Malthus Redux? Nutrition Transition, Population Growth, and World Food Markets in 2050

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Abstract

As countries become wealthier, people adopt more diversified diets and shift from starchy staples to meat, dairy, and other food categories that require more farmland per calorie produced. We build a transparent general equilibrium model of 82 regions, 8 food categories, and 76 crops to study how this nutrition transition, together with population growth, affects world food markets by 2050 if crop yields stay at their 2010 level. With income from non-land inputs growing along the middle-of-the-road Shared Socioeconomic Pathway (SSP2) and land rents adjusting with food prices, the median food price across regions rises 2.0-fold for sweeteners and up to 3.9-fold for vegetal oils, and world meat consumption grows by 51 percent versus the 112 percent projected at fixed prices. Regions with 2010 incomes below 2,000 dollars still see their per capita meat and dairy consumption increase by more than 70 percent. Higher food and crop prices also benefit landowners worldwide. A uniform annual yield growth of 1.45 percent of the 2010 level, or 2.07 percent if it occurs only in regions with large yield gaps, would offset most of the cost of higher food prices.

Keywords: nutrition transition, land allocation, consumer welfare, food prices

1 Introduction

> "The power of population is indefinitely greater than the power in the earth to produce subsistence for man."
>
> — Thomas Malthus, *An Essay on the Principle of Population (1798)*

Whether agriculture can feed a growing population is among the oldest questions in economics. For two centuries, doomsayers have answered no. Malthus argued in 1798 that population must outrun subsistence. William Crookes warned in 1898 that the world would exhaust its wheat supply within a generation (Crookes, 1899). Paul Ehrlich predicted in 1968 that hundreds of millions would starve within a decade (Ehrlich, 1968). The Club of Rome projected in 1972 that resource limits would halt growth within a century (Meadows et al., 1972). Lester Brown asked in 1995 who would feed China (Brown, 1995). History has proved them wrong each time. Between 1961 and 2011, world population more than doubled, real agricultural output more than tripled, and real farm prices fell (Alston and Pardey, 2014). Synthetic fertilizer and the Green Revolution raised yields on land already under cultivation, and international trade enabled surplus grain to feed the rapidly growing populations somewhere else. Famine has become rare, and its remaining causes are mostly political rather than economic (Sen, 1981; de Waal, 2018). The record of failed alarms is so complete that food scarcity has largely dropped off the list of things economists worry about.

However, two pressures are bringing the question back. The first comes from the supply side. Yield growth has slowed worldwide. Cereal yields grew by 2.35 percent per year between 1961 and 1990 but only 1.48 percent per year between 1990 and 2011 (Alston and Pardey, 2014; Pardey et al., 2014).[1] At the same time, policy is turning against the technologies behind past yield gains. Sexton (2025) documents how support for organic, local, and small-scale production, together with opposition to genetically modified crops, lowers output on existing farmland in the United States and Europe. These headwinds may or may not persist. Either way, the old confidence that supply growth will always arrive in time no longer looks safe.

The second pressure comes from the demand side. As incomes rise, consumers move away from starchy staples toward meat, dairy, and other animal products, a pattern known as the nutrition transition (Popkin, 1993; Drewnowski and Popkin, 2009). Per capita animal

[1] The slowdown in yield per harvest is not disputed, but whether world agricultural output growth has slowed is. Fuglie (2018) shows that rising cropping intensity has offset slower yield growth: farmers harvest each hectare of cropland more often, so output per hectare has kept growing at past rates. The ratio of harvested area to cropland rose from 0.70 in 1961 to 0.87 in 2014, but it cannot expand forever.

protein consumption rose by 426 percent in China and 82 percent in India between 1980 and 2013 (Zulauf, 2015). Animal products require several calories of feed crops for each calorie of food, so this shift multiplies crop demand even when total calorie intake stays flat. Global population growth has slowed below one percent per year (United Nations, Department of Economic and Social Affairs, Population Division, 2024), but incomes are now growing fastest in countries with large, young populations (Dellink et al., 2017; Kc and Lutz, 2017). Over the next generation, the pressure on crop markets will come from more mouths with richer diets.

This paper asks what happens to world food markets if crop productivity stops improving while diets keep changing. We hold yields at their current levels and let population and income grow to 2050 along the Shared Socioeconomic Pathways (O'Neill et al., 2014; Riahi et al., 2017). This design isolates the demand shock and works as a stress test. The scenario is deliberately extreme, and we do not expect it to happen in the end. Yield growth has slowed, but it has never stopped, and two centuries of failed doomsday predictions warn against betting that it will. Our point is to measure the challenge instead of simply predicting a crisis. Our counterfactual analysis shows how large the stress would be if productivity growth does not come, and how much of that growth is needed to keep food prices stable.

We answer the question with a quantitative equilibrium model of global agriculture covering 82 regions, 8 food categories, and 76 crops including grass. Consumers in each region have non-homothetic preferences over food categories, so diets respond to income growth. Each food is produced from crops through a two-tier technology adapted from Mérel, Qin, and Sexton (2023). Landowners allocate parcels across crops and pasture according to comparative advantage, following Costinot, Donaldson, and Smith (2016). Food and crops are traded bilaterally. A composite non-land factor moves between the food sector and an outside sector in each region, and its price clears the regional factor market. We express the 2050 equilibrium in relative changes, so the model needs only key behavioral parameters (mainly elasticities) and other share parameters, which we calibrate to FAOSTAT domains and BACI bilateral trade flows (FAO, 2024; Gaulier and Zignago, 2010).

We introduce a new demand system in this paper. Earlier quantitative trade models of agriculture impose homothetic preferences, so diets in those models do not respond to income (Costinot, Donaldson, and Smith, 2016; Sotelo, 2020; Gouel and Laborde, 2021; Mérel, Qin, and Sexton, 2023). Recent work introduces income effects through nested non-homothetic CES preferences, developed first for models of structural change and trade (Comin, Lashkari, and Mestieri, 2021; Caron and Fally, 2022; Sposi, Yi, and Zhang, 2024) and brought into agriculture by Cruz (2024), Nath (2025), and Corrêa-Dias, Norris, and Pellegrina (2026). These models carry an economy-wide general equilibrium and thus come at a cost for a

study focusing on the food sector: the outer CES tier ties food demand to prices in every other sector, and welfare changes can be computed but not easily decomposed as we do. Our specification keeps the non-homotheticity and income effects without that cost. The nutrition transition is captured by expenditure shares shifting across food categories as income grows. The model needs only one sector outside agriculture, which supplies the numeraire good and absorbs or releases the composite factor that farming and food processing use. Closing the general equilibrium therefore requires clearing conditions for land, the composite factor, and product markets in every region, and no economy-wide input-output structure is needed. Welfare changes decompose exactly into an income effect, a land rent component, a consumer price effect, and a taste-shifting component.

The general equilibrium closure matches how the SSP income paths are built. The marker projections of Dellink et al. (2017) come from an aggregate growth model with no agricultural sector and no land in the production function. The authors describe the output as reference paths for sectoral models downstream, and integrated assessment models use them exactly by calibrating per capita GDP to the macro path first and adding sectoral structure second (Riahi et al., 2017). In our work, the marker path determines the growth of non-land factor income in each region, and our model supplies the agricultural detail. Allowing land rents to respond endogenously captures a channel the marker path lacks.

Three findings stand out. First, the demand shock alone is large. Under the middle-of-the-road scenario SSP2, food prices rise in every one of the 82 regions, and aggregate food consumption falls in every region as well. In the median values across regions, food prices rise by factors of 2.0 for sweeteners to 3.9 for vegetal oils, per capita staple consumption falls to half of its 2010 level, and world meat consumption grows by 51 percent instead of the 112 percent projected at fixed prices. The pattern holds across all five SSP scenarios. Additionally, both population and income drivers matter. Shutting down either population growth or income growth removes a large part of the price increase. The median rise in starchy staple price is 3.4-fold with both drivers, against 1.9-fold with population growth alone and 1.6-fold with income growth alone. The combined increase exceeds the product of the two separate increases in nearly every region, because each shock raises land rents and leads to a less elastic crop supply.

Second, the nutrition transition redistributes welfare. Higher crop prices raise land rents and squeeze food consumers, so the shock acts as a global transfer from consumers to landowners. Under SSP2, land rents rise in all 82 regions, and income-constant compensating variation (CV) in the food market is negative in all 82. The endogenous part of the welfare changes, land rents gained plus the negative income-constant CV, is negative in 32 of the 82 regions. Africa is hit hardest, with 9 of its 13 regions worse off than SSP marker paths

because their food prices rise the most and a growing share of their food spending pays rents on land abroad. We also observe cropland expansion into pastureland in 71 of the 82 regions.

Third, productivity growth can offset much of the pressure. We compute the universal yield increase by 2050 at which the median income-constant CV is zero, so that food prices are generally close to their 2010 levels in the counterfactual. Yields 58 percent above their 2010 level do this when every region shares the growth, and 83 percent higher yields do it when the 24 regions whose yields are already near their potential stand still. These two numbers translate to 1.45 and 2.07 percent of the 2010 yield per year over 2010 to 2050, the pace at which yields have grown over the last decades and a little above it Ray et al. (2013); Alston and Pardey (2014). At that point, landowners keep little of the windfall, with median per capita land rents growing 1.33-fold instead of 16.8-fold, and median meat consumption reaching 1.54 times its 2010 level, next to 1.55 in the fixed-price projection. Modest and steady yield growth absorbs a large share of the demand shock, so ignoring technical progress overstates the danger. However, we should also be careful about policies that sacrifice yield for credence attributes, such as organic production, non-GMO sourcing, and local supply requirements, which would push in the opposite direction and tighten food markets further (Sexton, 2025; Mérel, Qin, and Sexton, 2023).

Our work relates to three groups of studies. The first group asks questions related to food supply and demand and builds large simulation models for projection. Early work treated demand and supply separately, extrapolating each from past trends or reconciling them through accounting balances and expert judgment, with no role for equilibrium prices (Tweeten and Thompson, 2008; Alexandratos and Bruinsma, 2012). Later models instead solve for prices and quantities that clear world markets. These include partial equilibrium models of the agricultural sector, such as IMPACT and GAPS (Robinson et al., 2015; Kavallari, 2016); models built to assess the land use effects of biofuel policy, such as GLOBIOM and MIRAGE-BioF (Valin et al., 2013; Laborde and Valin, 2012); economy-wide general equilibrium models, such as EPPA, ENVISAGE, and FARM (Chen et al., 2014; Van der Mensbrugghe, 2017; Sands, Jones, and Marshall, 2014); and integrated assessment models whose agriculture and land use components clear commodity markets jointly with energy markets, as in GCAM (Kyle et al., 2011). A related set of optimization models instead takes demand as given and allocates production to minimize costs or balance competing objectives, including MAgPIE and MOO-GAPS (Lotze-Campen et al., 2008; C. Castonguay et al., 2023).

These models offer rich sectoral and spatial detail, but the detail has a cost. The AgMIP comparison in Hertel, Baldos, and van der Mensbrugghe (2016) reports that projected crop output growth to 2050 ranges from 52 to 116 percent across models, and projected price

changes range from a 16 percent fall to a 46 percent rise. With hundreds of parameters, it is hard to tell which assumptions drive which result. Most of these models also aggregate trade into net flows and stop short of welfare analysis. Setting aside sub-national details, Baldos, Hertel, and Moore (2019) feed yield shocks from a statistical meta-analysis into the GTAP model, and decompose national welfare changes into direct productivity, terms-of-trade, and allocative efficiency effects, showing that trade spreads the burden of spatially uneven shocks. Our model trades spatial detail for transparency. Compared with an economy-wide GTAP model, ours has only a single outside sector that closes the general equilibrium; the model includes only the parameters needed to describe food and crop markets in 2050, each with a named role, and welfare changes have an exact four-term decomposition that we evaluate at the solved equilibrium.

Our paper borrows its tools from quantitative trade models of agriculture. One group of these models builds the allocation of land across crops from spatial data on potential yields and asks how production and trade adjust to supply shocks such as climate change (Costinot, Donaldson, and Smith, 2016; Sotelo, 2020; Gouel and Laborde, 2021; Farrokhi and Pellegrina, 2023; Domínguez-Iino, 2025; Porteous, 2026). A second group leaves land in the background and works with comparative advantage at the level of countries and sectors, where trade barriers and low elasticities decide how costly a shock to agriculture becomes (Fally and Sayre, 2018; Cruz, 2024; Nath, 2025; Conte, 2026). The papers closest to ours sit in this second group. Nath (2025) and Conte (2026) add subsistence preferences for food and show that climate change deepens the food problem of Gollin, Parente, and Rogerson (2007), because high trade barriers keep labor in agriculture exactly where yields fall most. In both groups, the shock comes from the supply side, and the question is how production and trade adjustments absorb it. In our counterfactuals, the shock is on the demand side, as income growth shifts diets toward animal foods, and the model's detail sits on the consumption side rather than the production side.

Across these papers, the shock of interest sits on the supply side: climate, technology, trade frictions, or regulation. Where non-homothetic demand enters, as in Nath (2025), Cruz (2024), and Conte (2026), it is the channel through which the supply shock moves labor across sectors; the demand shift itself is never the experiment. The closest paper to ours is Corrêa-Dias, Norris, and Pellegrina (2026), who quantify agricultural greenhouse gas emissions in a model where diets shift with income. We differ in focus and in structure. Our object of study is the demand shock itself and its welfare incidence, and our two-tier crop-to-food technology maps category-level dietary change into crop-level land reallocation. Our counterfactuals can also run the food problem in reverse: in Nath (2025), a negative supply shock pulls resources into agriculture because people must eat, while in our model

a positive income shock shifts diets, and the factor market clearing condition reports the composite factor moving out of crop and food production as incomes grow.

The third group measures the shock we feed into the model, the change in food demand as income grows. The regularities are old. As income grows, households spend a smaller share of it on food, and within food they shift from starchy staples toward animal products (Bennett, 1941). Gouel and Guimbard (2019) estimate a flexible demand system on cross-country data and project the nutrition transition to 2050. Micro evidence supports the pattern. Bellemare, Kandpal, and Thomas (2024) pool five conditional cash transfer RCTs and find that spending shifts toward protein and away from coarse staples, though by less than cross-sectional or large-transfer estimates suggest. Scenario studies ask how fast diets must move away from animal foods for the food system to meet climate goals (Hale, Oncescu, and Bhangale, 2025). These studies characterize demand paths without equilibrium feedback: they estimate how diets shift with income at fixed prices, or posit dietary scenarios outright. We take demand estimates from Gouel and Guimbard (2019) as inputs and supply the equilibrium response: prices, trade, land use, and the division of gains and losses all adjust to the dietary shift.

The rest of the paper proceeds as follows. Section 2 presents the model and derives the equilibrium in relative changes. Section 3 describes the data and the calibration of demand, technology, and land parameters. Section 4 presents the counterfactual design. Section 5 reports the 2050 stress test, the welfare decomposition, and the yield counterfactual. Section 6 concludes.

2 A Model of Food/Crop Production

We develop and calibrate a country-specific general equilibrium model of crop and food markets, closed by a composite non-land factor that moves between agriculture and an outside sector in each country, aimed at capturing the key aspects of food consumption and crop production in the year 2050. Our main objective is to evaluate two demand-side shocks, essentially the potential impacts on food prices and welfare in various countries resulting from population growth and the nutrition transition as a result of income growth. We also care about the associated changes in crop output and producer surplus across countries, as well as potential expansion of cropland and contraction of grassland, which can certainly raise environmental concerns. Exogenous yield changes are allowed to evaluate to what extent such demand-side shocks can be offset by advances in agricultural technology.

2.1 Model features

The model addresses crop and food markets across 82 countries and aggregated regions. We allow for country- and region-level differences in preferences for food categories and countries of origin, as well as in technologies for crop production and food processing. Specifically, the model has two types of goods: food category n (downstream) and crop l (upstream). A food category is produced with crops and labor, while crops are produced with land and labor. The factor "labor" here is a factor of production capturing all resources used except land (for crop production) or crops (for food production). The productivity of a specific land parcel can be characterized by a specific distribution surrounding expected yields.

Our model structure draws inspiration from Eaton and Kortum (2002) and Costinot, Donaldson, and Smith (2016), particularly in how we model land heterogeneity through random yields and bilateral trade with iceberg costs. We adopt our land reservation setup (producing the labor-free crop "grass") from Gouel and Laborde (2021), who also guide our methods in defining equilibrium in relative changes with the "exact hat algebra." Our crop-based food production framework, counterfactual welfare change computation, and parameter calibration with minimal information are informed by the methodologies of Mérel, Qin, and Sexton (2023) and Mérel and Hanon (2025).

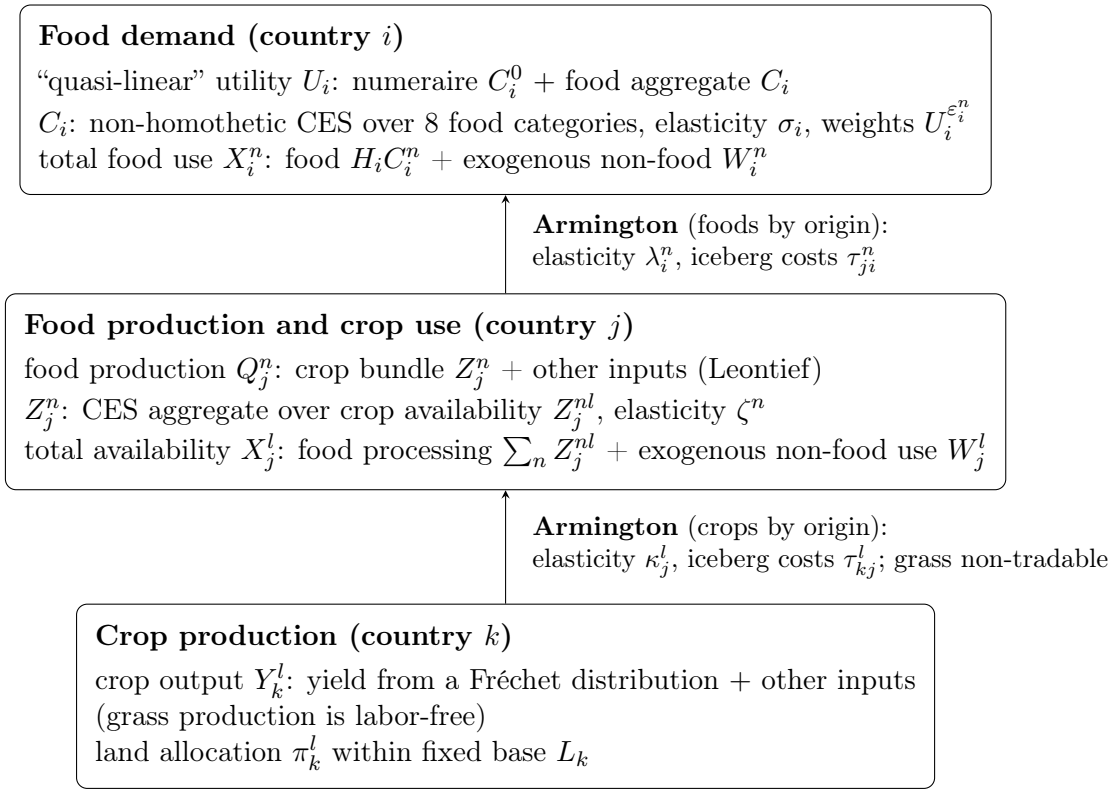
For each country i, we assume it has H_i consumers with identical preferences, so that social welfare is calculated as the product of population and per capita utility. The preference structure incorporates the non-homothetic CES aggregator of Comin, Lashkari, and Mestieri (2021), which is applied to food categories as in Corrêa-Dias, Norris, and Pellegrina (2026), but we change the upper tier structure to a Mérel, Qin, and Sexton (2023)-style "quasi-linear" form to keep a parsimonious model structure and focus more precisely on the food industry. Non-homotheticity and income effects arise in the middle tier as a result of varying endogenous preference weights for each food category, which will also be carried over to the upper tier. With properly calibrated behavioral parameters, an exogenous per capita income growth in the model replicates the counterfactual demand growth estimated by Gouel and Guimbard (2019) at baseline prices.

For crop production, each country has a fixed land area allocated to different cropping activities, including pasture. While all other crop production requires both land and non-land inputs (denoted as "labor"), we include a special crop "grass" as a labor-free reservation choice to reflect potential land that can be cultivated. Crops except grass can be traded across countries, and all crops, including grass, are processed into food categories, possibly by transformation of animal products. The transformation of crops into livestock and the transformation of livestock into animal-based foodstuffs are left implicit in the model. That is, in the model all crops (including those used as feed) are transformed into final foodstuffs

in a single processing stage. We adopt the standard Armington assumption to acknowledge the reality that countries do not fully specialize in certain products and that bilateral trade is widespread. We assume that both food categories and crops are differentiated by country of origin, and each country constructs its domestic availability of a product from its own production and net imports.

Our equilibrium is characterized by a system of equations and unknown variables, more specifically, unknown relative changes in endogenous prices, quantities, and cropland shares. These variables are all set equal to 1 in the baseline. The main impetus in our model is heterogeneous food demand changes driven by exogenous country-specific income growth. Together with other non-varying parameters like elasticities of substitution across food categories in demand and across crops in food production, solving the system of equations reveals the new price/quantity/land share as a ratio of its original value, which can be further used in welfare calculations. Figure 1 summarizes the nested structure of demand, trade, and production in the model.

Figure 1: Nested structure of demand, trade, and production



2.2 Country, food, and crop choices

Our country and crop choices respect previous works on the topic. Gouel and Guimbard (2019) propose their nutrition transition pattern based on 104 countries, representing over 83% of the world population, as the remaining countries either lack population/food consumption data or are outliers. Some island countries are too small and might have their own specific diet patterns; other countries, like North Korea (DPRK), are dependent on international food aid and cannot afford their own food consumption. For literature on the production side, Costinot, Donaldson, and Smith (2016) selects 50 countries accounting for 89.7% of world crop output value and 10 major crops for 71.1% of that. Gouel and Laborde (2021) has 50 countries and 35 crops, covering 88% of the global harvested area.

Clearly, the demand side requires more countries to be included in the model. We assume that the rest of the world also follows the nutrition transition pattern concluded by Gouel and Guimbard (2019), and we include all the countries with per capita GDP and population data available. We further perform some aggregation based on physical distances, considering that these countries are minor contributors to world agricultural production, and ultimately end up with 82 countries and regions.[2] After determining the countries in the model, our population and per capita income shifters $\hat{H}_i$ and $\hat{g}_i$ are calculated directly from the five Shared Socioeconomic Pathways (SSPs; Riahi et al., 2017). We use the OECD Env-Growth GDP projections (Dellink et al., 2017) and the corresponding IIASA–WiC population projections (Kc and Lutz, 2017). For crops, the model attempts to discuss all of those used in food production, but also aggregate some of them if they take small shares in both land and value. The full lists of countries and crops included in the model are provided in Appendix A.

The food categories in the model refer to those discussed in Gouel and Guimbard (2019). Separating the "oils & fats" category into vegetal- and animal-based subgroups, the model includes 5 vegetal-based categories, "starchy staples," "sweeteners," "other foods," "vegetables & fruits," and "vegetal oils & fats," gathered in the set $\mathcal{N}^V$, and 3 animal-based ones, "meat & seafood," "dairy," and "animal oils & fats," gathered in the set $\mathcal{N}^A$.

[2]For example, Hong Kong is put together with the Chinese mainland, and Singapore is put together with Malaysia.

2.3 Preferences and demand

Each country i has N_i identical consumers with individual utility function over foods and a numeraire good of the following form:

$$U_i = C_i^0 + (\beta_i)^{\frac{1}{\epsilon_i}} \frac{(C_i)^{1-\frac{1}{\epsilon_i}}}{1-\frac{1}{\epsilon_i}} ,$$

where $0 < \epsilon_i < 1$, $\beta_i > 0$ captures consumers' preference strength for food, C_i^0 denotes the quantity of numeraire, and C_i is defined as a constant-elasticity-of-substitution (CES) aggregate over the $N = 8$ food categories (C_i^n) discussed in Gouel and Guimbard (2019):[3]

$$C_i \equiv \left[\sum_n (\beta_i^n)^{\frac{1}{\sigma_i}} \left(U_i^{\varepsilon_i^n} \right)^{\frac{1}{\sigma_i}} (C_i^n)^{\frac{\sigma_i - 1}{\sigma_i}} \right]^{\frac{\sigma_i}{\sigma_i - 1}} , \tag{1}$$

where $\sigma_i > 0$ denotes the elasticity of substitution among food categories, and $\beta_i^n > 0$ captures consumer i's relative strength of preference for food category n to others. Non-homotheticity and income effects are introduced here with endogenous preference weight $U_i^{\varepsilon_i^n}$ for each food category as in Corrêa-Dias, Norris, and Pellegrina (2026), while ε_i^n controls the income elasticity of food n.

Because U_i is implicitly defined, we derive the Hicksian rather than the Walrasian demand function. We denote by P_i^n the price of food category n in region i and by $\mathbf{P}_i \equiv \left(P_i^1, \ldots, P_i^N\right)$ the corresponding price vector. The expenditure minimization problem then reads:

$$\min_{C_i^0,\, C_i^1, \ldots, C_i^N \geq 0} \; C_i^0 + \sum_n P_i^n C_i^n \qquad \text{s.t.} \qquad C_i^0 + (\beta_i)^{\frac{1}{\epsilon_i}} \frac{(C_i(U_i))^{1-\frac{1}{\epsilon_i}}}{1-\frac{1}{\epsilon_i}} \geq U_i,$$

Solving the first-order condition, we obtain $C_i^n = (\beta_i)^{\frac{\sigma_i}{\epsilon_i}} \; C_i^{1-\frac{\sigma_i}{\epsilon_i}} \; \beta_i^n \, U_i^{\varepsilon_i^n} \, (P_i^n)^{-\sigma_i}$. Substituting it back into Equation (1), we end up with a closed-form Hicksian demand function for C_i:

$$C_i(\mathbf{P}_i, U_i) = \beta_i \, (P_i)^{-\epsilon_i} , \tag{2}$$

[3]The utility function is only seemingly quasi-linear: since the aggregate C_i depends on U_i through the endogenous preference weights introduced below, the utility level U_i is implicitly defined, as in Comin, Lashkari, and Mestieri (2021).

where P_i is a food price index defined as

$$P_i(\mathbf{P}_i, U_i) \equiv \left[\sum_n \beta_i^n U_i^{\varepsilon_i^n} \left(P_i^n\right)^{1-\sigma_i} \right]^{\frac{1}{1-\sigma_i}} . \tag{3}$$

One can subsequently plug Equation (2) back into the first-order condition to obtain the closed-form Hicksian demand function for each food category:

$$C_i^n(\mathbf{P}_i, U_i) = \beta_i \beta_i^n U_i^{\varepsilon_i^n} \left(P_i\right)^{\sigma_i - \epsilon_i} \left(P_i^n\right)^{-\sigma_i} . \tag{4}$$

It is easy to check that $P_i C_i = \sum_n P_i^n C_i^n$. Equation (4) also serves to interpret the parameter ϵ_i: because $C_i^n(\lambda \mathbf{P}_i, U_i) = \lambda^{-\epsilon_i} C_i^n(\mathbf{P}_i, U_i)$, ϵ_i represents the elasticity of individual food demand with respect to a proportional increase in all food prices, holding utility constant. The expenditure function can be computed as

$$e_i(\mathbf{P}_i, U_i) = U_i + \frac{\beta_i P_i(\mathbf{P}_i, U_i)^{1-\epsilon_i}}{1-\epsilon_i} .$$

By duality, one can obtain the indirect utility function by solving for U_i in the following fixed-point equation, given per capita income Y_i and food prices $\mathbf{P}_i$:

$$U_i = Y_i - \frac{\beta_i P_i(\mathbf{P}_i, U_i)^{1-\epsilon_i}}{1-\epsilon_i} . \tag{5}$$

2.4 Food production

Each country uses its own technology to produce food products Q_i^n from crops and then trades these foods with other countries to construct a national supply of food category X_i^n for both domestic human consumption and industrial/non-food use.

For each food category, we assume its domestic production combines crops and a composite input per a Leontief technology:

$$Q_i^n = \min\left(Z_i^n, \frac{N_i^n}{\nu_i^n} \right),$$

where N_i^n is the labor use, $\nu_i^n > 0$ is the labor use per unit of output, and Z_i^n is defined as a CES crop aggregator:

$$Z_i^n = \left[\sum_l \left(\gamma_i^{nl}\right)^{\frac{1}{\zeta^n}} \left(Z_i^{nl}\right)^{\frac{\zeta^n - 1}{\zeta^n}} \right]^{\frac{\zeta^n}{\zeta^n - 1}} ,$$

where Z_i^{nl} is crop l used for food n's production and ζ^n is the elasticity of substitution among crops for food category n. Note that the usage Z_i^{nl} of crop l refers to the crop aggregate across all origin countries, rather than being limited to that domestically produced. γ_i^{nl} represents the share of each input crop. Denoting the price of Z_i^{nl} as v_i^l, cost minimization implies that

$$Q_i^n = Z_i^n, \tag{6}$$

$$Z_i^{nl} = \gamma_i^{nl}(\frac{v_i^l}{V_i^n})^{-\zeta^n} Z_i^n, \tag{7}$$

$$V_i^n = \left[\sum_l \gamma_i^{nl} \left(v_i^l\right)^{1-\zeta^n}\right]^{\frac{1}{1-\zeta^n}} , \tag{8}$$

where V_i^n represents the price of the aggregate crop Z_i^n. Denoting the price of labor as w_i, which is held fixed throughout our counterfactuals, the market price of food n produced in region i should exhaust its production cost, that is:

$$p_i^n = V_i^n + w_i \nu_i^n \ . \tag{9}$$

2.5 Trade of food categories and crops

As discussed before, our model allows for quality/taste differences and other types of implicit heterogeneity across food categories produced in different origin countries. Here, X_i^n is represented as an Armington aggregator over product n coming from different origin countries:

$$X_i^n = \left[\sum_j \left(\beta_{ji}^n\right)^{\frac{1}{\lambda_i^n}} \left(X_{ji}^n\right)^{\frac{\lambda_i^n - 1}{\lambda_i^n}}\right]^{\frac{\lambda_i^n}{\lambda_i^n - 1}} ,$$

where X_{ji}^n represents total use (both food and non-food) of food category n coming from region j, λ_i^n is the elasticity of substitution across different origin regions for a given food category n, and β_{ji}^n is a substitution parameter reflecting the strength of country i's reliance on a given origin j, conditional on the food category. Denote the market price of food category n produced in region j as p_j^n, cost minimization gives the following relationship with iceberg trade costs $\tau_{ji}^n \geq 1$:

$$X_{ji}^n = \beta_{ji}^n (\frac{\tau_{ji}^n p_j^n}{P_i^n})^{-\lambda_i^n} X_i^n \ , \tag{10}$$

$$P_i^n = \left[\sum_j \beta_{ji}^n \left(\tau_{ji}^n p_j^n\right)^{1-\lambda_i^n}\right]^{\frac{1}{1-\lambda_i^n}} . \tag{11}$$

Similarly, we construct X_i^l as the total availability of crop l in country i, which can be used for production of food and non-food products. We follow Gouel and Laborde (2021) and assume "grass" is not tradable; formally, $\beta_{ji}^g = 0$ for all $j \neq i$, so grass available in country i is entirely domestically produced. In the model, crops from different origins can substitute each other in production with a constant elasticity of substitution κ_i^l. Formally, X_i^l is an Armington aggregator:

$$X_i^l = \left[\sum_{j \in \mathcal{I}} \left(\beta_{ji}^l\right)^{\frac{1}{\kappa_i^l}} \left(X_{ji}^l\right)^{\frac{\kappa_i^l - 1}{\kappa_i^l}} \right]^{\frac{\kappa_i^l}{\kappa_i^l - 1}},$$

where X_{ji}^l denotes the physical quantity of crop l used in region i that is originally from region j, and β_{ji}^l is the substitution parameter.

