the indicators that have been developed to characterize the key determinants of food security (availability, access, stability, and utilization) and nutritional aspects such as diet diversity. A critical limitation is the lack of household food consumption data, thus there is the need to develop methods to collect these data with new approaches that can capture the dynamics of household consumption (e.g., mobile apps). Most research now utilizes multiple indicators to measure nutritional diversity which is becoming important to assess sustainable diets beyond assessments based on kilocalories (Müller, Elliott and Levermann, 2014). Recent emerging research on sustainable healthy eating behavior seeks to integrate eating or consumption attitudes and behavior towards changes in diets (Fanzo *et al.*, 2012); (Geiger, Fischer and Schrader, 2018). Additional research is needed to bring these dimensions into quantitative models.

Poverty and Income Distribution: Within agricultural populations, estimates of some components of farm household income are usually included in most economic household or farm models. However, a complete characterization of farm income sources (e.g., off-farm income) is needed to accurately assess poverty and income distribution in a population of farms. In addition, the distribution of income among household is required to estimate indicators such as poverty rates. The Headcount Poverty rate (i.e. the proportion of households below the poverty line) is the most frequent indicator used in TOA. Other indicators such as the poverty gap (i.e. the degree to which individuals are below the poverty line) and food-based poverty indicators Smith and Urey, 2002; Antle, Adhikari and Price, 2015) can be used to represent other dimensions of poverty. Going beyond farm households to other rural and urban populations involves broader data and models that are typically highly aggregated and thus not capable of representing income distributions or predicting changes in poverty rates. Linking disaggregate data and models with more aggregate models is the solution to this challenge that is currently at the frontier of research.

Gender and Age: Despite the growing research on gender impacts and related outcomes, there is little representation of gender in most models, at least quantitatively. Similarly, analysis of children's labor and their nutrition and health has also been limited, due to lack of data. Distributional impacts of new technologies or policy interventions on gender and intra-household equity, including asset ownership, health, education and nutrition could be incorporated in quantitative or qualitative impact assessment models with better age and sex-disaggregated data that is context-specific.

Climate: Climate (and weather) have been included in many bio-physical and economic models to assess the impacts of climate change on crop yields. However, many of these analyses are crop-based. In order to have a better assessment of the vulnerability of farms to climate change, farm and household system-based analyses are needed. For climate change analysis, forward-looking assessments require the use of foresight techniques to represent plausible future socio-economic and bio-physical conditions that can be matched to global emission scenarios (RCPs) and socio-economic projections (SSPs). A new approach to climate change and adaptation impact assessment has been developed by the Agricultural Model Inter-comparison and Improvement Project (AgMIP) (Rosenzweig *et al.*, 2018). This multi-scale, multi-model, protocol-based approach links climate, crop, livestock and economic data and models with pathways and scenarios to assess the likely impacts of climate change and adaptation of farmers' livelihoods.

Environment: Field or point level agricultural models (e.g., crop simulation models) can capture the water, soil carbon, nitrogen and nutrients and environment fluxes. At this level, these models can be linked to economic models to assess the tradeoffs between socio-economic and environmental outcomes. For example, Valdivia, Antle and Stoorvogel, 2012 links the TOA-ME economic model to DSSAT and the Nutrient Monitoring model (NUTMON, De Jager, Nandwa and Okoth, 1998) to assess the tradeoffs between maize production, poverty and soil N depletion. At the landscape scale, upscaling the field level processes increase the complexity of the system. Landscape or watershed level models like SWAT is commonly used to simulate hydrology, sediment and contaminant transport and cycling (pesticides, bacteria, and nutrients) in soils and streams, and crop/vegetative uptake, growth and yields (Antle, Jones and Rosenzweig, 2017).

4. Tradeoff Tools and Capacity Building

A key TOA principle is that the types of data and models used are dictated by the indicators and the scales at which they are relevant. For example, impacts may pertain to individuals or economic units such as farms, social units such as households, or may be other species or aspects of the environment (water quality, quantity in a watershed), or may involve the *distribution* of impacts at higher scales, i.e., average per capita income of farm households, poverty rates among rural or urban households, proportion of waterways exceeding an environmental standard, etc. In most cases, multiple disciplinary models are required. When indicators cannot be quantified, qualitative approaches can be used. When resources are not available to quantitatively model some impacts, findings of syntheses and meta-analyses can be adapted to the conditions of a particular case.

