Modeling Actions for Transforming Agrifood Systems

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1 Introduction

The 2030 Agenda for Sustainable Development calls for transformational change that aims to achieve economically dynamic, socially inclusive and environmentally sustainable change. The 2030 Agenda has raised awareness of the key role that agrifood system transformation can play as an entry point for accelerating progress to achieve many of the SDGs, but also highlighted the complexity of promoting transformational change. SDG 2 alone draws attention to several related challenges: the need to eliminate hunger and all other forms of malnutrition by ensuring that sufficient quantities of safe, nutritious and affordable food are available to all while also recognizing the importance of raising the productivity and incomes of small producers, and calling for a variety of measures, including investment, trade and market development to promote the inclusive, sustainable development of agriculture and agrifood systems. Yet, the 2030 Agenda also emphasizes the interconnectedness of the SDGs beyond SDG2 and requires that Member States achieve this while creating the growth and employment opportunities needed to eradicate poverty, protect biodiversity and the natural resource environment, and address the growing pressures of climate change.

Addressing the multidimensionality of agrifood systems requires using a multisectoral, dynamic multi-country model to properly capture the various

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trade-offs.[1] Specifically, this model will allow us to grasp the interactions among different food value chains (primary production, processing, distribution), as well as with the rest of the economy. This is important for economic interactions (demand for inputs and outputs, income generation flows) and for environmental aspects: the carbon footprint of food production and consumption depends on the energy system in which it operates. Agrifood systems cannot be studied independently from the wider economic structure, both because these structures condition a number of drivers shaping agrifood systems (income distribution, availability and costs of technologies, inputs) and because agrifood systems represent a major source of employment and income generation for a large number of low- and middle-income economies. Therefore, the transformation of agrifood systems will have macroeconomic implications (employment, income, cost of living, fiscal consequences) and economy-wide trade-offs.

Secondly, this model structure will allow us to consider the dynamic evolutions of agrifood systems and their environment, since policy reform does not occur in a frozen universe. A static analysis could describe current systems. But it is essential to develop a dynamic framework to capture the evolution of the world, particularly in terms of economic growth, inequalities, demographic pressure and climate change. We cannot jump from current systems to a different one in a framework where other conditions remain the same. Even if such an exercise could shape the debate and provide important insights, any practical implications and guidelines for triggering the required transformation—a set of voluntary actions—need to consider future evolutions of the world that agrifood systems could help to shape, but not define. This is important when presenting roadmaps for action and dynamic trade-offs.

Finally, it will allow us to capture the plurality of agrifood systems (with an “s”) at a global level and understand the interactions that occur through the flows of goods, services, capital, people and ideas. The magnitude and speed of globalization have skyrocketed in recent years, but agrifood systems have been largely shaped by international exchanges for more than 6000 years. Regions with a high concentration of population, or volatile weather, have relied on external food producers to guarantee their food security. New crops and technologies have been traded and new products consumed, taking advantage of the diversity of agro-ecological systems at a global level. However, even as production and consumption decisions in one country could affect producers and consumers 10,000 miles away in just a few

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[1] Externalities generate trade-offs when people’s welfare is pitted against environmental objectives. Sometimes, trade-offs happen at a large scale, among food, land, water, energy and climate (Bleischwitz et al. 2018 and others). Other times, they emerge from biomass uses and the competition among food consumption, feed for animals and biofuels (Muscat et al. forthcoming). In addition, many different dimensions, such as time, geography, governance and technology, affect the links among the SDGs. Positive interactions, though not discussed here, can be used to build strategies across sectors. Negative interactions are the targets of regulations and policies or the topic of public investment in technologies and solutions. The ultimate goal is to support coherent strategies and policies that neutralize the negative impact of SDG interactions, while achieving food and nutrition security and socioeconomic and environmental sustainability.

weeks, we do not have a homogenous and global, fully integrated food system. We have a web of interconnected (at various degrees) and heterogenous agrifood systems. Our modeling system should capture them. In particular, while prices in different locations interact with one another, we should not imagine that they are cleared in one global market. Beyond the market linkages, the global perspective is essential for non-marketed outcomes. We have to take into account the fact that the transformation of domestic agrifood systems will have external environmental footprints, and that global production and consumption involve trade-offs that require international cooperation.

In addition to the above features, we need to think about the type of model we need. The traditional modeling toolbox has recently been expanded beyond the econometric models and the equilibrium models. At the same time, other instruments (machine learning, evolutionary behavioral models) have been proposed. However, we can narrow down the choice of the instrument easily. Indeed, our goal is not to provide a foresight tool or to forecast the future using econometric models or machine learning models. Both of them heavily rely on reduced forms, and, as such, the traditional Lucas' critique (1976)[2] would be a notable weakness for them. Transformative change requires structural and disaggregated models. We need a modeling framework based on a strong economic theory, which would allow us to compare various "equilibriums"—or the state of the world and agrifood systems under different conditions and policies. For this reason, we need models for which the equilibrium's unicity and stability are theoretically grounded.

For these reasons, we have selected, in this paper, a global, computable general equilibrium model (CGE): the MIRAGRODEP model has the core element of the modeling framework. It is a dynamic, multisectoral, global model that generates unique market equilibria across goods, services and factors of production, in which economic agents (farms, firms, households, governments) are fully described with structural equations, and have clear optimization programs and constraints. Such a model has the virtue of being completely consistent: there is no leakage, "free lunch," or elements outside the system. Agrifood systems would be properly defined within a multisectoral context, and the framework itself would allow for the investigation of different definitions when drawing borders across systems. In addition, while providing a framework within which countries interact while facing individual constraints—through their balance of payments and domestic endowments, including labor and land—we can still operate with imperfectly integrated markets, leading to various price dynamics in different countries.

The MIRAGRODEP model has been developed to capture various social and environmental outcomes so as to track the various trade-offs at stake, going beyond the traditional CGE model. It can also be paired with various models upstream, or downstream, that could provide key inputs (e.g., crop technology, nutrient balance for the soil or human consumption) or downscale or extend the results generated by the CGE model. The MIRAGRODEP framework has been used to study social and

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[2] Lucas (1976).

environmental implications of various policies and economic changes. For instance, see Laborde and Martin (2018) for the link between economic growth and rural poverty; Laborde (2011) and Laborde and Valin (2012) for an assessment of biofuel policies; and Laborde et al. (2020a) for GHG accounting of farm policies. The MIRAGRODEP model has also contributed to policy and political processes in various countries.

The modeling initiative proposed in this chapter brings the modeling innovations of the last decade into an integrated framework and builds on existing partnerships to extend its scope. It builds and extends the existing development for the Ceres2030 project,[3] looking at several aspects of SDG2 (hunger, environmental sustainability, poverty, and smallholders' income). In particular, a strong comparative advantage of the MIRAGRODEP CGE is its integration with household data and the use of detailed household information. We will discuss this issue at greater length in the next section, but it is very important to be able to capture household heterogeneity, in terms beyond income-level structure, production opportunities, food consumption patterns and potential locations, in order to properly assess the socio-economic and health implications of agrifood system transformation.

The model is based on a set of macro and sectoral accounts updated for 2017 (GTAP database of social accounting matrix), and where national data can be modified easily. In addition, it has been made compatible with the last release of the latest FAO food balance sheets and the *State of Food Security and Nutrition in the World 2020*s prevalence of undernourishment and cost of healthy diets numbers. It also benefits from a large dataset on farm and trade policies, in particular, from the Ag-Incentives project.[4] It is also compatible with various emissions (farm and non-farm databases) and satellite accounts. The household dataset is largely based on the POVANA database, not only comprising LSMS surveys, but also reconciled with other macroeconomic accounts and data sources. In terms of commodity and sector coverage, the GTAP database covers 67 sectors, of which 21 are food or agri-food products. The MIRAGRODEP dataset has been extended to cover additional products. In particular, some key staples like cassava and key inputs like fertilizers have been disaggregated.

This chapter is organized as follows: after the introduction, Sect. 2 presents the main objectives of the agrifood systems summit that will be targeted through the modeling and how the different objectives will be used to develop the scenarios to be modeled. Section 3 presents an overview of the model, its attributes and limitations, and describes the baseline scenario. Section 4 features the results of all the scenarios modeled and, finally, a section of conclusions is presented.

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[3] Laborde et al. (2020b).

