Chapter 4
Equilibrium Conditions and General Assumptions for a Quantitative Geospatial Economic Model

Iman Haqiqi

In this chapter, we introduce the general conditions for mathematical representation of the model theory. This theory draws heavily on the methods underpinning many computable general equilibrium models, including the widely used GTAP (Global Trade Analysis Project) model initially developed by Hertel (1997), one of the authors of this book. The innovation in SIMPLE-G comes in implementing this theory at the grid-cell level and developing a structure that can readily incorporate the biophysical information typically available at this level. The spatial resolution ranges from 30 arcmin (Liu et al. 2017) to 5 arcmin (Haqiqi et al. 2023). We start with the production side of the model, where grid-cell resolution comes into play, then move to consumer demand and trade. The latter elements are unchanged from those of the (nongridded) SIMPLE model (Baldos and Hertel 2013).

1 Introduction

SIMPLE-G is a computational model that links human and environmental systems. It connects changes in global food demand to the dynamics of local land and water resources used in agricultural production. This model is designed for "what if" (counterfactual) analyses to evaluate the impacts of environmental shocks, global socioeconomic changes, and local and global policies on different components of the system. Counterfactual analysis involves asking "what if" questions to explore the possible outcomes of different events or decisions. It is frequently used to evaluate the potential impacts of changes in government policies, technological advancements, and climate change on food production, consumption, and prices. For instance, what

I. Haqiqi (✉)
Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, West Lafayette, IN, USA
e-mail: ihaqiqi@purdue.edu

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effect would a major grain-producing country choosing to regulate fertilizer applications have on global food prices? Or, what impact would adopting a new agricultural technology have on food production and land use? Alternatively, if a government were to provide subsidies for locally grown fruits and vegetables, how would that affect consumer behavior and diets? These are the kinds of questions being asked in the context of achieving the United Nations Sustainable Development Goals that relate to the food system and associated environmental changes (see Fig. 1.1).

Figure 4.1 illustrates the major components of the SIMPLE-G model using a partial equilibrium modeling framework that characterizes demand for, and supply of, various food commodities and associated production factors. The major elements of this framework are regional food consumption, regional production, global trade, and nutrition.

The model has three main features. First, it considers human systems' responses to environmental changes. This includes changes in decisions about food consumption, agricultural production, land use, and water withdrawals informed by new market prices. Second, it provides a framework for measuring spillover effects transmitted from one location to another location through markets. The main advantage of SIMPLE-G over traditional biophysical models is the inclusion of market-mediated effects and feedback from human systems to natural systems. Including these effects and feedback is critical for designing effective conservation and sustainability policies. By simulating international trade, SIMPLE-G accounts for telecoupled distant regions, enabling analysis of interregional dependencies at a global scale. Third, SIMPLE-G incorporates rich information from the biophysical sciences to inform spatially heterogeneous economic decisions. The ability to address the spatial distribution of activities and explicitly model the spatial heterogeneity associated with biophysical and socioeconomic systems is a significant advance over more aggregated economic models. This feature is critical when analyzing environmental changes or conservation policies that have spatially heterogeneous implications.

1.1 Socioeconomic Determinants of Food Demand

For all the SIMPLE-G specifications that follow, the demand system follows the same SIMPLE (nongridded) regional model. At the regional scale, the consumption of different commodities is a function of population, income, prices, and biofuel demand. Prices are determined endogenously as a function of supply and demand, while population and income changes are exogenous to the model, with increases in per capita income driving diet changes. Within this framework, global food and agricultural markets link changes in population, income, and diet to gridded crop production and associated stresses on land and water resources.

Global food demand is linked to local land use through the derived demand for crops. Total demand for crops in each region comes from four sources. Direct crop demand (i.e., crops consumed directly without processing, including fresh fruits and vegetables and household consumption of grains and oils) is obtained by multiplying