Modeling Issues and Needed Improvements. There are many issues that arise in the use of models for technology impact assessments and TOA, and recent research has identified areas for data and model improvements (Antle, Jones and Rosenzweig, 2017; Jones *et al.*, 2017).

- *Linking Models Across Disciplines (e.g. Crop-Livestock-Economic-Environmental Models):* In order to link different models at farm-system level, protocols and tools need to be created for standardized inputs and outputs (i.e., data and model harmonization).
- *Linking Models Across Scales:* Methods are required to link household or farm system level economic models to market equilibrium models (e.g., partial or general equilibrium models). There is need to address aggregation and dis-aggregation issues.
- *Behavioral Assumptions:* Most of the economic models are based on profit-maximization assumptions (in some cases adjusted for risk). However, recent literature on behavioral economics and risk modeling could be incorporated in the TOA.
- *Economic Model Inter-comparison and Improvement*: The wide array of household and farm level economic models use different approaches and assumptions, however they

can be used for the same objective (e.g., assessing impacts of climate change on a specific farming system). Responses to each model are likely to be different. Thus, there is the need to understand the differences and explore options to improve models and be able to use model ensembles to capture the inherent uncertainty of the models. Inter-comparison and improvement of crop simulation models have been conducted by the Agricultural Model Inter-comparison and Improvement Project (AgMIP). Also, a comparison activity that involved 10 global economic models was carried out under AgMIP (Nelson *et al.*, 2014).

- *Representation of Pests and Diseases:* Crop and livestock process models are limited in the way they represent pest and diseases. However, there are advances on methods to incorporate pest and diseases in modeling approaches (statistical and process-based approaches).
- *Documentation and Availability*: Models and tools should be publicly available and well documented. This is crucial for capacity building and knowledge transfer. Likewise, model or method improved should also be documented.

Foresight and TOA. Agriculture and food systems face complex challenges: population growth, crop and livestock yield gaps, environmental degradation, climate change and variability, social conflicts and economic stressors. There is need for long-term informed decision-making, to provide a base for future generations. Research approaches and investments aim to provide more accurate information, while accounting for these complexities, to accelerate transformation to sustainability. There is the need for an approach that can characterize plausible future socio-economic conditions and the state of agricultural production under those conditions. Integrating improved technology with governance and institutional development, in a way that is gender sensitive, is critical for attaining sustainable and resilient agriculture and food systems. A stronger integration of science and stakeholder-based knowledge is needed to enable priority setting and to support decision-making processes effectively, guided by joint strategy development (Valdivia et al., 2020). Pathways and scenarios that represent possible future states of the food system can be quantified for used with TOA tools and assess the impacts of technological or policy intervention on socio-economic and environmental outcomes.

At global level, socio-economic trends have been established and are commonly used in climate change impact assessments. The Shared Socio-economic Pathways (SSPs) include trajectories of population growth, GDP, and other global drivers. Global economic models have been used to quantify the effects of scenarios that combine SSPs with different emission levels (RCPs) on international trade, international price of specific commodities, productivity trends, etc.

At national level, pathways can be developed to represent the country's agricultural policies, for example, following a strategy for a sustainable development pathway conducive to meet the SDGs. The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) have developed multi-country future scenarios for West and East Africa (Vervoort *et al.*, 2014; Palazzo *et al.*, 2017)

At farming system level, pathways can be developed to create scenarios that can be quantified and provide input parameters to crop, livestock and economic models. One issue is that the SSPs, being global and economy-wide, lack of the necessary detail to describe future conditions for agricultural systems and at the farming system scale. For climate impact assessment, AgMIP has been developing systematic approaches to development of "pathways" (plausible future conditions) and "scenarios" (specific parametric representations of a system consistent with a pathway), using the concept of Representative Agricultural Pathways (Valdivia *et al.*, 2015; 2020).