Assuming iceberg trade costs $\tau_{ji}^l \geq 1$ and denoting the price of crop l from country j as q_j^l, cost minimization also implies that

$$X_{ji}^l = \beta_{ji}^l \left(\frac{\tau_{ji}^l q_j^l}{v_i^l}\right)^{-\kappa_i^l} X_i^l, \tag{12}$$

$$v_i^l = \left[\sum_j \beta_{ji}^l \left(\tau_{ji}^l q_j^l\right)^{1-\kappa_i^l} \right]^{\frac{1}{1-\kappa_i^l}}, \tag{13}$$

where v_i^l represents the price of the Armington aggregated crop l in region i.

2.6 Crop production and land allocation

We assume a fixed land base $L_i > 0$ is used for crop and grass production in each country i, which can be further divided into a continuum of parcels ω. Fixing the land base rules out conversion between agricultural and non-agricultural land, so land-use adjustments in the model occur only through reallocation across crops and grass within L_i. Except for grass, all crops require both land and labor for production:

$$Y_i^l(\omega) = \min\left(A_i^l(\omega), \frac{N_i^l(\omega)}{\nu_i^l} \right),$$

where $A_i^l(\omega)$ is crop l's yield on parcel ω in region i, $N_i^l(\omega)$ is the amount of labor used on that parcel, and ν_i^l denotes the labor required per unit of output. Cost minimization implies $Y_i^l(\omega) = A_i^l(\omega) = \frac{N_i^l(\omega)}{\nu_i^l}$. Consequently, we can represent the land rent conditional on growing

crop l as

$$r_i^l = q_i^l - w_i \nu_i^l \ , \tag{14}$$

under the zero-profit assumption. For the labor-free crop, grass (g), we simply have $Y_i^g(\omega) = A_i^g(\omega)$ and

$$r_i^g = q_i^g \ , \tag{15}$$

The model setup thus captures the fact that as long as the revenue of growing a crop is smaller than the natural output value of grass, a rational farmer will grow grass.

Crop yields in all parcels ($A_i^l(\omega)$) within the same land base L_i are independently drawn from the same Fréchet distribution

$$\Pr\left[A_i^l(\omega) \leq a^l\right] = \exp\left\{-\eta_i \left(\frac{a^l}{A_i^l}\right)^{-\theta_i}\right\} \ .$$

where $\eta_i = \left[\Gamma(1 - \frac{1}{\theta_i})\right]^{-\theta_i}$ guarantees that $A_i^l = \mathbb{E}\left[A_i^l(\omega)\right]$ denotes the unconditional yield of crop l in region i, and the shape parameter $\theta_i > 1$ captures parcel heterogeneity. To determine the land allocation, a crop will be grown on a given land parcel only if it generates the largest net revenue. Its final share in the land base L_i is exactly its probability of having the largest return:

$$\pi_i^l = \Pr\left[r_i^l A_i^l(\omega) = \max_{l'} r_i^{l'} A_i^{l'}(\omega)\right] = \frac{(r_i^l A_i^l)^{\theta_i}}{\sum_{l'}(r_i^{l'} A_i^{l'})^{\theta_i}} \ . \tag{16}$$

As we see in the land allocation formula, $\theta_i \to \infty$ exaggerates the difference in profits for different crops and induces dominance of one crop grown in the land base L_i. By contrast, $\theta_i \to 1$ captures extreme land heterogeneity where each crop will be grown. Given the land allocation, one can derive the country-level crop supply function:

$$Y_i^l = L_i \pi_i^l \mathbb{E}\left[A_i^l(\omega) \mid r_i^l A_i^l(\omega) = \max_{l'} r_i^{l'} A_i^{l'}(\omega)\right] = L_i A_i^l (\pi_i^l)^{1-\frac{1}{\theta_i}} \ . \tag{17}$$

2.7 Manufacturing sector and national income

We assume that each country i has a manufacturing sector that produces the numeraire good using labor alone:

$$Q_i^0 = \frac{N_i^0}{\nu_i^0} \ ,$$

where Q_i^0 is the total output of the numeraire good, N_i^0 is the total labor used in manufacturing, and ν_i^0 is the labor use per unit of output. The numeraire is freely traded (no

iceberg costs) and its price is 1 everywhere. With the zero-profit assumption, the following condition holds in each country:

$$w_i \nu_i^0 = 1 \ . \tag{18}$$

The manufacturing sector, together with the food and crop sectors, should exhaust all "labor" endowment available in country i, which we denote as N_i:

$$\nu_i^0 Q_i^0 + \sum_n \nu_i^n Q_i^n + \sum_l \nu_i^l Y_i^l = N_i \tag{19}$$

Capturing all factors except land, changes to the income of this endowment $w_i L_i$ serve as the exogenous shock in the counterfactual scenarios. Finally, the total return to the composite input "labor" and land constitutes the national income of an economy i:

$$H_i Y_i = w_i N_i + \sum_l r_i^l Y_i^l \ . \tag{20}$$

2.8 Equilibrium in levels

Market clearing (foods and crops) The model addresses non-food demand at both food and crop levels. We introduce H_i to denote the total population in country i, and W_i^n and W_i^l to represent the non-food/industrial use of food n and crop l, respectively, in country i, to account for the foods and crops leaving the food consumption/production system. Since we assume crops are traded, the following market-clearing conditions are necessary:

$$X_i^n = H_i C_i^n + W_i^n \ , \tag{21}$$

$$Q_i^n = \sum_j \tau_{ij}^n X_{ij}^n \ , \tag{22}$$

$$X_i^l = \sum_n Z_i^{nl} + W_i^l \ , \tag{23}$$

$$Y_i^l = \sum_j \tau_{ij}^l X_{ij}^l \ . \tag{24}$$

Equations (22) and (24) indicate that region i's production of food n and crop l should be distributed in full amount to all regions. Equation (21) means all available food n should be either consumed as food or used for non-food production. Equation (23) means that all crop l available in region i should be utilized to produce either different food categories or other non-food products. One should note that H_i, W_i^n and W_i^l are exogenous in the model, that is, they do not serve as variables in the equilibrium. Treating non-food use as

exogenous makes it perfectly price-inelastic; this is a simplification for uses such as biofuel, whose demand may, in practice, respond to prices of certain agricultural products. For this paper, we assume that W_i^n and W_i^l are fixed at the base year level.

Market clearing (numeraire good) Assuming that the non-food uses W_i^n and W_i^l are bought at market prices by a competitive activity that turns them into numeraire goods of equivalent values and sells them with no markup, total consumption of the numeraire good in country i can be represented as

$$H_i C_i^0 = Q_i^0 + \sum_n P_i^n W_i^n + \sum_l v_i^l W_i^l + X_i^0 \ , \tag{25}$$

with X_i^0 capturing net imports of the numeraire good. As proved in Appendix D, X_i^0 equals the net export value of foods and crops:

$$X_i^0 = \sum_n \left(p_i^n Q_i^n - P_i^n X_i^n \right) + \sum_l \left(q_i^l Y_i^l - v_i^l X_i^l \right) \ . \tag{26}$$

Also, the condition $\sum_i X_i^0 = 0$ is automatically satisfied such that each country's overall trade is balanced.

Equilibrium Equations (2)–(26) together define a competitive equilibrium including U_i, C_i^0, Q_i^0, X_i^0, C_i, P_i, C_i^n, X_i^n, P_i^n, X_{ji}^n, p_j^n, Q_i^n, Z_i^n, V_i^n, Z_i^{nl}, X_i^l, v_i^l, X_{ji}^l, q_j^l, Y_i^l, π_i^l, r_i^l, w_i.

2.9 Equilibrium in relative changes

We consider the counterfactual case where both population H_i and the composite input "labor"'s per capita income $g_i \equiv \frac{w_i N_i}{H_i}$ change exogenously per five Shared Socioeconomic Pathways (SSPs). Following previous work, we denote the new equilibrium value of a variable using a "prime" and the relative change using a "hat." For example, $\hat{P}_i \equiv \frac{P_i'}{P_i}$ defines the relative change in P_i as the ratio of its new equilibrium value to its original one.

The relative changes in the composite factor's income ($\hat{w}_i \hat{N}_i$) and population ($\hat{H}_i$) , which are treated as exogenous, cause endogenous changes in food/crop prices and quantities. All other primitives are held constant across counterfactuals: iceberg trade costs τ_{ji}^n and τ_{ji}^l, origin-preference parameters β_{ji}^n and β_{ji}^l (for which we have no empirical basis to project future changes), and all substitution and demand elasticities. We characterize such changes using a system of equations, classified into three subgroups, plus one that addresses utility

changes. The first set of equations represents the food consumption and market clearing:

$$\hat{C}_i^n = \left(\hat{P}_i\right)^{\sigma_i - \epsilon_i} \left(\hat{P}_i^n\right)^{-\sigma_i} \hat{U}_i^{\varepsilon_i^n} \qquad I \times N \tag{27}$$

$$\hat{X}_i^n = (1 - h_i^n)\hat{H}_i \hat{C}_i^n + h_i^n \qquad I \times N \tag{28}$$

$$\hat{X}_{ji}^n = (\frac{\hat{p}_j^n}{\hat{P}_i^n})^{-\lambda_i^n} \hat{X}_i^n \qquad I \times I \times N \tag{29}$$

$$\hat{Q}_i^n = \sum_j a_{ij}^n \hat{X}_{ij}^n \qquad I \times N \tag{30}$$

$$\hat{P}_i = \left(\sum_n b_i^n \hat{U}_i^{\varepsilon_i^n} \left(\hat{P}_i^n\right)^{1-\sigma_i}\right)^{\frac{1}{1-\sigma_i}} \qquad I \tag{31}$$

$$\hat{P}_i^n = \left(\sum_j b_{ji}^n \left(\hat{p}_j^n\right)^{1-\lambda_i^n}\right)^{\frac{1}{1-\lambda_i^n}} \qquad I \times N \tag{32}$$

The second set of equations describes food production and derived demand for crops:

$$\hat{X}_i^l = \sum_n (1 - h_i^l) s_i^{nl} \left(\frac{\hat{v}_i^l}{\hat{V}_i^n}\right)^{-\zeta^n} \hat{Q}_i^n + h_i^l \hat{W}_i^l \qquad I \times L \tag{33}$$

$$\hat{V}_i^n = \left(\sum_l c_i^{nl} \left(\hat{v}_i^l\right)^{1-\zeta^n}\right)^{\frac{1}{1-\zeta^n}} \qquad I \times N \tag{34}$$

$$\hat{p}_i^n = \psi_i^n \hat{V}_i^n + (1 - \psi_i^n)\hat{w}_i \hat{\nu}_i^n \qquad I \times N \tag{35}$$

$$\hat{v}_i^l = \left(\sum_j \alpha_{ji}^l \left(\hat{q}_j^l\right)^{1-\kappa_i^l}\right)^{\frac{1}{1-\kappa_i^l}} \qquad I \times L \tag{36}$$

The third set of equations is about cropping and trade of crops:

$$\hat{q}_i^g = \hat{r}_i^g \qquad I \times 1 \tag{37}$$

$$\hat{q}_i^l = \varphi_i^l \hat{r}_i^l + (1 - \varphi_i^l)\hat{w}_i \hat{\nu}_i^l \qquad I \times (L-1) \tag{38}$$

$$\hat{Y}_i^l = \sum_j \rho_{ij}^l \left(\frac{\hat{q}_i^l}{\hat{v}_j^l}\right)^{-\kappa_j^l} \hat{X}_j^l \qquad I \times L \tag{39}$$

$$\hat{Y}_i^l = \left(\hat{\pi}_i^l\right)^{1-\frac{1}{\theta_i}} \qquad I \times L \tag{40}$$

$$\hat{\pi}_i^l = \frac{\left(\hat{r}_i^l\right)^{\theta_i}}{\sum_{l'} \pi_i^{l'} \left(\hat{r}_i^{l'}\right)^{\theta_i}} \qquad I \times L \tag{41}$$

The fourth set of equations clears the market for the composite input "labor" and closes the

model with changes in per capita income and utility:

$$\hat{w}_i \hat{N}_i = \ell_i^0 \hat{w}_i \hat{\nu}_i^0 \hat{Q}_i^0 + \sum_n \ell_i^n \hat{w}_i \hat{\nu}_i^n \hat{Q}_i^n + \sum_l \ell_i^l \hat{w}_i \hat{\nu}_i^l \hat{Y}_i^l \qquad I \qquad (42)$$

$$\frac{\hat{Y}_i}{\tilde{b}_i} = (\frac{1}{\tilde{b}_i} - \frac{1}{1-\epsilon_i})\hat{U}_i + \frac{(\hat{P}_i)^{1-\epsilon_i}}{1-\epsilon_i} \qquad I \qquad (43)$$

$$\frac{\hat{Y}_i}{\tilde{b}_i} = (\frac{1}{\tilde{b}_i} - \varphi_i \delta_i)\frac{\hat{w}_i \hat{N}_i}{\hat{H}_i} + \varphi_i \delta_i \frac{\sum_l \pi_i^l \hat{r}_i^l \hat{Y}_i^l}{\hat{H}_i} \qquad I \qquad (44)$$

We introduce several key share parameters above. At the food category level, $b_i^n \equiv \frac{P_i^n C_i^n}{P_i C_i}$ is the budget share of food n in total food consumption in country i; $h_i^n = \frac{W_i^n}{X_i^n}$ is the share of food product n for non-food use in country i; $b_{ji}^n \equiv \frac{\tau_{ji}^n p_j^n X_{ji}^n}{P_i^n X_i^n}$ is the share of food n from country j in total use of food n in country i; and $a_{ij}^n \equiv \frac{\tau_{ij}^n X_{ij}^n}{Q_i^n}$ is the share of country i's food n production exported to country j.

At the crop processing stage, $c_i^{nl} \equiv \frac{v_i^l Z_i^{nl}}{V_i^n Z_i^n}$ is the share of crop l in the total crop cost of food n in country i; $s_i^{nl} \equiv \frac{Z_i^{nl}}{X_i^l - W_i^l}$ is the share of food n in the food use of crop l in country i; $\psi_i^n \equiv \frac{V_i^n}{p_i^n}$ is the crop share of a dollar spent on food n in country i; and $h_i^l = \frac{W_i^l}{X_i^l}$ is the share of crop l used for non-food production in country i.

At the crop level, $\alpha_{ji}^l \equiv \frac{\tau_{ji}^l q_j^l X_{ji}^l}{v_i^l X_i^l}$ is the share of crop l originating from country j in total expenditure on crop l in country i; $\rho_{ij}^l \equiv \frac{\tau_{ij}^l X_{ij}^l}{Y_i^l}$ is the share of country i's crop l production exported to country j; and $\varphi_i^l \equiv \frac{r_i^l}{q_i^l}$ is the ratio of land rent to the price of crop l in country i.

Regarding the composite input market, $\ell_i^n \equiv \frac{\nu_i^n Q_i^n}{N_i}$ is the share of labor used in production of food n, $\ell_i^l \equiv \frac{\nu_i^l Y_i^l}{N_i}$ is the share of labor used in production of crop l, and $\ell_i^0 \equiv \frac{\nu_i^0 Q_i^0}{N_i}$ is the share of labor used in the manufacturing sector.

For per capita income and utility, $\tilde{b}_i \equiv \frac{P_i C_i}{Y_i}$ represents share of food budget in total expenditure in country i, $\varphi_i \equiv \frac{\sum_l r_i^l Y_i^l}{\sum_l q_i^l Y_i^l}$ represents country i's overall land share of a crop dollar, and $\delta_i \equiv \frac{\sum_l q_i^l Y_i^l}{H_i \sum_n P_i^n C_i^n}$ represents country i's ratio of crop production value to food consumption value. Equations (43) and (44) hence relate endogenous variables $\hat{U}_i$, $\hat{Y}_i$, $\hat{P}_i$, $\hat{r}_i^l$, and $\hat{Y}_i^l$ with exogenous income and population shifters $\hat{g}_i = \frac{\hat{w}_i \hat{N}_i}{\hat{H}_i}$ and $\hat{H}_i$.

Across the system of equations, $\hat{w}_i$ captures the change in unit return to composite input, and $\hat{\nu}_i^n$, $\hat{\nu}_i^l$, and $\hat{\nu}_i^0$ measure productivity changes in the food, crop, and manufacturing sectors. Since the numeraire is always sold at the price of 1, we have $\hat{w}_i \hat{\nu}_i^0 \equiv \frac{w_i \nu_i^{0\prime}}{w_i \nu_i^0} = 1$. If we assume the composite input's productivity in agricultural sectors grows as fast as in the manufacturing sector, i.e., $\hat{\nu}_i^n = \hat{\nu}_i^l = \hat{\nu}_i^0$, the terms $\hat{w}_i \hat{\nu}_i^n$ and $\hat{w}_i \hat{\nu}_i^l$ in Equations (35) and (38)

reduce to 1. Also, Equation (42) becomes

$$\hat{w}_i \hat{N}_i = \ell_i^0 \hat{Q}_i^0 + \sum_n \ell_i^n \hat{Q}_i^n + \sum_l \ell_i^l \hat{Y}_i^l \ . \tag{45}$$

We present our main results under the sector-neutral productivity growth assumption, which replicates the results of a partial-equilibrium model where the composite input is supplied with perfect elasticity at a constant price. Under the assumption, $\hat{w}_i$ and $\hat{N}_i$ never enter the system separately. All remaining conditions depend on them only through the factor income growth $\hat{w}_i \hat{N}_i = \hat{g}_i \hat{H}_i$ calibrated from the SSP scenarios.

We also study cases with uneven productivity growth in further counterfactual analysis. In such cases, we need to specify how N_i and its price w_i move individually and report two boundary cases. We first take $\hat{N}_i = \hat{H}_i$, so the composite input supply grows proportionally to population. Our second case detaches N_i from population change and fixes it at the base year level.

Equilibrium in relative changes Equations (27)–(44) together define a competitive equilibrium including $\hat{U}_i$, $\hat{Y}_i$, $\hat{Q}_i^0$, $\hat{C}_i^n$, $\hat{X}_i^n$, $\hat{P}_i$, $\hat{X}_{ji}^n$, $\hat{P}_i^n$, $\hat{p}_i^n$, $\hat{Q}_i^n$, $\hat{V}_i^n$, $\hat{X}_i^l$, $\hat{v}_i^l$, $\hat{Y}_i^l$, $\hat{q}_i^l$, $\hat{r}_i^l$, and $\hat{\pi}_i^l$. The system has as many equations as unknowns.

2.10 Counterfactual welfare effects

Given relative changes in key endogenous variables, we calculate the counterfactual welfare changes in terms of Compensating Variation (CV) and producer surplus. As in previous work, we present these changes as the ratio of differences in welfare measures to some normalizing base values for clearer economic interpretation. We also present the change in the ratio of food expenditure to per capita income for each country as a further measure of food security, which is a direct expression of the Engel curve for food.

Compensating Variation The model aims to capture the welfare implications of the nutrition transition driven by an exogenous per capita income increase for each country. Accordingly, our analysis first measures per capita CV, as growth in a country's total welfare can also be driven by population increases.

For each individual, the new per capita income level Y_i' should reflect both the exogenous change in non-land factor income $w_i N_i$ and the endogenous changes in land rent $\mathrm{LR}_i = \sum_l r_i^l Y_i^l$:

$$Y_i' - Y_i = \left(\frac{w_i' N_i'}{H_i'} - \frac{w_i N_i}{H_i}\right) + \left(\frac{\mathrm{LR}_i'}{H_i'} - \frac{\mathrm{LR}_i}{H_i}\right) \ .$$

Using the definition $CV \equiv e(\mathbf{P}', U') - e(\mathbf{P}', U) = Y' - e(\mathbf{P}', U)$, we calculate the per capita

Compensating Variation CV_i under our model setup as

$$\begin{aligned}
CV_i &= (Y_i' - Y_i) + \frac{\beta_i}{1-\epsilon_i}\Big[P_i(\mathbf{P}_i, U_i)^{1-\epsilon_i} - P_i(\mathbf{P}_i', U_i)^{1-\epsilon_i}\Big] \\
&= (\frac{w_i' N_i'}{H_i'} - \frac{w_i N_i}{H_i}) + (\frac{\sum_l r_i^{l'} Y_i^{l'}}{H_i'} - \frac{\sum_l r_i^l Y_i^l}{H_i}) + \frac{\beta_i P_i(\mathbf{P}_i, U_i)^{1-\epsilon_i}}{1-\epsilon_i}\Big[1 - \frac{P_i(\mathbf{P}_i', U_i)^{1-\epsilon_i}}{P_i(\mathbf{P}_i, U_i)^{1-\epsilon_i}}\Big] \\
&= \frac{w_i N_i}{H_i}(\frac{\hat{w}_i \hat{N}_i}{\hat{H}_i} - 1) + \frac{\sum_l r_i^l Y_i^l}{H_i}(\sum_l \frac{\pi_i^l \hat{r}_i^l \hat{Y}_i^l}{\hat{H}_i} - 1) + \frac{P_i C_i}{1-\epsilon_i}\Big[1 - \left(\sum_n b_i^n \left(\hat{P}_i^n\right)^{1-\sigma_i}\right)^{\frac{1-\epsilon_i}{1-\sigma_i}}\Big] .
\end{aligned}$$

Normalizing the term with respect to the base year per capita income Y_i yields

$$\frac{CV_i}{Y_i} = \underbrace{(1 - \tilde{b}_i \varphi_i \delta_i)(\frac{\hat{w}_i \hat{N}_i}{\hat{H}_i} - 1)}_{\Delta\text{composite factor income}} + \underbrace{\tilde{b}_i \varphi_i \delta_i (\frac{\pi_i^l \hat{r}_i^l \hat{Y}_i^l}{\hat{H}_i} - 1)}_{\substack{\Delta \text{ land rents} \\ \text{(producer surplus)}}} + \underbrace{\frac{\tilde{b}_i}{1-\epsilon_i}\left(1 - (\tilde{P}_i)^{1-\epsilon_i}\right)}_{\substack{\Delta\text{compensating variation} \\ \text{(holding income constant)}}} , \tag{46}$$

where $\tilde{P}_i = \left(\sum_n b_i^n \left(\hat{P}_i^n\right)^{1-\sigma_i}\right)^{\frac{1}{1-\sigma_i}}$ captures the food price changes under the baseline year's preference ($\hat{U}_i = 1$). This equation provides a clean decomposition of the CV: the first two terms exactly capture the total income changes as in Equation (44), and the last term measures CV changes purely due to food price changes.

Equivalent Variation The Compensating Variation values the price change at the base-year utility level. Its counterpart, the Equivalent Variation, values it at the counterfactual utility level. Using the definition $EV \equiv e(\mathbf{P}, U') - e(\mathbf{P}, U) = e(\mathbf{P}, U') - Y$ together with $Y' = e(\mathbf{P}', U')$, we calculate the per capita Equivalent Variation EV_i under our model setup as

$$\begin{aligned}
EV_i &= (Y_i' - Y_i) + \frac{\beta_i}{1-\epsilon_i}\Big[P_i(\mathbf{P}_i, U_i')^{1-\epsilon_i} - P_i(\mathbf{P}_i', U_i')^{1-\epsilon_i}\Big] \\
&= (\frac{w_i' N_i'}{H_i'} - \frac{w_i N_i}{H_i}) + (\frac{\sum_l r_i^{l'} Y_i^{l'}}{H_i'} - \frac{\sum_l r_i^l Y_i^l}{H_i}) + \frac{\beta_i P_i(\mathbf{P}_i', U_i')^{1-\epsilon_i}}{1-\epsilon_i}\Big[\frac{P_i(\mathbf{P}_i, U_i')^{1-\epsilon_i}}{P_i(\mathbf{P}_i', U_i')^{1-\epsilon_i}} - 1\Big] \\
&= \frac{w_i N_i}{H_i}(\frac{\hat{w}_i \hat{N}_i}{\hat{H}_i} - 1) + \frac{\sum_l r_i^l Y_i^l}{H_i}(\sum_l \frac{\pi_i^l \hat{r}_i^l \hat{Y}_i^l}{\hat{H}_i} - 1) + \frac{P_i' C_i'}{1-\epsilon_i}\Big[\left(\sum_n b_i^{n\prime} \left(\frac{1}{\hat{P}_i^n}\right)^{1-\sigma_i}\right)^{\frac{1-\epsilon_i}{1-\sigma_i}} - 1\Big] ,
\end{aligned}$$

where $P_i' C_i' = \beta_i P_i(\mathbf{P}_i', U_i')^{1-\epsilon_i}$ is the counterfactual per capita food expenditure and $b_i^{n\prime} \equiv \frac{P_i^{n\prime} C_i^{n\prime}}{P_i' C_i'} = b_i^n \hat{U}_i^{\varepsilon_i^n} (\hat{P}_i^n)^{1-\sigma_i} / (\hat{P}_i)^{1-\sigma_i}$ is the counterfactual budget share of food n in total food consumption.

Normalizing the term with respect to the counterfactual per capita income $Y_i' = Y_i \hat{Y}_i$,

with $\hat{Y}_i$ given by Equation (44), yields

$$\frac{EV_i}{Y_i'} = \underbrace{\frac{(1-\tilde{b}_i\varphi_i\delta_i)}{\hat{Y}_i}\left(\frac{\hat{w}_i\hat{N}_i}{\hat{H}_i}-1\right)}_{\Delta\text{composite factor income}} + \underbrace{\frac{\tilde{b}_i\varphi_i\delta_i}{\hat{Y}_i}\left(\sum_l \frac{\pi_i^l\hat{r}_i^l\hat{Y}_i^l}{\hat{H}_i}-1\right)}_{\substack{\Delta\text{ land rents}\\(\text{producer surplus})}} + \underbrace{\frac{\tilde{b_i}'}{1-\epsilon_i}\left((\check{P}_i)^{\epsilon_i-1}-1\right)}_{\substack{\Delta\text{equivalent variation}\\(\text{holding income constant})}}, \tag{47}$$

where $\tilde{b_i}' \equiv \frac{P_i'C_i'}{Y_i'} = \frac{\tilde{b}_i(\hat{P}_i)^{1-\epsilon_i}}{\hat{Y}_i}$ is the counterfactual food budget share and $\check{P}_i = \left(\sum_n b_i^{n\prime}\left(\hat{P}_i^n\right)^{\sigma_i-1}\right)^{\frac{1}{\sigma_i-1}}$ captures the food price changes under the counterfactual preference ($\hat{U}_i$ fixed at its new value), weighted by the counterfactual budget shares. This equation mirrors Equation (46) term by term: the first two terms are the same income changes, now measured against the counterfactual income; the last term measures EV changes purely due to food price changes, with the price index evaluated under the counterfactual preference ($\check{P}_i$) rather than the baseline one ($\tilde{P}_i$), and weighted by the counterfactual rather than the baseline food budget share.

Producer surplus In addition to per capita measurement as appeared in CV, we also calculate the total land rent change in country i with respect to its baseline value as

$$\frac{\Delta\text{LR}_i}{\text{LR}_i} = \hat{\text{LR}}_i - 1 = \sum_l \pi_i^l\hat{r}_i^l\hat{Y}_i^l - 1\ . \tag{48}$$

Compared to the baseline country-level food expenditure, the change in country i's land rents is

$$\frac{\Delta\text{LR}_i}{H_iP_iC_i} = \frac{\Delta\text{LR}_i}{\text{LR}_i}\frac{\text{LR}_i}{\sum_l q_i^lY_i^l}\frac{\sum_l q_i^lY_i^l}{H_i\sum_n P_i^nC_i^n} = \varphi_i\delta_i\left[\sum_l \pi_i^l\hat{r}_i^l\hat{Y}_i^l - 1\right], \tag{49}$$

A further aggregation over world food consumption gives

$$\frac{\sum_i \Delta\text{LR}_i}{\sum_j N_jP_jC_j} = \sum_i \frac{\Delta\text{LR}_i}{H_iP_iC_i}\frac{H_iP_iC_i}{\sum_j H_jP_jC_j} = \sum_i \varphi_i\delta_ib_i\left[\sum_l \pi_i^l\hat{r}_i^l\hat{Y}_i^l - 1\right].$$

Budget share on food Engel's Law proposes a decreasing budget share on food as a household's income rises. We here consider the food-expenditure-to-income ratio $\tilde{b_i} \equiv \frac{P_iC_i}{Y_i}$

as a measure of food security for country i, and compute it in the counterfactual case as

$$\tilde{b_i}' = \frac{P_i' C_i'}{Y_i'} = \frac{P_i C_i \hat{P}_i \hat{C}_i}{(Y_i - \frac{\mathrm{LR}_i}{H_i})\hat{Y}_i + \frac{\mathrm{LR}_i}{H_i}(\frac{\hat{\mathrm{LR}}_i}{\hat{H}_i} - 1)}$$
$$= \frac{\hat{P}_i \hat{C}_i}{(\frac{1}{\tilde{b}_i} - \varphi_i \delta_i)\hat{Y}_i + \varphi_i \delta_i (\frac{\hat{\mathrm{LR}}_i}{\hat{H}_i} - 1)} .$$

Comparing the counterfactual $\tilde{b_i}'$ to the baseline $\tilde{b_i}$, we can express each country's relative change in their budget share on food as

$$\hat{\tilde{b}}_i = \frac{\tilde{b_i}'}{\tilde{b_i}} = \frac{\hat{P}_i \hat{C}_i}{(1 - \tilde{b_i}\varphi_i \delta_i)\hat{Y}_i + \tilde{b_i}\varphi_i \delta_i (\frac{\hat{\mathrm{LR}}_i}{\hat{H}_i} - 1)} . \tag{50}$$

3 Data and Model Calibration

This section describes the data used for calibration and then discusses two classes of parameters in the equilibrium in relative changes. The first class is inherited from the equilibrium in levels: elasticities that capture the essence of food demand and production. The second contains the share parameters introduced in Section 2.9. These shares are inherently related, and some can be deduced from others through market-clearing identities.

3.1 Data

We draw on a varied set of sources for information on quantities, trade flows, prices, and expenditure and factor-income structures. All data except GTAP ones are averaged over 2010–2012 to smooth out noise from particular weather events and measurement errors, the same window as in Gouel and Guimbard (2019), and are aggregated to the 82 countries and composite regions of the model.

Quantity and land acres. Commodity balances come from the FAOSTAT Supply Utilization Accounts (SUA) (FAO, 2024), which report production, trade, food supply, feed, processing, seed, losses, and other (non-food) uses in product tonnes for about 475 products. This granularity is essential for our purposes, as we need to know not only how much wheat a country grows, but how much of it becomes flour, how much of the flour is eaten, and how much bran returns to the feed market. It is also the reason we prefer the SUA over the more commonly used Food Balance Sheet (FBS), which converts processed products into primary equivalents and is not transparent (Zhao et al., 2025). The FBS is retained only where

the SUA lacks coverage, mostly in cases for fish and seafood. Production quantities and harvested areas of primary crops come from the FAOSTAT "Crops and livestock products" domain.

Commodity classification. Every commodity must be assigned to the crop side or the food side of the model, and the assignment matters because animal food categories in the model rely only on feed use of the crop commodities. We thus adopt a "feed rule": a processed product with animal feed use (soybean cake, rice bran, etc) is classified as a crop commodity, while one without (bread, wheat flour, soybean oil, husked rice) is classified as a food commodity. Tracking the data, processed products classified as crops send 73 percent of their world use to animal feed in the SUA accounts (over 90 percent for oil cakes and brans), while products classified as foods send only about 4 percent. Six milling products (maize and sorghum flours, potato flour and flakes, rolled oats, pearled barley, and the residual cereal flours) carry small feed entries, each below 4 percent of the product's world use and mostly contributed by a single country, so we classify them as foods. Overall, the SUA products are aggregated to the 8 food categories and 76 model crops based on their classification.

Trade data. Bilateral trade values and quantities come from the CEPII BACI database (HS07, 2010–2012), available at the six-digit level of the Harmonized System. This paper aggregates the BACI trade data to match the level of FAO SUA items, and uses them for calibration of each food category's by-country-origin expenditure shares b^n_{ji}, each crop's by-destination exporting shares ρ^l_{ij}, and the trade unit values (TUVs) described below. For a small set of products whose official FAO–HS correspondence is unusable, the FAOSTAT detailed trade matrix substitutes for BACI at the FAO item level. Trade of each commodity goes to either trade of model food categories or model crops according to our proposed classification rule.