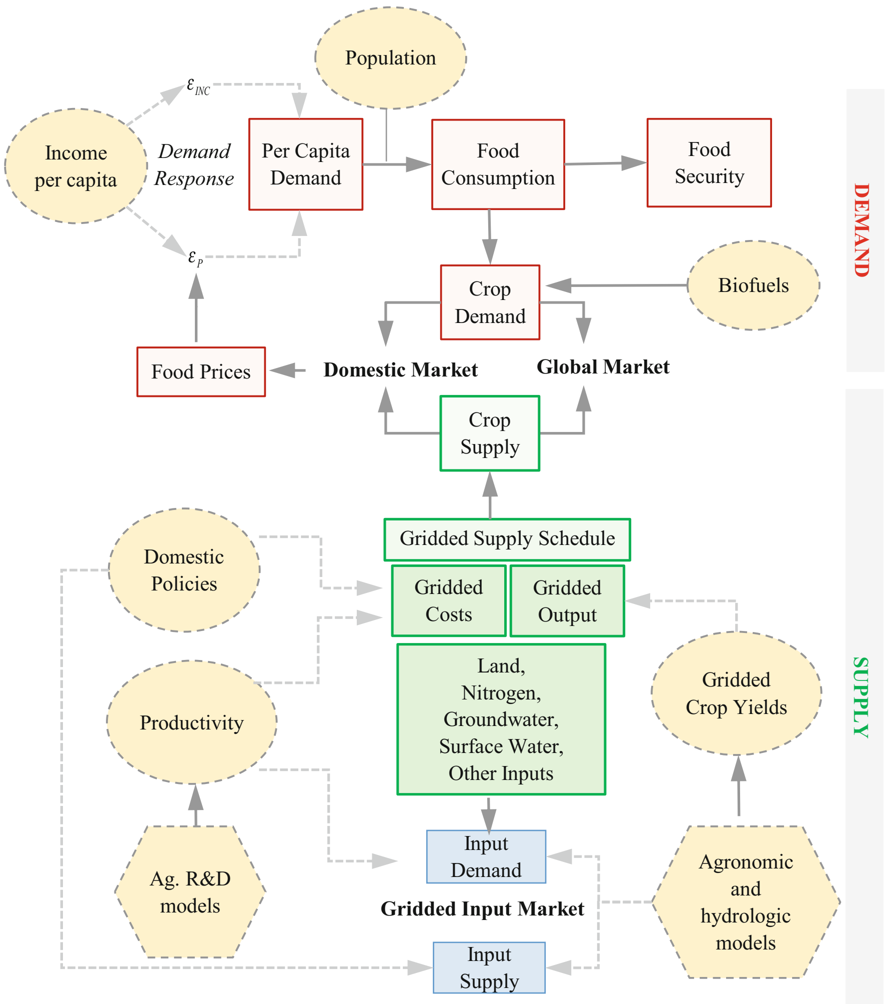

Fig. 4.1 Overview of the SIMPLE-G model
The crop production boxes are in *green*, the gridded input markets are in *blue*, and the demand side boxes are in *red*. The *dashed* shapes are information and models that provide input to SIMPLE-G. The SIMPLE-G model determines the changes in prices and quantities of agricultural inputs (i.e., land, water, fertilizer, labor, and others) and agricultural outputs considering the demand and supply forces

per capita demand for direct crop consumption by population in each region. The three additional components of total demand for crops are indirect demands by the livestock, food processing, and biofuel sectors. Demand for crops in biofuel production is assumed to be exogenously determined by government mandates, but the other demands are a function of income and prices.

The price and income responses of food demand are governed by the regional income elasticities of demand and the regional price elasticities of demand. These factors vary by type of demand (e.g., livestock versus processed foods) and by income level. Food demand generally becomes more inelastic as incomes rise (i.e., wealthier households are less inclined to alter their food consumption in response to higher prices or income changes).

International trade is handled in the same manner as it is in most computable general equilibrium (CGE) models, by differentiating between domestic and foreign goods following Armington's (1969) approach. This imperfect substitution between locally produced food commodities and those imported from global markets is governed by the Armington elasticity of substitution, which permits the model to be calibrated to observed import demand responses. Transformation of local production to exports is also imperfect, reflecting the fact that some producers cannot easily access global markets, thereby allowing the model to mimic observed export supply elasticities.

The nongridded version of SIMPLE (Baldos and Hertel 2013) has just one regional production function, and land use is not disaggregated below the regional level. However, in the SIMPLE-G framework, production is modeled at the grid-cell level; the size of agricultural production units can vary from 50 to 10,000 hectares, depending on the model's resolution. For example, one popular version of SIMPLE-G for the United States (see Chap. 12) disaggregates crop production to the level of 5 arcminutes resulting in more than 75,000 crop production units (grid cells) of about 55–77 km^2 in the continental United States. In SIMPLE-G-US, the other world regions are not disaggregated, allowing for applications focused on the United States, even as the background responses of other regions are accounted for. Of course, such a regional focus is not always desirable, and two applications in Part IV utilize a global-gridded version of SIMPLE-G (Chaps. 16 and 17).