[4] http://ag-incentives.org/

2 Addressing the Objectives of the Agri-Food Systems

An agrifood systems approach is centered around people by aiming to achieve food and nutrition security, improve diets and reduce poverty for all. People-centered objectives are embedded in the broad performance of the system with regards to social, economic and environmental sustainability. Goals and targets in the 2030 Agenda that relate to the food system are owned by all stakeholders involved in its management and operations. They are owned by the global development community, which aims to promote sustainable development now and in the future.

The success of the food system approach depends on the actions and conduct of a large number of actors that are engaging with it. Among them, governments and the development community play a key role in coordinating the food system so that the objectives are achieved in a sustainable way.

The four core objectives are:

*Objective 1: End hunger and malnutrition***.** The principal objective of sustainable agrifood systems is to provide food and nutrition for people. While the last few decades have seen progress on this front, it is no longer sufficient to focus only on increased production, calorie consumption and low food prices. Increasing production at any cost has damaged the Earth. Calorie consumption alone does not constitute a healthy diet. Lower food prices can hurt producers and discourage them from investing in technologies to protect the ecosystem.

Objective 2: Achieve high-quality diets for all. Failure to deliver high-quality diets for everyone is holding back SDG progress. Yet, there is no mention of it in any of the SDG targets or indicators. Just ensuring stable access to food is not sufficient. Rather, we must understand the interactions among diets, health and agrifood systems to make progress toward SDG Goals and targets in agriculture, inequality, poverty and sustainable production and consumption.

Objective 3: Achieve 1 and 2 while enabling the sustainable use of biodiversity and ecosystems. Safeguarding land, oceans, freshwater and climate is a precondition for social justice and robust economic development for current and future generations (Arrow et al. 2014). Agrifood systems' operations have to be compatible with ecosystem services. Restricting the use of natural resources and the effects of climate change can limit agricultural productivity. Sustainable agrifood systems need to find ways to address this trade-off. Agroecological farming practices are one way to move in this direction.

Objective 4: Eliminate poverty to the level necessary to achieve 1, 2, and 3. Poverty and hunger are interlinked, and reduction of extreme poverty has a direct impact on the elimination of hunger and all forms of malnutrition. In this sense, under this objective, we want to identify the level of extreme poverty reduction that is needed to achieve all three of the above objectives.

However, all four of these objectives should be seen as different pieces of an overarching objective: Achieve high-quality diets for all, while enabling the sustainable use of biodiversity and ecosystems.

It is quite useful to see that objectives 1–4, as previously defined, are composed of caloric consumption, healthy diets, environmental sustainability and inclusiveness. As shown in Fig. 1 and Table 1, these elements are bricks. They can theoretically be achieved independently. Combined together, and in an incremental way, they form our four objectives. Therefore, we use the model to illustrate each of these bricks and the impacts of achieving this goal on a number of indicators.

However, the implementation of the model requires defining scenarios to achieve these goals. Instruments and interventions are the actual means of achieving our set of objectives. They are policy actions by nature. We propose to use a set of definitions developed by Laborde et al. (2020b): (a) an *Intervention* is a public action aimed at altering the existing state of the world. The action is intended to solve a problem (such as a market failure). It targets a specific population. It is associated with a set of expenditures paid by one (or several) economic agent(s). It has a given

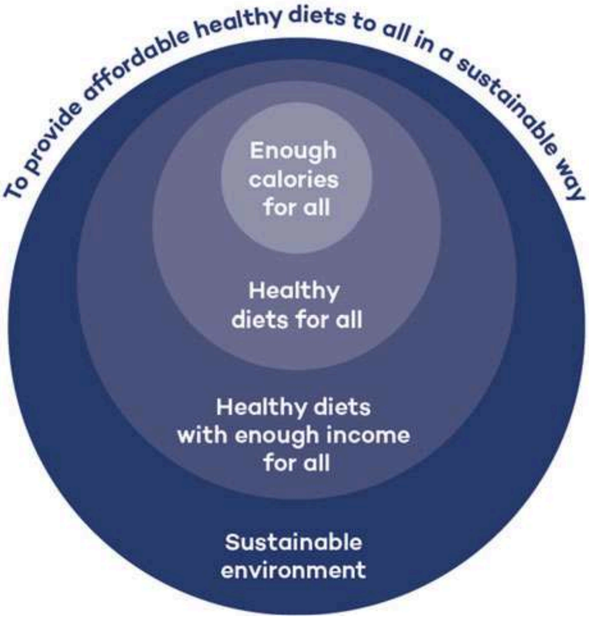

Fig. 1 An integrated vision of the objectives of agrifood systems. (Source: Authors' own elaboration)

Table 1 Breaking down the Objectives

<table>
<tr><th>A</th><th>Caloric consumption</th><th>B</th><th>Healthy diets</th><th>C</th><th>Environmental sustainability</th><th>D</th><th>Inclusiveness</th></tr>
<tr><td colspan="2">Objective 1: Ending hunger</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="4">Objective 2: Ending malnutrition</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="6">Objective 3: Sustainable food system</td><td></td><td></td></tr>
<tr><td colspan="8">Objective 4. End poverty & sustainable food system</td></tr>
</table>

Source: Authors' own elaboration

set of direct effects; (b) an *Instrument* is the projection (i.e., translation) of the intervention in the model space.

The combination of various policy instruments is necessary to achieve the various objectives, while balancing trade-offs. This could be seen as an illustration of the famous Tinbergen rule (1952).[5] Scenarios are a combination of objectives (the end) and instruments (the means). This is an important issue, since a structural model could achieve the same goal through different pathways: We can eliminate hunger by implementing a major redistribution of income, massively subsidizing production, or investing massively in agricultural R&D. These different pathways will generate different trade-offs. The model allows us to tailor such a story in an *ad hoc* way (we define the mix of instruments to be used qualitatively and quantitatively). Or the model can be used to define an optimal mix of instruments, taking into account one or several constraints (fiscal optimization, social preferences[6]).

In the current context, and for the initial use of the model, we propose not crafting complex policy mixes, whether exogenous or endogenous, that will reshape incentives within agrifood systems. We will use a simple set of policy instruments to illustrate the core trade-offs. In particular, we will achieve: (a) brick A: ending hunger, with a producer subsidy on staple products. The value is endogenous, determined for each country to reduce its prevalence of undernourishment (PoU) below three percent; (b) brick B: sustainable diets, with a differentiated consumption subsidy by food groups to target a recommended diet pattern by country (relative contribution of various food groups in terms of calorie intake). The total value of subsidies per country will be constrained to zero, meaning that the final vector of subsidies will include positive and negative values (e.g., tax); and (c) brick C: when introducing environmental sustainability, we will implement a carbon tax instrument that could be extrapolated to other sustainability dimensions, like biodiversity and water use, to internalize externalities and target pre-defined constraints (e.g., first of all, a carbon budget for agriculture, based on the Paris NDC plans).

From A to C, the goal is to modify relative prices so as to shift production and consumption patterns. Brick D will introduce another set of instruments, including a progressive tax system (e.g., negative income tax), allowing for household redistribution. This will significantly change the required amount of distortions needed to achieve [A] and [B], since we will directly help poor consumers to expand their food consumption in both quality and quantity without having to alter the market prices. These choices of instruments are obviously quite conservative and far from optimal, but they do not require “new technologies” or strong behavioral shifts in preferences. They are quantifiable outcomes. In addition, we do not change trade policies; trade flows will adjust. In this regard, the different instruments that we propose in order to achieve bricks A and B are not neutral—since a consumption subsidy is “neutral” in

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[5] See Tinbergen (1952): https://repub.eur.nl/pub/15884/. Also see Preston (1974) for generalization: https://www.jstor.org/stable/2296399?seq=1

[6] See Laborde et al. (2020a) for discussion.

terms of trade implications, but a production subsidy is not, except if we assume a global homogenous subsidy.

As an illustration, let us consider Country X. Country X has a prevalence of undernourishment above 25% of the population, which is high. It also enjoys a relatively diversified food consumption pattern, but has high levels of greenhouse gas emissions due to a large livestock sector. Country X can pursue a number of pathways to achieve SDGs 1, 2, 3 and 4 (as set out in Fig. 2). On a traditional pathway, Country X would likely have adopted a production-focused approach, aimed at reducing its PoU through increasing the supply of staple foods. This approach encourages a sectoral focus, with an emphasis on technical fixes to increase production. The interventions would be under the mandate of the agriculture ministry or sector-specific agency.