Price data. All quantities are converted into values with their country-specific prices. Producer prices come from the FAOSTAT "Producer Prices" domain, and trade unit values (TUVs) are computed from BACI as value over quantity. Both price series are screened against world medians to remove measurement errors. Because the same physical commodity carries different prices at the farm gate and at the border, we construct two prices for every country–item pair: a farm-gate price to value crop production and crop use, and a trade-based price to value the fraction consumed as food. Using a single price for both roles necessarily distorts one side of the accounts as a result of ruling out the value added from the farm gate to the wholesale level.

Table 1: Country-specific elasticities and land heterogeneity

Parameter	Definition	Source
ϵ_i	negative of the price elasticity of food demand	USDA
σ_i	elasticity of substitution among food categories	Gouel and Guimbard (2019)
ε_i^n	parameter controlling income elasticity of food category n	Gouel and Guimbard (2019)
λ_i^n	elasticity of substitution for food n across origin countries	GTAP
κ_i^l	elasticity of substitution for crop l across origin countries	GTAP
ζ^n	elasticity of substitution among crops in food n production	literature review (Table 2)
θ_i	land productivity heterogeneity measurement	Gouel and Laborde (2021)

GTAP Factor-income structures, such as the land rent share of a crop dollar and the crop share of a food category dollar, are calculated from GTAP version 11 (reference year 2011) with proper mapping to our countries. GTAP also supplies information to calculate the value and land share of grass for each country.

Income and counterfactual paths Three sources of GDP values are used. The food share of income, $\tilde{b_i}$, is calculated as the ratio of the FAOSTAT-based food consumption value described above to the FAOSTAT-documented GDP. Construction of counterfactual scenarios, instead, uses World Development Indicators (WDI) data on per capita GDP for 2010 as the baseline per capita income (as in Gouel and Guimbard (2019)), and the IIASA SSP database for the counterfactual paths, with ratio changes in GDP from the OECD Env-Growth model and population from IIASA-WiC.

3.2 Elasticities and land heterogeneity

Our equilibrium in relative changes features canceling out some model primitives (such as β_i^n and γ_i^{nl} in the CES structure) and focusing on CES elasticities capturing the substitution behavior of consumers and producers. We introduce our methods for these elasticities and land heterogeneity calibration in this section. Table 1 summarizes the definition of these parameters and the source data we use.

Food demand elasticities, ϵ_i and σ_i Regarding the two food demand elasticities, ϵ_i and σ_i, we assume constant numbers for each country despite their variation across income levels. For ϵ_i, Seale et al. (2003) and the subsequent USDA International Food Consumption Patterns dataset report compensated own-price elasticities for food demand for 144 countries. For σ_i, we derive a one-on-one mapping from per capita income to this elasticity with the MAIDADS demand system estimated in Gouel and Guimbard (2019), and take averages

under the baseline and counterfactual income levels for each country. Our method is rationalized as both ϵ_i and σ_i do not vary significantly with respect to local changes in national income levels. The reason why we do not use Gouel and Guimbard (2019) to estimate ϵ_i is their MAIDADS model's inflexibility in price elasticities. The implied ϵ_is there are mostly smaller than 0.3 and even as small as 0.03 for developed countries.

Income elasticity parameter, ε_i^n

We use predicted food consumption changes from Gouel and Guimbard (2019) to calibrate ε_i^n. Holding food prices constant, Gouel and Guimbard (2019) gives disaggregated food category consumption for all income levels. Therefore, we can use this information to compute values of $\hat{C}_i^n$ for each country-food combination, given the prediction in income level changes $\hat{Y}_i$.

Our first step is to compute the relative change in U_i resulted from income changes. Holding food prices P_i^n constant, Equations (27) and (31) imply that food consumption should change by the following ratio:

$$\hat{C}_i^n = \left(\hat{P}_i\right)^{\sigma_i - \epsilon_i} \hat{U}_i{}^{\varepsilon_i^n} = \left(\sum_n b_i^n \hat{U}_i{}^{\varepsilon_i^n}\right)^{\frac{\sigma_i - \epsilon_i}{1-\sigma_i}} \hat{U}_i{}^{\varepsilon_i^n}, \tag{51}$$

with which we can easily show that $\sum_n b_i^n \hat{C}_i^n = \left(\sum_n b_i^n \hat{U}_i{}^{\varepsilon_i^n}\right)^{\frac{1-\epsilon_i}{1-\sigma_i}} = \left(\hat{P}_i\right)^{1-\epsilon_i}$. Applying the "exact hat algebra" to Equation (5) under the same constant prices, we can solve the following equation for $\hat{U}_i$ given exogenous information $\hat{Y}_i$ and $\hat{C}_i^n$:

$$\begin{aligned} \hat{Y}_i &= (1 - \frac{\tilde{b_i}}{1-\epsilon_i})\hat{U}_i + \frac{\tilde{b_i}}{1-\epsilon_i}\left(\hat{P}_i\right)^{1-\epsilon_i} \\ &= (1 - \frac{\tilde{b_i}}{1-\epsilon_i})\hat{U}_i + \frac{\tilde{b_i}}{1-\epsilon_i}\left(\sum_n b_i^n \hat{C}_i^n\right) \end{aligned} \tag{52}$$

Once we know the value of $\hat{U}_i$, we can solve N Equations (51) for N unknown ε_i^ns for each country i, given all other parameters (σ_i, ϵ_i, $\tilde{b_i}$, b_i^n) calibrated. We deduce the following relationships using Equations (51) for each food category and calibrate ε_i^n with them:

$$\begin{aligned} \hat{U}_i{}^{\varepsilon_i^n} &= \hat{C}_i^n \left(\sum_n b_i^n \hat{C}_i^n\right)^{-\frac{\sigma_i - \epsilon_i}{1-\epsilon_i}} \\ \varepsilon_i^n &= \frac{\log\left(\hat{C}_i^n\right) - \frac{\sigma_i - \epsilon_i}{1-\epsilon_i}\log\left(\sum_n b_i^n \hat{C}_i^n\right)}{\log\left(\hat{U}_i\right)} \end{aligned}$$

Source substitution elasticities, λ_i^n and κ_i^l

In our model, a single Armington elasticity λ_i^n governs substitution between country i's domestic supply of food n and its imports from every foreign source directly; κ_i^l plays the same role for crop l. GTAP instead reports two nested elasticities: the "Armington CES for domestic/imported allocation," λ_D^n, and the "Armington CES for regional allocation of imports," λ_M^n, with the latter set to twice the former under the "rule of two" (Hertel, 2024). Neither number maps one-for-one into our one-tier structure. We therefore derive the substitution elasticity between domestic supply and each individual foreign source from the GTAP-style nested aggregator, and use it to calibrate λ_i^n and κ_i^l.

We measure the substitutability between country i's domestic supply and its imports from an individual source j with the direct elasticity of substitution $\lambda_{j,i}^n$: the percentage change in the quantity ratio per percentage change in the marginal rate of substitution, moving along the isoquant of X_i^n while holding all third sources fixed,

$$\lambda_{j,i}^n \equiv -\frac{d\log\left(X_{ji}^n/X_{ii}^n\right)}{d\log MRS_{ij}^n}\Bigg|_{X_i^n \text{ and } X_{ki}^n\,(k\neq i,j) \text{ constant}}.$$

Rewriting our food availability X_i^n in the GTAP nested form and differentiating along the isoquant, Appendix E shows that this elasticity has the closed form

$$\lambda_{j,i}^n = \left[\frac{\omega_{j,i}^n}{\lambda_D^n} + \frac{1-\omega_{j,i}^n}{\lambda_M^n}\right]^{-1}, \qquad \omega_{j,i}^n \equiv \frac{s_{j,i}^n + w_{j,i}^n}{1+w_{j,i}^n} \in [0,1], \tag{53}$$

where $s_{j,i}^n$ is country j's value share in country i's total imports of food n, and $w_{j,i}^n$ is country i's spending on imports from j relative to its spending on its domestic variety. The closed form is a weighted harmonic mean of the two GTAP elasticities and has intuitive limiting cases. When country j is country i's only supplier ($s_{j,i}^n = 1$, hence $\omega_{j,i}^n = 1$), shifting X_{ji}^n moves the entire import bundle against domestic supply and $\lambda_{j,i}^n = \lambda_D^n$. When source j is negligible ($s_{j,i}^n, w_{j,i}^n \to 0$), the relevant curvature is that of the import nest and $\lambda_{j,i}^n \to \lambda_M^n$. In all intermediate cases, $\lambda_D^n \leq \lambda_{j,i}^n \leq \lambda_M^n$, so the two GTAP elasticities bracket every domestic–foreign substitution elasticity implied by the nested structure.

Both weights, $s_{j,i}^n$ and $w_{j,i}^n$, can be calculated from the same data that other share parameters use for calibration. Writing b_{ji}^n for source j's share in country i's total spending on food n (including the domestic share b_{ii}^n), we have $s_{j,i}^n = b_{ji}^n/(1-b_{ii}^n)$ and $w_{j,i}^n = b_{ji}^n/b_{ii}^n$, so that

$$\omega_{j,i}^n = \frac{b_{ji}^n}{(1-b_{ii}^n)\left(b_{ii}^n + b_{ji}^n\right)}.$$

We calibrate λ_i^n in two steps. First, for each importer–food pair we evaluate Equation (53) at the base-year expenditure shares for every source j, with λ_D^n and λ_M^n taken from GTAP after mapping GTAP commodities to our food categories using trade-value weights. Second, since our model admits a single elasticity per importer–food pair, we aggregate the pairwise elasticities using import-value weights:

$$\lambda_i^n = \sum_{j \neq i} s_{j,i}^n \, \lambda_{j,i}^n \ .$$

The identical derivation applied to the crop Armington aggregator delivers κ_i^l, with the crop expenditure shares α_{ji}^l in place of b_{ji}^n. Because every pairwise elasticity lies in $[\lambda_D^n, \lambda_M^n]$, we also re-run all counterfactuals setting λ_i^n (κ_i^l) to the lower bound λ_D^n (κ_D^l) and the upper bound λ_M^n (κ_M^l) to bound the role of this parameter.

Food-specific crop substitution elasticity ζ^n

We calibrate ζ^n category by category from the literature. Table 2 collects the baseline values and the sensitivity ranges; the evidence behind each vegetal category is documented in Appendix F.

Table 2: Calibration of ζ^n: baseline values and sensitivity ranges

Food category n	Baseline	Low	High	Evidence
Starchy staples	0.99[a]	0.8	1.2	Household demand, China/Indonesia/US
Vegetables & fruits	0.7	0.4	1.0	Household demand, US/China/Malawi
Sweeteners	4	3.24	6	Sweetener demand, US; cane–beet homogeneity
Other foods	1.5	0.9	2.7	Household demand, Malawi/US
Vegetal oils & fats	1.1	0.85	2.0	Oil demand, US; GLOBIOM assumption
Meat & seafood	0.9	—	—	Feed substitution, GTAP-AGR
Dairy	0.9	—	—	Feed substitution, GTAP-AGR
Animal oils & fats	0.9	—	—	Feed substitution, GTAP-AGR

[a] Set marginally below one: the CES price index in Equation (8) is undefined at $\zeta^n = 1$.

For the three animal-based food categories, crops enter production as feed, so the relevant evidence concerns substitution among feedstuffs. We set $\zeta^n = 0.9$ for all three. This value aligns with the calibration by Keeney and Hertel (2005), whose elasticity of substitution among livestock feedstuffs is computed as a share-weighted average of pairwise crop substitution elasticities from Surry (1990). Further support comes from Gouel and Laborde (2021), who derive a theoretical relationship between this substitution elasticity and feed demand elasticities, and use empirical estimates of the latter to calibrate the former.

For the five vegetal-based categories, no production-side estimates exist at our level of crop aggregation, so we turn to household food demand studies. Although ζ^n appears in

a production function, it describes a choice that in reality belongs to consumers. In the model, consumers only pick among the eight food categories, and the food producer decides how each category is disaggregated into crops; in these household food demand studies, households make that division themselves when they choose, say, rice over wheat. If ζ^n essentially reflects the within-category part of household preferences, household estimates of substitution between crops in the same category measure ζ^n itself, not a proxy for it.

Regarding the identification strategy, by its definition, the elasticity of substitution ζ^n is close to a set of parameters that these studies can estimate, the Morishima elasticities of substitution (Blackorby and Russell, 1989). A Morishima elasticity considers two crops and is calculated as the difference between the cross-price elasticity and the own-price elasticity. As shown in the Appendix, given a CES structure, Morishima elasticities for all crop pairs are equal to ζ^n. We can therefore average estimated Morishima elasticities over crop pairs to recover ζ^n.

Our selection of literature meets two standards. First, the crops covered (or a subset of crops covered) should match our crop choices in the corresponding food category. Such studies exist because, once feed and industrial uses are set aside, each crop's food use falls almost entirely in one category: virtually all rice and most wheat and maize eaten as food are eaten as starchy staples, so ζ^n for "starchy staples" measures how easily staple crops substitute for one another in staple consumption, and so do other vegetal categories.

Second, the estimates should come from household food consumption rather than from feed or industrial markets. This is not because non-food uses lie outside ζ^n; we do have the same ζ^n pick the crop mix for all of food n's output, including the part that leaves the food system as non-food use W_i^n. Instead, it is because the model also handles the other uses elsewhere: feed enters through the animal categories' own aggregators, and crop-level industrial demand W_i^l bypasses the food aggregators altogether. Such substitution patterns observed in feed or industrial markets speak to parameters other than the vegetal ζ^n, leaving household consumption the dominant user of vegetal food output and making it the natural benchmark for calibration.

Vegetable oils are the one vegetal category where we depart from this strategy. Crushing is close to a fixed-proportion technology: each oilseed yields its own oil and meal in fixed ratios, and processors do not substitute oilseeds within a crushing plant. Instead, substitution happens downstream across oils. We therefore calibrate ζ^n from substitution among vegetable oils, cross-checked against the vegetable-oil substitution elasticity assumed in GLOBIOM (Appendix F.7).

The selected studies give varying estimates across countries, which could either result from heterogeneity in diets or measurement error. Since our model imposes a single global ζ^n

per category, we treat each baseline as the center of an interval rather than a point estimate. We re-run all counterfactuals at the low and high values in Table 2 for robustness check purposes.

Land heterogeneity parameter, θ_i

The last parameter to identify is heterogeneity in land productivity. We take the number from Gouel and Laborde (2021) since our paper has a similar structure in cropping and land allocation to theirs, but adjust it slightly for countries with different territory sizes. By nature, countries with larger territories are more likely to have diversified cropland, which could mean a smaller θ_i. We assign 1.01 to countries with cropland size ranking in the top 1/3 of the world, 1.05 to countries in the middle 1/3, and 1.1 to countries in the bottom 1/3.

3.3 Share parameters

Table 3 lists the 25 share parameters that appear in the equilibrium in relative changes. Several market-clearing identities and other intrinsic mathematical relationships link them: once the shares in the top panel are measured, those in the bottom panel follow recursively.

On the food side, expenditure on food is calculated with quantity and price data mentioned in section 3.1, and the production shares are deduced from calibrated consumption and trade shares; on the crop side, production is directly observed, so expenditure shares are deduced from measured production and trade shares. This subsection presents the identities, the minimum calibration requirements, and economic logic behind the directly calibrated shares. Appendix G describes the procedures and assumptions used to compute them from the raw data.

3.3.1 Non-food/industrial use of food products and crops

Non-food use is distinct and not trivial for certain food products and crops, such as soybean oil and corn used for biofuel production. We identify food products and crops that are widely used for non-food purposes and calibrate their corresponding non-food use shares h_i^n and h_i^l using both the FAOSTAT Food Balance Sheet (FBS) and Supply Utilization Account (SUA) data. The terms $\hat{W}_i^n$ and $\hat{W}_i^l$ capture the exogenous change in non-food demand for food n and crop l in country i, allowing us flexibility in accounting for their exogenous changes. The potential effects of increasing non-food demand can be revealed when solving the equilibrium in relative changes.

We rely on the FAOSTAT SUA domain for both shares. SUA reports the non-food use of each crop, each food product, and their processed forms in quantities, which we convert to values with country–item prices. The FBS complements the SUA only where the latter lacks

Table 3: Land and expenditure shares

Share	Definition	Source
$\tilde{b_i}$	share of food expenditures in total income in country i	FAOSTAT
b_i	country i's share in world food consumption	FAOSTAT
b_i^n	the budget share of food n in total food consumption in country i	FAOSTAT
b_{ji}^n	the share of food n from j in total consumption of food n in i	FAOSTAT & CEPII BACI
h_i^n	the share of food product n for non-food use in country i	FAOSTAT
h	the global share of food products for non-food use	FAOSTAT
ρ_j	country j's share in the value of world crop production	FAOSTAT
ρ_j^l	the share of crop l in the value of crop production in country j	FAOSTAT
ρ_{ij}^l	the share of country i's crop l production exported to country j	FAOSTAT & CEPII BACI
h_i^l	the share of crop l used for non-food production in country i	FAOSTAT
δ_i	the ratio of crop production value to food consumption expenditure in country i	FAOSTAT
ψ_i	the overall crop share of the food dollar in country i	FAOSTAT
ψ_i^n	the crop share of a food dollar n in country i	FAOSTAT & GTAP
s_i^{nl}	the share of food n in the food use of crop l in country i	FAOSTAT & solving (66)
φ_i	the land rent share of a crop dollar in country i	GTAP
π_i^l	land share of crop l in country i	FAOSTAT & GTAP
a_j	country j's share in world food production	deduced from (57)
a_j^n	food n's share in country j's domestic food production	deduced from (56)
a_{ij}^n	the share of country i's food n production exported to country j	deduced from (55)
α_i	the share of total crop value used in food production in country j	deduced from (61)
α_i^l	crop l's share of total crop use value in country i	deduced from (60)
α_{ji}^l	the share of crop l originating from j in total expenditure on crop l in i	deduced from (59)
c_i^{nl}	the share of crop l in the total crop cost of food n in country i	deduced from (64)
h_i	the share of total crop value used for non-food production in country i	deduced from (67)
φ_i^l	the ratio of land rent to the producer price of crop l in country i	deduced from (69)
ℓ_i^l	the share of labor used in production of crop l	deduced from (70)
ℓ_i^n	the share of labor used in production of food n	deduced from (71)
ℓ_i^0	the share of labor used in the manufacturing sector	deduced from (72)

Notes: The top panel lists share parameters calibrated directly from the data; the bottom panel lists shares deduced from the top panel through the identities referenced in the Source column. Appendix G describes the construction of the top-panel shares.

coverage, mostly for fish and seafood. Appendix efapp:uses documents how these quantities compute h_i^l and h_i^n; h and h_i then follow from their definitions.

We rely entirely on the FAOSTAT SUA domain for h_i^l. SUA reports non-food use (those for industrial use, neither for feed nor food production) of each primary crop and its processed products in quantity. By multiplying these quantities with their corresponding prices (coming from Trade Unit Values (TUVs) calculated with the BACI database from Centre for Prospective Studies and International Information (CEPII)), we recover the value share of each crop that is for non-food use and denote it as h_i^l. This method is better than simply using numbers from the Food Balance Sheet, as the quantity in the FBS could be a mixture of food and crops. Also, the underlying aggregation process is not transparent (Zhao et al., 2025). h_i is later computed with h_i^l and crop production data.

For the same reason, we mainly rely on the SUA data to calculate the value of food products used for non-food/industrial purposes. The Food Balance Sheet is only used when more detailed entries are missing in the Supply Utilization Accounts, such as for all kinds of fish in seafood. This non-food value will later be utilized together with food consumption data to compute h and h_i^n.

We exclude crops like natural rubber that are completely inedible. Partially edible cash crops require additional care. Raw cotton, for instance, is harvested and ginned into lint and seed with a relatively stable physical weight ratio, and the model crop "seed cotton" is valued as the whole cotton boll, because land competes on the crop's total expected revenue. The inedible lint, which accounts for about 83% of the boll's value, is booked as non-food use of the crop, so it exits the food system through h_i^l exactly like an industrial use, and only the cottonseed value remains available to food production.

Additionally, since alcoholic beverages are not one of the model's food categories, crops that are brewed into beer or made into wine therefore leave the food system, and we book them as non-food use. For grass, since livestock produce also byproducts (wool, hides, tallow, etc.), the crops used as feed and grass for these byproducts (by value share) are booked as non-food use of those inputs, so that the crop cost of the animal-based food categories reflects food alone.

3.3.2 Food expenditure and production shares

Global expenditure on food product n should be equal to its global food production value, i.e.,

$$\sum_i \sum_n P_i^n X_i^n = \sum_i H_i P_i C_i + \sum_i \sum_n P_i^n W_i^n = \sum_j \sum_n p_j^n Q_j^n \tag{54}$$

This fact allows us to relate food expenditure shares in country i to production shares in country j. Denoting $h \equiv \frac{\sum_i \sum_n P_i^n W_i^n}{\sum_i H_i P_i C_i + \sum_i \sum_n P_i^n W_i^n}$ as the global share of food products for non-food use, $b_i \equiv \frac{H_i \sum_n P_i^n C_i^n}{\sum_j H_j P_j C_j}$ as country i's share in world food product consumption, $a_j \equiv \frac{\sum_n p_j^n Q_j^n}{\sum_i \sum_n p_i^n Q_i^n}$ as country j's share in world food production, and $a_j^n \equiv \frac{p_j^n Q_j^n}{\sum_n p_j^n Q_j^n}$ as food n's share in country j's domestic food production, we should have the following equation hold:

$$a_j a_j^n a_{ji}^n = \frac{1-h}{1-h_i^n} b_i b_i^n b_{ji}^n \tag{55}$$

The left-hand side is the value of country j's production of food n shipped to country i, as a share of world food production. On the right-hand side, $b_i b_i^n b_{ji}^n$ is country i's spending on food n from j as a share of world food consumption; the ratio $\frac{1-h}{1-h_i^n}$ addresses non-food use and realigns the term to the world production base.

Summing Equation (55) over destination countries i and food n leads to:

$$a_j a_j^n = (1-h) \sum_i \frac{b_i b_i^n b_{ji}^n}{1-h_i^n} \tag{56}$$

$$a_j = (1-h) \sum_i b_i \sum_n \frac{b_i^n b_{ji}^n}{1-h_i^n} \tag{57}$$

Once we know the non-food use shares h and h_i^n and those consumption shares b_i, b_i^n, and b_{ji}^n, we can recursively get production shares a_j, a_j^n, and a_{ji}^n. Following the methodology of Gouel and Guimbard (2019), we calculate country-level expenditures on each food product to calibrate b_i, b_i^n, and b_{ji}^n. The two non-food use shares, h and h_i^n, are calculated using these expenditure data and values of non-food/industrial use of food products from the last section.

3.3.3 Crop demand and production shares

The total crop expenditure should be equal to the total crop production value on the world level, i.e.,

$$\sum_i \sum_l v_i^l X_i^l = \sum_i \sum_l q_i^l Y_i^l \tag{58}$$

Denote $\alpha_i \equiv \frac{\sum_l v_i^l X_i^l}{\sum_i \sum_l v_i^l X_i^l}$ as the share of global crop value used in country i, $\alpha_i^l \equiv \frac{v_i^l X_i^l}{\sum_l v_i^l X_i^l}$ as crop l's share in the total crop value used in country i, $\rho_j \equiv \frac{\sum_l q_j^l Y_j^l}{\sum_j \sum_l q_j^l Y_j^l}$ as country j's share in the value of world crop production, and $\rho_j^l \equiv \frac{q_j^l Y_j^l}{\sum_l q_j^l Y_j^l}$ as the share of crop l in the value of

crop production in country j, we have

$$\alpha_i \alpha_i^l \alpha_{ji}^l = \rho_j \rho_j^l \rho_{ji}^l \tag{59}$$

Summing Equation (59) over origin countries j and crop l leads to:

$$\alpha_i \alpha_i^l = \sum_j \rho_j \rho_j^l \rho_{ji}^l \tag{60}$$

$$\alpha_i = \sum_j \rho_j \sum_l \rho_j^l \rho_{ji}^l \tag{61}$$

We can thus derive the values of α_i, α_i^l and α_{ji}^l recursively after calibrating ρ_j, ρ_j^l and ρ_{ji}^l. FAOSTAT documents primary crops' output quantities in its "Crops and livestock products" domain. Valued at farm-gate prices and combined with the bilateral trade flows of BACI, these give ρ_j, ρ_j^l and ρ_{ji}^l. The value of the non-traded crop "grass" is not reported by FAOSTAT. Thus, we follow Gouel and Laborde (2021) in using the value-added accruing to land in live-animal sectors calculated from GTAP, realigned to the FAOSTAT basis by the ratio of FAOSTAT to GTAP non-grass crop production values.

Two measurement choices on the crop side are worth mentioning. First, bilateral trade in the few products whose border prices sit far above the farm gate (malt, cocoa beans, sugar beet) is repriced to embodied-crop value. Second, re-exports are cleared, so entrepôt margins drop out of the crop accounts and no country's crop exports exceed its production; the identical clearing is deliberately not applied to food trade, where production is itself recovered from trade data. Appendix G.2 details both.

Additionally, since we have both information on each country's crop production value and food consumption value, we can calculate $\delta_i \equiv \frac{\sum_l q_i^l Y_i^l}{H_i \sum_n P_i^n C_i^n}$ using its definition: crop production value, grass included, over domestic food consumption expenditure. Unlike other shares, no identity bounds it by one, since the numerator contains export-destined production while the denominator covers resident consumption only. It exceeds one exactly where it should, in small-population net agricultural exporters (Paraguay 1.88, Uruguay 1.27, Argentina 1.17); in the welfare decomposition, only the product $\varphi_i \delta_i$ enters, and it remains well below one everywhere.

3.3.4 Food crop-cost shares and crop usage share

In a specific country i, the value of domestically available crop should be equal to the total crop value used in food and non-food production, i.e.,

$$\sum_l v_i^l (X_i^l - W_i^l) = \sum_l v_i^l \sum_n Z_i^{nl} = \sum_n \sum_l v_i^l Z_i^{nl} = \sum_n V_i^n Z_i^n \tag{62}$$

We can thus define $\psi_i \equiv \frac{\sum_l v_i^l (X_i^l - W_i^l)}{\sum_n p_i^n Q_i^n}$ as the overall crop share of a food dollar in country i and reexpress it as

$$\psi_i = \frac{\sum_n V_i^n Z_i^n}{\sum_n p_i^n Q_i^n} = \sum_n \frac{V_i^n Z_i^n}{p_i^n Q_i^n} \frac{p_i^n Q_i^n}{\sum_n p_i^n Q_i^n} = \sum_n \psi_i^n a_i^n. \tag{63}$$

We also show the relationship between c_i^{nl}, the share of crop l in the total cost of food n in country i, and s_i^{nl}, the share of food n in the crop l usage:

$$(1 - h_i^l)\psi_i \alpha_i^l s_i^{nl} = (1 - h_i) c_i^{nl} \psi_i^n a_i^n \tag{64}$$

where $h_i \equiv \frac{\sum_l v_i^l W_i^l}{\sum_l v_i^l X_i^l}$ is the share of total crop value used for non-food production in country i. Summing Equation (64) over the crop index l, we get:

$$\psi_i \sum_l (1 - h_i^l)\alpha_i^l s_i^{nl} = (1 - h_i)\psi_i^n a_i^n \tag{65}$$

Although the exact value of s_i^{nl} for each food and crop combination is not observable, the FAOSTAT SUA can be used to construct informative priors $\bar{s}_i^{nl}$ and to solve a program for the values that s_i^{nl} is most likely to take. In addition to "non-food/industrial" use of each crop, the SUA gives its "food" (direct consumption) and "feed" use in quantity [4]. The measured "feed" share of a crop is divided equally among the three animal-based food products: if we know a certain share of wheat is used for feed, we divide it by 3 and assign the result to $\bar{s}_i^{nl}$ for each of them. The measured "food" share is distributed across the vegetal food categories according to the crop's product family: cereals and starchy roots to starchy staples, sugar crops to sweeteners, fruit and vegetable crops to vegetables & fruits, and so on. The vegetable oil category also takes a share if the crop can be used in oil extraction.

For each country i, we have N independent equations corresponding to each food cate-

[4] Crops in their original forms sometimes have another use called "processed," which is reallocated to either "food," "feed," or "non-food." Taking oilseeds as an example, their crushed value is split between the oil and the cake in proportion to the value of each output. Only the oil share counts as crop use for vegetal food; the cake share feeds the animal chain instead.

gory. Also, we have L independent equations from the constraint that $\sum_n s_i^{nl} = 1$. These do not suffice to identify $N \times L$ independent s_i^{nl}. Therefore, we first assign zeros to certain s_i^{nl} when crop l is not used in food n production. For example, crop wheat should not be used by certain vegetal food categories, like "vegetables & fruits", in any meaningful quantity; therefore, we set the corresponding s_i^{nl} to zero. This step reduces the number of s_i^{nl} left to determine.

We then solve the following calibration program for food $n \in \mathcal{N}$ that minimizes the deviation of s_i^{nl} from priors $\bar{s}_i^{nl}$ for each country i:

$$\min_{s_i^{nl} \geq 0} \sum_{n \in \mathcal{N}} \sum_l \left(s_i^{nl} - \bar{s}_i^{nl}\right)^2 \quad \text{subject to} \quad \begin{cases} \psi_i^n = \frac{\psi_i \sum_l (1-h_i^l)\alpha_i^l s_i^{nl}}{(1-h_i)a_i^n} & n \in \mathcal{N} \\ \sum_{\mathcal{N}} s_i^{nl} = 1 & l = 1, \ldots, L \end{cases}, \tag{66}$$

once we know the values of ψ_i, ψ_i^n, α_i^l, h_i, and a_i^n. After that, we can calculate c_i^{nl} with Equation (64).

We have already calibrated α_i^l and a_i^n in previous sections. The crop non-food use share h_i can be computed using the relation that

$$h_i \equiv \frac{\sum_l v_i^l W_i^l}{\sum_l v_i^l X_i^l} = \sum_l \frac{v_i^l X_i^l}{\sum_l v_i^l X_i^l} \frac{W_i^l}{X_i^l} = \sum_l \alpha_i^l h_i^l \ . \tag{67}$$

The parameter ψ_i can be directly calibrated as the ratio of the total crop value available to the total food value that is produced. With the adding-up constraint (63), the crop shares ψ_i^n, weighted by the production shares a_i^n, must sum to the overall crop share ψ_i. Calibrating the ψ_i^n therefore amounts to allocating a known total of crop value across the eight food categories.

Most of this allocation can be measured directly. The crop value behind the three animal-based food categories equals the measured value of feed, including grass. The crop value behind "vegetables & fruits" equals the food-destined value of the fruit and vegetable crops, because these crops are eaten in no other category. The crop value behind "vegetal oils & fats" equals the oil share of the oilseed crush, and the crop value behind "other foods" equals the remaining, non-oil food use of pulses, nuts, and oil-bearing crops. Whatever crop value is left belongs to "starchy staples" and "sweeteners".

Two of these five pieces still cover more than one food category: the feed piece covers "meat & seafood," "dairy," and "animal oils & fats," and the leftover piece covers "starchy staples" and "sweeteners." Only here do we use GTAP. Its input-output accounts show how crop value is distributed across the production of different foods; in particular, they track the crop value that reaches meat and dairy indirectly, as crops become feed and feed becomes

livestock. We use these GTAP proportions to divide each piece among its categories and solve for ψ_i^n. We do not take dollar values from GTAP itself, because GTAP food sectors do not map one-to-one to our food categories, and GTAP's cost structure for agriculture is partly imputed rather than observed.