The production functions in SIMPLE-G determine crop outputs as well as local demand for agricultural inputs (i.e., land, water, fertilizer, labor, and other inputs) for any given set of policies and climate regime (i.e., weather). In some versions of SIMPLE-G, we disaggregate rainfed and irrigated crop production, resulting in two distinct production functions in each grid cell, each competing for irrigable land, which allows us to estimate local demand for irrigation water. This approach is important when modeling the impacts of, for example, groundwater sustainability policies as well as adaptation to climate change, which has sharply different impacts on irrigated and nonirrigated crops due to differing responses to heat and water stress.

1.2 Local to Global Supply Linkages

Figure 4.2 illustrates the local-to-global supply of crops. The composition of crop production at the grid-cell level—the most granular level for understanding crop production patterns—is expected to vary by location due to agroecological

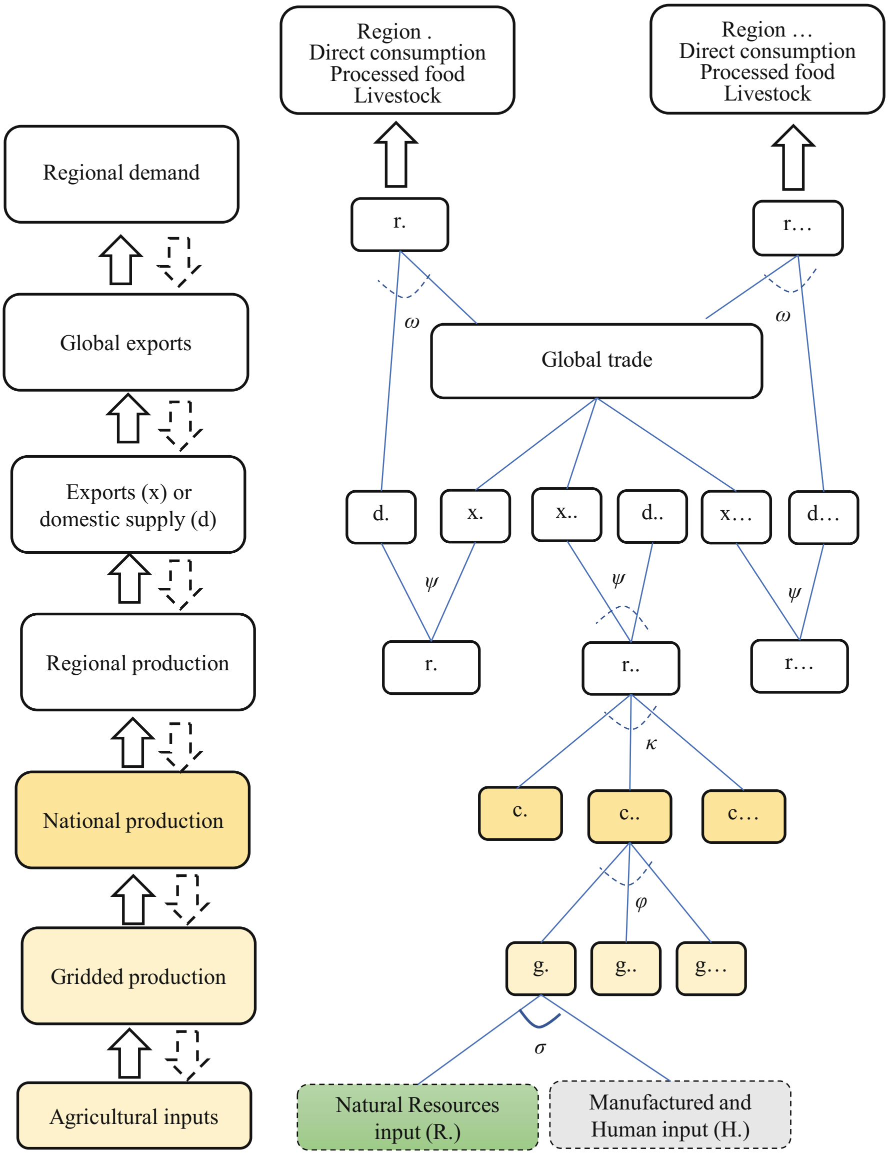

Fig. 4.2 Schematic representation of local-to-global supply linkages in SIMPLE-G
The boxes on the lefthand side describe the activity occurring in the "tree structure" of this figure. At the bottom are the inputs used in crop production at each grid cell (*g*). The resulting outputs are aggregated to the country level (*c*) via a CES (constant elasticity of substitution) function. Each region (*r*) contains multiple countries, and the outputs of these countries are also aggregated using a CES function. The disposition of sales between domestic and export markets is determined at the regional level via a constant elasticity of transformation (CET) function. Exports enter the global market, where supply must equal demand, with global prices adjusting to assure this equilibrium condition. Domestic sales are available for purchase by the four sources of final demand. Domestic and imported goods substitute imperfectly in use according to a CES function

conditions. These diverse commodities differentiated by location can be aggregated at the national or regional level based on assumptions about product differentiation. The greater the variety of crops grown within a region is, the smaller the elasticity of substitution between these gridded crop outputs.

Regional crop production can either be exported or supplied domestically (i.e., consumed within the country where they are produced). The decision to export or supply domestically a crop is based on several factors, including the relative price of crops informed by production costs.