Using a systems-thinking approach, however, Country X would aim to achieve several goals simultaneously by developing a policy package that uses multiple systems to reduce the PoU and greenhouse gas emissions at the same time. This would necessitate the engagement of a number of ministries, including energy, environment and agriculture, and a coordinated policy response, as illustrated in Fig. 2.

In the Appendix, we provide an analytical and formal representation of our method for integrating the various Objectives in our modeling framework.

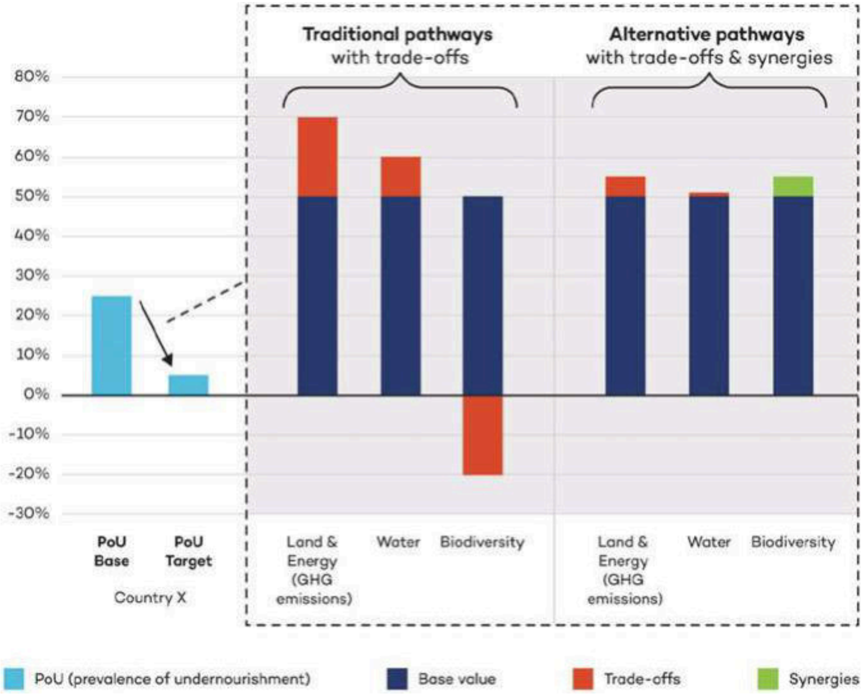

Fig. 2 Illustrating trade-offs: a simple PoU case. (Source: Authors' own elaboration)

3 The Model

3.1 Model Overview

The model used in this paper is the MIRAGRODEP model. This model is an extension of the widely used MIRAGE model of the global economy.[7] The model was developed and improved with the support of the African Growth and Development Policy Modeling Consortium (AGRODEP). It is a multi-region, multi-sector, dynamically recursive CGE model. The model allows for a detailed and consistent representation of the economic and trade relations between countries.[8]

The model assumes perfect competition in each market. In each country, a representative consumer maximizes a CES-LES (Constant Elasticity of Substitution-Linear Expenditure System) utility function subject to an endogenous budget constraint to generate the allocation of expenditures across goods. This functional form replaces the Cobb-Douglas structure of the Stone-Geary function (that is, LES) with a CES structure that retains the ability of the LES system to incorporate different income elasticities of demand, with those for food typically being lower than those for manufactured goods and services. The demand system is calibrated around the income and price elasticities estimated by Muhammad et al. (2017).

Once total consumption of each good has been determined, the origin of the goods consumed is determined by another CES nested structure, following the Armington assumption of imperfect substitutability between imported and domestic products. On the production side, demands for intermediate goods are determined through a Leontief production function that specifies intermediate input demands in fixed proportions to output. Total value added is determined through a CES function of unskilled labor and a composite factor of skilled labor and capital. This specification assumes a lower degree of substitutability between the last two production factors.

In agriculture and mining, production also depends on land and natural resources. Labor markets are differentiated by gender, assuming an imperfect substitution between male and female labor for each category of skills. Unskilled labor is imperfectly mobile between agricultural and non-agricultural sectors, according to a constant elasticity of transformation function. Land is also imperfectly mobile among agricultural sectors. Capital in a given region, whatever its origin (domestic or foreign), is assumed to be obtained by assembling intermediate inputs according to a specific combination. The capital good is the same regardless of the sector. In this version, we assume that all sectors operate under perfect competition, there are no fixed costs, and price equals marginal cost.

The model dynamic is recursive in nature: capital in year t + 1 is based on the capital of year t, increased by the previous year's investment, and corrected for

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[7] Decreux and Valin (2007).

[8] Laborde et al. (2013).

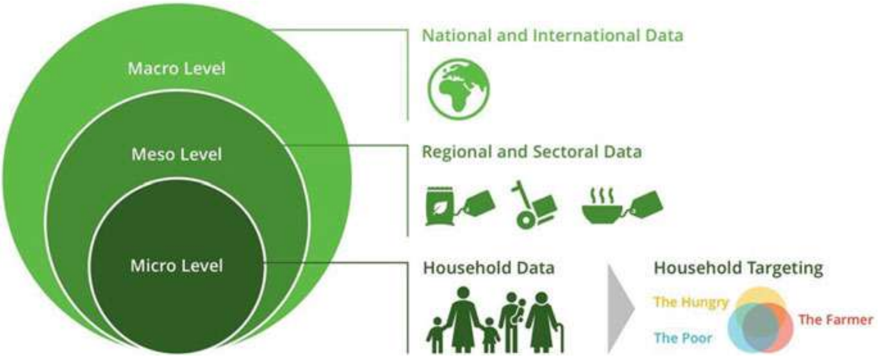

Fig. 3 An integrated modeling framework: the MIRAGRODEP CGE. (Source: Authors' own elaborations)

depreciation. Total factor productivity at the sectoral level and labor supply follow the exogenous trend. The macroeconomic assumptions used for the analysis were designed to be relatively "neutral" to avoid situations in which macroeconomic adjustments such as real exchange rate changes outweigh the impacts of interest, and to allow us to focus on the impacts of agricultural support policies on emissions. These assumptions were: (a) the investment dynamics (savings driven) and the real exchange rates evolve to keep the current account constant relative to national GDP; (b) global savings balance is achieved through a proportional change in the demand of foreign capital by net capital importers; (c) aggregate real public expenditures are kept constant, and a consumption tax is adjusted to keep the government budget balance fixed as a share of GDP and (d) total employment in the economy is constant.

A comprehensive modeling is depicted in stylized ways in Fig. 3. The figure summarizes the scope of the model, showing the added value of having these different layers in an integrated framework.

3.2 How Do We Couple This Model with Other Models?

The core contribution of the MIRAGRODEP CGE model is to provide an integrated framework in which economic and biophysical constraints can be implemented and markets will clear in a consistent way. As a matter of fact, markets are the nexus where final decisions on production and consumption are determined. In addition, explicitly representing market equilibria for goods and factors of production is essential in order to capture both the real income impacts and their social implications.

However, the MIRAGRODEP CGE does not aim to answer all relevant questions about agrifood systems. Nor is it meant to be used on its own. It is designed to be integrated with other modeling platforms, either as an element of a knowledge value chain (using inputs from other models or providing inputs to other models) or in a coupled way (the integrated approach). As result, model integration or connectivity should be done with parsimony and under strict scientific principles regarding the compatibility of the approaches, including theoretical underpinnings, the definition of model solutions and data consistency.

We have identified IIASA with the GLOBIOM modeling team as our main research partner. They have global modeling capacity and a global model with a detailed land use component. As such, they provide a strong complementarity to the MIRAGRODEP CGE framework and could downscale MIRAGRODEP results and develop a targeted biodiversity indicator. They could also provide a more detailed description of technology and technology changes, with their GHG implications, in the farm sector. They also have deep experience in addressing climate change issues. It is critical when combining modeling frameworks into a unified analytical platform to guarantee data consistency at the initial stage.

We are exploring other downstream linkages in the fields of health, nutrition, gender and inequalities. While our modeling framework “stops” at the household level, some socio-economic drivers such as food availability parameters at that level could break down the analysis and investigate intra-household challenges.