3.3.5 Crop value share and land share

Considering the fact that $\varphi_i^l \rho_i^l = \frac{r_i^l Y_i^l}{\sum_l q_i^l Y_i^l}$ is proportional to $r_i^l Y_i^l$, Equation (C.1) implies that

$$\pi_i^l = \frac{\varphi_i^l \rho_i^l}{\sum_l \varphi_i^l \rho_i^l} \tag{68}$$

Using $\varphi_i = \sum_l \varphi_i^l \rho_i^l$ to represent the land rent share of a crop dollar in country i, we can recover the crop-specific land rent share φ_i^l using

$$\varphi_i^l = \frac{\pi_i^l \varphi_i}{\rho_i^l} \tag{69}$$

We calibrate φ_i as the GTAP-based land rent share of agricultural output, with both the numerator (crop land rents plus the grass value) and the denominator (crop output plus the grass value) constructed entirely from GTAP. The land shares π_i^l need more care. Equation (C.1) interprets π_i^l as a share of land rents, in addition to a share of the land base L_i, and the two are equal only if every hectare earns the same rent. In GTAP, a hectare of pasture earns only a small fraction of what a hectare of cropland earns, so measuring the grass entry with physical pastureland acres would largely overstate the value of grass, especially where pasture is vast (Australia). We instead set π_i^{grass} to the GTAP-based grass share of agricultural land rents, and the cropland entries follow the detailed harvested areas of the FAOSTAT "Crops and livestock products" domain, rescaled so that all shares sum to one. The construction is self-consistent: because $\varphi_i^{\text{grass}} = 1$, Equation (69) applied to grass returns exactly the GTAP-based φ_i, an equality the calibration program checks at every run. Appendix G.5 documents the grass valuation and the caps that discipline GTAP's imputed pasture rents.

3.3.6 Labor share across sectors

The labor shares can be calibrated directly with previously introduced share parameters. with $\rho_i^l = \frac{q_i^l Y_i^l}{\sum_l q_i^l Y_i^l}$, $\varphi_i = \frac{\sum_l r_i^l Y_i^l}{\sum_l q_i^l Y_i^l}$, $\delta_i = \frac{\sum_l q_i^l Y_i^l}{H_i \sum_n P_i^n C_i^n}$, and $\tilde{b_i} = \frac{\sum_n P_i^n C_i^n}{Y_i}$, we have the share of labor

used in production of crop l as

$$\begin{aligned}\ell_i^l &\equiv \frac{\nu_i^l Y_i^l}{N_i} = \frac{(1-\varphi_i^l)\, q_i^l Y_i^l}{H_i Y_i - \sum_l r_i^l Y_i^l} = \frac{(1-\varphi_i^l)\, q_i^l Y_i^l}{(1-\varphi_i \delta_i \tilde{b_i}) H_i Y_i} \\ &= \frac{(1-\varphi_i^l)\, \rho_i^l \delta_i \tilde{b_i}}{1-\varphi_i \delta_i \tilde{b_i}}\end{aligned} \tag{70}$$

Similarly, with $a_i = \frac{p_i^n Q_i^n}{\sum_n p_i^n Q_i^n}$, $a_i^n = \frac{\sum_n p_i^n Q_i^n}{\sum_i \sum_n p_i^n Q_i^n}$, $b_i = \frac{\sum_n P_i^n X_i^n}{\sum_i \sum_n P_i^n X_i^n}$, $h = \frac{\sum_n P_i^n X_i^n - H_i \sum_n P_i^n C_i^n}{\sum_n P_i^n X_i^n}$, and Equation (54), the share of labor used in production of food n is

$$\begin{aligned}\ell_i^n &\equiv \frac{\nu_i^n Q_i^n}{N_i} = \frac{(1-\psi_i^n)\, p_i^n Q_i^n}{H_i Y_i - \sum_l r_i^l Y_i^l} = \frac{(1-\psi_i^n)\, p_i^n Q_i^n}{(1-\varphi_i \delta_i \tilde{b_i}) H_i Y_i} \\ &= \frac{(1-\psi_i^n)\, a_i^n a_i \tilde{b_i}}{(1-\varphi_i \delta_i \tilde{b_i})(1-h) b_i}\end{aligned} \tag{71}$$

Lastly, the share of "labor" used in the manufacturing sector can be calculated with

$$\ell_i^0 = 1 - \sum_n \ell_i^n - \sum_{l \neq g} \ell_i^l \tag{72}$$

4 Counterfactual Design

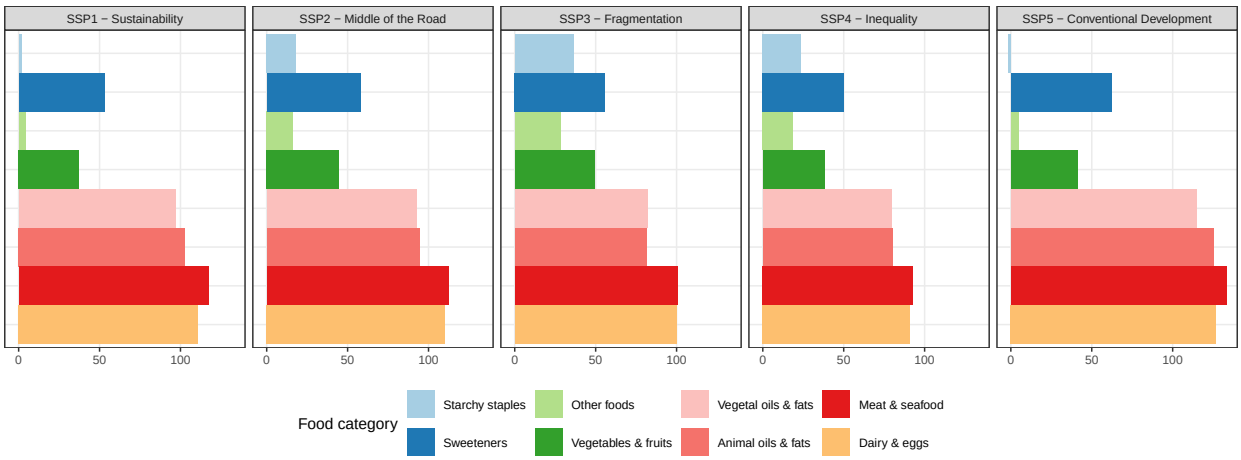
We set model counterfactuals with two demand shifters: $\hat{H}_i$ for population growth, and $\hat{g}_i$ for growth in the per capita composite factor's return. The calibrated $\hat{H}_i$ and $\hat{g}_i$ collectively drive the changes in food and crop prices, land use, and welfare. We compute $\hat{H}_i$ and $\hat{g}_i$ for all five SSPs and treat SSP2, the middle-of-the-road scenario, as the central case. We take population from the IIASA-WIC projections and per capita GDP from the OECD Env-Growth projections, the standard quantifications in the SSP database (Riahi et al., 2017). Under SSP2, population grows by a factor of 0.8 in Lithuania to 2.3 in Rest of Western Africa, with a median of 1.2. Per capita income grows by a factor of 1.4 in Norway to 8.9 in Côte d'Ivoire, with a median of 2.6. The poor regions grow faster, and the correlation between the log of 2010 per capita income and the log of $\hat{g}_i$ is -0.89 across the 82 regions.

We also evaluate the two shifters individually. We build the population counterfactual by setting $\hat{g}_i = 1$ and letting $\hat{H}_i$ follow the SSP population path. In addition, we estimate the pure nutrition-transition effect by setting $\hat{H}_i = 1$ and letting factor income alone shift diets through the expenditure functions estimated by Gouel and Guimbard (2019).

Our GE model structure allows productivity growth of the composite factor to vary across sectors. The main results in Sections 5.1 through 5.4 assume sector-neutral growth

under SSP2, which replicates exactly a PE model where the composite factor is available at perfect elasticity at constant price. Section 5.6 reports four alternative cases in which productivity in the crop sector, or in both the crop and the food sectors, stays at its 2010 level while the rest of the economy grows. The land share of a crop dollar or the crop share of a food dollar therefore decreases, and food prices increase further than in the sector-neutral scenario.

Figure 2: World food demand change 2010–2050 at 2010 prices under the five SSP scenarios (percent)

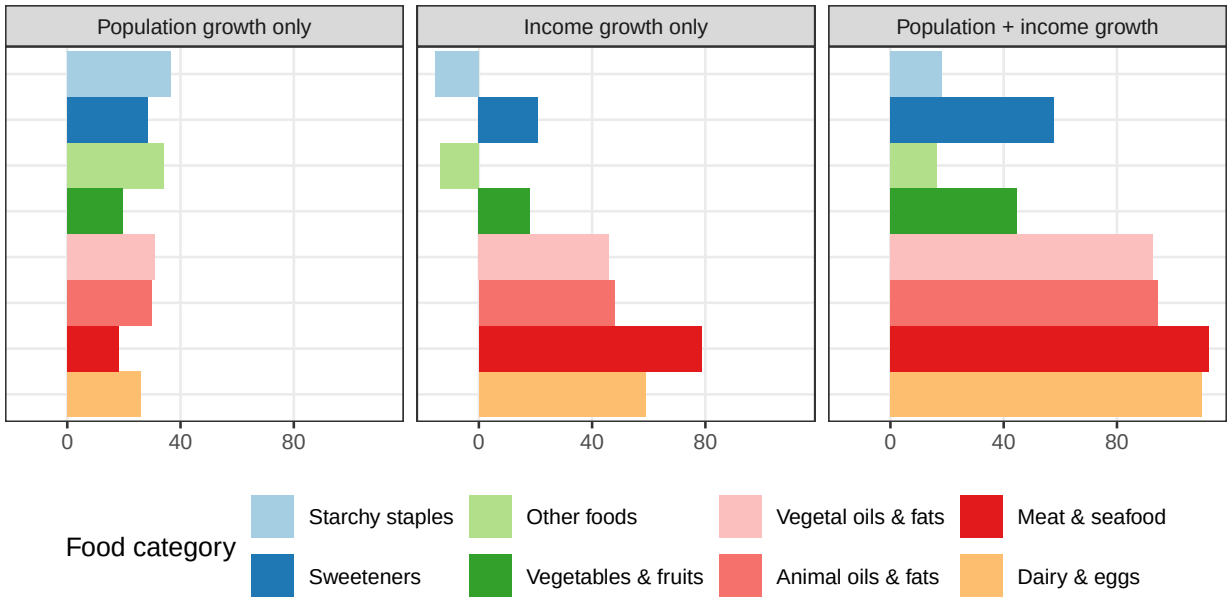


Source: authors' calculations from the five SSP population and per capita GDP paths of the SSP database (Riahi et al., 2017), IIASA–WiC and OECD Env-Growth quantifications. We weight and aggregate changes in food demand across countries by their observed expenditure.

Figure 2 reproduces the 2050 food demand projections in Figure 3 of Gouel and Guimbard (2019) category by category, holding both food and non-food prices constant. The figure shows the total demand shock without supply-side responses, calculated as the projected population change times per capita consumption growth. When population and income grow together, the shock looks similar across five SSP scenarios. World demand for meat and seafood and for dairy and eggs roughly doubles (91 to 133 percent), vegetal and animal oils grow by 79 to 125 percent, sweeteners by 50 to 62 percent, and vegetables and fruits by 37 to 49 percent. The SSPs differ mainly in staples and other foods, where population growth and income growth pull in opposite directions: starchy staples grow by 36 percent in SSP3, with its fast population growth, and fall by 2 percent in SSP5, with its fast income growth. SSP2, the middle-of-the-road scenario by design, also sits in the middle of the five demand shocks. The projected food demand change is the median in six of the eight categories and the second highest in the other two, sweeteners (58 percent) and vegetables and fruits (45 percent).

Figure 3 splits the SSP2 shock into its two drivers, which play very different roles.

Figure 3: World food demand change 2010–2050 at 2010 prices under SSP2 (percent)



Source: authors' calculations from the SSP2 population and per capita GDP paths of the SSP database (Riahi et al., 2017), IIASA–WiC and OECD Env-Growth quantifications. Aggregation is the same as in Figure 2.

Population growth alone raises demand for every category, from 18 percent for meat and seafood to 36 percent for starchy staples. It leans toward staples because population grows fastest in the poorest regions, where staples take a much larger share of the food budget. In the 15 regions with their 2010 per capita income below 2,000 US dollars, the median population growth factor is 1.67, and the median budget share of staples is 26 percent; in the 41 regions above 10,000 dollars, the two numbers are 1.18 and 10 percent. The poorest regions supply 29 of the 36 percentage points of the increase in staples.

Income growth changes the composition of demand very differently. At fixed prices, it raises world demand for meat and seafood by 79 percent and for dairy and eggs by 59 percent, while it lowers demand for starchy staples by 15 percent and for other foods by 14 percent. Most of this shift comes from the 26 middle-income regions between 2,000 and 10,000 dollars, which supply 52 of the 79 percentage points of meat growth and about three quarters of the fall in starchy staples. The two drivers both push for a demand increase in animal products but offset each other in starchy staples, so the combined shock is concentrated in meat, dairy, and oils. Section 5.3 revisits the two drivers with general equilibrium effects.

All of these counterfactuals hold yields and the land base at their 2010 levels, so they isolate the demand shock under deliberately extreme supply conditions. A last experiment

releases the constraint and asks how much yield growth would offset the cost that the higher food prices impose on consumers. We raise the expected yield of every crop by a common factor $\hat{A}$, let prices and crop production adjust, and search for the value of $\hat{A}$ at which the income-constant CV is zero in the median, so that the price change leaves consumers in half of the regions better off than in 2010 and half worse off. We run the search twice, once with the same $\hat{A}$ in all 82 regions, and once with $\hat{A}$ in the 58 regions with a yield gap only, while the 24 regions whose yields are already near their potential, such as Western Europe, the United States, and Japan, keep their 2010 yields. Section 5.5 reports the two required growth rates next to the historical pace of yield growth.

5 Results

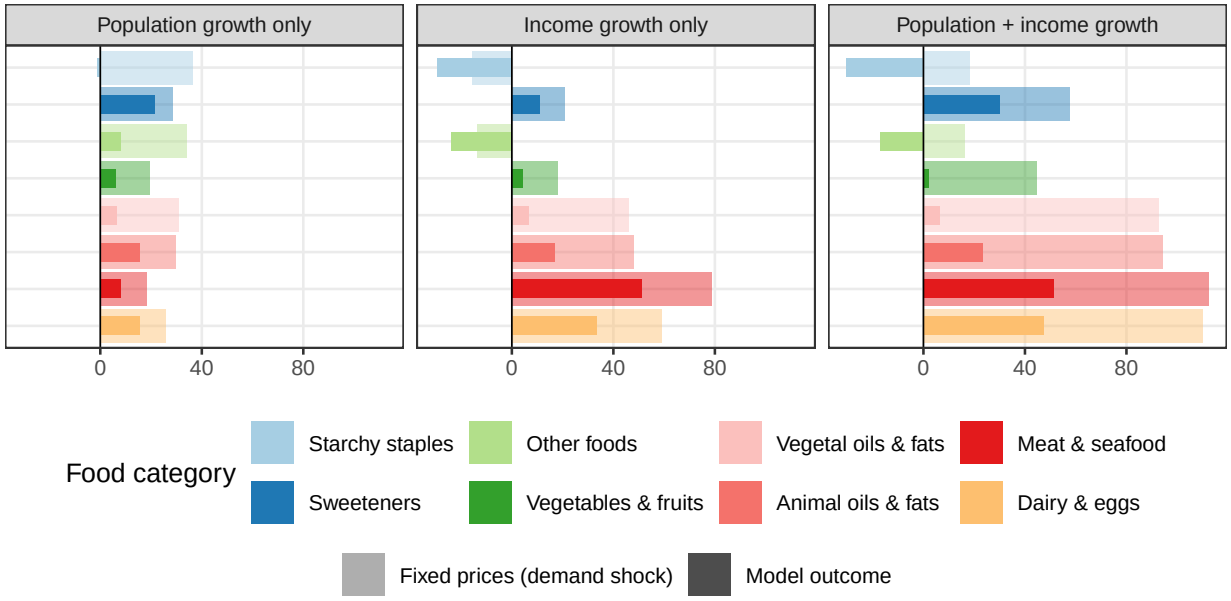
This section reports the model outcomes for SSP2 in 2050. Section 5.1 starts with world food demand by category and compares the model outcome with the fixed-price projection. Section 5.2 turns to prices and per capita consumption across the 82 regions under the full counterfactual, with both population and income growth. Section 5.3 separates the two drivers and shows how they interact. Section 5.4 decomposes the welfare change, measured by the CV and EV, into income growth, land rents, and the cost of higher food prices, and identifies winners and losers. Section 5.6 checks the robustness of the results to productivity growth in the food and crop sectors. Section 5.5 closes with the yield growth that would mostly offset the consumer cost of the higher food prices.

5.1 World food demand in 2050

As the factor land experiences no increase in either productivity or total availability, global population and income growth make this resource more scarce and drive up crop and food prices. Allowing food prices and crop production to respond therefore largely suppresses the projected increase in food demand. Figure 4 adds the model outcome to the SSP2 demand shock of Figure 3. We use the light bars to repeat the shock at fixed prices, and the dark bars give the outcome with prices responding. Food demand growth shrinks compared with the fixed-price projection in 19 of the 24 category-counterfactual pairs. The five exceptions are all in starchy staples and other foods, where higher prices turn projected growth into a decline or deepen a projected decline.

Table 4 lists the numbers behind Figure 4. Growth in sweeteners, meat, and dairy falls by about half, and growth in animal oil falls by three quarters, but all four categories still grow by at least 24% in the full counterfactual. Vegetal oils and vegetables and fruits

Figure 4: World food demand change 2010–2050 under SSP2 (percent)



Notes: Light bars denote the fixed-price demand projection (Figure 3); dark bars denote model outcome with prices responding.

Table 4: World food demand change 2010–2050 under SSP2 (percent)

	Population only		Income only		Population + income	
Category	Fixed prices	Model	Fixed prices	Model	Fixed prices	Model
Starchy staples	36	−1	−15	−29	18	−30
Sweeteners	28	21	21	11	58	30
Other foods	34	8	−14	−24	16	−17
Vegetables & fruits	20	6	18	4	45	2
Vegetal oils & fats	31	7	46	7	93	7
Animal oils & fats	30	15	48	17	94	24
Meat & seafood	18	8	79	51	112	51
Dairy & eggs	26	16	59	34	110	48

Note: The column "Fixed prices" lists the demand shock at 2010 prices; "Model" lists the outcome from our model.

barely grow by 7 and 2 percent. Staples and other foods end 30 and 17 percent below their 2010 level, and regions with 2010 incomes between 2,000 and 10,000 US dollars contribute two-thirds of the staples decline. Looking at the two drivers separately, after prices respond, population growth alone raises world demand by at most 21 percent (sweeteners), and staples do not grow at all. Income growth largely shifts the composition, where meat consumption grows by 51 percent, and starchy staples fall by 29 percent, against 79 and 15 percent at fixed prices.

5.2 Prices and consumption across regions

Figure 5 shows the same comparison region by region. For each region and food category, an arrow runs from the fixed-price projection of per capita consumption to the model outcome, so its length on the log scale measures how much demand the higher food prices take away. The outcome lies below the projection in almost every region and category. In the medians, prices take away 45 percent of the projected per capita consumption of vegetal oils, 39 percent for staples, and 27 to 30 percent for meat, dairy, animal oils, and other foods.

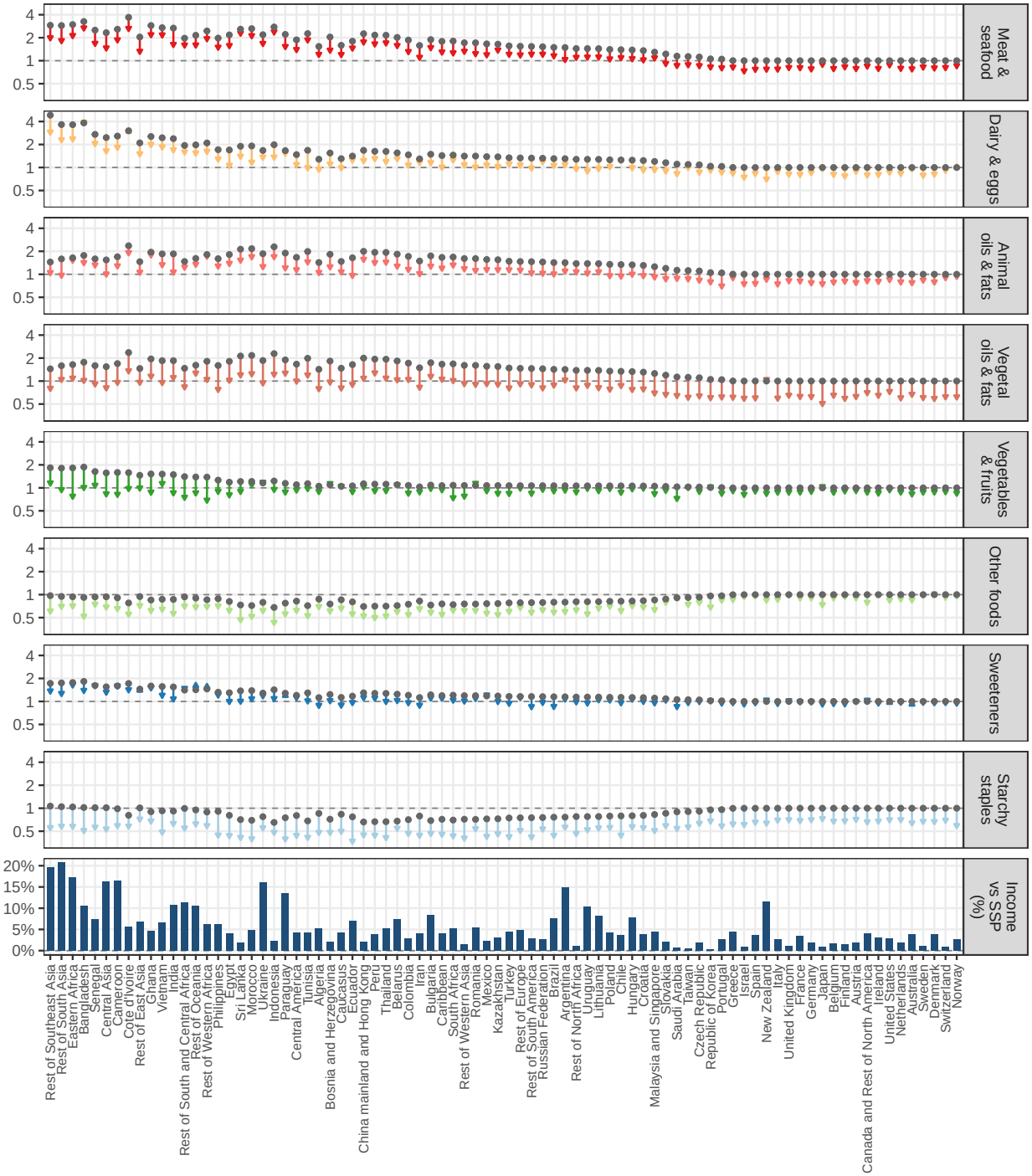
The arrowheads also give the 2050 levels directly. Per capita consumption of starchy staples and of other foods falls in all 82 regions, to 51 and 62 percent of the 2010 level in the medians. Vegetables & fruits and vegetal oils fall to 83 and 79 percent. Meat consumption still rises in 51 of 82 regions (with a median of 1.11), but dairy & eggs, animal oils, and sweeteners end close to their 2010 levels (medians 0.98, 0.97, and 0.94).

The arrows are longest in poor regions. Eastern Africa was projected to raise per capita meat consumption 3.0-fold and ends at 2.0. Its dairy consumption was projected to rise 3.6-fold and ends at 2.2. Its vegetable and fruit consumption was projected to rise by 82 percent and instead falls to 72 percent of the 2010 level.

The sign of changes for many region and category pairs is reversed. Per capita consumption is projected to rise with fixed food prices, but ends below its 2010 level. This happens most often for vegetables and fruits (54 of 82 regions), vegetal oils (47), and sweeteners (35). Reversals are most common in upper-middle-income regions such as Poland and the Republic of Korea, where the projected dietary shifts are small and the price effects dominate.

Demand growth raises the price of every food category in all 82 regions. Figures 7 and 8 plot the consumer prices by region. With both population and income growth (green squares), prices rise most for vegetal oils and starchy staples, with medians of 3.9 and 3.4, by factors of 2.4 to 2.6 for animal oils, meat, other foods, and dairy, and by 2.1 and 2.0 for vegetables and fruits and sweeteners. Prices rise more where total demand grows faster. Across regions, the log price of each category is positively correlated with the log of $\hat{H}_i\hat{g}_i$, the

Figure 5: Country per capita food demand change 2010–2050 under SSP2 (population and income growth)

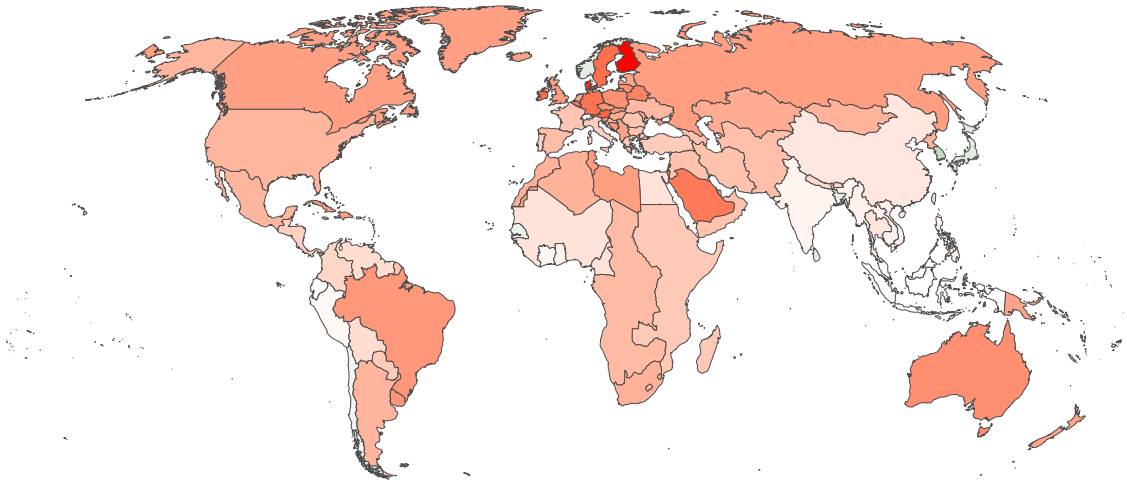


Notes: In each category row, the grey dot is the projected per capita consumption at fixed 2010 prices and the arrow head marks the model outcome, both relative to 2010 on a log scale shared across eight categories. The bottom row indicates how far the model's per capita income growth $\hat{Y}_i$ lies above the SSP path $\hat{g}_i$. Regions are ordered by 2010 per capita income.

growth of total composite-factor income, from 0.33 for vegetal oils to 0.81 for other foods. Eastern Africa, with population and per capita income rising by 2.1 and 5.0, has the largest price increase for staples, vegetables and fruits, and dairy.

The higher crop rents also pull land out of pasture. Grass is the reservation use of land in the model, so land parcels move into crops wherever crop rents outgrow the grass rent. As shown in Figure 6, the grassland share of land falls in 71 of 82 regions, with the largest falls in Europe, followed by Oceania and North America. This type of model is not good at telling the magnitude, so we only look at the results qualitatively. It is still a concern since the conversion is an environmental cost that the welfare measures in Section 5.4 do not price.

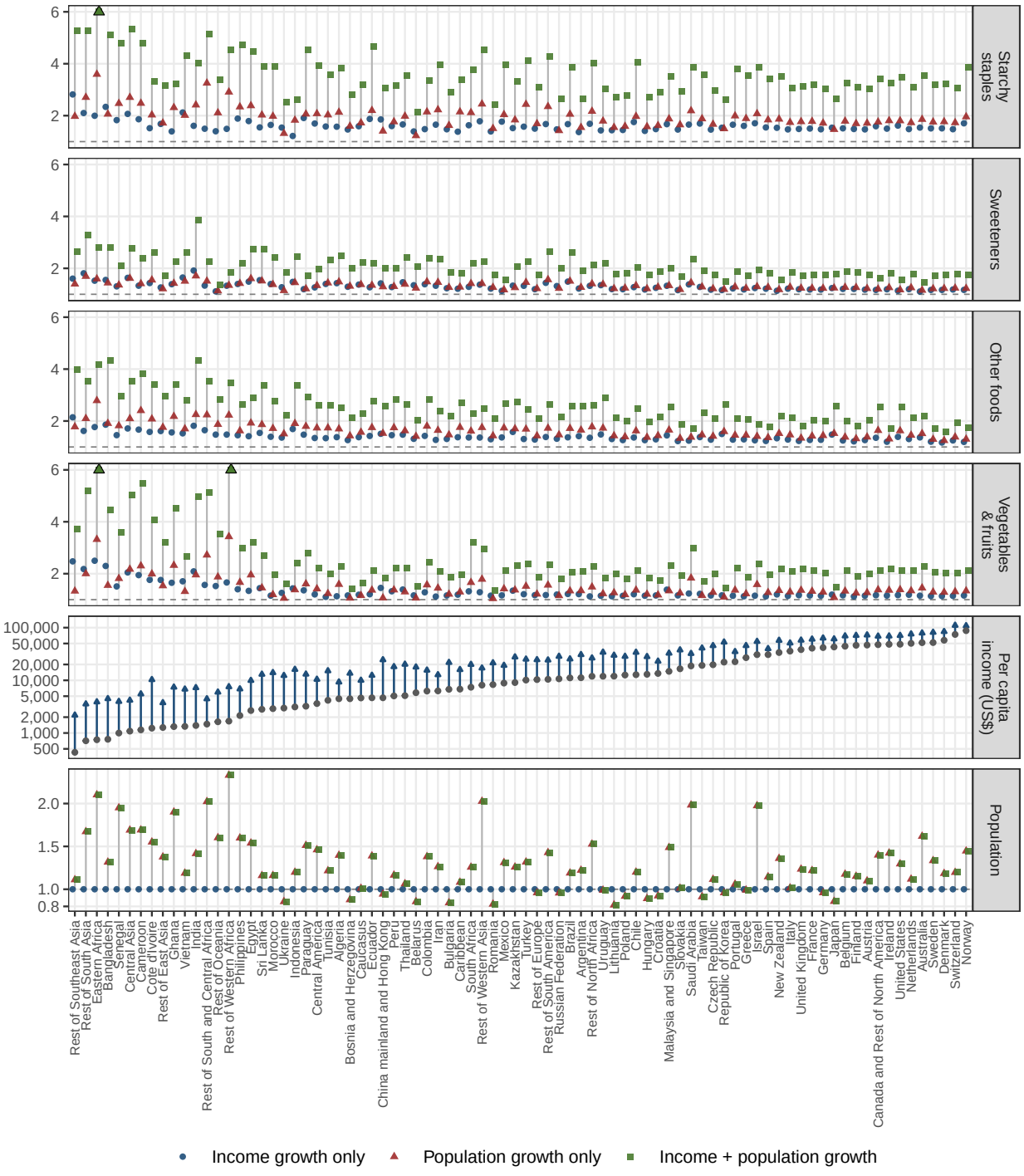
Figure 6: Change in the grassland share of land from 2010 to 2050, in percentage points (SSP2, population and income growth). Red regions shift land from grassland to crops and green regions shift toward grassland, with darker shades marking larger changes.



In the 21 regions with a 2010 per capita income above 26,000 US dollars, diets no longer change with income at fixed prices, so their arrows start at one. Eighteen of them consume less of every category in 2050, and their median meat and staples consumption ends at 0.74 and 0.62 of the 2010 level. The three exceptions (sweeteners in Australia and the United States, dairy in Norway) are the categories with the smallest price rise in each country, so they reflect substitution toward the relatively cheapest food.