Data. One of the main limitations or data gaps is that most available data are collected for disciplinary research and are often not readily accessible, or not suitable for use in impact assessment due to differences in spatial and temporal scale or lack of adequate documentation (Antle, Jones and Rosenzweig, 2017). For example, multiple detailed data sets exist on crop production or yields, but since the goal is to assess changes in crop yields or capture other bio-physical processes, key economic data (e.g., production costs) is frequently ignored and not recorded. A relatively new initiative within the CGIAR is the Rural Household Multi-Indicator Survey (RHoMIS, van Wijk *et al.*, 2020). RHoMIS is a tool that aims at reducing the cost and time required to carry out and analyze surveys. It provides a structure and standard format to collect data that describes farm productivity and practices, nutrition, food security, gender equity, climate and poverty. However, one limitation is that it does not include economic data such as production costs which are critical for TOA. There is the need to advance data standards with the aid of digital technologies for collection. The Platform for Big Data in Agriculture of the CGIAR has defined a common core of cross-sectional household survey as a first building block for a standardization of survey data (van Wijk *et al.*, 2019).

The CGIAR's Big Data initiative can play a key role in facilitating collaboration across the CGIAR research portfolio and outside of the CGIAR and the CGIAR's socio-economic data community of practice that aims to make data FAIRER (Findable, Accessible, Interoperable, Ethical and Reproducible) through: 1) identification of key concepts, indicators and questions commonly addressed in socio-economic surveys; 2) developing a socio-economic ontology, building on existing ontologies and focusing on the key concepts, indicators, and questions from the socio-economic team; 3) developing a standard for documenting and archiving metadata; and 4) identifying best practices in electronic data capture and development of data capture tools.

Capacity Building. A strategy for capacity building is needed to enable the priority setting process that incorporates FA and TOA. The objective of the capacity building should include CGIAR Management, local and international CGIAR scientists, local NARS and international scientists, collaborators and stakeholders. There are two levels of capacity building to be considered. First, there is a need to build capacity within CGIAR, including in-house modeling approaches and tools (e.g., IFPRI's IMPACT model). There is also a need to collaborate with other institutions for capacity building and use of modeling tools developed by partner institutions. Examples are established modeling groups like DSSAT (DSSAT Foundation); TOA-MD Impact Assessment Courses (Tradeoff Analysis Project at Oregon State University); and IFPRI's IMPACT modeling group. A strategy will need to be created to make use of complex models that lack training courses, e.g., the GLOBIOM of IIASA.

Private and Public Partnerships. International presence of the CGIAR is a key advantage to develop strategic partnerships with the private and public sectors to leverage the research strategy and contribute to deliver measurable success on the five One CGIAR impact areas. These partnerships could improve access and knowledge to products that are not public but that can contribute to the process of priority setting and development of innovations as public goods. One example of this is the advances in digital technologies that are happening in the private realm. Digital innovation in the private sector focuses on the creation, use, combination, analysis and sharing of agricultural and other data in digital format to improve the sustainability and productivity of agriculture and food systems (OECD, 2019).

5. Foresight and Tradeoff Analysis: Opportunities and Challenges for One CGIAR

The currently available FA methods (Zurek, Hebinck and Selomane, 2020; Lentz, 2020) and the TOA methods and tools discussed in this report present an unprecedented opportunity for the One CGIAR to help One CGIAR1 and its stakeholders efficiently and effectively set priorities among potential innovations to balance inevitable tradeoffs and exploit synergies. FA and TOA can help accomplish efficient management through coordination of research design and evaluation at the project level with identified global One CGIAR priorities. Achieving these results also presents significant challenges in terms of FA and TOA data and methods, as well as CGIAR resources and capabilities.

The principal recommendation of this report is to implement a research management system that integrates FA and TOA to inform the One CGIAR global and regional priority setting (Figure 1). This research management system should be based on data and evidence created through the use of FA, TOA and ME in the design and evaluation of technologies at the farm, sub-regional and temporal scales appropriate to impact indicators. Impact indicators from the five One CGIAR areas should be identified through participatory processes at corresponding scales.