1.3 All Grid Cells Are Connected: Leakage and Spillovers

Leakage and spatial spillover effects are two important concepts in the context of conservation, sustainability, and climate change. Leakage refers to the displacement of environmental problems from one location to another as a result of conservation or sustainability policies (Meyfroidt et al. 2020). For example, a policy implemented to reduce deforestation in one area may lead to increased deforestation in other areas, as loggers and farmers move to new locations. Spatial spillover effects refer to the environmental impacts of conservation or sustainability policies that extend beyond the boundaries of the policy area (Johnson et al. 2023). For example, the creation of a protected area may lead to increased economic activity in surrounding areas. These environmental impacts can be both positive and negative, depending on the nature of the economic activity. Leakage and spatial spillover effects can be important considerations for policy makers when designing and implementing conservation, sustainability, and climate change policies. Understanding how these effects may play out is important for designing effective and efficient policies.

This book and the closely related literature contain many examples of leakage and spatial spillover effects in the context of conservation, sustainability, and climate change. Figure 4.3 illustrates how changes in one location can affect close and remote farms. A policy that reduces the use of fertilizer in one area may lead to increased fertilizer use in other areas as farmers and growers seek to maintain their yields (Chap. 14). A policy that reduces deforestation in one country may lead to increased deforestation in other countries as agriculture and industries relocate (Meyfroidt et al. 2010). The development of a renewable energy project (e.g., biofuels or co-firing of coal power plants with biomass) may increase land-use change in surrounding areas as development spreads to new areas (Sun et al. 2020). A groundwater sustainability policy in the Western United States can cause an increase in land use and fertilizer application in Florida (Chap. 16) and affect labor markets, both locally and elsewhere in the country (Ray et al. 2023). By design, SIMPLE-G captures unintended consequences, spillover effects, and leakages stemming from policy interventions.

Leakage and spatial spillover effects can be complex and difficult to predict. There is no one-size-fits-all solution for addressing these effects; the best approach will vary depending on context. However, SIMPLE-G can shed light on the