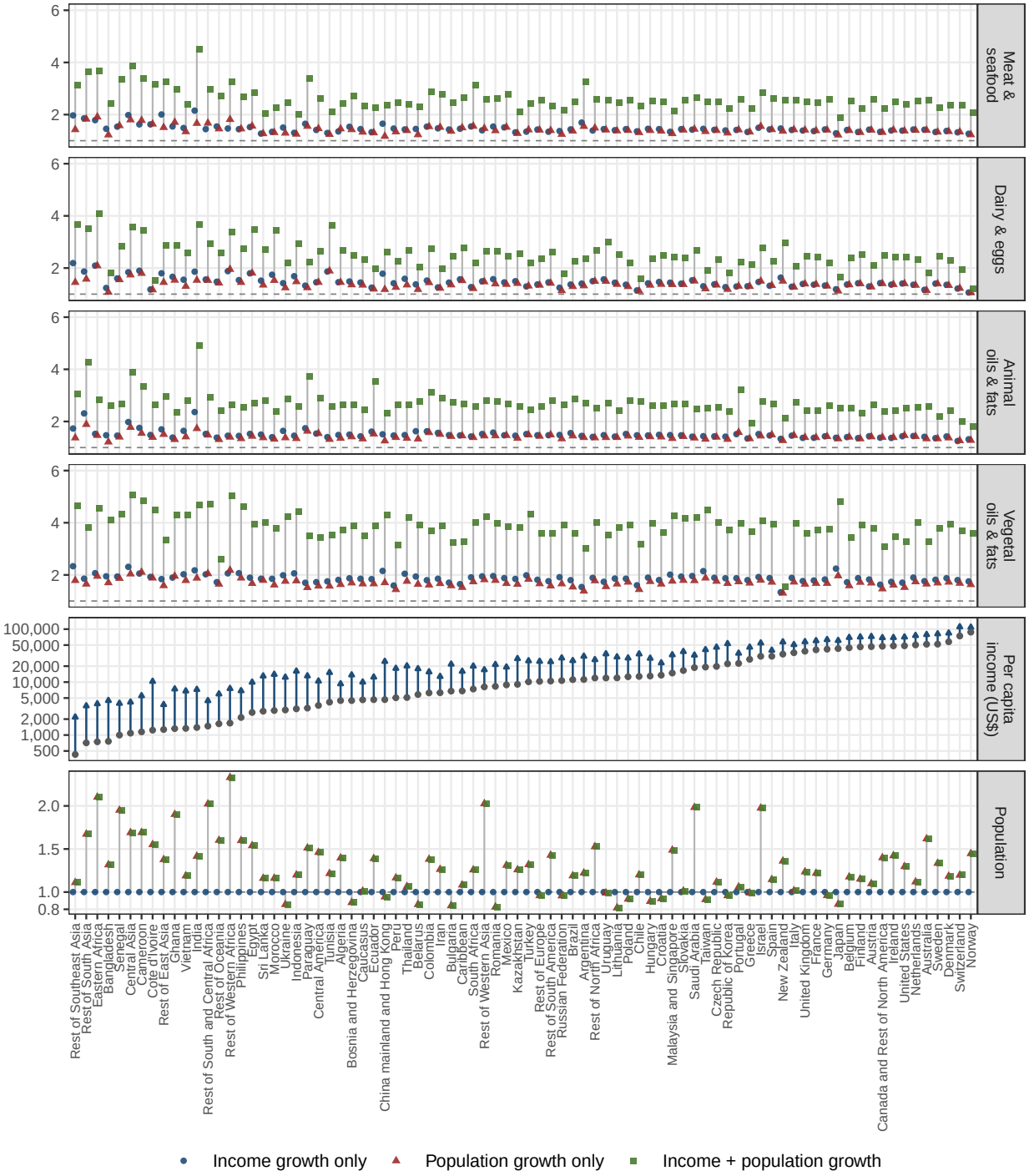
Outside these 21 regions, the nutrition transition continues amid higher food prices. Figure 9 plots the 2050 per capita consumption of each category against the 2010 per capita

Figure 7: Prices, income, and population by region under SSP2 in 2050 (part 1, vegetal food categories)



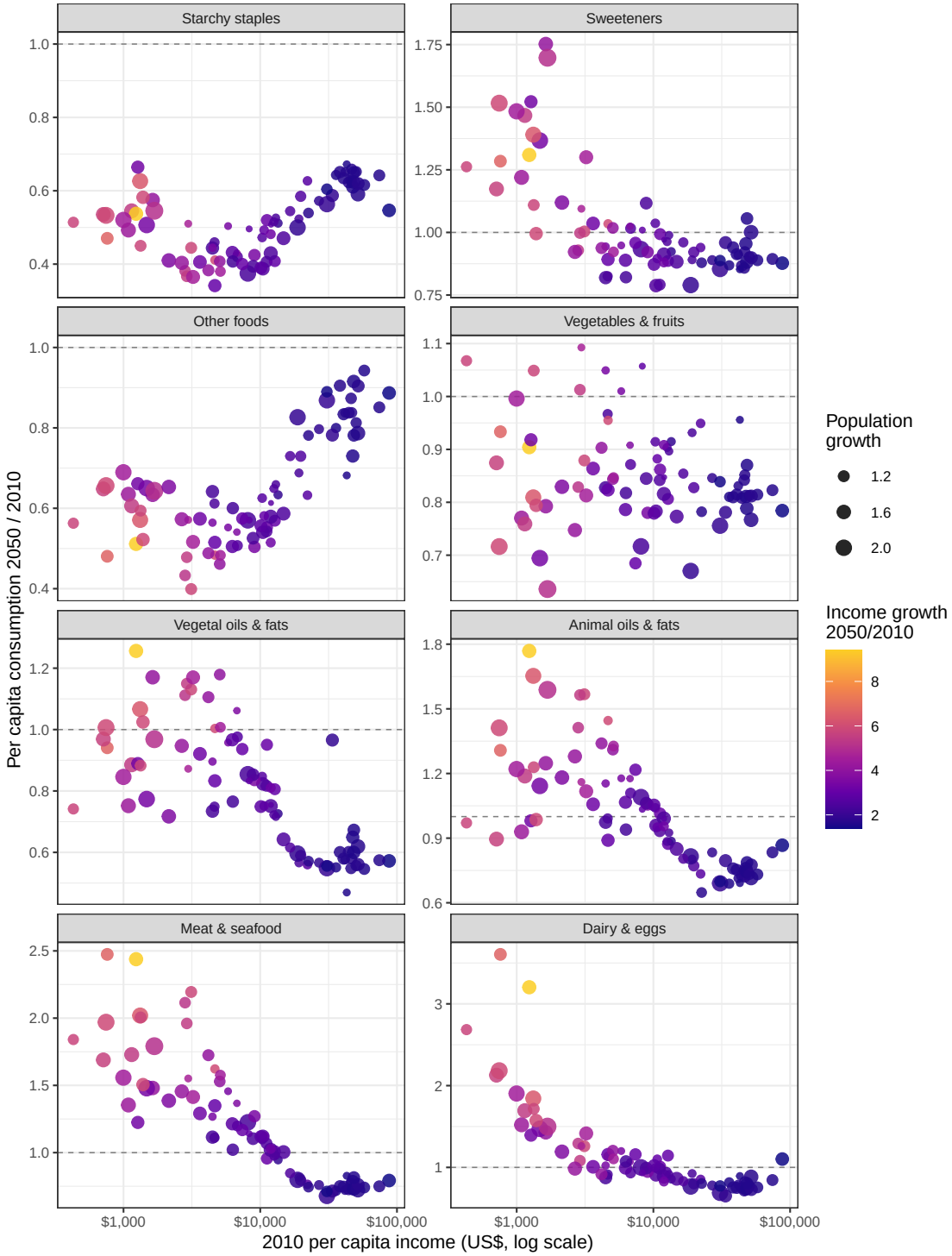
Note: Rows from the bottom represent population growth $\hat{H}_i$ under the three counterfactuals (equal to one with income growth only); per capita income, an arrow from the 2010 level to the 2050 level Y_i' in the full counterfactual (US dollars, log scale); then the consumer price $\hat{P}_i^n$ of four vegetal food categories (2010 = 1) on the same vertical axis (up to 6). The remaining four are listed in Figure 8. Regions ordered by 2010 per capita income. Three values lie above 6 and are drawn as upward triangles at the top edge: vegetables and fruits in Eastern Africa (8.34) and Rest of Western Africa (6.30), and starchy staples in Eastern Africa (6.34), all with both shocks.

Figure 8: Prices, income, and population by region under SSP2 in 2050 (part 2, animal food categories and vegetable oil)



Note: Same layout as Figure 7.

Figure 9: Per capita food consumption in 2050 relative to 2010



Note: Color represents the growth in per capita income from 2010 to 2050. Marker size represents population growth.

income, and Table 5 reports the median changes in prices and consumption by income group. Animal foods and sweeteners rise in poor regions and fall in rich ones. In the 15 regions with per capita income below 2,000 US dollars, consumption of meat and of dairy and eggs rises by 73 and 72 percent in the medians, while in the 41 regions above 10,000 dollars meat, dairy, and animal oils fall by 17 to 21 percent. The threshold is sharp for meat, which rises in every region with a 2010 income below 11,000 dollars and falls in every region above 15,000. Poor regions get there with higher income despite the largest price increases, with staple price rising 4.8-fold below 2,000 dollars against 3.2-fold above 10,000, and the price of vegetables and fruits 4.5-fold against 2.1-fold. Their income grows fastest.

Consumption of other food categories falls almost everywhere. Starchy staples trace a U across the income groups, to 54, 41, and 57 percent of the 2010 level in the medians. Two forces meet in the middle. Income growth shifts diets away from staples most in middle-income regions, the only group whose fixed-price projection already falls (to 0.72, against 0.99 and 1.00 in the other two groups), and higher prices add to that shift. In poor regions, the shift away from staples has barely started, and in rich regions diets no longer move, so in both groups staples fall mainly through prices. Section 5.3 separates the two forces.

Table 5: Median food prices and per capita consumption changes in 2050

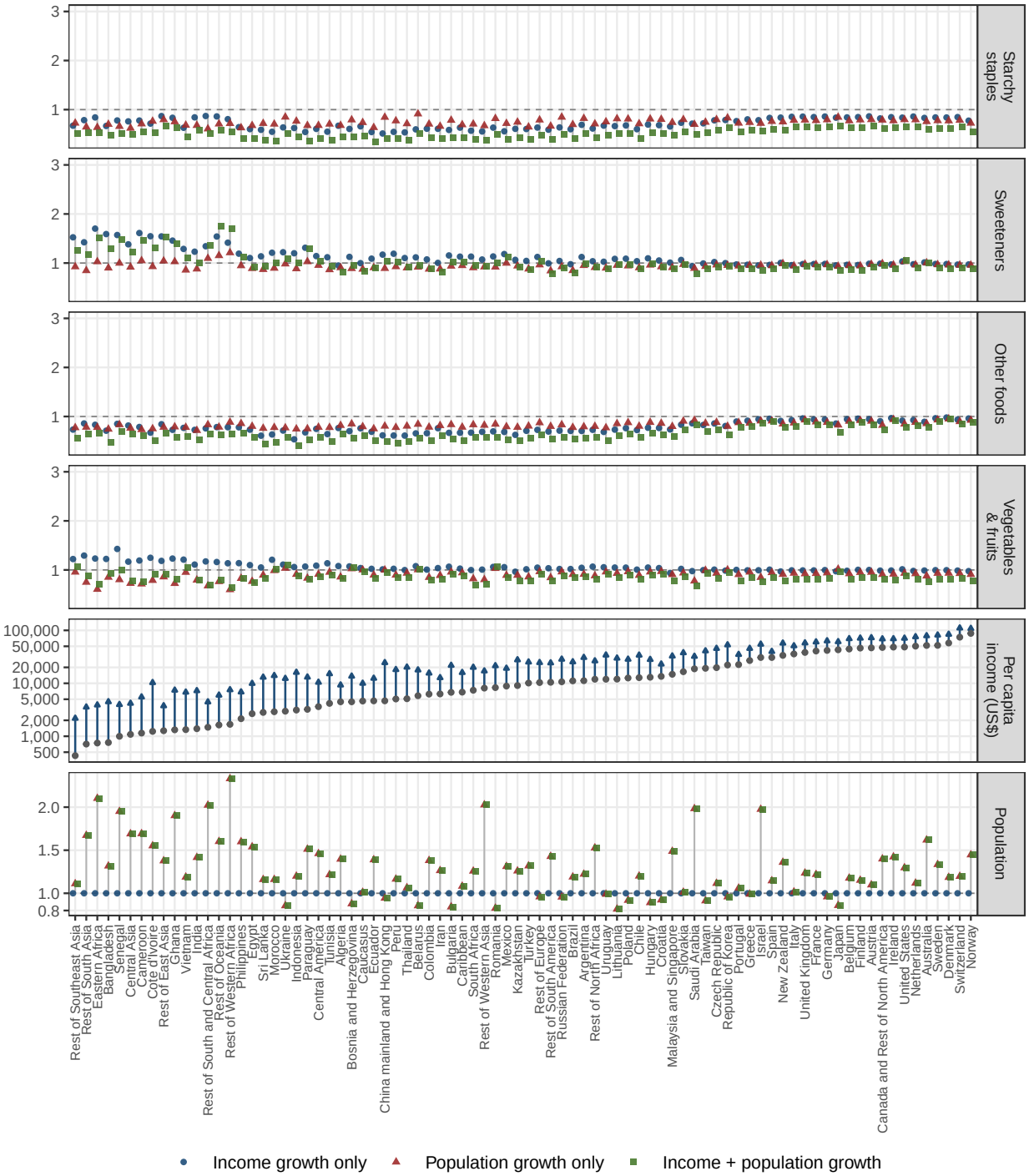
	Below 2,000 US$ (15 regions)		2,000–10,000 US$ (26 regions)		Above 10,000 US$ (41 regions)	
Category	Price	Consumption	Price	Consumption	Price	Consumption
Starchy staples	4.78	0.54	3.56	0.41	3.21	0.57
Sweeteners	2.60	1.37	2.19	0.95	1.79	0.90
Other foods	3.53	0.63	2.62	0.53	2.09	0.78
Vegetables & fruits	4.53	0.81	2.17	0.85	2.06	0.82
Vegetal oils & fats	4.50	0.94	3.88	0.94	3.77	0.60
Animal oils & fats	2.83	1.22	2.66	1.16	2.54	0.80
Meat & seafood	3.24	1.73	2.45	1.36	2.48	0.79
Dairy & eggs	2.93	1.72	2.62	1.07	2.35	0.83

Note: Regions are grouped by 2010 per capita income. Price is the Armington price of a food category. Consumption is per capita. Medians are taken separately for price and consumption within each income group.

5.3 Population and income as separate drivers

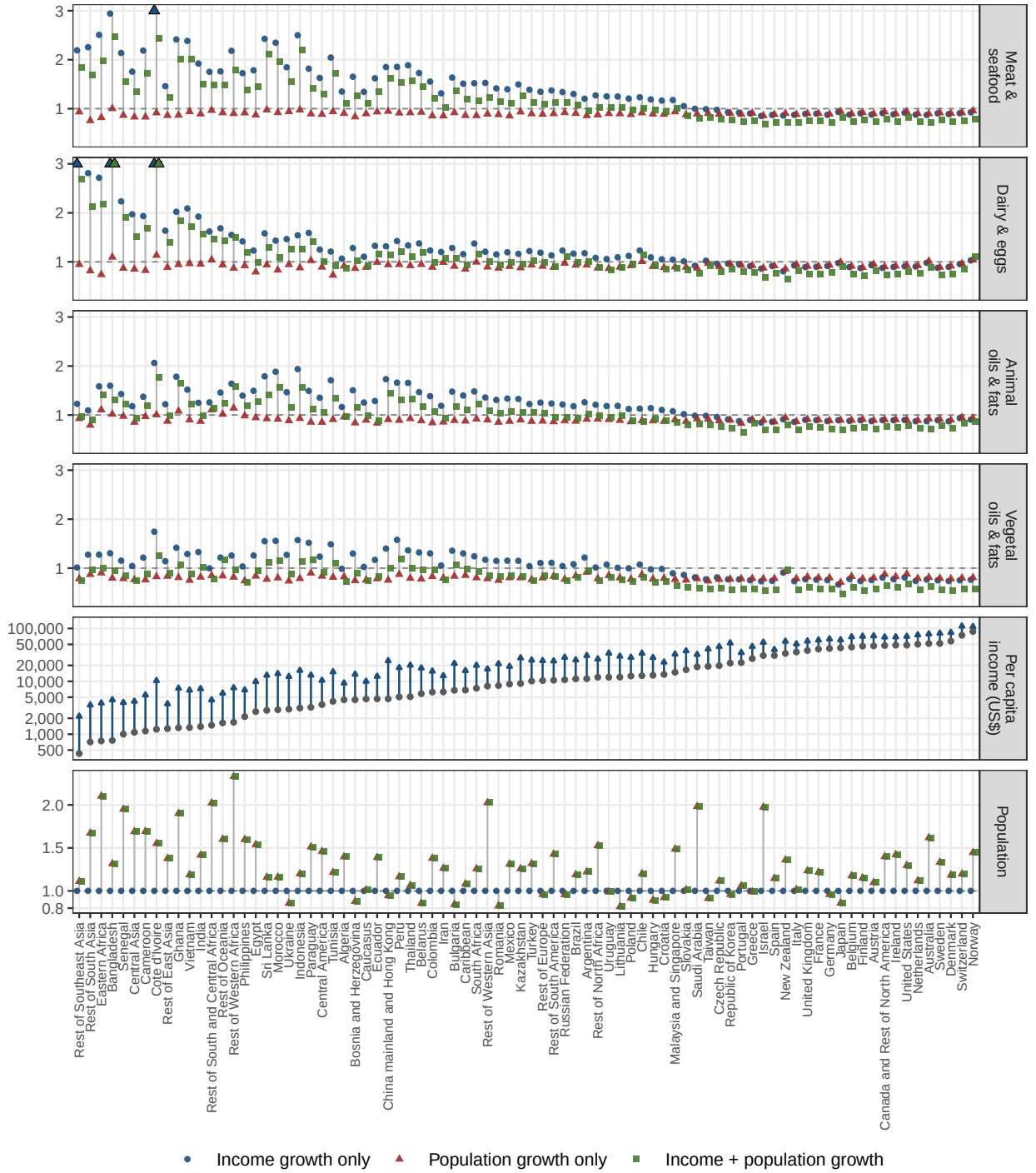
The full counterfactual mixes the effects of two drivers. To separate them, Figures 7 and 8 plot price changes under two more counterfactuals, one with income growth only (blue circles) and the other with population growth only (red triangles), and Figures 10 and 11 show the corresponding per capita consumption in the same layout.

Figure 10: Per capita consumption, income, and population by region under SSP2 in 2050 (part 1, vegetal food categories)



Note: Rows from the bottom represent population growth $\hat{H}_i$ under the three counterfactuals (equal to one with income growth only); per capita income, an arrow from the 2010 level to the 2050 level Y_i' in the full counterfactual (US dollars, log scale); then per capita consumption $\hat{C}_i^n$ of four vegetal food categories (2010 = 1) on the same vertical axis (up to 3). The remaining four categories are listed in Figure 11. Regions ordered by 2010 per capita income.

Figure 11: Per capita consumption, income, and population by region under SSP2 in 2050 (part 2, animal food categories and vegetable oil)



Note: Same layout as Figure 10, with the same vertical axis for the four consumption rows. Six values lie above 3 and are drawn as upward triangles at the top edge: dairy and eggs in Bangladesh (3.89 with income growth only, 3.61 with both shocks), Rest of Southeast Asia (3.32, income growth only), and Côte d'Ivoire (3.20 with both shocks, 3.05 with income growth only), and meat and seafood in Côte d'Ivoire (3.01, income growth only).

Income growth only Income growth is the driver of the nutrition transition, and the large deviations from 1 for blue circles concentrate at the bottom of the income distribution. With population held at its 2010 level, meat consumption rises in every region with a 2010 income below 17,000 US dollars and falls in every region above 19,000. Meat consumption at least doubles in 14 regions, all with per capita GDP below 4,200 dollars, and dairy consumption rises by half or more in 18 regions, all below 3,300 dollars. Even without population growth, per capita staple consumption falls in all 82 regions, and it falls most in the middle-income group with a median of 0.60, against 0.79 and 0.78 for countries with per capita GDP below 2,000 dollars and above 10,000 dollars. Starchy staples are inferior goods for these middle-income countries, and their diets shift away from staples fastest.

Across the 82 regions, the correlation between log per capita consumption and log income growth is 0.73 to 0.95 for the six categories the nutrition transition favors, and -0.43 for staples and -0.69 for other foods, the two where diets are shifting away from. Dietary patterns no longer change in rich countries, and consumption decreases result only from rising food prices. As the blue circles in Figures 7 and 8 show, prices rise by 1.2 to 1.9 times in the medians across food categories, and the pressure is concentrated in South and Southeast Asia, which account for 24 of the 40 top-five largest price increases across the eight categories.

Population growth only Population growth alone shifts diets only with small income changes from land rents and works mainly through prices, so per capita consumption falls almost everywhere (red triangles), and it falls most where population grows fastest. Even the 18 regions whose population shrinks by 2050, such as Japan and Germany, see every food price rise and consume less of nearly every category because the price increases come through world markets. Staple prices rise by 1.9 in the medians, and the log staple price rises with log population growth with a correlation of 0.82 across countries.

Pooling the eight categories, per capita consumption ends 16, 13, and 11 percent below its 2010 level in the regions below 2,000 US dollars, between 2,000 and 10,000 dollars, and above 10,000 dollars, which are in line with the three groups' median population growth factors of 1.67, 1.21, and 1.18. The response also differs by food category. The correlation between log per capita consumption and log population growth is -0.68 for staples and -0.86 for vegetables and fruits, close to zero for meat (-0.22), other foods (-0.14), and dairy (-0.13), and positive for animal oils (0.52), vegetal oils (0.35), and sweeteners (0.33).

Population growth raises a region's demand for every category by the same factor, so the differences across food consumption changes come from the supply side, especially from how much of each food category a region can supply itself. Staples and vegetables & fruits

rely heavily on domestic production as two large food categories. Imports of staples as food cover only 16 percent of domestic use in the medians. Regarding crops used for staple production, wheat is heavily traded, but rice and root crops are rarely, so the overall imports are still inelastic. Similarly, Vegetables and fruits cross borders only as food and account for 12 percent of domestic use in the medians.

When a region's own population grows, the domestic availability of these two food categories is re-divided among more people. The other six categories import 18 to 80 percent of their domestic use or rely on heavily traded crops, as meat does with its feed, so the world market absorbs much of the local shock. Where population grows faster, staples therefore become more expensive relative to the traded categories, and consumers substitute toward the latter, which is why the three positive correlations all belong to heavily imported categories. Median staple consumption falls to 0.70 in the poorest group against 0.78 in the richest, and vegetables and fruits fall to 0.76 against 0.93.

How the two shocks combine The two demand shocks have their price changes reinforce each other in the full counterfactual under fixed land base and productivity. The price increase with both shocks exceeds the product of the two separate increases by from 11 percent (other foods) to 29 percent (vegetables and fruits) in the medians, and it happens in 78 of 82 regions for every category. Each shock raises land rents and the share of land in crop costs, which makes crop supply less elastic, so each shock meets a steeper supply curve when the other is present. The land rent share of a crop dollar, φ_i, rises in every region, and the median goes up from 0.23 in 2010 to 0.61 with income growth alone, to 0.63 with population growth alone, and to 0.84 with both shocks.

The two shocks push in the same direction in consumption of starchy staples and in opposite directions for animal foods. Both the nutrition transition and the population effect lower staple consumption, so the full counterfactual cuts it most. For meat and dairy, income growth raises per capita consumption while population growth lowers it through higher prices, and the nutrition transition still wins in poor regions. In the group below 2,000 US dollars, median meat consumption increase is 73% with both shocks against 119% with income growth alone, and it still at least doubles in 6 of 15 regions (versus 14).

5.4 The welfare change and its incidence

Exogenous income growth follows the paths that the SSP narratives project and dominates the welfare change everywhere. Compared with the single-factor growth model in SSP, ours treats land as a separate factor, calculates its return as land rents, and redistributes welfare further through the agrifood system. Higher food prices hurt consumers at a constant

income, but income grows per SSP scenario, and land rents rise in all 82 regions and lift per capita income further above the SSP path ($\hat{Y}_i > \hat{g}_i$, as in the bottom row of Figure 12). What land rents add to per capita income is 11 percent in the medians of the regions below 2,000 US dollars, 4 percent between 2,000 and 10,000, and 3 percent above 10,000, with land-abundant exporters such as Argentina (15 percent) and New Zealand (12 percent) the main exceptions among richer regions.

Equation (46) provides a clean decomposition of the compensating variation (CV). The first two terms, the growth of composite-factor income and the change in land rents, exactly capture the total income changes. The third term, the income-constant CV, fixes income at its base-year level Y_i, lets the consumer face the counterfactual prices, and measures how much money can be taken from the consumer while keeping utility at its base-year level U_i. It is the cost of higher food prices to a consumer kept at the base-year utility and income levels. The equivalent variation (EV) has the same three terms with the utility and income levels held at their 2050 values, so the income-constant EV measures the cost of the same price change to a consumer kept at U_i' and Y_i'. The CV is in units of 2010 per capita income, and the EV is in units of 2050 per capita income.

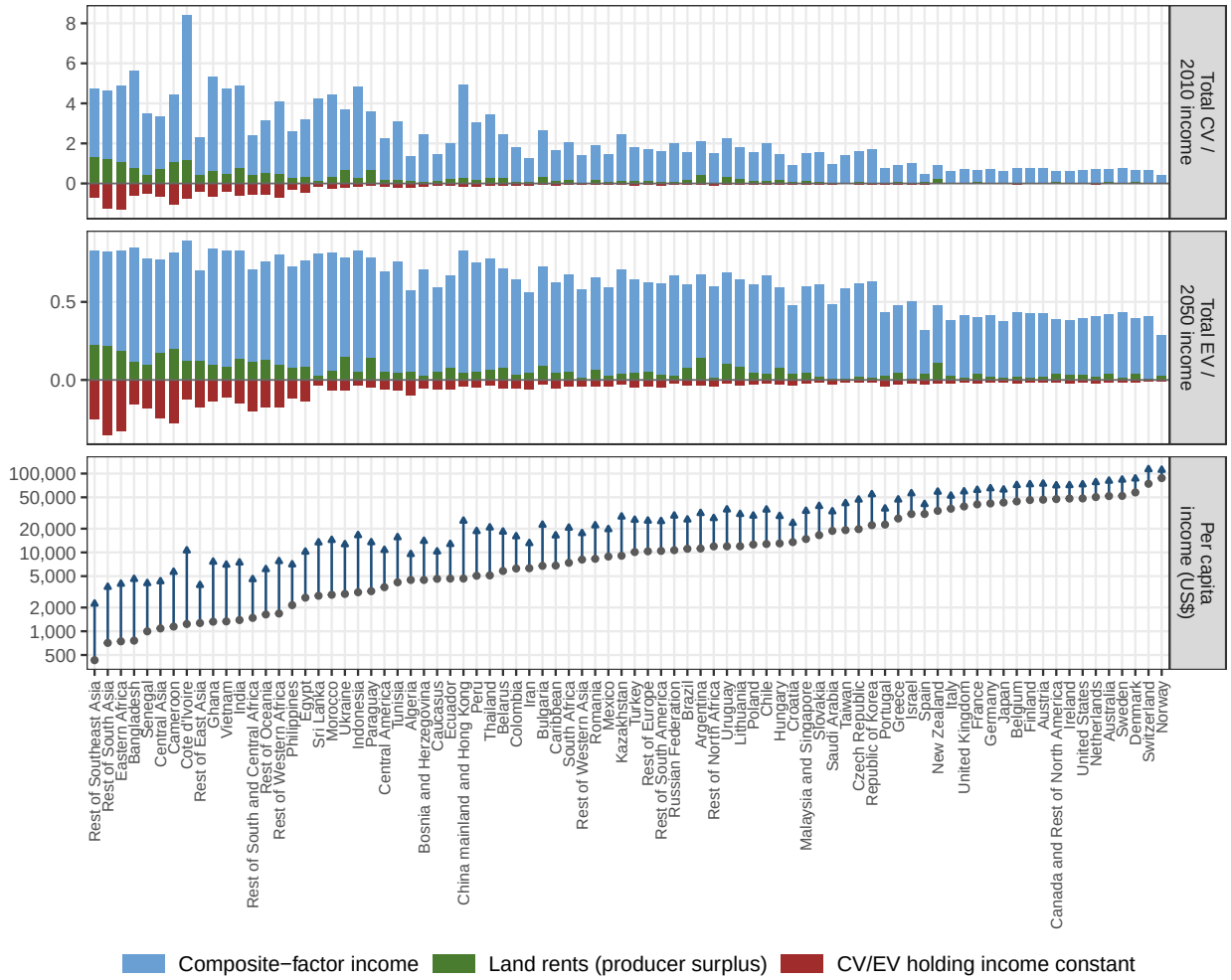
Three parts of the welfare change Table 6 reports the group means of the three terms by 2010 income group, and Figure 12 shows them region by region. Composite-factor income follows projected per capita GDP growth under SSP2 exogenously, averaging 3.67, 2.46, and 1.05 of 2010 income in the 15 regions below 2,000 US dollars, the 26 regions between 2,000 and 10,000, and the 41 regions above 10,000. The land rent term adds what SSP narratives leave out in agricultural land use. Land rents rise in all 82 regions, and the term averages 0.76, 0.22, and 0.09 of 2010 income in the three groups, making up a fifth of the total CV in the poorest group and under a tenth in the other two.

The third term is the consumer welfare loss from higher food prices. The income-constant CV is negative in all 82 regions and averages -0.71 of 2010 income in the poorest group, roughly a fifth of the group's composite-factor income term, and -0.05 in the richest, about a twentieth of the composite-factor income.

As Figure 12 shows, the second and third terms, the two that are endogenous in the model, have opposite signs but similar magnitudes in each region. Both are an order of magnitude smaller than the exogenous income growth, but they are large where food takes a large share of the budget.

In dollars per person, the two measures share the same income decomposition and differ only in the income-constant term. As in Figure 13, the income-constant EV is larger than CV in 61 of the 82 regions, with median values of 1,085 dollars versus 840. This is because

Figure 12: Welfare incidence by region under SSP2



Notes: Top row: per capita CV in units of 2010 per capita income. Middle row: per capita EV in units of 2050 per capita income. Bottom row: per capita income, an arrow from the 2010 level Y_i to the 2050 level Y_i' (US dollars, log scale). Regions ordered by 2010 per capita income.

Table 6: The three parts of the welfare change by 2010 income group

2010 income (US$)	Number of regions	Composite-factor income	Land rent	Income-constant CV/EV	Total CV/EV	Food system	Food system > 0
A. CV in units of 2010 per capita income							
Below 2,000	15	3.67	0.76	−0.71	3.73	0.05	8
2,000 to 10,000	26	2.46	0.22	−0.16	2.53	0.07	15
Above 10,000	41	1.05	0.09	−0.05	1.09	0.04	27
All regions	82	1.98	0.25	−0.20	2.03	0.05	50
B. EV in units of 2050 per capita income							
Below 2,000	15	0.664	0.140	−0.202	0.601	−0.062	1
2,000 to 10,000	26	0.647	0.058	−0.056	0.649	0.002	11
Above 10,000	41	0.467	0.037	−0.024	0.480	0.013	27
All regions	82	0.560	0.062	−0.067	0.556	−0.004	39

Note: Values are unweighted means within each group, so the composite-factor income, land rent, and income-constant columns add up to the total, and the land rent and income-constant columns add up to the food system column. The last column counts the number of regions where the sum of food-system terms is positive.

these regions all have non-homothetic demand and higher utility levels in the counterfactual. On the other hand, the two terms are equal to each other in the remaining 21 regions where diet no longer changes with income, whose compensated demand does not depend on utility.