Figure 1 presents a design concept for the places that FA and TOA fit in a prospective One CGIAR priority setting and research management system. Following the SRG recommendations for a new research modality, the figure shows the global research strategy being built around stakeholder consultations that identify major global challenges and associated Big Lift themes and corresponding impact indicators in the five priority impact areas, including goals for these indicators. For each Big Lift:

- FA with stakeholders and scientists identify a set of future development pathways and agri-food system innovation scenarios implied by the Big Lift for the first phase of investment (note, the relevant time horizon for the impacts will run beyond the investment phase).
- The pathways and innovation scenarios are used to implement TOA to evaluate the range (sets) of impacts that are feasible. These scenarios should include sufficient detail to enable project design in the following stages of the process.
- Based on the FA and TOA results, consultation with funders and stakeholders leads to the co-creation of a research strategy, including prospective research projects consistent with goals in the five impact areas, and allocation of resources among projects.
- The research strategy is communicated to the regional programs for consultation with partner countries and organizations, leading to regional and national research portfolios of projects consistent with capabilities in the regions.
- Research project implementation proceeds with activities to support project-level FA, TOA and ME. FA and TOA are implemented at the beginning of a project to inform the design of the initial technology “funnel” consistent with impact goals. Accumulation

of data over time and improvement of models allows updating of TOA analysis. This information is passed to project ME and also synthesized with data from other projects and Big Lifts and communicated to the global priority setting process.

- At the project level, a set of protocols should be followed to ensure cost-effective implementation of FA, TOA and ME.
    - Allocate resources to FA, TOA, and ME to ensure they are part of every project and scaled to the project's budget.
    - Identify quantifiable indicators in each impact area; if indicators are not quantifiable, then qualitative indicators should be identified.
    - Identify disciplinary data and models needed to carry out quantitative TOA. Data should meet standards for minimum data to support initial and ongoing TOA and be consistent with FAIRER principles.

Challenges. Based on recent experience with FA and TOA, a number of significant challenges will need to be addressed as they are integrated into the new One CGIAR research modality.

Building while Flying. A first challenge comes from the need to incorporate FA and TOA into a new organizational structure that is literally being designed as it is also being put into use. One solution to this challenge is to draw upon outside expertise to assist in the transition, demonstrate methods, and build capacity among CGIAR staff so they can "fly on their own."

The Transition to One CGIAR. A second challenge is the point at which this recommendation is being made in the aggressive transition process schedule. Given that schedule, our recommendation is to utilize existing information, together with expertise inside and outside the CGIAR, to expedite the key elements of FA and TOA outlined above.

Global and Regional Indicators. We recommend using the CGIAR's priority setting processes with stakeholders to identify sets of minimally sufficient impact indicators at global and project scales. Reaching a consensus on a relatively small number will be a major but critical challenge. A key finding of the foresight reports prepared for One CGIAR is that global-scale foresight studies do not adequately represent impacts in several of the One CGIAR priority areas – nutrition and food security; poverty reduction, livelihoods, and jobs; and, gender dimensions, youth, and social inclusion. This is also true for many important environmental impacts, and is a feature (or limitation) of the global and national impact assessment models discussed in this report. This condition is due in part due to the lack of consensus on impact areas and indicators, but mainly due to a lack of analysis at disaggregate scales (farm, eco-regional) that can be aggregated to national, regional and global scales. The recommendation in this report for project-level implementation of TOA will help fill this gap in available data.

Dealing with Complexity: Sufficiency and Parsimony. A major challenge in the implementation of FA and TOA of complex, multi-scale systems is to produce information that is low-cost and timely. One CGIAR should embrace the principle that information to support decisions under uncertainty needs to be *minimally sufficient* to identify options that are likely to meet goals and balance tradeoffs across multiple impact dimensions – not to achieve "optimal" decisions in a single dimension. Moreover, the need for timely information to support decisions argues for *parsimonious* quantitative modeling and analysis. One CGIAR has limited resources, therefore, this enhanced priority setting process should be designed to be cost-effective and fit-to-purpose, namely, to provide an objective evidence base to guide and justify priority setting decisions. The careful selection of impact indicators is a key element to addressing complexity through sufficiency and parsimony. For example, if acute health impacts of toxic pesticides on farmer health show that farmers are exposed to unacceptably high neurological risks, evidence of chronic health impacts such as cancer risks are not necessary to justify research that can help farmers to reduce the use of toxic pesticides while achieving other goals such as poverty reduction and food security.