Regarding upstream linkages, most of the ongoing investigations are focused on biophysical models that could inform the transformation of the production function and the input/output relations, including for non-priced inputs. Similarly, some ecosystem valuation approaches could expand our set of indicators and the illustration of trade-offs. But the investigations are at a very early stage.

3.3 Importance of Including Household-Level Modeling

As discussed, a significant amount of the changes in agrifood systems will have very heterogeneous impacts across households, in terms of income opportunities and consumption space. Therefore, having a proper representation of the household heterogeneity is essential.

The MIRAGRODEP CGE framework proposes two approaches to including household-level analysis (for details, see Laborde et al. 2021b). The choice of the precise method depends on the scale of the exercise (global assessment, or regional- or country-level requirements), data availability and the need to integrate feedback effects. Both approaches rely on our harmonized treatment of existing household surveys, which describe both the expenditures and the revenue account of each household, including the farm production module, when available (POVANA database). The household data is also used to reproduce non-economic indicators, such as the PoU by reconciling household expenditure pattern, food consumption and its caloric equivalence, as well as household energy requirements.

The first approach, which could be implemented in most low- and middle-income countries, is a top-down approach. It is where country-specific macroeconomic variables from the MIRAGRODEP CGE are implemented in our set of harmonized household surveys, which include prices of goods and services, factors of production, remittances and tax instruments, among other things. This approach allows for a systematic assessment of how a systemic change impacts households in terms of poverty (real income) or food consumption. The household-level modeling could include first order impacts alone or second order impacts as well, with production and demand function calibrated for each household, but consistent with the aggregated CGE response in the initial condition. Choosing this approach allows for the use of the GIS tagging available in some surveys to illustrate within-country heterogeneity.

The second approach incorporates a large set of households directly into the CGE model in a fully bottom-up way. Usually, using 75–150 household categories captures most of the relevant heterogeneity in terms of consumption pattern and income generation. This approach is more intensive in terms of computational power and requires additional data reconciliation between macroeconomic accounts and household-level data. But this approach may be needed when distributional issues have strong feedback effects and alter the sectoral or macroeconomic equilibrium. Indeed, even with the calibration used in the first approach, if prices and income changes are significant, the aggregated response of the CGE and sum of individual responses in the household surveys start to diverge, mainly because the economic weights of the various household groups change compared with the initial conditions.

Depending on the use of the modeling framework for the Agrifood Systems Summit (global or regional assessment, or country-level profiles), we propose using the two approaches alternatively. The existing coverage of countries for which we have detailed household data is available online[9] and is frequently updated. For countries that are not covered, we generate representative household distribution at the continental level based on available countries' data and reshape the distribution weights to target demographic and income macroeconomic indicators (e.g., Poverty and GINI for each country). The existing dataset and country coverage could be expanded easily, since the POVANA database is based on systematic templates and protocols that could be used to add new countries or update data for those already covered.

3.4 What Are We Missing?

While the modeling framework already covers a number of topics, there are still some limits and missing elements that should be acknowledged.

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[9] https://public.tableau.com/profile/laborde6680#!/vizhome/POVANA_Surveys/POVANA

(a) *Competition:* The first element is directly related to how we represent markets. While the choice of imperfectly integrated markets for goods and factors of production is satisfactory, the way we capture imperfect competition remains a major challenge. By default, our model operates in perfect competition. Therefore, the consumer at the end, leading to some optimistic view in terms of inequalities, captures all changes in production costs. The questions of imperfect competition and market power within agrifood systems are critical and could have significant implications for agrifood system transformation's social impacts. While there are modeling options to address this issue, the lack of data, especially on a global basis, remains a key challenge. In addition, considering how various consumers/producers at the household level may face differentiated mark-ups is not a trivial issue. For these reasons, we propose to flag this issue as one to be discussed as a major research question. In the meantime, existing results should be interpreted with caution. Most importantly, since our competition assumption changes the way that markets operate, this issue should not be fixed "outside" the model, with a complementary analysis upstream or downstream; rather, it should be tackled within the model.

(b) *Biophysical Balances and Soil Health:* While the issue of soil health constitutes a key topic for the sustainability of agrifood systems, systematic datasets and actual causal linkages between production systems and evolution of soil health remain scarce. In particular, we should aim to track soil health and nutrient balance, and be able to capture feedback effects through productivity channels within the model, since they will change relative to productivity and prices. However, the complex mechanisms at stake may not need to be implemented in the MIRAGRODEP CGE and could be developed externally. The CGE model will just adjust the input-output coefficient matrix describing farm technologies. It could include dynamic equations about the soil quality productivity as a new form of capital in the farm sectors. At this stage, a potential limitation is the reliance on only one aggregated item for mineral fertilizers. To be sure, the price and supply dynamics of various fertilizers are more complex. For future development, it may be required to break down this sector into sub-products. Similarly, the substitution between manure and mineral fertilizer is not currently integrated, while manure on cultivated soil is still monitored for emissions purposes. This could be addressed, assuming the availability of technical expertise.

(c) *Household Data in Developed Countries:* Due to the history of the modeling framework and the acuteness of food insecurity in developing economies, our household database does not include developed countries. Since the social and health implications in the developed economies should not be neglected, we should aim at addressing this data gap with the right set of partners.

3.5 Key Indicators Generated

The MIRAGRODEP CGE framework, with its satellite account, could generate a huge number of indicators to illustrate the evolution of agrifood systems and some of their trade-offs. Figure 4 provides an overview of such indicators. Some are based on

Fig. 4 Quantifying agrifood systems. (Source: Authors' own elaboration)

the detailed household impacts (e.g., poverty, hunger, overweight), others on macroeconomic accounts (e.g., public finance). Still others are linked to sectoral productions (e.g., water use, land, energy).

Some indicators are generated by default with MIRAGRODEP, using a set of fixed coefficients per unit of outputs or inputs (e.g., water requirement per ton of wheat per country), but are aimed at being fine-tuned by linking the MIRAGRODEP outputs (directly or indirectly) to other models. In particular, the biodiversity indicator and spatially explicit land use changes will be generated by IIASA through the GLOBIOM modeling framework. Similarly, we investigate some additional health- and nutrition-related indicators by linking food consumption and income distribution outcomes to specific models, like the LIST models suit.

An important issue not directly linked to the objectives and the core trade-offs is assessment of the risk of the system, in particular, the "systemic" risk when considering the complex interactions and the various profiles of variance/covariance at stake. As a starting point, we propose to use historical events, such as a historical catalog of productivity (weather-related or zoonotic disease), prices (world prices, exchange rate), consumer choices (the "mad cow disease" type of consumer reactions) and other disruptors to see how the system in its initial or modified situation reacts, and how to assess the vulnerability of various populations or components of the system. The Appendix provides an illustrative example.

4 Modeling Results

With this previously detailed modeling framework, six individual interventions are modeled in terms of their impact on agrifood systems, prevalence of undernutrition and ecological effects in terms of GHG emissions, land and energy use, and the use of chemical inputs. Due to synergies and complementarities among these scenarios, the authors also assess them as a package. The sensitivity to the results is also assessed under different governance principles, such as land use policies.[10] The scenarios are listed in Table 2 and organized around three main pillars, as shown in Fig. 5: achievement of a more efficient and more inclusive system, allowing consumers and producers to make better choices. The results of the different scenarios are based on the baseline consistent with the State of Food Security and Nutrition in the World 2020, which, by 2019, reported 690 million undernourished people and the fact that healthy diets were unaffordable for almost three billion people in the world.

A first key result is the confirmation that ending chronic hunger at a 5% level is reachable by 2030 with the right balance of interventions. While no intervention alone, at a realistic scale, could solve the problem, we see in Fig. 6 that key structural interventions to increase the efficiency of agrifood systems, through increased farm productivity and a reduction of food loss and waste, will reduce the number of people in chronic hunger by 314 million in 2030. Beyond hunger, 568 million people will be able to afford healthy diets, as shown in Fig. 7. To target the remaining population, safety nets and well-targeted programs, such as school feeding interventions, will be required. When adding such safety nets into the model by designing them endogenously so as to leave no one behind, it is possible to cover the 2.4 billion remaining people without economic access to healthy diets.