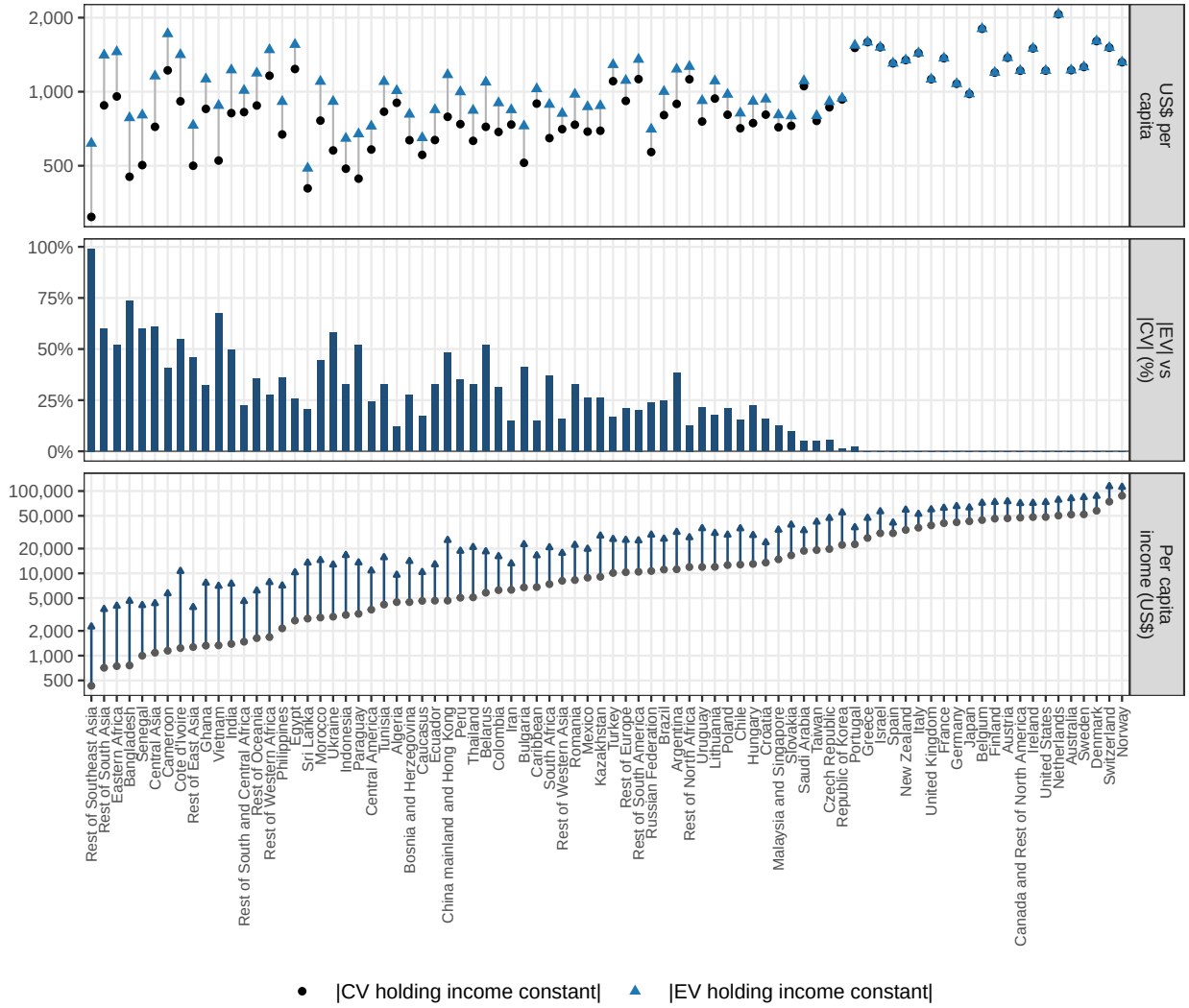
The sum of the two endogenous terms is the welfare change that the food system generates, and it is each region's gain or loss relative to the SSP narratives. It is positive in 50 regions and negative in 32 under the CV decomposition, with a median of +0.01, and positive in 39 regions under the EV, with the same sign as under the CV in 71 of 82. The split follows a clear geographical pattern and is hardly explained by income levels, as the correlation between the sum and log 2010 income is only −0.17.

As shown in Figure 14, South American countries, Eastern Europe, and South and Southeast Asia are mostly better off. On the other hand, Africa is hit hardest, with 9 of its 13 regions there worse off than the standard SSP scenarios. The Middle East follows behind, with Saudi Arabia, Rest of Western Asia, Iran, and Israel all losing smaller amounts.

Africa loses because food prices there rise the most and its own production cannot keep up. Across countries there, median use of the eight food categories in 2050 is 0.8 to 2.9 times the base-year quantity, while production is 0.6 to 1.7 times, and use outgrows production in seven of the eight. Imports fill the gap, and the import share of African food spending rises from 11 percent in the base year to 31 percent[5] in 2050, against a rise of 2.5 percentage points in the medians of the other 69 regions. A growing part of what African consumers pay therefore accrues to land abroad, and in the nine African losers the land rent term covers

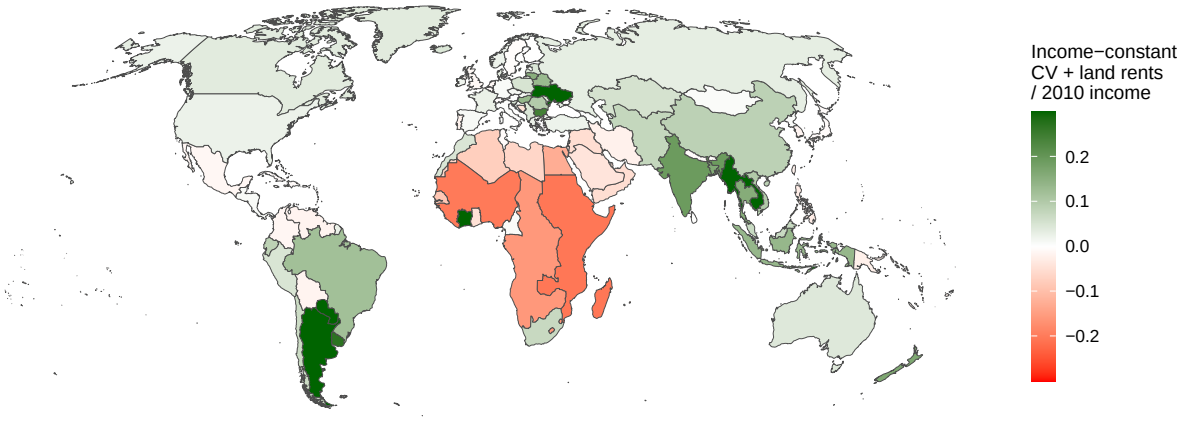
[5]This share is calculated as $\frac{\sum_n \sum_{j \neq i} b_i^n \, b_{ji}^n \, \hat{p}_j^n \, \hat{X}_{ji}^n}{\sum_n \sum_j b_i^n \, b_{ji}^n \, \hat{p}_j^n \, \hat{X}_{ji}^n}$.

Figure 13: Per capita CV vs EV holding income constant



Notes: Top row: absolute values of per capita CV (dots) and EV (triangles). Middle row: how large the absolute value of EV is compared with CV, holding income constant. Bottom row: per capita income, an arrow from the 2010 level Y_i to the 2050 level Y_i' (US dollars, log scale). Regions ordered by 2010 per capita income.

Figure 14: The food-system part of the welfare change by region



Notes: The land rent term plus the income-constant CV, in units of 2010 per capita income (SSP2, 2050, population and income growth). Green regions gain from the food system and red regions lose. Values are capped at ±0.3 for the color scale.

only 0.73 of the income-constant CV in the medians.

Rich regions see very small changes in both land rents and the income-constant CV, as the food and agricultural sector is a very small part of their economies. The share of the composite factor that the outside sector uses, averaged within the three income groups, is 0.95, 0.96, and 0.97 in 2050, against 0.70, 0.87, and 0.95 in the base year. This serves as a callback to the food problem.

5.5 Yield growth requirement

While the previous counterfactuals serve as a stress test that holds yields at their 2010 level, this subsection asks how much yield growth would largely offset price increases imposed on consumers. We raise the expected yield of every crop in selected regions or everywhere by a common factor and let prices and production adjust. The yield shifter $\hat{A}_i^l$ then enters

the two crop supply equations of the model

$$\hat{Y}_i^l = \hat{A}_i^l \left(\hat{\pi}_i^l\right)^{1-\frac{1}{\theta_i}} \qquad I \times L \ ,$$

$$\hat{\pi}_i^l = \frac{\left(\hat{r}_i^l \hat{A}_i^l\right)^{\theta_i}}{\sum_{l'} \pi_i^{l'} \left(\hat{r}_i^{l'} \hat{A}_i^{l'}\right)^{\theta_i}} \qquad I \times L \ ,$$

and the other equations are unchanged. With the same $\hat{A}_i^l = \hat{A}$ for every crop in a region, the shifter cancels out of the land allocation equation, so land shares still respond to rents alone, and at any given rents crop supply is simply $\hat{A}$ times larger.

We solve for the value of $\hat{A}$ at which the median income-constant CV is zero under the SSP2 full counterfactual sector-neutral case, first with $\hat{A}_i^l = \hat{A}$ in all 82 regions and then with $\hat{A}_i^l = \hat{A}$ in the 58 yield-gap regions only, as Section 4 describes. In the second case, we let the following 24 regions whose yields are already near their potential keep their 2010 yields: Western and Northern Europe, the United States, Canada, New Zealand, Japan, the Republic of Korea, Taiwan, Israel, and Chile. Central and Eastern Europe is not among them, because its yield gaps remain large (Mueller et al., 2012), and neither is Australia, where wheat reaches only about half of its water-limited yield potential (Hochman, Gobbett, and Horan, 2017). A region's income-constant CV is zero when its food price index at base-year preferences equals one, so the search is over that index. Table 7 reports the two solutions next to the historical pace of yield growth.

Table 7: Required and historical yield growth

Linear yield growth	% of yield in	Per year	Over 40 years
Maize, rice, wheat, soybeans, 1989–2008[a]	2008	0.9 to 1.6%	× 1.36 to 1.64
Cereals, 1961–90 / 1990–2011[b]	1990 / 2011	1.7% / 1.3%	× 1.7 / × 1.5
Doubling world crop output, 2008 to 2050[a]	2008	2.4%	× 2.0
Required, all 82 regions	2010	**1.45%**	× **1.58**
Required, 58 regions with yield gaps	2010	**2.07%**	× **1.83**

Note: [a]Ray et al. (2013). [b]Alston and Pardey (2014), compound rates converted to linear.

A universal yield growth of 58 percent from 2010 brings the median income-constant CV to zero, and a yield growth of 83 percent occurring in selected 58 regions does so when the 24 near-potential regions keep their 2010 yields. Spread over the 40 years to 2050, these are 1.45 and 2.07 percent of the 2010 yield per year if yields grow linearly, as they have. The first requirement sits at the upper end of the pace of the last two decades, and the second sits above it, though both are well below the 2.4 percent per year that would double world crop output by 2050 (Ray et al., 2013).

The requirement is modest because almost all of the food price increase in the stress test comes from higher land rents. A crop uses land and the composite input, so its price is a weighted average of the land rent and the unit cost of the composite input, with the 2010 cost shares as weights. Under sector-neutral growth, the unit cost of the composite input stays at one, so a crop's price moves only through its rent. The demand shock raises food prices by inflating the land rent of each crop, and yield growth works on the same part from the opposite direction, because it raises crop supply at any given rents. A moderate $\hat{A}$ therefore deflates the rents and pulls prices most of the way back to their 2010 level. The same logic sets a floor. Rents cannot fall below zero, so no crop price can fall below the non-land share of its 2010 cost, 0.92 of the crop dollar in the medians, and yield growth cannot make food much cheaper than in 2010, however fast yields grow.

With the price change costing consumers nothing in the medians, the nutrition transition runs its course as if prices had never moved. At $\hat{A} = 1.58$, median per capita meat consumption rises to 1.54 times its 2010 level and staple consumption falls to 0.86, next to medians of 1.55 and 0.87 in the fixed-price projections. Landowners still gain, but little of the stress-test windfall survives. Median per capita land rents grow 1.33-fold, against 16.8-fold with 2010 yields, and the land rent term of the full CV falls from 0.13 of 2010 income to 0.00. Even at $\hat{A} = 1.58$, consumers in Sub-Saharan Africa, South Asia, and Central Asia still lose 0.13 to 0.32 of their 2010 income to higher food prices, measured by the income-constant CV, because population grows fastest and food takes the largest budget share there.

5.6 Robustness: productivity growth in the food and crop sectors

6 Conclusion

This paper measures the pressure that population growth and the nutrition transition will put on world food markets by 2050. We build a general equilibrium model of 82 regions, 8 food categories, and 76 crops, hold crop yields and land base at their 2010 level, and let population and income grow along the SSP paths. The design is a stress test rather than a forecast. It shows what demand growth alone would do to prices, diets, land use, and welfare, and how much productivity growth it takes to absorb the shock.

The demand shock increases food prices a lot. Under SSP2, the median increase in food prices is 2.0-fold to 3.9-fold, and consumers in poor regions give up almost half of their starchy staple consumption while holding on to the animal foods their rising incomes newly afford. The nutrition transition survives the price increases it creates. In regions with 2010 incomes below 2,000 US dollars, per capita meat and dairy consumption still rises by

more than 70 percent. Because the land base is fixed, the higher prices end up as land rents, which rise in all 82 regions, so the shock works as a transfer from food consumers to landowners. Compared with what the SSP narrative counts, the regions that are worst off are mostly in Africa, where food prices rise the most and a growing share of food spending pays rents on land abroad. Changes in land rents of crops also incentivize cropland to expand into pastureland in 71 of the 82 regions, creating an environmental cost that our welfare measures do not price.

Steady yield growth can absorb most of the shock. Growth of 1.45 percent of the 2010 yield per year, which is close to the upper end of the pace of the last two decades, brings the median consumer cost of the food price change to zero, and if the 24 regions already near their yield potential keep their 2010 yields, the 58 regions with yield gaps would instead need 2.07 percent per year. Median per capita land rents then grow 1.33-fold instead of 16.8-fold, the nutrition transition proceeds almost as if prices had never moved, and consumers lose 0.13 to 0.32 of their 2010 income to higher food prices only where population grows fastest and food takes the largest budget share, in Sub-Saharan Africa, South Asia, and Central Asia. The warning and the comfort in our results are the same fact read from two sides. The food system of 2050 depends on productivity growth that history has delivered but that no law of nature guarantees. Policies that trade yield for credence attributes, such as organic mandates and non-GMO sourcing, would raise the requirement further (Sexton, 2025; Mérel, Qin, and Sexton, 2023).

The model points to three extensions. First, yields enter as exogenous shifters, so projections of climate-driven yield changes, crop by crop and region by region, can replace our uniform counterfactual without changing the model, and the welfare decomposition would then price the combined demand and supply shock. Second, we hold technology fixed, while the price and rent changes we project are the kind of signal that redirects agricultural innovation (Moscona and Sastry, 2025). Letting innovation respond to the returns the model generates would make yield growth an outcome instead of an assumption. Third, population follows the SSP paths no matter how expensive food becomes. A world where starchy staple prices more than triple is unlikely to be a world where fertility does not respond, which is the preventive check that Malthus described. Letting population growth respond to food prices would make the demographic path an outcome as well, and the response would depress the stress we measure.

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Appendices

A Countries, Regions, and Crops in the Model

This paper aims to quantify implications of the global nutrition transition and thus design its country, food, and crop lists to leave essentially nothing out. Countries are aggregated to the 82 model countries and composite regions, and commodities to the 8 food categories and 76 model crops (including grass). Table A.1 lists the countries and regions. Twenty-three of them are aggregates of several economies; Tables A.2 and A.3 detail their composition, with member economies named as in the underlying statistical sources for 2010–2012. Table A.4 lists the model crops, grouped by the crop families used in the calibration (Appendix G.6): except for use as feed, each crop family's food output goes almost entirely to one vegetal food category. The eight food categories are defined in Section 2.2 of the main text. Tables A.5–A.8 document the commodity classification behind the accounts of Appendix G: which SUA items enter as crop commodities under each model crop, and which enter as food commodities under each food category, following the feed rule of Section 3.1.

Data coverage On the country dimension, coverage is complete by construction. Every economy belongs to one of the 82 regions, so the model utilizes every country-level record the source datasets carry. We could miss data when these sources do not publish them at the country level. For example, the FAO Food Balance Sheet omits food accounts of a set of economies, including South Sudan, Singapore, Eritrea, Palestine, Puerto Rico, Qatar, Bahrain, and 27 smaller territories, accounting for roughly 34 million people or about half a percent of the world population in the baseline year; their food consumption is imputed from their net imports wherever they trade visibly, and Appendix G.3 details how the food and GDP sides of the ratio $\tilde{b}_i$ stay aligned for these economies and for Puerto Rico. Fifteen small territories lack harvested area records, and we assume they do not have crop outputs at meaningful quantities. Economies absent from the OECD–WiC projections (North Korea, South Sudan, and 28 micro-economies, together half a percent of world population) inherit their region's growth path, and the two partial-window reporters (Sudan from 2012, the former Netherlands Antilles only 2010) are upweighted to the full 2010–2012 window before regional aggregation.

On the crop dimension, the 75 model crops (grass has no harvested area and is excluded from these metrics) span 140 of the 157 primary crops with recorded harvested area and 97.7 percent of the world's harvested crop area. The uncovered 30.8 million hectares are almost entirely non-food crops, including coffee (10.2 million ha), natural rubber (9.7), tobacco

(4.1), tea (3.4), and jute and other fibre crops, which lie outside the model's food scope by construction. In value terms, the model crops account for 95.8 percent of world crop production.

These coverage rates compare with the 83 percent of world population covered by Gouel and Guimbard (2019), the 88 percent of global harvested area covered by Gouel and Laborde (2021), and the 89.7 percent of world crop output value (of which their ten crops cover 71.1 percent) covered by Costinot, Donaldson, and Smith (2016). While our interests in the global demand shocks drive the data coverage to the limit, the crop production mechanism allows us to abstractly model reactions of both major and residual crops in major countries and composite regions.

Table A.1: The 82 countries and regions of the model

Algeria	Germany	Rest of Oceania
Argentina	Ghana	Rest of South America
Australia	Greece	Rest of South and Central Africa
Austria	Hungary	Rest of South Asia
Bangladesh	India	Rest of Southeast Asia
Belarus	Indonesia	Rest of Western Africa
Belgium	Iran	Rest of Western Asia
Bosnia and Herzegovina	Ireland	Romania
Brazil	Israel	Russian Federation
Bulgaria	Italy	Saudi Arabia
Cameroon	Japan	Senegal
Canada and Rest of North America	Kazakhstan	Slovakia
Caribbean	Lithuania	South Africa
Caucasus	Malaysia and Singapore	Spain
Central America	Mexico	Sri Lanka
Central Asia	Morocco	Sweden
Chile	Netherlands	Switzerland
China mainland and Hong Kong	New Zealand	Taiwan
Colombia	Norway	Thailand
Côte d'Ivoire	Paraguay	Tunisia
Croatia	Peru	Turkey
Czech Republic	Philippines	Ukraine
Denmark	Poland	United Kingdom
Eastern Africa	Portugal	United States
Ecuador	Republic of Korea	Uruguay
Egypt	Rest of East Asia	Vietnam
Finland	Rest of Europe	
France	Rest of North Africa	

Table A.2: Composition of the aggregate regions (a)

Model region	Member economies
Australia	Australia; Christmas Island; Cocos (Keeling) Islands; Norfolk Island
Canada and Rest of North America	Bermuda; Canada; Greenland; Saint Pierre and Miquelon
Caribbean	Anguilla; Antigua and Barbuda; Aruba; Bahamas; Barbados; Bonaire, Sint Eustatius and Saba; British Virgin Islands; Cayman Islands; Cuba; Curaçao; Dominica; Dominican Republic; Grenada; Haiti; Jamaica; Montserrat; Puerto Rico; Saint Barthélemy; Saint Kitts and Nevis; Saint Lucia; Saint Vincent and the Grenadines; Saint-Martin (French Part); Sint Maarten (Dutch Part); Trinidad and Tobago; Turks and Caicos Islands; United States Virgin Islands
Caucasus	Armenia; Azerbaijan; Georgia
Central America	Belize; Costa Rica; El Salvador; Guatemala; Honduras; Nicaragua; Panama
Central Asia	Afghanistan; Kyrgyzstan; Pakistan; Tajikistan; Turkmenistan; Uzbekistan
China mainland and Hong Kong	China; China, Hong Kong SAR
Eastern Africa	Burundi; Comoros; Djibouti; Eritrea; Ethiopia; Kenya; Madagascar; Malawi; Mauritius; Mayotte; Mozambique; Rwanda; Seychelles; Somalia; South Sudan; Sudan; Uganda; United Republic of Tanzania; Zambia; Zanzibar
Finland	Finland; Åland Islands
France	France; Guadeloupe; Martinique; Réunion
Malaysia and Singapore	Malaysia; Singapore
Netherlands	Netherlands; Netherlands Antilles
Norway	Norway; Svalbard and Jan Mayen Islands
Rest of East Asia	China, Macao SAR; Democratic People's Republic of Korea; Mongolia

Table A.3: Composition of the aggregate regions (b)

Model region	Member economies
Rest of Europe	Albania; Andorra; Channel Islands; Estonia; Faroe Islands; Gibraltar; Holy See; Iceland; Isle of Man; Kosovo; Latvia; Liechtenstein; Luxembourg; Malta; Monaco; Montenegro; Republic of Moldova; San Marino; Serbia; Slovenia; The former Yugoslav Republic of Macedonia
Rest of North Africa	Libya; Western Sahara
Rest of Oceania	American Samoa; Cook Islands; Fiji; French Polynesia; Guam; Kiribati; Marshall Islands; Micronesia (Federated States of); Nauru; New Caledonia; Niue; Northern Mariana Islands; Palau; Papua New Guinea; Pitcairn Islands; Samoa; Solomon Islands; Tokelau; Tonga; Tuvalu; United States Minor Outlying Islands; Vanuatu; Wallis and Futuna Islands
Rest of South America	Bolivia (Plurinational State of); Falkland Islands (Malvinas); French Guiana; Guyana; Suriname; Venezuela (Bolivarian Republic of)
Rest of South and Central Africa	Angola; Botswana; Central African Republic; Chad; Congo; Democratic Republic of the Congo; Equatorial Guinea; Gabon; Lesotho; Namibia; Sao Tome and Principe; Swaziland; Zimbabwe
Rest of South Asia	Bhutan; Maldives; Nepal
Rest of Southeast Asia	Brunei Darussalam; Cambodia; Lao People's Democratic Republic; Myanmar; Timor-Leste
Rest of Western Africa	Benin; Burkina Faso; Cabo Verde; Gambia; Guinea; Guinea-Bissau; Liberia; Mali; Mauritania; Niger; Nigeria; Saint Helena, Ascension and Tristan da Cunha; Sierra Leone; Togo
Rest of Western Asia	Bahrain; Cyprus; Iraq; Jordan; Kuwait; Lebanon; Occupied Palestinian Territory; Oman; Qatar; Syrian Arab Republic; United Arab Emirates; Yemen

Notes: The 59 regions not listed in Tables A.2 and A.3 consist of the single country of the corresponding name.

Table A.4: The 76 model crops by calibration family

Family	Crops
Cereals and starchy roots (13)	Barley; Cassava; Cereals, Other; Cocoyam and Roots, Other; Maize; Millet; Oats; Potatoes; Rice; Rye; Sorghum; Sweet potatoes; Wheat
Sugar crops and cocoa (4)	Cocoa beans; Sugar beet; Sugar cane; Sugar Crops, Other
Vegetables and fruits (38)	Apples; Apricots; Asparagus; Avocados; Bananas, Plantains; Berries, Other; Cabbages; Carrot; Cauliflowers and broccoli; Cherries; Chillies and peppers (green); Citrus, Other; Cucumbers and gherkins; Dates; Eggplants; Fruits, Other; Garlic; Grapefruit and pomelo; Grapes; Lemons and limes; Lettuce and chicory; Mangoes, mangosteens, guavas; Melons, Cantaloupes; Onions, dry; Oranges; Papayas; Peaches and nectarines; Pears and Quinces; Peas, green; Pineapples; Plums; Pumpkins, squash and gourds; Spinach; Strawberries; Tangerines, mandarins, clementines, satsumas; Tomatoes, fresh; Vegetables, Other; Watermelons
Pulses, oilseeds, nuts, and other food crops (20)	Almonds; Beans, dry; Chestnuts; Chick-peas, dry; Coconuts; Groundnuts; Lentils, dry; Nuts, Other; Oilcrops, Other; Olives; Peas, dry; Pistachios; Pulses, Other; Rapeseed, mustardseed, colza seed; Seed Cotton; Sesame seed; Soybeans; Spices; Sunflower seed; Walnuts
Grass (1)	Grass

Notes: Family classification follows the "food" use destination of each crop. "Grass" is the non-tradable, labor-free reservation crop used only for "feed" and "non-food."

Table A.5: SUA items classified as crop commodities (a)

Model crop	SUA items on the crop account
Almonds	Almonds, in shell
Bananas, Plantains	Bananas; Plantains and cooking bananas
Barley	Barley; Pot barley*; Bran of barley*; Barley flour and grits*
Berries, Other	Raspberries; Gooseberries; Currants; Blueberries; Cranberries; Other berries and fruits of the genus vaccinium n.e.c.
Carrot	Carrots and turnips
Cassava	Cassava, fresh; Cassava, dry*
Cereals, Other	Buckwheat; Quinoa; Fonio; Triticale; Canary seed; Mixed grain; Cereals n.e.c.; Bran of buckwheat*; Bran of fonio*; Bran of triticale*; Flour of mixed grain*; Bran of mixed grain*; Bran of cereals n.e.c.*; Cereal preparations*
Cherries	Sour cherries; Cherries
Chestnuts	Chestnuts, in shell
Chick-peas, dry	Chick peas, dry
Chillies and peppers (green)	Chillies and peppers, green (Capsicum spp. and Pimenta spp.)
Citrus, Other	Other citrus fruit, n.e.c.
Cocoa beans	Cocoa beans; Cocoa husks and shells*
Coconuts	Coconuts, in shell; Copra*; Cake of copra*
Cocoyam and Roots, Other	Yautia; Taro; Yams; Edible roots and tubers with high starch or inulin content, n.e.c., fresh; Edible roots and tubers with high starch or inulin content, n.e.c., dry*
Eggplants	Eggplants (aubergines)
Fruits, Other	Other stone fruits; Other pome fruits; Figs; Persimmons; Cashewapple; Kiwi fruit; Other tropical fruits, n.e.c.; Other fruits, n.e.c.
Garlic	Green garlic
Grapefruit and pomelo	Pomelos and grapefruits
Groundnuts	Groundnuts, excluding shelled; Groundnuts, shelled*; Cake of groundnuts*
Maize	Maize (corn); Germ of maize*; Bran of maize*; Cake of maize*; Maize gluten*; Gluten feed and meal*
Mangoes, mangosteens, guavas	Mangoes, guavas and mangosteens; Mango pulp*
Melons, Cantaloupes	Cantaloupes and other melons
Millet	Millet; Bran of millet*
Nuts, Other	Brazil nuts, in shell*; Cashew nuts, in shell; Kola nuts; Hazelnuts, in shell; Areca nuts; Other nuts (excluding wild edible nuts and groundnuts), in shell, n.e.c.
Oats	Oats; Bran of oats*

Notes: An asterisk marks a processed product kept on the crop account by the feed rule of Section 3.1; items without an asterisk are primary crops. The 27 model crops not listed consist of the single primary item of the same name. "Grass" has no SUA items.

Table A.6: SUA items classified as crop commodities (b)

Model crop	SUA items on the crop account
Oilcrops, Other	Oil palm fruit; Karite nuts (sheanuts); Castor oil seeds; Tung nuts; Jojoba seeds; Safflower seed; Poppy seed; Melonseed; Tallowtree seeds; Kapok fruit; Linseed; Hempseed; Other oil seeds, n.e.c.; Cake, poppy seed*; Kapokseed in shell*; Kapokseed, shelled*; Palm kernels*; Cake of palm kernel*; Cake of safflowerseed*; Cake of kapok*; Cake of linseed*; Cake of hempseed*; Cake, oilseeds nes*; Flours and meals of oil seeds or oleaginous fruits, except those of mustard*
Onions, dry	Onions and shallots, dry (excluding dehydrated)
Pears and Quinces	Pears; Quinces
Pistachios	Pistachios, in shell
Plums	Plums and sloes
Potatoes	Potatoes; Starch of potatoes*; Tapioca of potatoes*
Pulses, Other	Broad beans and horse beans, dry; Cow peas, dry; Pigeon peas, dry; Bambara beans, dry; Vetches; Lupins; Other pulses n.e.c.; Flour of pulses*; Bran of pulses*
Rapeseed, mustard-seed, colza seed	Rape or colza seed; Mustard seed; Flour of mustard seed*; Cake of rapeseed*; Cake of mustard seed*
Rice	Rice; Husked rice*; Rice, broken*; Rice, gluten*; Bran of rice*; Cake of rice bran*
Rye	Rye; Bran of rye*
Seed Cotton	Cotton seed*; Cake of cottonseed*
Sesame seed	Sesame seed; Cake of sesame seed*
Sorghum	Sorghum; Bran of sorghum*
Soybeans	Soya beans; Cake of soya beans*
Spices	Pepper (Piper spp.), raw; Chillies and peppers, dry (Capsicum spp., Pimenta spp.), raw; Vanilla, raw; Cinnamon and cinnamon-tree flowers, raw; Cloves (whole stems), raw; Nutmeg, mace, cardamoms, raw; Anise, badian, coriander, cumin, caraway, fennel and juniper berries, raw; Ginger, raw; Other stimulant, spice and aromatic crops, n.e.c.
Sugar Crops, Other	Other sugar crops n.e.c.
Sunflower seed	Sunflower seed; Cake of sunflower seed*
Tangerines, mandarins, clementines, satsumas	Tangerines, mandarins, clementines
Tomatoes, fresh	Tomatoes
Vegetables, Other	Artichokes; Cassava leaves*; Onions and shallots, green; Leeks and other alliaceous vegetables; Other beans, green; Broad beans and horse beans, green; String beans; Okra; Green corn (maize); Chicory roots; Locust beans (carobs); Other vegetables, fresh n.e.c.; Vegetable products, fresh or dry n.e.c.*
Walnuts	Walnuts, in shell
Wheat	Wheat; Bran of wheat*; Germ of wheat*; Starch of wheat*; Wheat gluten*

Table A.7: SUA items classified as food commodities: vegetal categories

Food category	SUA items on the food account
Starchy staples	Barley, pearled; Bread; Breakfast cereals; Bulgur; Communion wafers, empty cachets of a kind suitable for pharmaceutical use, sealing wafers, rice paper and similar products.; Flour of buckwheat; Flour of cassava; Flour of cereals n.e.c.; Flour of fonio; Flour of maize; Flour of millet; Flour of rice; Flour of roots and tubers n.e.c.; Flour of rye; Flour of sorghum; Flour of triticale; Flour, meal, powder, flakes, granules and pellets of potatoes; Food preparations of flour, meal or malt extract; Infant food; Malt extract; Malt, whether or not roasted; Mixes and doughs for the preparation of bakers' wares; Oats, rolled; Pastry; Popcorn; Potatoes, frozen; Rice, milled; Rice, milled (husked); Starch of cassava; Starch of maize; Starch of rice; Tapioca of cassava; Uncooked pasta, not stuffed or otherwise prepared; Wheat and meslin flour
Sweeteners	Cane sugar, centrifugal; Cane sugar, non-centrifugal; Chocolate products nes; Cocoa paste not defatted; Cocoa powder and cake; Fructose, chemically pure; Glucose and dextrose; Isoglucose; Lactose; Maltose, chemically pure; Molasses; Natural honey; Other fructose and syrup; Other non-alcoholic caloric beverages; Raw cane or beet sugar (centrifugal only); Refined cane or beet sugar, in solid form, containing added flavouring or colouring matter; maple sugar and maple syrup; Refined sugar; Sugar and syrups n.e.c.; Sugar confectionery; Sugar flavoured; Sugar, beet, raw, centrifugal
Other foods	Almonds, shelled; Brazil nuts, shelled; Cashew nuts, shelled; Coconuts, desiccated; Food preparations n.e.c.; Hazelnuts, shelled; Peanut butter; Prepared groundnuts; Prepared nuts; Soya curd; Soya paste; Soya sauce; Walnuts, shelled
Vegetables & fruits	Apple juice; Apple juice, concentrated; Apricots, dried; Canned mushrooms; Citrus juice, concentrated n.e.c.; Dried mushrooms; Figs, dried; Flour of fruits; Fruit prepared n.e.c.; Fruit, nuts, peel, sugar preserved; Grape juice; Grapefruit juice; Grapefruit juice, concentrated; Homogenized cooked fruit, prepared; Homogenized vegetable preparations; Juice of citrus fruit n.e.c.; Juice of fruits n.e.c.; Juice of lemon; Juice of mango; Juice of pineapples, concentrated; Juice of plum; Juice of plum, concentrated; Juice of tangerine; Juice, tomato, concentrated; Lemon juice, concentrated; Mushrooms and truffles; Must of grape; Olives preserved; Orange juice; Orange juice, concentrated; Other fruit n.e.c., dried; Other tropical fruit, dried; Other vegetable juices; Other vegetables provisionally preserved; Paste of tomatoes; Pineapple juice; Pineapples, otherwise prepared or preserved; Plums, dried; Raisins; Sweet corn, frozen; Sweet corn, prepared or preserved; Tomato juice; Tomatoes, peeled (o/t vinegar); Vegetables frozen; Vegetables preserved (frozen); Vegetables preserved nes (o/t vinegar); Vegetables, canned nes; Vegetables, dehydrated; Vegetables, dried nes; Vegetables, pulses and potatoes, preserved by vinegar or acetic acid