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7. Appendix

Table A.1: Economic indicators and SDGs

	Economic Indicators	Unit	SDG
Farm	Crop or livestock productivity (yield)	quantity/ha or quantity/animal	SDG1: No Poverty, SDG2: Zero Hunger, SDG8: Promote Sustained Inclusive and Sustainable Economic Growth, SDG13: Climate Action
	Financial condition	Debts/assets (%)	
	Farm income	Currency units per farm, per ha, per animal unit	
	Technology: improved genetics; purchased inputs (seeds, fertilizers, pesticides); mechanical power and implements; information technology	use/non-use; application rates (quantity/ha)	
	Diversification or resilience	Crop or livestock species diversity index, drought or disease tolerance	
Household	Money Income	All farm and non-farm money income (currency units/time)	
	Full Income	Net value of all farm and household production and labor plus non-farm money income (currency units/time)	
	Poverty	% individuals or households with consumption or income below poverty line	
	Vulnerability	Possibility of suffering a decline in well-being due to an adverse shock	

Table A.2: Environmental indicators and SDGs

	Indicator	Unit	SDG
Soil	Soil organic matter	% of soil	SDG2: Zero Hunger, SDG6: Ensure Availability and Sustainable Management of Water and Sanitation, SDG12: Responsible Consumption and Production, SDG15: Halt biodiversity loss
	Soil fertility	Ph, macro-micro nutrient balance	
	Soil erosion	kg/ha	
Water	Depth of ground water	meters	
	Water quality	Ph, Salinity	
	Dissolved oxygen in water	%, mg pollutant/liter, ppm	
	Heavy metal concentration in water	%, mg pollutant/liter, ppm	
Emissions	Carbon dioxide (CO2), Methane (NH4), Nitrous Oxide (N2O)	kg GHG/year	
	Air pollution	Air quality indices (AQI)	
Land Use	Increase in forest cover	Share of land converted to protected forests, Share of degraded land recovered	
	Conservation of fragile eco-systems	Conserved eco-systems in coastal, mountains and island systems	
Bio-Diversity	Species richness	Gamma-diversity: count of species in a region	
	Protection for terrestrial and freshwater biodiversity	Share of land protected	

Table A.3: Social indicators for human development, equity and justice and SDGs

	Indicator	Unit	SDG
Food Security	Availability of culturally relevant food	calories/capita, expenditure/capita	SDG2: Zero Hunger,
	Access to food	Household Food Insecurity Access Scale (HFIAS), Food Insecurity Access Scale (FIES)	
	Diet Diversity	Food Consumption Score (FCS), Household Diet Diversity Scale (HDDS)	
	Food safety	% population with access to clean drinking water, Number of food contamination cases due to pathogens and agri-chemicals; Cases of food-borne illness or death	
Nutrition	Undernutrition	% of children stunted, wasted or underweight, % with micronutrient deficiency	
	Overnutrition	% obese, % calories from saturated fats,	
Health	Maternal Child Mortality	Maternal Mortality Ratio, Infant Mortality Rate	SDG3: Good Health & Wellbeing
	Mental health	Cases of illness or deaths	
Women's Empowerment	Women's Land Ownership, Control over assets and Autonomy in the household	% of land owned by women, % of assets controlled by women	SDG5: Gender Equality
	Pay Gap	Relative difference in wages of men and women	
	Intra-household resource allocation to female members	Difference in food allocation, and educational investments between girls and boys	

	Women's Empowerment in Agriculture Index (WEAI)	Index	
Safe Working Conditions	Worker safety	Number of injuries or deaths	SDG8: Decent Work and Economic Growth
	Exposure to Harmful Chemicals	% of workers without protective gear, % of workers exposed to harmful chemicals	
Community	Viability	Age distribution	SDG11: Sustainable Cities and Communities
		Educational, Medical, Social services	
Animal Welfare	Confinement practices	% confined	
	Animal health	disease and mortality rates	

8. Terms of Reference

TERMS OF REFERENCE

Assignment Details

The ISDC requires the support of an expert consultant with deep trade-off analysis experience relevant for the CGIAR impact areas of nutrition, poverty, gender, climate, and environment. The consultant will work under the overall thought leadership and guidance of ISDC Member Professor Chris Barrett and under the operational supervision of ISDC Senior Manager Dr. Amy Beaudreault.