Achieving the end of widespread hunger requires mobilization of significant resources, but the cost is manageable, and represents 8% of the size of food markets.[11] Figure 8 provides the decomposition of this total cost by action (Panel a) and the distribution by group of countries (Panel b). In regard to the actions referred to as "better choices" in Table 2, i.e., consumer incentives and the repurposing of farm subsidies, they do not contribute to the total costs because they have been designed to be income neutral for the government, as well as for the producers (farm subsidies) or consumers (food tax/subsidies) in each country. The cost structure is dominated (45%) by the combined large structural investment in physical, human and knowledge capital of the innovation package that impacts through value chains, national economies and social safety nets (36% of total cost). Of course, these two main items are different in nature, since the latter involves recurrent spending every year and will have to be managed, and financed, by the governments alone.

A critical finding of the analysis is the role of other interventions in minimizing the cost of the safety nets. Indeed, to cover the income gap of the three billion people who – without action - will not be able to afford healthy diets in 2030, countries will have to redistribute 1.4 trillion dollars (constant 2017) annually. By investing in the

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[10] Other aspects of the global agrifood systems, such as trade policies, are also analyzed to see how they interact with the main interventions considered.

[11] 2030 spending and food market values, as estimated by the model for guaranteeing full consistency.

Table 2 Scenario definitions

Action domain	Scenario label	Description
More justice	#1 Social Safety Net: Healthy Diets for Everyone	Provide food stamps (income transfer that should be spent on food products) to eliminate the "poverty gap" between the per capita income of each household and the affordability of healthy diets cost line. The cost is initial calibrated on SOFI 2019 and updated based on model dynamics
More justice	#2 School Feeding Program	All children between 6 and 11 years old have access to school feeding programs 200 days a year. Daily per capita ration includes 320 g of fruits, 102 g of grains, 51 g of animal proteins (meat, fish, eggs), 480 g of milk, and 100 g of vegetables
Better choices	#3 Farm Subsidy Repurposing	All farm subsidies (outputs, inputs, others) are redistributed in the form a subsidy to farmer revenue. The rate of support is computed endogenous by the model to maintain farm subsidy budget constant, but a sectoral bias is introduced. Nutritious and low-emissions products are subsidized at twice the average rate, while products with low nutrition value and high emissions are subsidized at half the average rate
Better choices	#4 Consumers' Incentive Reform	Taxation of red meat products in high- and middle-income countries. The level of tax is computed by the model to obtain a reduction of consumption of 15% in high- and upper middle income countries (HIC and UMIC in Europe), and 7.5% in UMIC (exc. Africa). The group of countries have been constructed by computing an index of "excess" consumption by comparing average daily intake with a sustainable and healthy diet reference (i.e. Flexitarian diet in this case, but alternative diets give the same ranking of countries)
More efficiency	#5 Innovation, Technology and Knowledge for Farmers	This package of interventions is aimed at increasing farm level productivity, while reducing environmental footprints. It has three components
		Increased/or Improved **Irrigation** systems. [X]% of each country cropland benefits from new investments by 2030. For regions with high rate of irrigated land (all Asian regions), we consider only an upgrade of existing materials, leading to no change in yield but a reduction in water inefficiency. For other regions, we consider an increase of water use (for irrigation, but with an improved average efficiency) but also a yield increase of [Z]%. With X = 10% in HIC, 20% in UMIC, 30% in LMIC and 40% in LIC; Z = 100% for all regions except Africa where Z = 200%. Initial cost of \$1000 per ha

(continued)

Table 2 (continued)

Action domain	Scenario label	Description
		Increased **livestock** genetics and better practices for higher productivity [Z%] and lower emissions per unit of output. [X]% of the herd of each country is improved by 2030 With X = 10% in HIC, 20% in UMIC, 30% in LMIC and 40% in LIC; Z = 10% for HIC, 25% for MIC and 50% for LIC Initial average cost of $400 per standard Livestock Unit
		Extension services and farmer **training** to increase all farm productivity (total factor productivity, TFP). [X]% of farmers in each country are covered. TFP is increased by [Z]%. In addition, carbon sequestration in soil is increased X = 10% in HIC, 20% in UMIC, 30% in LMIC and 40% in LIC; Z = 10% for HIC, 25% for MIC and 50% for LIC 1 extension agent per 100 farmers in average. Cost is indexed on labor cost across countries and calibrated at $10,000 for UMIC
More efficiency	#6 Reducing Food Waste and Loss	Reduction of 25% in all countries of food waste and food losses, including for left-on-the field. Recurrent cost per unit of food restored
Combined actions	All except Safety Nets	Include actions 2–6. Since the Safety Net is computed to provide enough income to everyone to be able to afford healthy diets, it is important to consolidate all the other actions before this one
Combined actions	All including Safety Nets	All actions, 1–6. While this package will take care of all vulnerable people, showing the consolidated impact on environmental and economic indicators is important (trade-off lens)
Combined actions	Everything with Land Use Regulation	In this consolidated scenario, we do not allow for land use change (fixed amount of agricultural land) by considering a stronger land governance

Source: Authors' own elaboration

various programs, the value of the required safety nets drops by about two thirds (428 billion dollars globally) in 2030. Using safety nets to make sure that everyone can afford healthy diets is required, but, if used alone, they will be far too expensive.

The second panel in Fig. 9 shows the distribution of the spending by region, i.e., where the money needs to be spent and/or invested. Since the needs are unevenly distributed globally, a significant effort in terms of global coordination, and even solidarity, will be required, especially to support the transformation of the agrifood systems of low-income countries.

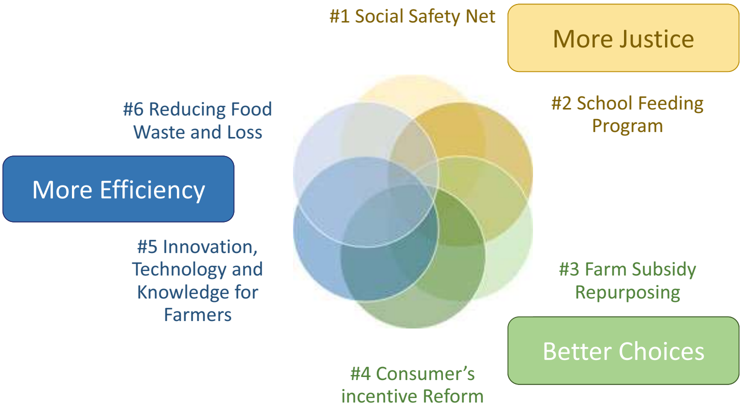


Fig. 5 Policy Action Scenarios. (Source: Authors' own elaboration)

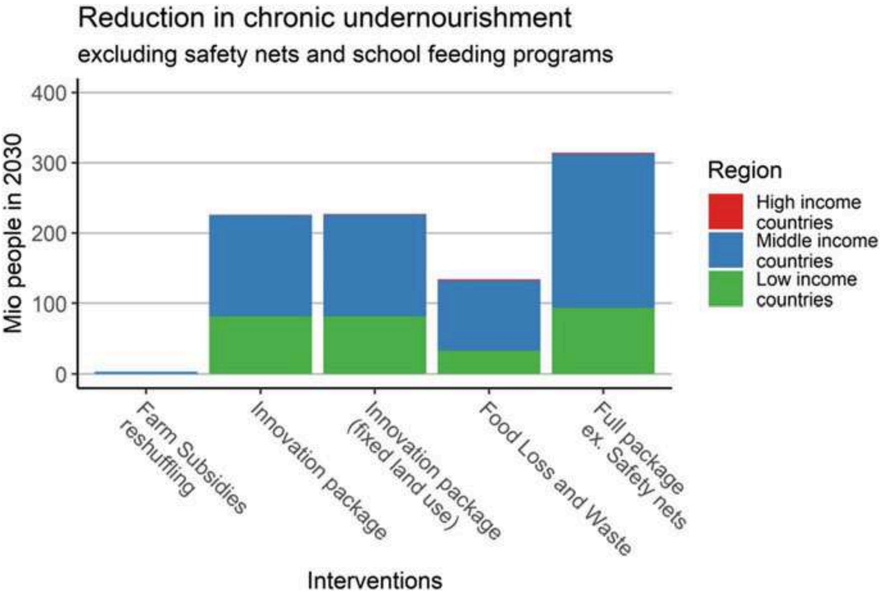


Fig. 6 Number of people (mio) removed from a chronic undernourishment situation in 2030. (Source: Authors' own elaboration)

As previously shown, no single intervention could achieve the end of malnourishment, and synergies are needed to tackle the various source causes of the problem, but also to minimize the total cost of the package. However, their complementarity goes beyond their impacts on household food security and their cost-effectiveness, and therefore we also need to combine them to address heterogeneous environmental trade-offs.