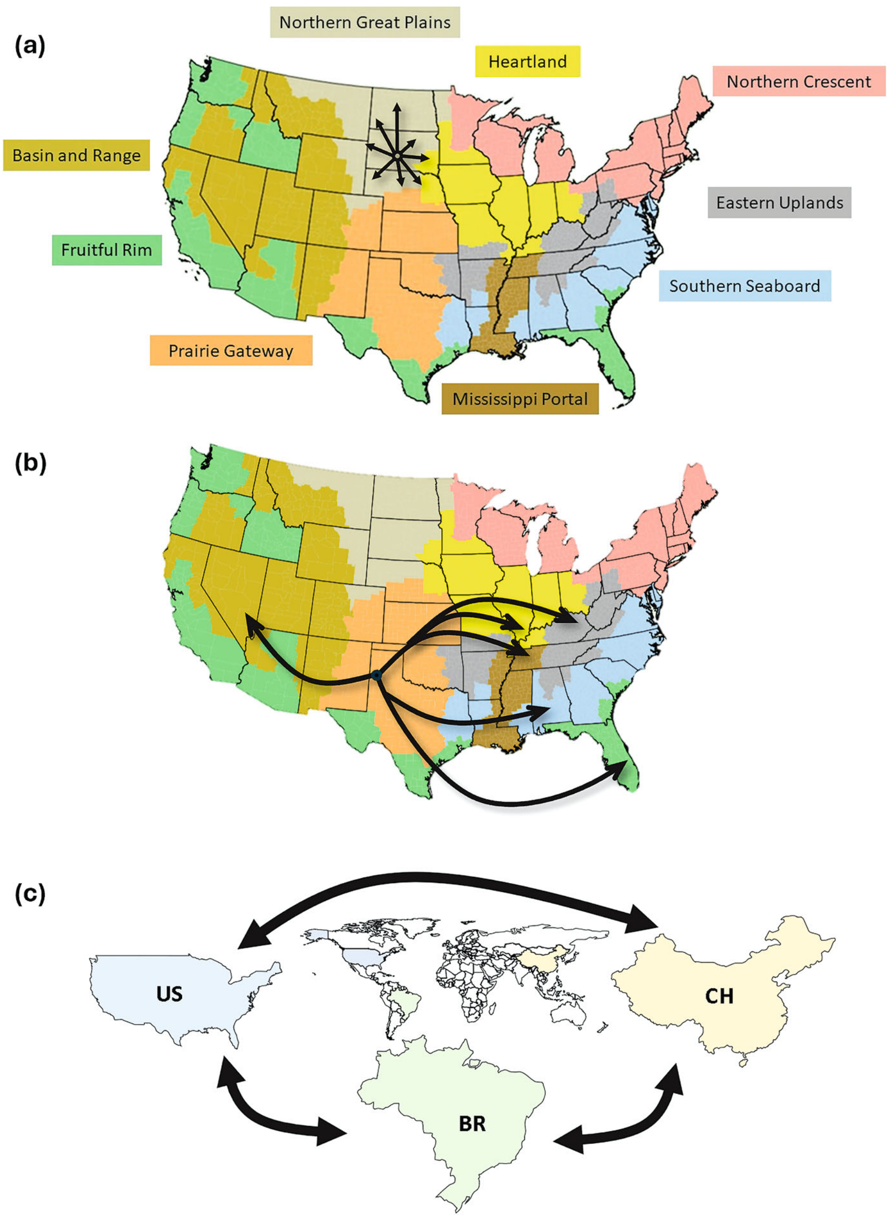

Fig. 4.3 Spillover effects (**a**) to similar crop-producing locations, (**b**) across subregions, and (**c**) across countries

Leakage and spillover effects depend on the degree of mobility of inputs and the degree of product differentiation. Unfavorable conditions in in the US Northern Great Plains can cause an increase in production in neighboring locations. A decline in agricultural activity in the US Prairie Gateway region may lead to changes in agricultural production in other regions of the United States. Here, labor migration can play a critical role. Telecoupled changes in the United States, China, and Brazil may have implications for all three regions. For example, growth in demand from China can cause an increase crop production in the United States and Brazil magnitude and direction of these effects, helping policy makers design policies that are comprehensive and coordinated across a variety of scales (Johnson et al. 2023). It can also serve as a foundation for developing new models and quantitative approaches to investigate leakage and spatial spillover effects.

2 Equilibrium Conditions

At its heart, any SIMPLE-G model is a model of economic equilibrium. Thus, the main equations in the model serve to determine the demand and supply of food commodities and agricultural inputs. Demand is written as a mathematical function that shows the relationships between the quantity demanded and other determinants of demand. It is negatively related to commodity price but positively related to income and scale of production. Similarly, supply is written as a mathematical function that shows the relationship between the quantity supplied and other economic and biophysical determinants of supply. A higher relative price for the commodity being produced motivates greater supply. Price is the equilibrating variable in this system. If an adverse climate shock in one location reduces supply, then a price increase will curb demand and induce additional supplies from other locations, thereby restoring equilibrium. Market equilibrium is defined as the price level at which the quantity of a commodity supplied by sellers (producers) is equal to the quantity demanded by buyers (consumers). In other words, there is no shortage or surplus. As such, this is not a short-run model. Rather, the time frame is long enough such that, if no other shocks were to occur, equilibrium would be restored following the shock or policy being implemented.