Table A.7 (continued)

Food category	SUA items on the food account
Vegetal oils & fats	Animal or vegetable fats and oils and their fractions, chemically modified, except those hydrogenated, inter-esterified, re-esterified or elaidinized; inedible mixtures or preparations of animal or vegetable fats or oils; Butter of karite nuts; Castor oil, hydrogenated; Cocoa butter, fat and oil; Coconut oil; Cotton-seed oil; Groundnut oil; hydrogenated oils and fats; Industrial monocarboxylic fatty acids; acid oils from refining; Jojoba oil; Liquid margarine; Margarine and shortening; Mustard seed oil, crude; Oil of castor beans; Oil of hempseed; Oil of kapok; Oil of linseed; Oil of maize; Oil of olive residues; Oil of palm kernel; Oil of poppy seed; Oil of rice bran; Oil of sesame seed; Oil of tung nuts; Oil, stillingia; Olive oil; Other oil of vegetable origin, crude n.e.c.; Palm oil; Rape-seed or canola oil, crude; Residues of fatty substances; Safflower-seed oil, crude; Soya bean oil; Sunflower-seed oil, crude; Vegetable tallow

Table A.8: SUA items classified as food commodities: animal categories

Food category	SUA items on the food account
Dairy (incl. eggs)	Buttermilk, curdled and acidified milk; Buttermilk, dry; Casein; Cheese from milk of buffalo, fresh or processed; Cheese from milk of goats, fresh or processed; Cheese from milk of sheep, fresh or processed; Cheese from skimmed cow milk; Cheese from whole cow milk; Dairy products n.e.c.; Egg albumin; Eggs from other birds in shell, fresh, n.e.c.; Eggs, dried; Eggs, liquid; Hen eggs in shell, fresh; Ice cream and other edible ice; Processed cheese; Raw milk of buffalo; Raw milk of camel; Raw milk of cattle; Raw milk of goats; Raw milk of sheep; Reconstituted milk; Skim milk and whey powder; Skim milk of buffalo; Skim milk of cows; Skim milk of goat; Skim milk, condensed; Skim milk, evaporated; Skim sheep milk; Standardized milk; Whey cheese; Whey, condensed; Whey, dry; Whey, fresh; Whole milk powder; Whole milk, condensed; Whole milk, evaporated; Yoghurt; Yoghurt, with additives
Animal oils & fats	Animal oils and fats n.e.c.; Aq M Oils; Buffalo fat, unrendered; Butter and ghee of sheep milk; Butter of buffalo milk; Butter of cow milk; Butter of goat milk; Cattle fat, unrendered; Cattle, butcher fat; Cream, fresh; Degras; Demersal Liver Oils; Dmrs Bdy Oil; Fat of camels; Fat of other camelids; Fat of pigs; Fat of poultry; Fat preparations n.e.c.; Frwt Bdy Oil; Frwt Lvr Oil; Ghee from buffalo milk; Ghee from cow milk; Goat fat, unrendered; Lard stearine and lard oil; Marine nes Liver Oils; Marn Bdy Oil; Pelg Bdy Oil; Pelg Lvr Oil; Pig fat, rendered; Pig, butcher fat; Poultry fat, rendered; Sheep fat, unrendered; Tallow; Wool grease and lanolin

Table A.8 (continued)

Food category	SUA items on the food account
Meat & seafood	Aq A Cured; Aq A Prep Ns; Aq M Meat; Aq M Prep Ns; Aquatic Animals Meals; Aquatic plants, dried; Aquatic plants, fresh; Aquatic plants, other preparations; Aqutc Anim F; beef and veal preparations nes; Bovine meat, salted, dried or smoked; Cephlp Fresh; Cphlp Canned; Cphlp Cured; Cphlp Frozen; Cphlp Meals; Cphlp Pr nes; Crstaceans F; Crstc Canned; Crstc Cured; Crstc Frozen; Crstc Meals; Crstc Pr nes; Dmrsl Canned; Dmrsl Cured; Dmrsl Fillet; Dmrsl Fresh; Dmrsl Fz Flt; Dmrsl Fz Whl; Dmrsl Meals; Dmrsl Pr nes; Edible offal of buffalo, fresh, chilled or frozen; Edible offal of cattle, fresh, chilled or frozen; Edible offal of goat, fresh, chilled or frozen; Edible offal of pigs, fresh, chilled or frozen; Edible offal of sheep, fresh, chilled or frozen; Edible offals and liver of chickens and guinea fowl, fresh, chilled or frozen; Edible offals and liver of ducks, fresh, chilled or frozen; Edible offals and liver of geese, fresh, chilled or frozen; Edible offals and liver of turkey, fresh, chilled or frozen; Edible offals of camels and other camelids, fresh, chilled or frozen; Edible offals of horses and other equines, fresh, chilled or frozen; Extracts and juices of meat, fish, crustaceans, molluscs or other aquatic invertebrates; Fatty liver preparations; Frwtr Canned; Frwtr Cured; Frwtr Diad F; Frwtr Fillet; Frwtr Fz Flt; Frwtr Fz Whl; Frwtr Meals; Frwtr Pr nes; Game meat, fresh, chilled or frozen; Homogenized meat preparations; Horse meat, fresh or chilled; Liver preparations; Marin Canned; Marin Cured; Marin Fillet; Marin Fz Flt; Marin Fz Whl; Marin Meals; Marin Pr nes; Marine nes F; Meat of asses, fresh or chilled; Meat of buffalo, fresh or chilled; Meat of camels, fresh or chilled; Meat of cattle boneless, fresh or chilled; Meat of cattle with the bone, fresh or chilled; Meat of chickens, fresh or chilled; Meat of ducks, fresh or chilled; Meat of geese, fresh or chilled; Meat of goat, fresh or chilled; Meat of mules, fresh or chilled; Meat of other domestic rodents, fresh or chilled; Meat of pig boneless, fresh or chilled; Meat of pig with the bone, fresh or chilled; Meat of pigeons and other birds n.e.c., fresh, chilled or frozen; Meat of rabbits and hares, fresh or chilled; Meat of sheep, fresh or chilled; Meat of turkeys, fresh or chilled; Meat prepared n.e.c.; Meat, beef, canned; Meat, other camelids; Mlluscs Frsh; Molsc Canned; Molsc Cured; Molsc Frozen; Molsc Meals; Offals n.e.c. (excluding mammals), fresh, chilled or frozen; Offals, other camelids; Other meat and edible meat offal, salted, in brine, dried or smoked; edible flours and meals of meat or meat offal; Other meat n.e.c. (excluding mammals), fresh, chilled or frozen; Pelagic Frsh; Pelgc Canned; Pelgc Cured; Pelgc Fillet; Pelgc Fz Flt; Pelgc Fz Whl; Pelgc Meals; Pelgc Pr nes; Pig meat preparations; Pig meat, cuts, salted, dried or smoked (bacon and ham); Poultry meat preparations; Sausages and similar products of meat, offal or blood of beef and veal; Sausages and similar products of meat, offal or blood of pig; Snails, fresh, chilled, frozen, dried, salted or in brine, except sea snails

Notes: Fish and seafood enter from the Food Balance Sheets at the FBS item level: Aquatic Animals, Others; Aquatic Plants; Cephalopods; Crustaceans; Demersal Fish; Freshwater Fish; Marine Fish, Other; Meat, Aquatic Mammals; Molluscs, Other; Pelagic Fish go to "meat & seafood," and Fish, Body Oil; Fish, Liver Oil go to "animal oils & fats." The 11 alcoholic-beverage items of the SUA are outside the model's food set (Appendix G).

B Properties of the proposed demand system

C Derivation

In our model, there is no profit from food production due to constant returns to scale and perfect competition. At the farm level, land is the residual claimant to farm output sales after paying the input factor labor, so the country-level land rent is $\mathrm{LR}_i = \sum_l r_i^l Y_i^l$. The relative change in total land rent is therefore expressed as

$$\begin{aligned}\hat{\mathrm{LR}}_i \equiv \frac{\mathrm{LR}_i'}{\mathrm{LR}_i} &= \frac{\sum_l r_i^{l\prime} Y_i^{l\prime}}{\sum_l r_i^l Y_i^l} \\ &= \sum_l \frac{r_i^l Y_i^l}{\sum_l r_i^l Y_i^l} \hat{r}_i^l \hat{Y}_i^l \\ &= \sum_l \delta_i^l \hat{r}_i^l \hat{Y}_i^l \ ,\end{aligned}$$

where $\delta_i^l = \frac{r_i^l Y_i^l}{\sum_k r_i^k Y_i^k}$ denotes the share of crop l in total land rent in country i. We can easily show that

$$\begin{aligned}\delta_i^l &= \frac{r_i^l Y_i^l}{\sum_k r_i^k Y_i^k} \\ &= \frac{r_i^l L_i A_i^l (\pi_i^l)^{1-\frac{1}{\theta_i}}}{\sum_k r_i^k L_i A_i^k (\pi_i^k)^{1-\frac{1}{\theta_i}}} \\ &= \frac{(\pi_i^l)^{\frac{1}{\theta_i}} (\pi_i^l)^{1-\frac{1}{\theta_i}}}{\sum_k (\pi_i^k)^{\frac{1}{\theta_i}} (\pi_i^k)^{1-\frac{1}{\theta_i}}} \\ &= \pi_i^l \ .\end{aligned} \tag{C.1}$$

Thus, we have

$$\hat{\mathrm{LR}}_i = \sum_l \pi_i^l \hat{r}_i^l \hat{Y}_i^l \tag{C.2}$$

and

$$\frac{\Delta \tilde{U}_i}{P_i C_i} = \varphi_i \delta_i \left(\frac{\sum_l \pi_i^l \hat{r}_i^l \hat{Y}_i^l}{\hat{H}_i} - 1\right) + \frac{1 - (\tilde{P}_i)^{1-\epsilon_i}}{1-\epsilon_i} \ . \tag{C.3}$$

D Market clearing of the numeraire good

Equation (25) essentially gives the interpretation of X_i^0 as the residual of the domestic numeraire market:

$$X_i^0 \equiv N_i C_i^0 - Q_i^0 - \sum_n P_i^n W_i^n - \sum_l v_i^l W_i^l \ .$$

Therefore, we can derive (26) with the following steps

$$
\begin{aligned}
X_i^0 &= N_i Y_i - N_i \sum_n P_i^n C_i^n - \sum_n P_i^n W_i^n - \sum_l v_i^l W_i^l - Q_i^0 && \text{by Walras's law} \\
&= w_i \bar{L}_i + \sum_l r_i^l Y_i^l - \sum_n P_i^n (X_i^n - W_i^n) - \sum_n P_i^n W_i^n - \sum_l v_i^l W_i^l - Q_i^0 && \text{by (20) and (21)} \\
&= w_i (\sum_n \nu_i^n Q_i^n + \sum_l \nu_i^l Y_i^l) + \sum_l r_i^l Y_i^l - \sum_n P_i^n X_i^n - \sum_l v_i^l W_i^l && \text{by (18) and (19)} \\
&= \sum_n (p_i^n - V_i^n) Q_i^n + \sum_l (q_i^l - r_i^l) Y_i^l + \sum_l r_i^l Y_i^l - \sum_n P_i^n X_i^n - \sum_l v_i^l W_i^l && \text{by (9) and (14)} \\
&= \sum_n (p_i^n Q_i^n - P_i^n X_i^n) - \sum_l v_i^l (X_i^l - W_i^l) + \sum_l q_i^l Y_i^l - \sum_l v_i^l W_i^l && \text{by (62)} \\
&= \sum_n (p_i^n Q_i^n - P_i^n X_i^n) + \sum_l (q_i^l Y_i^l - v_i^l X_i^l)
\end{aligned}
$$

Also, by Equations (54) and (58), we can show $\sum_i X_i^0 = 0$ directly with

$$
\sum_i X_i^0 = \sum_i \sum_n (p_i^n Q_i^n - P_i^n X_i^n) + \sum_i \sum_l (q_i^l Y_i^l - v_i^l X_i^l) = 0
$$

E Derivation of the one-tier Armington elasticity

This appendix derives the closed-form expression in Equation (53) for the substitution elasticity between domestic supply and an individual foreign source implied by the GTAP nested Armington structure. Denoting S_i^n as the GTAP-style foreign food Armington aggregator, we can rewrite our food availability X_i^n as

$$
X_i^n = \left[\alpha_{domestic} \, X_{ii}^{n\,D^n} + \alpha_{import} \, (S_i^n)^{\frac{D^n}{M^n}} \right]^{\frac{1}{D^n}}, \qquad S_i^n \equiv \sum_{j \neq i} \beta_{ji}^n X_{ji}^{n\,M^n} \, ,
$$

where the substitution parameters D^n and M^n relate to the two GTAP elasticities through $\lambda_D^n = \frac{1}{1-D^n}$ and $\lambda_M^n = \frac{1}{1-M^n}$. The marginal rate of substitution between country i's imports from country j and its domestic supply is

$$
MRS_{ij}^n = \frac{\partial X_i^n / \partial X_{ji}^n}{\partial X_i^n / \partial X_{ii}^n} = \frac{\alpha_{import}}{\alpha_{domestic}} \, \beta_{ji}^n \, (S_i^n)^{\frac{D^n}{M^n} - 1} \, X_{ji}^{n\,M^n - 1} \, X_{ii}^{n\,1 - D^n} \, .
$$

To derive the analytical solution for $\lambda_{j,i}^n$, we express both $d \log S_i^n$ and $d \log X_{ii}^n$ as functions of $d \log X_{ji}^n$, holding X_i^n and $X_{ki}^n \, (k \neq i, j)$ constant. First, differentiating S_i^n with only

X^n_{ji} varying gives

$$d\log S^n_i = M^n\, s^n_{j,i}\, d\log X^n_{ji}\ , \qquad s^n_{j,i} \equiv \frac{\beta^n_{ji} X^{n\,M^n}_{ji}}{S^n_i}\ ,$$

where, as a result of cost minimization, $s^n_{j,i} = \frac{\tau^n_{ji} p^n_j X^n_{ji}}{\sum_{j'\neq i} \tau^n_{j'i} p^n_{j'} X^n_{j'i}}$ is country j's value share in country i's total imports of food n. Second, staying on the isoquant requires $\frac{\partial X^n_i}{\partial X^n_{ii}}\, dX^n_{ii} + \frac{\partial X^n_i}{\partial X^n_{ji}}\, dX^n_{ji} = 0$, i.e.,

$$d\log X^n_{ii} = -w^n_{j,i}\, d\log X^n_{ji}\ , \qquad w^n_{j,i} \equiv \frac{X^n_{ji}\, \partial X^n_i/\partial X^n_{ji}}{X^n_{ii}\, \partial X^n_i/\partial X^n_{ii}}\ ,$$

where, again by the first-order conditions, $w^n_{j,i} = \frac{\tau^n_{ji} p^n_j X^n_{ji}}{p^n_i X^n_{ii}}$ equals country i's spending on imports from j relative to its spending on its domestic variety. Substituting both into the log-differential of MRS^n_{ij} yields

$$\begin{aligned} d\log MRS^n_{ij} &= \left(\tfrac{D^n}{M^n} - 1\right) d\log S^n_i \ +\ (M^n - 1)\, d\log X^n_{ji} \ +\ (1 - D^n)\, d\log X^n_{ii} \\ &= \left[\, (D^n - M^n)\, s^n_{j,i} \ +\ (M^n - 1) \ -\ (1 - D^n)\, w^n_{j,i}\, \right] d\log X^n_{ji} \\ &= -\left[\frac{s^n_{j,i} + w^n_{j,i}}{\lambda^n_D} + \frac{1 - s^n_{j,i}}{\lambda^n_M}\right] d\log X^n_{ji}\ , \end{aligned}$$

where the last line uses $1 - D^n = 1/\lambda^n_D$, $1 - M^n = 1/\lambda^n_M$, and $M^n - D^n = 1/\lambda^n_D - 1/\lambda^n_M$. Combining this with $d\log(X^n_{ji}/X^n_{ii}) = (1 + w^n_{j,i})\, d\log X^n_{ji}$ delivers the closed form in Equation (53).

F Literature-based calibration of ζ^n

This appendix documents the calibration of ζ^n for the five vegetal-based food categories. Section F.1 derives the result that maps household demand estimates into ζ^n; Section F.2 describes how we use published estimates and discusses limitations; the remaining sections work through the evidence category by category.

F.1 From the CES technology to Morishima elasticities

With Equation (8), Shephard's lemma gives

$$\frac{\partial \log V^n_i}{\partial \log v^l_i} = \gamma^{nl}_i \left(\frac{v^l_i}{V^n_i}\right)^{1-\zeta^n} = \frac{v^l_i Z^{nl}_i}{V^n_i Z^n_i} \equiv c^{nl}_i\ ,$$

the cost share of crop l in food n. Taking logs of Equation (7) and differentiating with respect to $\log v_i^l$, the conditional own- and cross-price elasticities of crop use (holding Z_i^n fixed) are

$$\eta_{ll}^{\text{cond}} = \frac{\partial \log Z_i^{nl}}{\partial \log v_i^l} = -\zeta^n\big(1 - c_i^{nl}\big)\,, \tag{F.4}$$

$$\eta_{l'l}^{\text{cond}} = \frac{\partial \log Z_i^{nl'}}{\partial \log v_i^l} = \zeta^n\, c_i^{nl}, \quad l' \neq l. \tag{F.5}$$

The Morishima elasticity of substitution between crop inputs l and l' (with respect to the price of l) is therefore

$$M_{l'l} \;\equiv\; \eta_{l'l}^{\text{cond}} - \eta_{ll}^{\text{cond}} \;=\; \zeta^n\, c_i^{nl} + \zeta^n\big(1 - c_i^{nl}\big) \;=\; \zeta^n \tag{F.6}$$

for every crop pair (l', l). As argued in the main text, the CES aggregator can be interpreted as the within-category part of household preferences, so the conditional input demand elasticities (η_{ll}^{cond}, $\eta_{l'l}^{\text{cond}}$) correspond to the Hicksian demand elasticities (η_{ll}^{H}, $\eta_{l'l}^{H}$) estimated from household surveys, and

$$M_{l'l}^{\text{survey}} \;\equiv\; \eta_{l'l}^{H} - \eta_{ll}^{H} \;\approx\; \zeta^n. \tag{F.7}$$

Equation (F.6) also implies three restrictions the data can violate: under a single CES parameter, Morishima elasticities are symmetric, identical across crop pairs, and positive. The estimates below display asymmetry, dispersion across pairs, and occasional negative values (complementarity). We read this dispersion as the projection loss from summarizing heterogeneous substitution patterns with one parameter per category, which is the reason we report an interval for each ζ^n and re-run counterfactuals at its endpoints, rather than a reason to discard the CES structure, whose parsimony the model's scale requires.

F.2 Converting published estimates

When a study reports Marshallian cross-price elasticities $\eta_{l'l}^{M}$, we convert them to Morishima elasticities in two steps:

1. **Slutsky correction:** $\eta_{l'l}^{H} = \eta_{l'l}^{M} + s_l\, \varepsilon_{l'}$, where s_l is the budget share of crop l and $\varepsilon_{l'}$ is the income elasticity of good l', and $\eta_{l'l}^{H}$ is the Hicksian cross-price elasticity.[6]

2. **Morishima:** $M_{l'l}^{\text{survey}} = \eta_{l'l}^{H} - \eta_{ll}^{H}$.

[6] At the budget shares relevant here (s_l between 0.002 and 0.04), the Slutsky term is on the order of 0.001–0.01, so the two elasticities are numerically indistinguishable; the correction matters mainly for conceptual consistency.

We compute the simple average of all Morishima elasticities in a study and take it as that study's reference point for ζ^n. Budget shares and income elasticities are measured against the same expenditure base; where a study reports within-group shares, we rescale them to total expenditure (see the Malawi notes below).

Some measurement gaps remain between the estimates and ζ^n. Household surveys record prices and quantities at the retail rather than the processing level, and retail margins can differ across crops. The quantity gap between production and consumption also varies across crops if some are more perishable than others. Lastly, as the produced food products are traded before reaching consumers, imports would make observed consumption reflect the post-trade composition of supply rather than the crop mix facing domestic food producers, while exports could cause similar concerns from the production side. It will not be a large concern since ζ^n is assumed to be the same across all countries. Acknowledging all of these, we identify a plausible interval for each ζ^n and conduct sensitivity analysis at its endpoints.

F.3 Starchy staples

We use three studies from China (Chen et al., 2016), Indonesia (Java) (Deaton, 1990), and the US (Gao, Wailes, and Cramer, 1994) to calibrate ζ^n for starchy staples. We finally set the baseline $\zeta^{\text{starchy staples}} = 0.99$ with a range of $[0.8,\ 1.2]$.

China (Chen et al., 2016). This meta-analysis covers 85 studies of household food demand in China. Table F.9 reproduces the relevant subset of its Table 4: the Marshallian price elasticity matrix for wheat, rice, and coarse grains, with rows indicating the product whose demand responds and columns indexing the price of which crop that changes, together with each crop's budget share s_l and income elasticity ε_l.

Table F.9: Selected rows and columns of Table 4 in Chen et al. (2016)

			Marshallian elasticity $\eta^M_{l'l}$		
Product	Budget share s_l	Income elasticity ε_l	Wheat	Rice	Coarse grains
Wheat	0.007	0.285	−0.945	1.290	0.089
Rice	0.016	0.433	0.601	−0.598	0.055
Coarse grains	0.002	0.239	0.321	0.463	−0.859

As one worked example of the two-step conversion, for the (wheat, rice) pair:

$$\begin{aligned}
\eta^{H}_{\mathrm{wr}} &= \eta^{M}_{\mathrm{wr}} + s_{\mathrm{r}}\,\varepsilon_{\mathrm{w}} = 1.290 + 0.016 \times 0.285 = 1.295, \\
\eta^{H}_{\mathrm{rr}} &= \eta^{M}_{\mathrm{rr}} + s_{\mathrm{r}}\,\varepsilon_{\mathrm{r}} = -0.598 + 0.016 \times 0.433 = -0.591, \\
M^{\mathrm{survey}}_{\mathrm{w,r}} &= \eta^{H}_{\mathrm{wr}} - \eta^{H}_{\mathrm{rr}} = 1.295 - (-0.591) = 1.886.
\end{aligned}$$

Table F.10 reports all six Morishima elasticities computed this way. They range from 0.915 to 1.886, with an average of 1.270.

Table F.10: Morishima elasticities $M_{l'l}$ for China staple crops

Responder l'	Price-changing crop l		
	Wheat	Rice	Coarse grains
Wheat	—	1.886	0.949
Rice	1.547	—	0.915
Coarse grains	1.266	1.058	—

Indonesia, Java (Deaton, 1990). This study estimates Marshallian elasticities from the 1981 round of the Indonesian National Socioeconomic Survey (SUSENAS). Table F.11 reproduces the relevant subset of its Table 5a, including own- and cross-price elasticities for rice, wheat, maize, cassava, and roots, together with each commodity's budget share (its Table 1) and total-expenditure elasticity (its Table 2). Table F.12 reports the twenty implied Morishima elasticities; row l' is the responding product and column l is the product whose price changes. They span 0.07 to 1.57, with an average of 0.76. The low average is expected: rice is the dominant staple food; measured substitution is weak, with tiny budget shares on the other staples.

Table F.11: Selected rows and columns of Table 5a in Deaton (1990)

			Marshallian elasticities $\eta^{M}_{l'l}$				
Product	s_l	ε_l	Rice	Wheat	Maize	Cassava	Roots
Rice	0.245	0.490	−0.424	−0.005	−0.032	0.088	0.025
Wheat	0.005	1.567	−0.461	−0.692	0.011	−0.000	−0.188
Maize	0.058	0.088	1.245	0.090	−0.822	−0.256	−0.100
Cassava	0.014	0.139	0.151	0.078	0.186	−0.325	−0.003
Roots	0.006	0.709	0.795	0.125	0.150	0.084	−0.953

Table F.12: Morishima elasticities of substitution $M_{l'l}$ for Java staple products

Responder l'	Price-changing crop l				
	Rice	Wheat	Maize	Cassava	Roots
Rice	—	0.68	0.81	0.42	0.98
Wheat	0.23	—	0.92	0.34	0.77
Maize	1.57	0.77	—	0.07	0.85
Cassava	0.49	0.76	1.01	—	0.95
Roots	1.27	0.81	1.01	0.42	—

United States (Gao, Wailes, and Cramer, 1994). Table 1 of this study reports compensated price elasticities directly, so we skip the Slutsky step and compute the Morishima matrix in Table F.13. Bread and pasta are both processed from wheat, so this example deviates from crop-level substitution, but the range 0.52–0.86 could serve as a lower bound.

Table F.13: Morishima elasticities of substitution $M_{l'l}$ for U.S. staple products

Responder l'	Price-changing product l			
	Rice	Potatoes	Bread	Pasta
Rice	—	0.61	0.52	0.83
Potatoes	0.54	—	0.58	0.85
Bread	0.52	0.58	—	0.86
Pasta	0.53	0.65	0.78	—

F.4 Vegetables and fruits

We employ the same strategy with studies from the United States (Zhikang You, James E. Epperson, and Chung L. Huang, 2026), China (Chen et al., 2016), and Malawi (Ecker and Qaim, 2008), spanning high-, upper-middle-, and low-income settings. The evidence consistently points below one; we set the baseline $\zeta^n = 0.7$ with a range of $[0.4,\ 0.99]$.

United States (Zhikang You, James E. Epperson, and Chung L. Huang, 2026). This study estimates a complete demand system over aggregate food groups on U.S. data for 1960–1993, also reporting estimates for separate fresh-fruit and fresh-vegetable subsystems. Table F.14 collects the four produce groups (fresh/processed vegetables/fruits); Table F.15 reports the implied Morishima matrix. Vegetables and fruits substitute for each other weakly.

Regarding the substitution patterns within the separate fresh-fruit and fresh-vegetable subsystems, the result shows low substitution elasticity again: for the ten fruits listed in Table

Table F.14: Selected rows and columns of Table 1 in Zhikang You, James E. Epperson, and Chung L. Huang (2026)

			Marshallian elasticities $\eta^M_{l'l}$			
Product	s_l	ε_l	F. fruit	F. veg	P. fruit	P. veg
F. fruit	0.008718	−0.132	−0.273	0.154	0.023	0.063
F. veg	0.010564	0.152	0.124	−0.029	−0.098	0.054
P. fruit	0.006009	0.290	0.030	−0.174	−0.290	−0.171
P. veg	0.010241	0.372	0.049	0.054	−0.101	−0.109

U.S. food-group aggregate demand system, 1960–1993. F. represents fresh; P. represents processed.

Table F.15: Morishima elasticities $M_{l'l}$ for U.S. produce food groups

Responder l'	Price-changing group l			
	F. fruit	F. veg	P. fruit	P. veg
F. fruit	—	0.18	0.31	0.17
F. veg	0.40	—	0.19	0.16
P. fruit	0.31	−0.14*	—	−0.06*
P. veg	0.33	0.08	0.19	—

* Negative Morishima indicates a complementary relationship: processed fruits are consumed jointly with fresh and processed vegetables rather than substituted for them.

F.16, the positive-only/overall off-diagonal mean is 0.73/0.51; for the nine vegetables listed in Table F.17, the positive-only/overall off-diagonal mean is 0.32/0.25. Negative Morishima elasticities can be caused by low quality in the estimation, as not every Marshallian elasticity reported is statistically significant in the paper. Regardless, this will imply a ζ_n smaller than 1.

Within the separate fresh-fruit and fresh-vegetable subsystems, substitution is also modest: for the ten fruits in Table F.16, the positive-only/overall off-diagonal mean is 0.73/0.51; for the nine vegetables in Table F.17, it is 0.32/0.25. Negative Morishima values likely reflect imprecise estimation, since not every underlying Marshallian elasticity is statistically significant in the paper. Regardless of excluding negative numbers or not, the U.S. evidence implies ζ^n below one.

China (Chen et al., 2016). The meta-analysis reports vegetables and fruits as two aggregate groups only. Table F.18 shows the selected rows and the implied Morishima elasticities. The numbers exceed those in Zhikang You, James E. Epperson, and Chung L. Huang (2026)

Table F.16: Morishima elasticities $M_{l'l}$ for U.S. fresh fruits

Responder l'	Price-changing fruit l									
	Apple	Cherry	Grpfrt	Grape	Lemon	Orange	Peach	Pear	Strwbry	Wtrmln
Apples	—	−0.12	0.85	1.20	0.35	1.09	0.94	−0.36	0.35	0.65
Cherries	−0.37	—	0.80	0.99	0.20	0.88	0.99	−0.22	0.04	0.99
Grapefruit	0.07	−0.11	—	1.29	0.37	1.31	0.87	−0.28	0.30	0.49
Grapes	0.62	−0.10	1.06	—	0.29	0.75	1.02	−0.38	0.25	0.78
Lemons	0.10	−0.14	0.89	0.85	—	1.12	1.20	−0.40	0.01	0.95
Oranges	0.31	−0.11	1.03	0.81	0.40	—	0.98	−0.30	0.36	0.65
Peaches	0.62	−0.06	0.94	1.32	0.60	1.33	—	−0.34	0.36	0.25
Pears	−0.12	−0.07	0.93	0.86	0.27	1.03	0.76	—	−0.18	0.98
Strawberries	0.65	−0.15	0.94	1.01	0.14	1.29	0.96	−0.68	—	0.76
Watermelon	0.29	−0.04	0.79	1.21	0.52	1.08	0.55	−0.14	0.34	—

Table F.17: Morishima elasticities $M_{l'l}$ for U.S. fresh vegetables

Responder l'	Price-changing vegetable l								
	Aspgs	Cabg	Carrt	Celry	Cucmb	Lettc	Onion	Peppr	Tomat
Asparagus	—	−0.21	0.68	0.60	0.30	−0.05	0.27	−0.26	0.22
Cabbage	0.61	—	0.45	0.06	0.24	0.12	0.20	0.20	0.51
Carrots	0.69	−0.04	—	−0.16	0.39	−0.04	0.22	0.21	0.53
Celery	0.75	0.00	0.30	—	0.43	−0.03	0.10	0.12	0.46
Cucumbers	0.65	−0.10	0.58	0.22	—	0.09	0.04	0.33	0.41
Lettuce	0.65	0.00	0.46	0.02	0.31	—	0.16	0.24	0.43
Onions	0.67	0.01	0.51	−0.01	0.24	0.00	—	0.22	0.36
Peppers	0.55	−0.07	0.43	−0.11	0.36	−0.04	0.11	—	0.39
Tomatoes	0.64	0.01	0.51	0.06	0.31	0.08	0.15	0.26	—

but remain below one. Because these are broad two-group estimates, they likely understate substitution among individual crops within each group.

Malawi (Ecker and Qaim, 2008). This study pools vegetable and fruit crops in a single system, serving as the closest match to our category definition. Table F.19 collects the inputs, and Table F.20 reports the Morishima matrix. The average of 0.756 again indicates moderate substitution among vegetable and fruit crops.