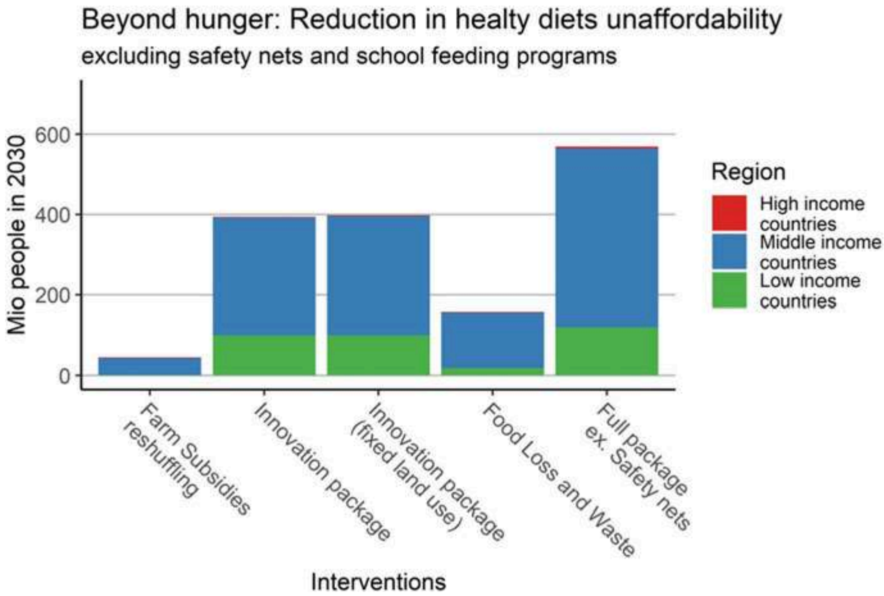


Fig. 7 Number of previously deprived people (mio) who will gain access to healthy diets by 2030. (Source: Authors' own elaboration)

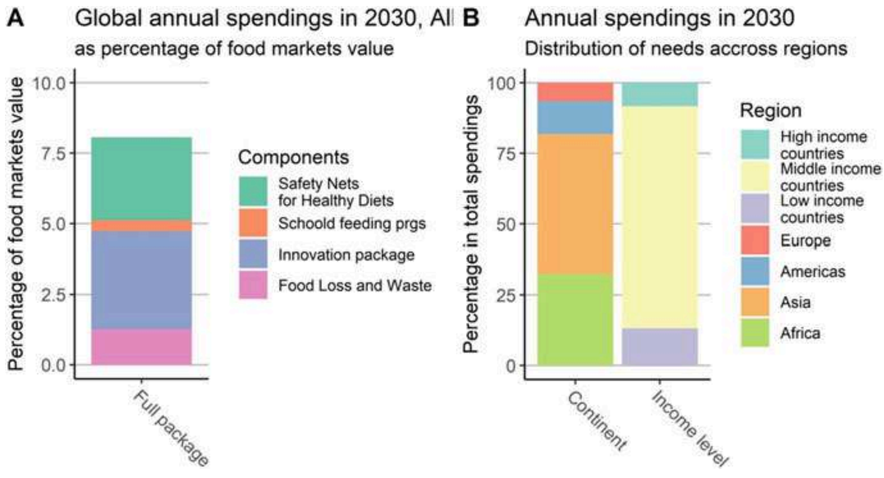


Fig. 8 The cost of actions: magnitude and distribution. (Source: Authors' own elaboration)

Finally, it is important to mention that the actions modeled will generate trade-offs in regard to GHG emissions (emissions from agricultural production, and net emissions from AFOLU), agricultural land, an increase in the use of chemical inputs (index of chemical inputs per hectare), biodiversity (i.e., reduction of forest habitat

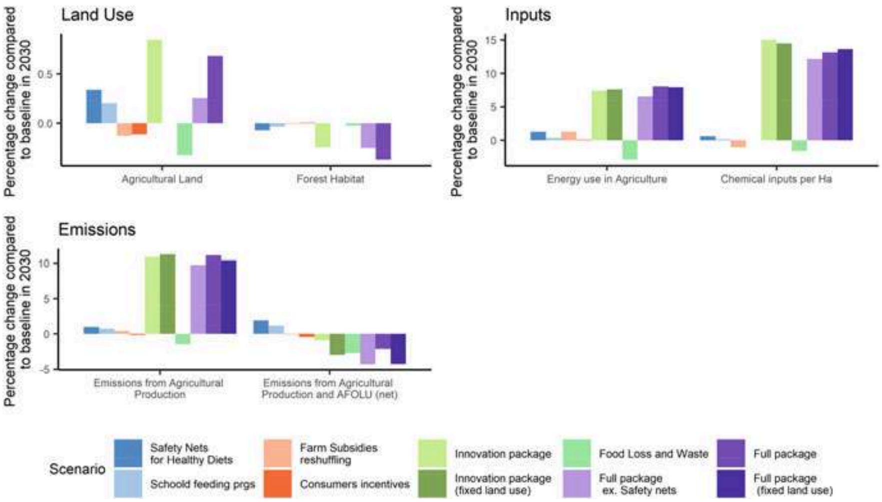


Fig. 9 Impacts of actions on environmental indicators. (Source: Authors' own elaboration)

and agricultural land) and energy consumption, as shown in Fig. 9. As shown, the levels of trade-offs across all interventions are relatively small, the highest being for the innovation and full package, but the effects are negative (i.e., an improvement) for the case of food loss and waste across all trade-offs. However, when looking at net agricultural emissions and AFOLU, the effect is negative, as in the case of forest land. This highlights the need for policies that stimulate investments in innovations for carbon farming (growing carbon in soil and trees as a tradable commodity) and related payment schemes for ecosystem services.

5 Conclusions

While identifying the conceptual linkages at play within the agrifood systems and the different trade-offs involved is essential, providing a quantification of these mechanisms is required to illustrate concepts, support informed decisions and trigger proper actions. Considering these interactions is a necessity during the whole process: at the diagnostic stage (i.e., quantifying trade-offs), on the way to achieving core SDG targets (i.e., the roadmap to 2030) and, finally, when designing policy responses that may also lead to various indirect effects.

This chapter tries to develop a proper quantification approach based on a modeling platform that combines state-of-the-art and up-to-date databases covering all the metrics of interest (hunger, poverty, nutrition, and environmental indicators) and dynamic simulation models that explore future pathways and optimal policy responses.

Various modeling approaches could be considered, however, the task to be addressed leads to very specific requirements. Tackling trade-offs within the agrifood system requires a holistic strategy, considering not only the supply side and the primary production sectors, but also the full set of value chains operating and interacting within the food system. It also needs to capture how the food system interacts within the broader economy within, and across, countries. Indeed, various market failures leading to inefficient and unsustainable agrifood systems take place in the initial stages of production.

Beyond these macro and meso requirements, the most important challenge is to capture the essence of the SDGs and the livelihood of people, in particular, the most vulnerable parts of the population. In this context, the modeling platform used includes explicit representation of household heterogeneity. Households differ in terms of income sources, production and consumption patterns. The conditions they face regarding food, labor and input markets are various, even within a country, and determine their choices regarding the food that they produce, buy and eat. Representing their features explicitly is a necessity for providing a realistic picture of the situation and a policy package that will be inclusive for all.

The quantitative framework used builds on an economic state-of-the-art dynamic global Computable General Equilibrium (CGE) model, MIRAGRODEP. The model includes many household groups and is combined with land use, farm and livestock components to approximate essential biophysical trade-offs. The model is able to capture both macroeconomic linkages (within and between countries), multisectoral interactions (agrifood systems are not limited to agriculture activities), and interaction for different households, including the poor and most vulnerable. Indeed, it will be presumptuous to properly assess specific SDG targets without addressing heterogeneity among households and inequalities.

Six interventions are modeled to study their impact on agrifood systems, undernutrition, and the environment. We also assessed the interventions as a group to consider the impact of synergies and complementarities. The first finding confirmed that ending chronic hunger at a 5% level by 2030 is possible, with key structural interventions to ramp up agrifood systems' efficiency. Through increased farm productivity and a reduction of food loss and waste, the number of chronically hungry people could be cut by 314 million. In addition, 568 million people would be able to afford healthy diets by 2030. Under these interventions, the cost of ending hunger represents 8% of the size of global food markets, a sum that can be mobilized and invested to generate impact through food value chains, national economies, and social safety nets. Furthermore, the use of well-targeted social safety nets could provide an additional 2.4 billion people with access to healthy diets.