2.1 Global Crop Market Equilibrium

Global crop market equilibrium is the state of the market in which the total quantity of crops exported by all countries is equal to the total quantity of crops imported by all countries. This equilibrium is determined by a complex interplay of factors, including the relative prices of crops, the cost of production in each region, and policies. Equation 4.1 represents global crop market equilibrium:

$$\underbrace{\sum_r QGS_{c,r}}_{\text{Total exports}} = \underbrace{\sum_r \sum_b QGD_{c,r,b}}_{\text{Total imports}}, \tag{4.1}$$

where $QGS_{c,\ r}$ is the total quantity of global supply of crop c exported by region r and $QGD_{c,\ r,\ b}$ is the total quantity of global demand for crop category c imported by buyer type b in region r. The base version of SIMPLE-G employed in this book includes 17 global regions (r), one composite crop category (c), and four types of buyers (b): direct consumers and the livestock, processed food, and biofuels sectors.

Equation 4.1 states that, in long-run equilibrium, the total quantity of crops exported must be equal to the total quantity of crops imported. If there were more crops exported than importers demanded, then the global market would experience a surplus of crops, which would drive prices down until equilibrium was restored. Conversely, if there were more demand for crops to be imported than were actually exported, then the global market would experience a shortage of crops, driving prices up, thereby restoring equilibrium.

2.2 Regional Crop Market Equilibrium

Regional crop market equilibrium is the state of the market in which the total quantity of crops supplied domestically in a region is equal to the total quantity of domestic crops purchased in the region by buyers, including the total quantity of crops used for biofuel production. This equilibrium is determined by an interplay of factors, including the relative prices of crops, the costs of production, and biofuel policies. For each crop category, Eq. 4.2 represents the regional crop market equilibrium:

$$QLS_{c,r} = \sum_{b} QLD_{c,r,b}, \tag{4.2}$$

where $QLS_{c,\ r}$ is the total quantity of locally supplied crops (domestically produced and supplied to domestic consumers) in the region, and $QLD_{c,\ r,\ b}$ is the quantity of local demand for regionally produced crops that are purchased by each buyer in the region. Total regional crop production, $QTS_{c,\ r}$, is the sum of gridded production in each region, which is equal to exports plus domestic sales:

$$\underbrace{QGS_{c,r} + QLS_{c,r}}_{\text{Total regional supply}} = QTS_{c,r} = \underbrace{\sum_{g \in r} Q_{c,g}}_{\text{Total gridded production}}. \tag{4.3}$$

2.3 Local Input Market Equilibrium (Immobile Inputs)

For agricultural inputs tied to a specific location (e.g., land), the gridded quantity of the factor demanded should be equal to the gridded quantity supplied at the equilibrium price for each location. For example, for each immobile factor i in each grid cell g, we can write

$$QS_{i,g} = QD_{i,g} = Q_{i,g}, \tag{4.4}$$

where $QS_{i,\ g}$ is the total quantity supply of input i in grid cell g and $QD_{i,\ g}$ is the total quantity of gridded demand for input i in grid cell g.

2.4 Subregional Input Market Equilibrium (Mobile Inputs)

For mobile factors (e.g., labor, capital, and fertilizer), the quantity of the factor demanded should be equal to the quantity supplied at the equilibrium price of the marketshed shown by index s. Here, the marketshed is defined as a neighborhood of grid cells within which the factor can commute or move. This could be the commuting zone for labor or a regional market for capital or purchased inputs.

$$QS_{j,s} = QD_{j,s} = \sum_{g \in s} Q_{j,g} \tag{4.5}$$

The main difference between the agricultural input market equilibrium conditions for mobile (Eq. 4.4) and immobile (Eq. 4.5) factors of production is that the equilibrium price for mobile factors of production will be equalized across all grid cells, while the equilibrium price for immobile factors of production will vary by grid cell. This is because mobile factors of production can move freely between grid cells in response to differences in prices and wages. As a result, if the price of a mobile factor of production is higher in one location than in another, then mobile factors of production will flow from the lower-price grid cell to the higher-price location until the prices are equalized. On the other hand, immobile factors of production cannot move between grid cells. As a result, the equilibrium price for an immobile factor of production will vary by grid cell depending on local supply and demand for that factor. This is reflected in the evidence that labor wages move together within a commuting zone, but land rents are highly spatially heterogeneous.