The trade-off report will be a follow-on project that uses two desk reviews, currently in process, synthesizing and translating existing foresight studies to inform the CGIAR 2030 Research Strategy. One review focuses on nutrition, poverty, and gender and the other on climate and the environment. These reviews will be presented at the ISDC meeting scheduled for 21-23 April 2020 virtually due to the COVID-19 pandemic. The dates and times of the virtual meeting are being scheduled. An expectation is that the consultant will attend relevant sessions and actively participate with a neutral and unbiased perspective to this trade-off analysis' deliverables.

Deliverables

The following deliverables are required for this consultancy.

1. Attendance in virtual ISDC meetings (approximately 20 April to 23 April)
2. A detailed 3- to 5-page outline of the report
3. 1st draft report for the purpose of being distributed internally among a subset of ISDC members for review; feedback provided will be consolidated
4. 2nd draft report that incorporates feedback from 1st draft, including a 2-page executive summary and full citations. This draft will be distributed to all ISDC members
5. An approximately 20-minute presentation and follow-up discussion led by consultant(s) of the findings at a virtual ISDC meeting (date: approximately 27 May)
6. A final 15- to 25-page final report
7. Participation in conference calls when necessary

Scope of Work

Building on the two foresight reviews' presentations and discussions, the consultant will include the following key aspects in the trade-off analysis (please note that the consultant *is not* expected to develop a new model; the consultant should use an unbiased lens when conducting this research):

- Advance knowledge on how trade-off analyses may provide diverse pathways in obtaining the One CGIAR research-for-development goals in the five impact areas of nutrition, poverty, gender, climate, and environment
- Include a review and analysis of several (minimum of 3 but open for discussion during outline phase) with each model presented with an accompanying case study (i.e., scenario) that summarizes where CGIAR is well-positioned to influence within and across its impact areas

- Models and accompanying case studies should showcase a variety that focus on internal (within impact areas) and external (across impact areas)
  - Models should range in timescales and techniques
  - While quantitative models are preferred, some CGIAR impact areas may not have the evidence and qualitative (preferably ordinal) models will be acceptable
  - Case studies should contain different trajectories for complementary private and public investments to spark explicit consideration and discussion of where CGIAR research for development fits across its research portfolio. The trajectory data sources should be included in the outline

- Describe the advantages and disadvantages of each model and case study from the perspective of CGIAR stakeholders
  - Define what models are used most and why, and their relevance for CGIAR priority setting

- Translate complex trade-off examples into understandable implications for all CGIAR stakeholders (including but not limited to donors, policymakers, implementors, and evaluators)
- Report should be framed to provide strategic planning implications for practical decision-making for One CGIAR. This element should be incorporated in the executive summary.

Timeline

Start Date: 15 April
The consultancy is expected to commence on April 15 when drafts of the two foresight studies will be internally disseminated.

Deliverable 1: Attendance at Virtual Meeting 21-23 April
An expectation is the consultant should not do heavy work prior to the ISDC meeting, except reading of foresight drafts and commencing conceptualization of analysis.
Deliverable 2: Detailed Outline, April 28 (3:00 p.m. CET)
Draft a 3- to 5-page detailed outline for ISDC feedback that provides what models, case studies, and trajectory data sources will be included. ISDC will give feedback on outline no later than 1 May. If required, a conference call will be scheduled.
Deliverable 3: 1st Draft, 8 May (3:00 p.m. CET)
A full draft of the report is due. Placeholders for citations are acceptable. ISDC will respond with all feedback on 18 May.
Deliverable 4: 2nd Draft: 22 May (3:00 p.m. CET)
A near final draft (including 2-page executive summary and full citations) is due. This will be shared with the full ISDC as a pre-read for the presentation and discussion.
Deliverable 5: ISDC Presentation, 27 May
Consultant will present and lead discussion during virtual ISDC meeting (time TBD).
Deliverable 6: Final Report, May 29 (3:00 p.m. CET)
Final report that is fully proofed, formatted, and incorporates any remaining items conversed during presentation and discussion.

Conference calls will be scheduled when necessary.