The second critical finding was that various interventions could create synergies that not only address different causes of hunger, but also minimize the total cost of interventions. In addition, the levels of trade-offs across all interventions are relatively small, the highest being for the innovation and full package of technological innovation, but the effects are negative (i.e., an improvement) for the case of food loss and waste across all trade-offs. This highlights the need for policies that stimulate investments in innovations for carbon farming (growing carbon in soil and trees as a tradable commodity) and related payment schemes for ecosystem services.

Countries would have to redistribute \$1.4 trillion annually to fill the income gap of the 3 billion people who cannot afford healthy diets. However, by investing in various interventions, countries can drive down the cost of the safety nets by about two thirds, or \$428 billion, globally in 2030. Combined interventions can also address environmental trade-offs that are bound to occur.

Appendix

A Formal Representation of Our Objectives

The defined objective could be interpreted as an objective function in an optimization program. This section provides an illustration of this approach, with a rewriting of the problem in such terms. It also shows where the actual objectives will need to be more properly formulated, especially if we want to illustrate trade-offs correctly. In a second part, we provide graphical illustrations.

Mathematically, an optimization program can be seen as looking for the maximum (maximization) or minimum (minimization) of an objective function, X, subject to a number of constraints, Y, X, etc. Constraints could be written as $y \leq \overline{y}$, meaning that the variable y should not exceed a given upper limit $\overline{y}$, or $z \geq \overline{z}$, meaning that z remains above a given level. When these inequalities are replaced by equalities, we say that these constraints are binding.

In our setting, we can see X as a function defining the PoU. So, the function objective could be the minimization of X, the level of caloric hunger. But asking how to minimize hunger without a number of constraints is a useless question; there are many ways to achieve it: letting the hungry people die, spending trillions of dollars on inefficient measures, and so forth. Therefore, defining the right set of constraints is critical. We will not specify the obvious ones (e.g., a given level of population, the various technological constraints, etc.), but will instead focus on the most relevant one.

An important additional feature of such optimization is that maximizing X subject to $y \leq \overline{y}$ leads to the same results as maximizing/minimizing Y subject to $x \geq \overline{x}$. This is the duality principle, a key instrument in microeconomics analysis. The standard example is the consumer optimal choice: *Maximizing the utility U* provided by the consumption of a bundle of goods given, or subject to an available budget (or income, noted as y), such as $\leq \overline{y}$, generates the same optimal allocation of money across goods as minimizing the budget Y needed to achieve the least level of satisfaction, or utility, $u \geq \overline{u}$. We are going to use such properties in our example.

If we consider Objective 1, eradication of hunger, we can formulate it as the desire to minimize hunger, measured as the PoU, subject to some constraints. Indeed, we know that the PoU is bounded by 0, and, as pointed out above, a large number of pathways could lead to the same outcome. We can actually see two simple programs related to hunger:

Minimizing PoU subject to existing public budget $\overline{B}$ *i.e.,* $B \leq \overline{B}$. This program will identify how to allocate existing budget $\overline{B}$ across various policy instruments in order to achieve the lowest possible level of undernourishment. In this case, the starting point is to define the budget constraint $\overline{B}$. This can be seen as a **repurposing of public expenditures** to achieve better objectives. The symmetric program is to *Minimize public expenditure B* subject to a *PoU* target—for instance, 5%, i.e., $PoU \leq 5\%$. This is the approach actually used in the Ending Hunger project and detailed in Laborde et al. (2017).

In this framework, we can express **the trade-offs**. Assuming that we focus only on GHG emissions, and we do not care about fiscal constraints, **Objective 1** could be represented as ***Minimizing GHG emissions*** **subject to** ***PoU*** $\leq$ **5%**. This is the simplest representation of minimizing trade-offs. It is qualitatively equivalent to ***Minimize PoU*** **subject to** $\boldsymbol{GHG \leq \overline{GHG}}$, where GHG is an acceptable carbon footprint for agrifood systems (for instance, compatible with the 1.5C scenario).

The situation becomes more challenging to represent when we have several elements in our objective. Let's consider **Objective 2** now, and translate it with two indicators, the **PoU** (element A) and the **prevalence of overweight** (PoO, proxy for element B), while we also take GHG emissions into consideration (GHG, a proxy for element C). Conceptually, we want to achieve the lowest level of these three variables. However, this is mathematical nonsense. We can optimize only one variable. So, two approaches are possible:

(a) We define a multi-criteria objective function. This will be a social objective function. We can call it D, as it represents a Damage Function. It is a combination of PoU and PoO, for instance: $(PoU, PoO) = PoU^a PoO^b$. Two important things should be noticed: This is the logic beyond many **composite indices** showing how good, or bad, a multi-dimensional system is, and a and b are actual weights on the various dimensions. There are different ways to obtain these weights, knowing that none are perfect; the key challenge is to properly capture the social preferences regarding these different dimensions. These preferences are not universal, and should be specific to a specific community at a specific period. So, in this approach, we can represent our previous optimization problem as *Minimizing* $D(PoU, PoO)$ *subject to existing public budget* $\overline{B}$*, i.e.,* $B \leq \overline{B}$, or, if we think about environmental trade-off, we can represent it as ***Minimize*** $\boldsymbol{D(PoU, PoO)}$ **subject to** $\boldsymbol{GHG \leq \overline{GHG}}$ or ***Minimize GHG*** **subject to** $\boldsymbol{D(PoU, PoO) \leq \overline{D}}$.

(b) We maintain one objective, but combine different constraints, such as: ***Minimize GHG*** **subject to** $\boldsymbol{U \leq 5\%}$ $\boldsymbol{PoO \leq 10\%}$, if we assume a 5% for PoU and 10% threshold for overweight.

Objective 3 will be achieving all of the elements at once, i.e., having three constraints binding. $\boldsymbol{GHG \leq \overline{GHG}}$, $\boldsymbol{PoU \leq 5\%}$ and $\boldsymbol{PoO \leq 10\%}$. There are no other dimensions for optimization, except the cost of achieving this goal. In this case, we will be in a similar framework as the one used in Ceres2030, which is actually

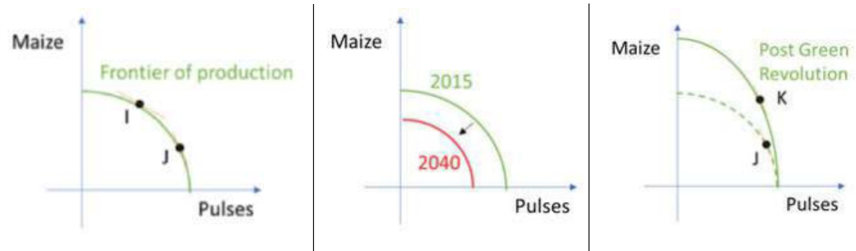
Minimizing B:public expenditures subject to SDG2.1: $PoU \leq 5\%$, SDG2.3: $Income2030 \geq 2 * Income2015$ with Income: the small-scale food producer income, and SDG2.4: $GHG \leq \overline{GHG}$. In the agrifood systems framework, the small-scale food producer constraint is replaced by the malnutrition target. So, it can be *Minimizing B:public expenditures subject to* $GHG \leq \overline{GHG}$, $PoU \leq 5\%$ *and* $PoO \leq 10\%$. Of course, we will also have many more indicators, and therefore constraints (water, etc.).

We will discuss below the exact interpretation of **Objective 4**. But it can be seen as finding the minimal level of poverty compatible with Objective 3. Therefore, it is Maximizing **Poverty subject to $GHG \leq \overline{GHG}$, $PoU \leq 5\%$** and **$PoO \leq 10\%$**.

We will now propose some basic illustrations of the issues at stake. We will limit all illustrations to two-dimensional choices for the sake of easiness of visual representation.

First, let's start with a representation of the **frontier of production possibilities** (FPP) between two goods: Maize and Pulses, as displayed in Fig. A.1. It shows, for a given set of technologies and institutions, as well as endowments (factors of production: land, labor, capital), how much you can produce of each good. For the sake of simplicity, we will consider that this analysis is done globally (so there is no need to represent trade, although that is doable), and that we do not have other economic activities to consider, meaning that, for example, labor in agriculture is constant.