3 Behavioral Assumptions

Overall, the SIMPLE-G model accounts for a variety of factors that influence the human and environmental systems. The model's assumptions are based on empirical evidence, but it is important to note that the model is still a significant simplification of the real world (hence its name, SIMPLE!). Here, we review these assumptions and their empirical bases.

On the demand side of food markets, the SIMPLE-G model considers estimated price and income elasticities empirically; that is, the quantity of a product demanded is assumed to be sensitive to changes in its price and consumers' income. Clements and Si (2018) and Gouel and Guimbard (2019) nicely summarize the extensive literature on food demand that has evolved over the past century (Working 1925). The overall conclusion of this literature is that demand for food changes as income increases. At lower income levels, consumers derive the bulk of their calories from cereals and other carbohydrates, with proteins coming from plant-based sources. As incomes rise, consumers add more livestock products (which tend to be more expensive) as well as fresh fruits and vegetables, oils and fats, and sweeteners. Rising incomes translate into more overall consumption as well as more diverse diets. Recent research on the cost of diets across the world suggests that households require an income of roughly US$3/person/day to be able to afford a healthy diet (Bai et al. 2021). However, reaching this threshold does not mean that they will consume a healthy diet. Recent research suggests that the emerging "triple burden" of malnutrition includes households consuming excessive calories but still not attaining a healthy diet (Gómez et al. 2013).

Another important aspect of food demand that has recently received increasing attention is food waste. From a resource point of view, there is little difference between food purchased and consumed and food that is purchased and later discarded. (Food waste generally goes to landfills, where it can contribute to methane gas emissions, Krause et al. 2023.) There is evidence that global food waste is positively correlated with per capita income. Lopez Barrera and Hertel (2020) estimate an S-shaped curve: food waste is very low at the lowest per capita income levels but then increases rapidly in middle income countries (e.g., China over the past two decades) before leveling off at the highest income levels. To date, most international studies of food demand have been unable to distinguish food intake from food waste; therefore, our estimated income elasticities will combine these two sources of demand.

The other important characteristic of food demand is its responsiveness to price. At low-income levels, this price response tends to be quite strong. After all, low-income households have little choice but to curb consumption when food prices increase sharply since food comprises a large share of their total income. However, the price responsiveness of food demand diminishes as incomes rise (Muhammad et al. 2011), Capturing this change is important for any long-run projections as it reflects the fact that consumers' overall willingness to curb consumption in response to scarcity will diminish with economic growth, leading to increased price volatility.

Our assumptions on the producer side of the food system are conventional for economic models. First, we assume that producers choose inputs to minimize their production costs. This hypothesis is testable and has been subjected to statistical testing with mixed results at the level of individual farms (Zereyesus and Featherstone 2017). While not all producers are economically rational in this way, we are not modeling individuals but rather groups of producers (albeit within a given grid cell), and the cost-minimization hypothesis is more likely to hold in groups of producers, where competitive pressures cause irrational producers to downsize or exit the market (Hertel et al. 1996). We assume that, at the margin, producers that are not making an economic profit will eventually cede their land to other, more profitable producers. This is indeed what has been observed over time: The size of individual farms has tended to increase with consolidation (MacDonald 2020). The form of the SIMPLE-G production functions follows the well-established tradition in CGE modeling of nested CES (constant elasticity of substitution) functional forms. This means that the production of crops depends on a combination of different inputs, such as land–water, labor–capital, or a composite of remaining inputs. By carefully specifying the elasticity of substitution between individual inputs or groups of inputs, we are able to mimic observed economic and biophysical responses to changing relative prices. For example, the elasticity of substitution between nitrogen fertilizer and land can be calibrated to reproduce the observed yield response to fertilizer applications (Chap. 14).

On the international trade front, the model assumes that imports are governed by an Armington function. When countries import crops, they consider not only relative prices but also unobserved factors including product variety and other desirable qualities (e.g., taste, transportation restrictions, regulations). Capturing this product differentiation is important for modeling trade in SIMPLE-G, as it determines the degree of connectedness between domestic and international markets in the model. This is handled using Armington (1969) elasticities, which have been the subject of extensive empirical investigation (Hillberry and Hummels 2013); we rely on these estimates to parameterize the model. There is a symmetric Armington elasticity on the export side, where a constant elasticity of transformation (CET) function allocates produced crops between global and local markets. This allows the strength of export supply response from a region to be specified by the model developer.