Panel (a) shows the basic story: If you want to produce more of one good, you need to sacrifice a number of units of the second good. This "marginal rate of transformation" (MRS) varies, and is indicated by the slope of the green curve. Producers make choices by equalizing this MRS to the relative prices between the two goods, maize and pulses. This is a first result of an optimization problem and an actual trade-off ("if I produce more of X, I need to produce less of Y"). Policies could change incentives between the two goods by changing relative prices through taxes



Panel (a): Simple case

Panel (b): Illustrating an unsustainable production system

Panel (c): Green Revolution

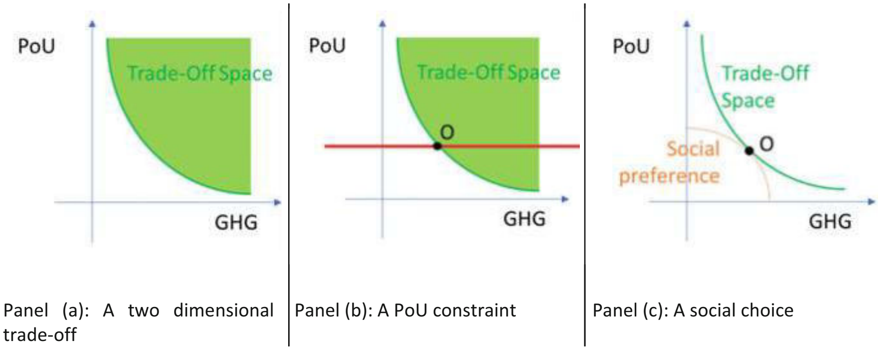
Fig. A.1 Frontier of production possibilities or subsidies. They could move the *free-market* choice of J to I, for instance, by subsidizing maize.

While, in the next paragraph, we are going to show how we move from this frontier of production to our objective and trade-off space, it is quite relevant to see how the FPP illustration could be used to show the impact of non-sustainable practices that can lead to a collapse of the space of potential production over time (Panel b), or how major technological innovation could modify this frontier, including in a biased way. Panel c illustrates a green revolution scenario in which a technological innovation has benefited one crop, maize, although it was not "against" pulses, but the new market equilibrium (from J to K) still results in more maize, and in this case, fewer pulses. So, some public policies could have **unintended consequences**.

Since the entire weight of production is consumed, and for a given distribution of income, we can associate the production of maize and pulses in terms of supply of calories, and therefore PoU outcome. Similarly, the production of maize and corn represented by the FPP is associated with a volume of GHG. So, each point of the FPP, within the space of quantity produced, could be projected in the space of objectives, with our two elements PoU (for Objective 1) and GHG emissions (for trade-off or Objective 3). This is displayed in Fig. A.2, Panel a. While we can end up having more hunger, and more emissions, for any combination of pulse and maize production by wasting resources and making sub-optimal choices, we are mainly interested in the **frontier of optimal trade-off** between undernourishment and GHG emissions. Visually, this frontier is inverted compared to the FPP, mainly because we are displaying "damages," and not positive outcomes.

The various analyses we will conduct will help us to move along this frontier, and potentially displace it, with new technologies or institutions.

Panel b shows the outcome of fixing a maximum level of acceptable PoU, represented by the red line (e.g., 5%). In this case, minimizing the environmental



Panel (a): A two dimensional trade-off

Panel (b): A PoU constraint

Panel (c): A social choice

Fig. A.2 Trade-off space

damage created the PoU objective leads to selection of the point O. We can also generate such a result by specifying our social utility function, or preference, within the space of these two variables. Here, the curve represented is also a "reverse" iso-utility function, since the origin of the graph is the absolute best point for the social planner (0 PoU and 0 GHG, but still an unachievable utopia). The tangency between what is possible (green frontier) and what is desired (orange curve) is the optimal way to achieve our various objectives.

The representation introduced in Panel c has additional implications and mathematical properties, but we will not discuss them in the present document.

Illustrating Risk

In this appendix, based on Laborde et al. (2020a, 2021a), we illustrate how using 40 years of past data on weather could be used to assess the risk exposure of various populations (here, the example of select provinces in the DRC) using our analytical framework (Figs. A.3 and A.4).

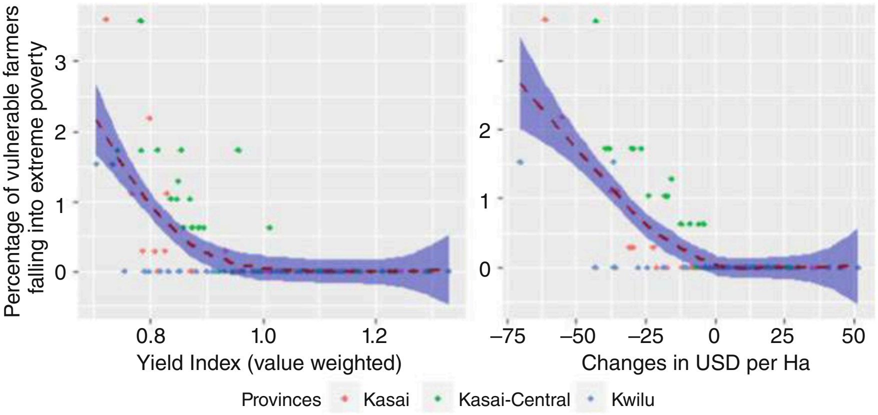


Fig. A.3 Poverty, yield changes and land rents: a 40-year simulation exercise in the DRC

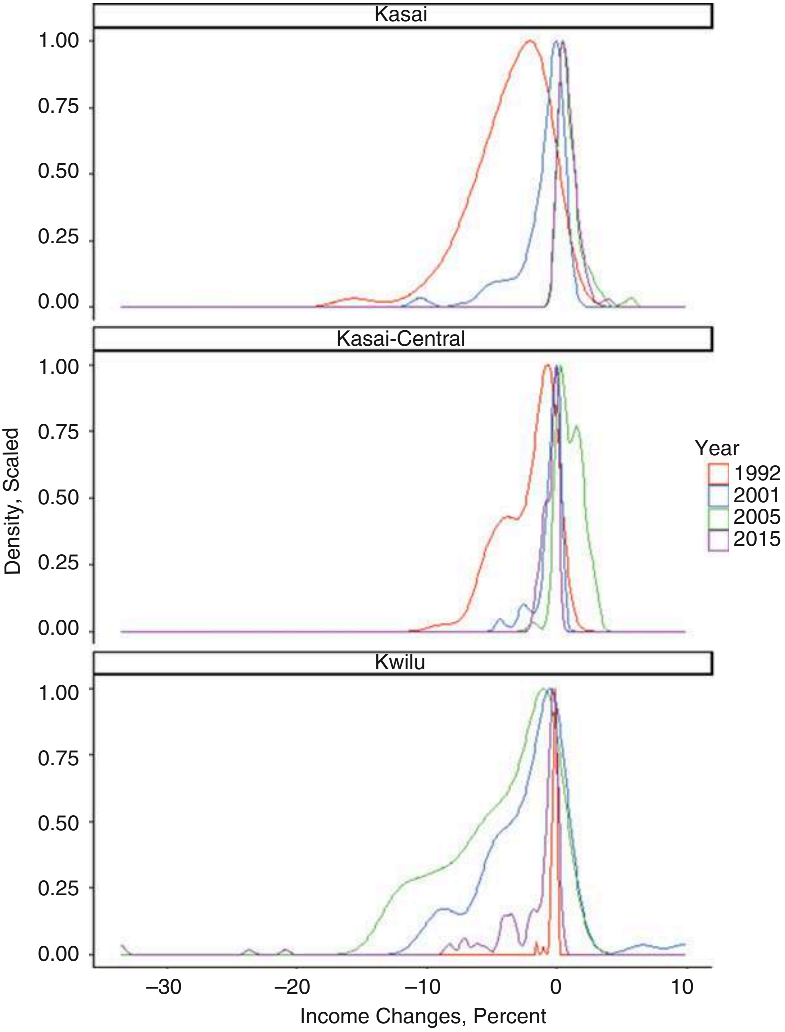


Fig. A.4 Value of production changes as a share of income for vulnerable farmers in select years

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