Finally, for land use, the model assumes grid-cell-specific land supply functions. This means that the model accounts for the various characteristics of land in different locations when determining how much land will be used for agricultural production. Locations will differ in their responses to changes and policies, with implications of the spatial patterns of agricultural production and land use.

Each element of the model (variable) has an assigned value and quantity. The quantity of the variable can be shown as an index (i.e., US$ at constant prices) or as a physical quantity (e.g., tons of crops, hectares of land, cubic meters of water, or kilograms of fertilizer). The model includes equations that describe food demand as well as food production linked to natural resources. There are also parameters that describe behavioral responses or other biophysical dynamics of the system. The model is written as a system of simultaneous equations that determines the decisions on land and water use endogenously along with market prices for food and agricultural inputs. Tables 4.1 and 4.2 summarize the major conditions and functional forms used in SIMPLE-G.

To capture the dynamics necessary to analyze sustainability and food security, the model of the supply side of the economy includes four sets of equations: First, the equations that illustrate the supply of agricultural inputs. Second, the equations that Determine the demand for agricultural inputs. Third, the equations that illustrate the price and expenditure indices to ensure zero profit conditions. Fourth, the equations that determine the spatial allocations of inputs in case of imperfect mobility. The combination of these equations provides the basis for assessing spillover effects. This is a significant feature of SIMPLE-G, and it is important in explicitly modeling

Table 4.1 Market equilibrium conditions in the SIMPLE-G model

Description	Condition	Equation
Global market clearing	$\underbrace{\sum_r QGS_{c,r}}_{\text{Total exports}} = \underbrace{\sum_r \sum_b QGD_{c,r,b}}_{\text{Total imports}}$	Eq. (4.1)
Domestic market clearing	$QLS_{c,r} = \sum_b QLD_{c,r,b}$	Eq. (4.2)
Total regional supply	$\underbrace{QGS_{c,r} + QLS_{c,r}}_{\text{Total regional supply}} = QTS_{c,r} = \underbrace{\sum_{g \in r} Q_{c,g}}_{\text{Total gridded production}}$	Eq. (4.3)
Immobile input gridded market clearing	$QS_{i,\ g} = QD_{i,\ g} = Q_{i,\ g}$	Eq. (4.4)
Mobile input subregional or regional market clearing	$QS_{j,s} = QD_{j,s} = \sum_{g \in s} Q_{j,g}$	Eq. (4.5)

Table 4.2 Major assumptions in the SIMPLE-G model

	Assumption and functional forms	Reference
Food demand	Based on empirically estimated price and income elasticities	Muhammad et al. (2011)
Production structure	Composite output based on nested CES (constant elasticity of substitution) inputs	Dixon et al. (1982)
Imports	Using Armington CES: Imperfect substitution between imports and domestic crops	Hertel et al. (2007)
Exports	Using CET (constant elasticity of transformation) for allocation of local production to global and domestic markets	van der Mensbrugghe (2019)
Land use	CET representation of land supply response	Ahmed et al. (2008)
Input supply	Estimated fixed supply elasticities and CET for spatial allocation	Baldos et al. (2020) and Ray et al. (2023)
Relocation	Subregional Armington and product differentiation	Haqiqi et al. (2022)

the spatial reallocation of production in response to socioeconomic and environmental shocks. Overall, the model equations are derived based on multiple assumptions. Table 4.2 summarizes some of these assumptions.

4 Summary

The SIMPLE-G modeling framework requires multiscale market equilibrium for global, regional, and local markets. At each scale, total demand of a commodity or production input should be equal to total supply. Prices will adjust to eliminate any excess supply or demand. Production and consumption are linked through markets and international trade, where prices provide signals about changes in production costs and consumer preferences due to changes in environmental or human systems.

The SIMPLE-G models often employ functional forms that are widely tested and used in many economic studies. Leveraging well-established functional forms with strong empirical grounding, SIMPLE-G is a robust and comprehensive analytical tool for understanding the complex interactions within human and environmental systems.

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