F.5 Other foods (Pulses, nuts, and oil crops)

Oil crops here exclude their portions crushed into vegetable oil; the category covers soybeans made into tofu, sesame seeds consumed directly, and similar direct food uses. Two studies inform the calibration: a Malawi study covering pulses and groundnuts, with an average Morishima elasticity of 1.52, and a U.S. EASI demand model covering nine nut products, with an average of 1.06. We set the baseline $\zeta^n = 1.5$ with a range of $[0.9,\ 2.7]$;

Table F.18: Selected rows and columns of Table 4 in Chen et al. (2016) and the implied Morishima elasticities $M_{l'l}$

			Marshallian $\eta^M_{l'l}$		Morishima $M_{l'l}$	
Product	s_l	ε_l	Vegetable	Fruit	Vegetable	Fruit
Vegetable	0.033	0.418	−0.568	0.111	—	0.82
Fruit	0.020	0.517	0.066	−0.708	0.64	—

Table F.19: Selected rows and columns of Table 3 in Ecker and Qaim (2008)

			Marshallian elasticities $\eta^M_{l'l}$				
Product	s_l	ε_l	Tomatoes	Pumpkins	Green leafy	Other veg	Fruits
Tomatoes	0.0253	0.424	−0.691	−0.194	0.091	−0.095	−0.271
Pumpkins	0.0089	0.373	−0.169	−0.855	0.132	−0.061	−0.077
Green leafy veg	0.0422	0.211	0.184	0.111	−0.891	0.084	−0.060
Other vegetables	0.0108	0.432	−0.181	−0.118	0.129	−0.881	0.254
Fruits	0.0122	0.424	−0.370	−0.116	−0.168	0.191	−0.631

s_l are total-expenditure budget shares, obtained from the within-group conditional shares of Table 1 $(0.236, 0.083, 0.394, 0.101, 0.114)$ rescaled by the food share and the vegetables-&-fruits-in-food share, $s_l = 0.728 \times 0.147 \times s_l^{\text{within}}$. ε_l are expenditure elasticities w.r.t. total expenditure (Table 3). This matches the total-expenditure scale of the U.S. and China extraction tables.

the baseline leans toward Malawi as the U.S. study mainly focuses on treenuts.

Malawi (Ecker and Qaim, 2008). The Malawi study covers pulses, soybeans, and groundnuts. Table F.21 collects the relevant inputs, and Table F.22 reports the implied Morishima matrix. The average of 1.52 suggests relatively flexible substitution among these crops.

United States (Bakhtavoryan et al., 2022). This study estimates an EASI demand system over nine nut products from U.S. household expenditure data. The paper reports compensated (Hicksian) price elasticities directly (its Table 5). Then, we skip the Slutsky step and obtain the Morishima matrix by subtraction. Table F.23 shows both. Macadamia seems like an outlier with its smaller budget share (0.0028) and higher own-price compensated elasticity (−2.384) relative to the rest of the system. Accounting for macadamia, all 72 Morishima elasticities average 1.23; excluding macadamia, the remaining 56 elasticities are remarkably uniform, ranging from 0.99 to 1.12 with an average of 1.06.

Table F.20: Morishima elasticities $M_{l'l}$ for Malawi vegetables & fruits

Responder l'	Price-changing item l				
	Tomatoes	Pumpkins	Green leafy	Other veg	Fruits
Tomatoes	—	0.66	0.99	0.79	0.36
Pumpkins	0.52	—	1.03	0.82	0.55
Green leafy veg	0.87	0.97	—	0.96	0.57
Other veg	0.51	0.74	1.03	—	0.89
Fruits	0.32	0.74	0.73	1.07	—

Table F.21: Selected rows and columns of Table 3 in Ecker and Qaim (2008)

			Marshallian $\eta^M_{l'l}$		
Product	s_l	ε_l	Beans	Peas & soy	Groundnuts
Phaseolus beans	0.0259	1.026	−1.198	−0.056	−0.255
Peas & soybeans	0.0142	0.568	−0.017	−0.987	0.802
Groundnuts	0.0186	1.412	−0.368	0.765	−1.940

F.6 Sugar, sugar crops, and sweeteners

For sugar and sweeteners, consumer substitution among sweetener products proxies the cross-crop substitution that ζ^n governs, because each product maps to a distinct crop: sugar to sugar cane and beet, high-fructose corn syrup (HFCS) and glucose to maize. Lakkakula, Schmitz, and Ripplinger (2016) estimates a quadratic almost ideal demand system (QUAIDS) over sugar, HFCS, and glucose. Excluding the statistically insignificant Hicksian elasticity of glucose with respect to sugar, the implied Morishima elasticities in Table F.24 all exceed 2, with an average of 3.24; HFCS and glucose, both maize-based, substitute even more freely.

As sugar made from either sugar cane or beet bears almost no quality difference and is typically recognized as a homogeneous product (Elobeid and Beghin, 2006; Sinclair and Countryman, 2019), sugar cane and beet, as two crops, should be perfectly substitutable. Therefore, 3.24 can serve as the lower bound of ζ^n. We use 4 as the initial value.

F.7 Vegetal oils

The "vegetal oils & fats" category aggregates the crops crushed into edible oils: oil palm, soybean, rapeseed/mustard, sunflower, groundnut, coconut, cottonseed, maize germ, rice bran, sesame, olive, and other oil crops. The truest production-side analogue of ζ^n would be substitution among oilseed inputs in the crushing cost function, but crushing is nearly a

Table F.22: Morishima elasticities $M_{l'l}$ for Malawi other foods

Responder l'	Beans	Peas & soy	Groundnuts
Beans	—	0.94	1.68
Peas & soy	1.17	—	2.73
Groundnuts	0.84	1.76	—

Table F.23: Selected Hicksian elasticities from Table 5 in Bakhtavoryan et al. (2022) and the implied Morishima elasticities $M_{l'l}$

	Hicksian $\eta^H_{l'l}$									Morishima $M_{l'l}$								
Resp. l'	Pnut	Pec	Alm	Cash	Wal	Pist	Mix	Oth	Mac	Pnut	Pec	Alm	Cash	Wal	Pist	Mix	Oth	Mac
Pnut	−0.80	0.09	0.12	0.13	0.13	0.11	0.17	0.11	−0.05	—	1.05	1.01	1.06	1.11	1.10	1.09	1.09	2.33
Pec	0.23	−0.96	0.15	0.17	0.09	0.04	0.13	0.08	0.07	1.04	—	1.04	1.09	1.08	1.03	1.05	1.06	2.45
Alm	0.19	0.09	−0.89	0.10	0.10	0.08	0.17	0.10	0.07	0.99	1.04	—	1.02	1.09	1.07	1.09	1.08	2.45
Cash	0.23	0.12	0.12	−0.92	0.11	0.13	0.12	0.07	0.02	1.03	1.08	1.01	—	1.10	1.12	1.05	1.05	2.40
Wal	0.25	0.07	0.15	0.13	−0.99	0.05	0.15	0.04	0.16	1.05	1.03	1.03	1.05	—	1.05	1.07	1.02	2.55
Pist	0.25	0.04	0.14	0.17	0.08	−0.99	0.14	0.10	0.06	1.05	1.00	1.03	1.10	1.07	—	1.06	1.08	2.45
Mix	0.25	0.07	0.17	0.11	0.11	0.08	−0.92	0.05	0.09	1.05	1.03	1.06	1.03	1.10	1.07	—	1.03	2.47
Oth	0.28	0.09	0.19	0.12	0.07	0.13	0.11	−0.98	−0.01	1.08	1.05	1.08	1.05	1.06	1.12	1.03	—	2.37
Mac	0.01	0.28	0.39	0.20	0.66	0.32	0.48	0.04	−2.38	0.82	1.24	1.28	1.13	1.65	1.31	1.41	1.02	—

Abbreviations: Pnut = peanuts, Pec = pecans, Alm = almonds, Cash = cashews, Wal = walnuts, Pist = pistachios, Mix = mixed nuts, Oth = other nuts, Mac = macadamia nuts.

fixed-proportion technology, as each oilseed yields its own oil and meal in fixed ratios, and no such estimates exist. Substitution instead operates downstream across oils, and the derived demand for oilseeds inherits it. Thus, we use oil-level demand estimates as a benchmark rather than a point identification.

Kojima, Parcell, and Cain (2014) reports compensated demand elasticities for eight vegetable oils in the US wholesale market (Table F.25). The mean of all 56 off-diagonal Morishima elasticities is 0.85; excluding corn and cottonseed oil, which are byproducts of crops grown for other purposes, the mean over the remaining 30 pairs is 1.07. There is also a close model reference, the vegetable-oil substitution elasticity assumed in GLOBIOM (Valin et al., 2015; Escobar et al., 2025). It takes a baseline value of 2 and is an assumption rather than an estimate. We prefer the demand-based number and set the baseline $\zeta^n = 1.1$, with a range of $[0.85,\ 2.0]$ whose upper end covers the GLOBIOM value.

Table F.24: Selected Hicksian elasticities from Table 6 in Lakkakula, Schmitz, and Ripplinger (2016) and the implied Morishima elasticities $M_{l'l}$

	Hicksian $\eta^H_{l'l}$			Morishima $M_{l'l}$		
Product	Sugar	HFCS	Glucose	Sugar	HFCS	Glucose
Sugar	−0.42	0.33	0.09	—	2.95	4.75
HFCS	1.60	−2.62	1.01	2.02	—	5.67
Glucose	0.07	4.59	−4.66	0.49	7.21	—

Table F.25: Selected Hicksian elasticities from Table 7 in Kojima, Parcell, and Cain (2014) and the implied Morishima elasticities $M_{l'l}$

	Hicksian $\eta^H_{l'l}$								Morishima $M_{l'l}$							
Resp. l'	Soy	Can	Palm	Corn	Coco	Cot	Sun	Pnut	Soy	Can	Palm	Corn	Coco	Cot	Sun	Pnut
Soy	−0.19	0.07	0.04	−0.02	0.00	0.01	0.07	0.01	—	1.65	1.28	0.25	0.44	0.28	1.06	0.36
Can	0.59	−1.58	0.36	−0.19	0.15	0.05	0.29	0.34	0.78	—	1.60	0.08	0.59	0.32	1.28	0.69
Palm	0.34	1.02	−1.24	0.03	0.16	−0.30	0.02	−0.03	0.53	2.60	—	0.30	0.60	−0.03	1.01	0.32
Corn	0.14	−0.19	0.06	−0.27	0.00	0.25	0.09	−0.08	0.33	1.39	1.30	—	0.44	0.52	1.08	0.27
Coco	−0.04	0.23	0.11	−0.05	−0.44	0.08	0.15	−0.06	0.15	1.81	1.35	0.22	—	0.35	1.14	0.29
Cot	−0.01	0.07	−0.17	0.38	0.09	−0.27	−0.19	0.10	0.18	1.65	1.07	0.65	0.53	—	0.80	0.45
Sun	0.69	1.04	−0.03	0.09	0.26	−0.54	−0.99	−0.53	0.88	2.62	1.21	0.36	0.70	−0.27	—	−0.18
Pnut	−0.19	1.56	−0.06	−0.42	−0.22	0.21	−0.54	−0.35	0.00	3.14	1.18	−0.15	0.22	0.48	0.45	—

Abbreviations: Soy = soybean oil, Can = canola/rapeseed oil, Palm = palm oil, Corn = Corn oil, Coco = coconut oil, Cot = cottonseed oil, Sun = sunflower oil, Pnut = peanut/groundnut oil.

G Calibration of the Share Parameters

This appendix documents how the share parameters in the top panel of Table 3 are calibrated from the raw data and how the full share parameter system is constructed from them. In the following content, Section G.1 constructs the price system that converts commodity quantities into values. Sections G.2 and G.3 build value accounts for all country-crop and country-food pairs. Section G.4 distinguishes each crop's uses for vegetal food products, animal feed, and industrial goods and each food category's use between direct human consumption and industrial purposes. Section G.5 calibrates land shares of a crop dollar and the value of grass. Section G.6 calibrates crop shares of a food dollar and the allocation program (66). Section G.7 presents the consistency checks and validation.

Valuation is a difficult problem throughout the calibration process. The same physical commodity carries different prices at the farm gate versus at the border, and each share in Table 3 is a ratio of values that must be measured on the same price basis. Most of the decisions and choices documented below serve this purpose. Double counting can be another problem. Since the SUA records a crop and its processed products as separate items, the same tonne of wheat could be valued once as grain and once more as flour, and the rules of Section G.4 remove such overlaps.

G.1 Prices

All quantities are converted into values with a country–item price, and we construct a crop-role and a food-role price for all vegetal country–item pairs. The crop-role price helps value crop production and use for calibration of ρ_j^l, α_i^l, and h_i^l. Crop production value is a farm-gate concept, so this price uses the FAOSTAT producer price (PP) when available. The food-role price helps value the food quantities for calibration of b_i^n, a_i^n and h_i^n. This consumption is on the same wholesale level as internationally traded food and must be valued on the same basis as the trade flows in b_{ji}^n, so this price is trade-based wherever trusted trade prices exist, and should be floored by the producer price.

The distinction between the two prices is quantitatively serious. For example, Mexican tomatoes trade at US$ 1,271 per tonne while the farm price is US$ 438, so valuing Mexican tomato production at the border price would overstate ρ_j^l by a factor of three, and valuing Mexican tomato consumption at the farm price would understate the food side by the same factor against those imported ones. Using one price for both roles necessarily distorts one side. Valuing world crop production at the trade-based food-role prices instead of the farm-gate prices would raise it from US$ 2.6 to US$ 3.9 trillion per year, about half again its farm-gate value.

Animal products only need a food-role price, but some of them can face a similar problem when both producer price and trade unit value are available. For example, China's pork consumption (48 million tonnes of food use) can be either valued with its domestic carcass price of US$ 3,096 per tonne or China's thin import unit value of US$ 2,120 per tonne, a cheap-cuts composition price. We trust the producer price in this case, and the general rule is proposed below.

Trade unit values. Trade unit values (TUVs) are computed from BACI. Bilateral flows at the HS six-digit level are first mapped to FAO items through the official FAO–HS correspondence and summed, and the TUV of a country–item pair is its total trade value over its total quantity, computed separately on the export and the import side. A country's TUV is then taken from whichever side carries the larger quantity, on the logic that the thicker side of the market prices the good. Unit values below US$ 10 or above US$ 100,000 per tonne are discarded as measurement errors. Within each item and year, we run another screening against the value-weighted median unit value and discard observations outside $[0.1, 10]$ times that median. We also screen the producer prices below in the same way. These screens only affect prices, and a country–item pair excluded from the TUV computation keeps all its trade flows in the bilateral trade values of Sections G.2 and G.3. Missing TUVs are filled by continent and then world aggregates, computed from the surviving observations as total

value over total quantity.

The official FAO–HS correspondence is unusable for five items, which we exclude from BACI: fresh and dried cassava share one HS6 heading that cannot carry two price levels, sugar cane maps to a residual heading dominated by chicory roots, palm kernels map to seeds for sowing, and mustard flour maps to prepared mustard. Other than sugar cane, these items are priced from the FAOSTAT detailed trade matrix at the FAO item level; sugar cane, essentially non-traded, is priced by the producer price. After the substitution, the producing countries price palm kernels at about US$ 1,100–1,700 per tonne, replacing the roughly US$ 10,000 sowing-seed level from the official correspondence.

Producer prices. Producer prices come from the FAOSTAT Producer Prices domain in current US$ per tonne for both crops and animal products. FAOSTAT producer price series contain occasional breakdowns, mostly from local-currency conversion problems. We screen each country–item observation against the production-weighted world median of the item and discard prices outside $[0.1, 10]$ times the median, but keep the quantity record so the country falls back on continent prices rather than disappearing. Japan and Korea are exempted from screening as their prices sit far above world medians because their markets are protected.

A short manual override list handles cases the screen cannot: China's sugar cane, whose annual price series is four times its own monthly series in 2010 (we use the monthly level of about US$ 73 per tonne, confirmed by FAOSTAT's constant-dollar production value); US and Australian almonds, where FAOSTAT applies a shelled-basis farm price to an in-shell quantity (we rescale by the official shelled-to-in-shell production ratio); and Greece's olives, where a table-olive price is attached to a crop that is 92% oil-destined (the price is nulled; the continent average, computed after the screen, then excludes the contaminated record, and Greece falls back to it). Croatia's "green corn" production quantity is overridden, as an official 891-kilotonne entry is forage maize misfiled as sweet corn (the SUA itself keeps only 0.5–0.7 kilotonnes, the level we force).

Assembling the two chains. Whether a country's own TUV can be trusted depends on how much it trades. We admit TUV only when the country's trade in the item exceeds 10% of its production. Below that threshold, the observed TUVs are too thin to represent prices of domestic supply. The crop-role price is producer-price first for every row. When it is missing, for thick traders the fallback order is the own TUV, then continent producer price and continent TUV, then world producer price and world TUV; for thin traders the chain uses continent and world average producer prices first, then continent and world average TUVs, and lastly the country's own TUV, which is never used effectively.

For every item whose own trade is thick, vegetal or animal, the food-role price is the maximum of the country's own TUV and the producer price. When trade is thin, vegetal items take the maximum of the borrowed continent or world TUV and the producer price, while animal products use the producer price first, with continent and world producer prices as fallbacks. TUV is not used here because thin animal trade reflects specialty-cut and packaged compositions rather than the domestic product. For products classified as crop commodities, the food-role price is additionally floored by the crop-role price, so that processing margins are never negative.

Three groups of commodities are treated separately. First, milled rice does not have a producer price, so for countries that barely trade milled rice, the fallback chain would price this staple at the continent trade unit value. It would cause problems for countries like Japan: Japanese food rice would be valued at US$ 657 per tonne against a domestic paddy price of US$ 2,569 per tonne, understating the food side of rice more than fivefold. We therefore construct a derived producer price for husked and milled rice as a country's paddy producer price divided by the milling extraction rate (0.80 and 0.70, from the FAO technical conversion factors). This price will be used for thin traders of milled rice to calculate its rice consumption.

The second group is liquid dairy byproducts. Fresh whey, buttermilk, and liquid skim milks have no producer price and no own trade, and their TUVs are contaminated by their dried counterparts sharing the same HS headings. Following the milk conversion used by Gouel and Guimbard (2019), we price these liquids at one tenth of the same country's whole-milk-powder price.

The third group is the residual baskets. Items such as "vegetables fresh n.e.c." are heterogeneous across countries, and borrowing a continent price from whichever few countries report the residual item is hazardous: China's 157 million tonnes of unclassified vegetables, accounting for 40% of Chinese vegetable production, would be priced from a 7-million-tonne reporter pool. For these items, we use the country's own production-weighted average producer price over the named items of the same product family, computed whenever at least three named family items report prices, so that the average is from a "true" basket. Processed residual items, such as "Vegetables, canned nes" and "Fruit prepared n.e.c.", are exempt here and follow the general pricing rule, since the named items of their families carry farm-gate prices of the primary stage, which differs from the processing level for a canned or prepared product. All residual items, processed or not, are excluded from the family average calculation.

G.2 The crop accounts

Crop production values are FAOSTAT primary production quantities valued at crop-role prices. We intentionally avoid using the FAOSTAT "value of agricultural production" domain directly because certain values reported there inherit producer prices that our screen removes (for example, China's sugar cane). Seed cotton is the only exception. Its production is valued as the whole unginned boll, taken directly from the FAOSTAT gross production value where a country reports it and elsewhere scaled up from the cottonseed value by the data-driven ratio of the two among areas reporting both (0.19). This imputation is applied at the FAO-area level before areas are summed into model regions, and the world seed-cotton production ends with US$ 96.7 billion in the baseline year. Additionally, six country–crop pairs with production but no recorded harvested area (e.g. Malaysian maize) receive areas imputed from continent-average yields.

We make three adjustments when building bilateral crop trade values from BACI. We first adjust values for three crop commodities with border prices far above the farm gate, including malt, which carries a processing margin over barley, and cocoa beans and sugar beet, whose raw border prices embed a large farm-to-border wedge (cocoa passes through marketing boards). Valued at border prices against farm-gate, the exported share would be overstated, and a country could ship more crop value than its production. For each such trade flow, we replace the border value with its embodied crop value.

For cocoa beans and sugar beet, this simply reprices the traded tonnage at the exporter's implied farm-gate price; for malt, we first convert the tonnage into the grain it embodies and then price that grain the same way. Both estimates are capped at the flow's market value, and the few flows without recorded quantities are scaled by the corresponding world value ratio instead. The adjustment reduces these flows from US$ 14.7 to US$ 8.2 billion per year. Trade flows of oil cakes and brans, in contrast, keep their original border values. The crush split of Section G.4 prices the feed share of each oilseed at exactly these byproduct prices, so cake trade is already on the same valuation basis as the account it draws on.

We also remove recorded flows whose exporters do not grow the crop at that scale.[7] Each importer's purchases are reallocated proportionally to its remaining suppliers, so the fake origin disappears while the importer's measured purchases are preserved. The third adjustment concerns HS headings shared by several model crops, whose trade value is allocated across those crops in proportion to their separately recorded trade flows between the same exporter and importer.

We then clear re-exports using the method as in Kastner, Kastner, and Nonhebel (2011).

[7] Swiss soybeans, maize, and sunflower to Middle Eastern partners; Slovenian soybeans; Namibian dry beans to India; a barley flow from Central America to Israel; and Argentine "other pulses" to most partners.

Writing A as the matrix of a crop's export shares (ρ^l_{ij}s) and $\hat{P}$ as the diagonal matrix of production values, the matrix $(I - A)^{-1}\hat{P}$ redistributes each country's production to its ultimate absorbers under proportional sourcing. Consequently, value-added in processing stages drops out of the crop accounts, and a country's crop exports can never exceed its production. The validity of this clearing rests on production being measured independently of trade, a condition that holds on the crop side. The clearing requires exports not to exceed supply, so exporters exceeding this beforehand have their outgoing flows scaled down to 95 percent of production plus imports. After the clearing, all imports are for domestic use, so the requirement tightens to exports not exceeding production alone; the few remaining problem exports are scaled down once again to 95 percent of production. Every exporter therefore keeps at least a 5 percent home share of each crop.

With production and trade in the crop account, availability is calculated as the maximum of 0 and production plus net import, and production is recomputed from the floored availability so the accounts balance exactly. The not-traded crop grass enters as an additional crop whose value is constructed in Section G.5. These data serve the calibration of ρ^l_{ij}, ρ^l_i, and ρ_i, further of α^l_{ji}, α^l_i, α_i as in Section 3.3.3.

G.3 The food accounts

We compute food consumption values as the product of the food-use quantity of SUA items classified as food commodities and their food-role prices, with the FBS supplying fish and seafood. The model allows food products two destinations: human consumption (food) or leaving the food system (non-food), so feed use of food products (whey fed to calves, fish reduced to meal) is treated as a non-food exit. Both exits are minor compared to eating. Of total food-side use, 3.8 percent leaves as non-food use and 2.4 percent (US$ 119 billion per year, almost entirely dairy byproducts and fish meal) as feed. We prepare food trade values using BACI trade flows mapped from HS headings to food groups, with headings shared between groups split equally across them. Bilateral trade flows are averaged over 2010–2012 to smooth out noise, the same convention as crop trade.

Food production is not observed, and we recover it from the accounting identity that production equals total food use plus exports minus imports. We do not apply the same re-export clearing as for the crop account here since recovered production is not measured independently of trade, and feeding it back is circular and problematic. If executed, the clearing misreads genuine exporters, cutting Dutch production of "vegetables & fruits" from US$ 6.5 to US$ 0.7 billion. Food trade therefore enters at its raw values.

The recovery identity can fail and give a negative residual production when recorded

imports exceed domestic use plus exports. Separately, our calibration of a_{ij}^n generally requires every country's food exports to be covered by its own production. We thus set production to the maximum of the recovered residual and 1.05 times exports, which guarantees every country a home share a_{ii}^n of at least $1 - 1/1.05 = 4.8$ percent in every food category. The floor binds for 101 of the 656 country–food pairs and injects about US$ 59 billion per year of production, roughly 1.2 percent of world food production. The injection is concentrated in the trade hubs and amounts to about one third of measured Dutch and Belgian food production. On these rows, availability is recomputed as production plus imports minus exports so the accounts balance. This is the crudest patch in the food accounts, as it books these trade hubs' re-export margins as domestic production, but no cleaner treatment exists without an independent measure of food production.

After preparing the food accounts, these values calibrate b_{ji}^n, b_i^n, b_i, h_i^n, and h, and the production-side parameters a_{ji}^n, a_i^n, and a_i are recovered from the world market-clearing identities of Equations (55)–(57), so these share parameters are consistent by construction.

We also use total food expenditure for the share parameter $\tilde{b}_i$. GDP at market exchange rates comes from the FAOSTAT macro indicators (UN-sourced current US$, averaged over 2010–2012). As some members of composite regions (Singapore, Qatar, Bahrain, South Sudan, and other smaller economies) appear in BACI trade but have no FAOSTAT SUA and FBS account, we impute their food consumption as their net BACI food imports by food group, floored at zero, which for city and island economies is the food that actually enters their borders, and add it to the region's food use.

The imputation is applied only where the macro accounts can follow: a member without a GDP record of its own (Gibraltar, Mayotte, Guam, and eighteen other non-UN territories, together US$ 0.3 billion of net food imports per year) is not imputed and stays out of both the denominator and numerator of the share $\tilde{b}_i$. A region's GDP then covers exactly the member economies whose consumption the model observes, through the food accounts or through this imputation. Puerto Rico, whose trade moves inside the United States customs territory and SUA and FBS are also unavailable, is not used for the Caribbean's $\tilde{b}_i$, although Puerto Rico's FAOSTAT farm production remains in the Caribbean's crop account (about two percent of the region's crop value). Because the consumption values are built from wholesale and border prices, with no retail margin, $\tilde{b}_i$ is a conservative Engel share.

G.4 Uses of crops and foods

For every crop commodity, the SUA use-side elements are classified into three groups: non-food (other uses plus seed), feed, and food-destined use (food supply plus processing

and tourist consumption), with reported losses allocated proportionally. Food-destined use includes processing because, for a primary crop, sending grain to the mill is precisely how a crop becomes food. Quantities are valued at crop-role prices, aggregated over the FAO items in each model crop, and h_i^l is the non-food share of the total; its availability-weighted aggregate is $h_i = \sum_l h_i^l \alpha_i^l$, as Equation (67) requires. We handle the following issues to best reflect how a model crop is used for different purposes.

Double counting. Because the SUA reports a crop and its processed forms as separate products, the parent item's processing use and the child item's own supply describe the same physical flow, and a naive aggregation would count the value twice on the crop account. We only allow each tonne of crop value to appear on the crop account once, either inside the parent item's food-destined use (when the processed output lives on the food account) or on the child item's own rows (when the processed output lives on the crop account and its uses are recorded there at its own prices).

Concretely, for each parent crop and its recorded processing chain,[8] we collect the recorded production of every processed output and value each output at its own price. We then convert these output tonnages back into parent-crop tonnes with the FAO technical conversion factors (FAO, 1997) and take the smaller of this implied input and the parent's recorded processing quantity as the tonnage the outputs can account for. Of this tonnage, the value share of the outputs that live on the crop account (bran, cakes, dried and shelled forms) is removed from the parent's food-destined use, because their values already sit on their own rows; the value share of the outputs that live on the food account (flours, milled rice, starches) stays, being exactly the crop content of those foods. The conversion back to parent tonnes matters for drying and extraction chains. When a tonne of copra stands for about 4.5 tonnes of coconuts, comparing output tonnes directly with the processing quantity does not make much sense.

Oilseed crush. The SUA records crushing as the oilseed item's processing, so without correction the entire crush (both oil and cakes) would count as vegetal food use. The rule above applies with the cake as the crop-account output: for each of the eleven recorded crush chains,[9] we split the crushed quantity by the value shares of the recorded oil and cake outputs and remove the cake share from the seed's food-destined use. In value terms, only

[8] Wheat into flour, bran, germ, and starch; paddy into husked, milled, and broken rice and bran; barley into malt and pot and pearled barley; maize into germ, flour, bran, gluten, starch, and high-fructose syrup; potatoes and cassava into flours, starches, and dried forms; groundnuts into shelled nuts; coconuts into copra; oil palm fruit into palm oil and kernels.

[9] Soybeans, groundnuts, sunflower, rapeseed, mustard, sesame, cotton seed, copra, palm kernels, linseed, and maize germ.

the oil share of the crush output is treated as input for vegetal food production and stays in the parent item's food use. The cake share is mainly for feed and has already been captured by the cake items belonging to the same model crop as a child item, so these values need to be deducted.

Another reason to treat oil cakes separately is to handle their trade flows. Trade of oil cakes is treated as trade of the corresponding oilseed crop. Argentina grows and crushes a lot of soybeans but exports 89 percent of its soybean cakes, and it ends up with a low feed share of 24 percent with this correction (the United States, which feeds most of its cake at home, has a feed share of 59 percent). Otherwise, the exported soybean cakes' value would still be counted as food-destined use of Argentina's soybean crop.

Olives are excluded from the split, since olive crushing has no feed byproduct. The same computation yields two aggregates used in Section G.6: the oil-destined share of each model crop's food use, and the country's own SUA production value of vegetal oils, which serves as an alternative denominator for import-dominated oil markets.

Alcohol. Alcoholic beverages are not one of the model's food categories, so a crop use for alcohol production is treated as non-food and enters h_i^l. The quantity is identified case by case from recorded downstream production. For barley, malt production is converted at 1.333 tonnes of grain per tonne of malt; for grapes, wine and vermouth production is converted at 1.333 tonnes of grapes per tonne of wine; both factors sit at the center of the extraction ranges in the FAO technical conversion factors (FAO, 1997). For sorghum and millet without downstream production information, the quantity takes the milling residual. Every quantity calculated here is capped by the crop's own processing quantity, so a chain never removes more than what the country actually processed. World totals are about US$ 49 billion per year (69 million tonnes) moved out of crops' food use, and the correction lowers ψ_i in wine countries by economically sensible magnitudes (France by 0.13).

When the alcohol input is itself a food commodity, the exit is booked on the food side instead and raises h_i^n. This concerns milled rice, whose processing flows into rice wine or into downstream products with no SUA account at all (in Myanmar, 8.4 million tonnes per year of milled rice enters processing with zero recorded downstream production), and maize and sorghum flours, whose processing feeds traditional beers and unrecorded food preparations. A food commodity's processing quantity is not part of any of its use groups. Its recorded outputs, here rice flour and rice starch, reappear as food items with accounts of their own, so counting the processing again would double count them. The part of processing with no recorded output would then vanish from the books entirely. We therefore net out the recorded outputs and book the remainder, rice wine plus unrecorded flows, as non-food

use of the food commodity. This is an addition to the item's measured total use rather than a reallocation within it; because food production is recovered from use and trade in Section G.3, the recovered production rises by the same amount, while measured human consumption is unchanged.

Partially edible cash crops. We exclude completely inedible crops (natural rubber, fibres other than cotton). Cotton requires care because the model crop "seed cotton" is valued as the whole ginned boll (Section G.2) while the SUA carries use rows only for cottonseed; the lint, about 83% of the boll's value and destined to textiles, has no use row at all. We therefore add lint production, valued at lint producer prices, to the crop's non-food use, so the lint exits the food system through h_i^l exactly like an industrial use. The injection covers 45 producing countries and about US$ 52 billion per year.

G.5 Land shares and the value of grass

Our land allocation structure assumes that expected land rents are equal on each land parcel, so Equation (C.1) also reads π_i^l as a share of land rents. Valuing the physical rangeland hectare at cropland rents would badly overstate the value of grass. We therefore calculate the GTAP-based grass share of total agricultural land rents π_i^g, and deduce other crops' π_i^l with their harvest acres reported by FAOSTAT and the equation $\sum_l \pi_i^l = 1$. We also calibrate φ_i as the GTAP-based land-rent share of agricultural output, which ranges from 0.04 (Canada and Rest of North America) to 0.63 (Egypt). The grass value in FAOSTAT units then follows the closed form

$$q_i^g Y_i^g = \frac{\pi_i^g \, \varphi_i}{1 - \pi_i^g \, \varphi_i} \sum_{l \neq g} q_i^l Y_i^l \ , \tag{G.8}$$

and is used in the calibration of ρ_i and ρ_i^l. Such construction is self-consistent and satisfies $\varphi_i^l = \pi_i^l \varphi_i / \rho_i^l$ with $\varphi_i^g = 1$ for the land rent share of a crop l's dollar.

As in Gouel and Laborde (2021), the grassland rent is calculated as the land factor's income across livestock activities. We further apply a 15% cap there so that a country's grassland rent cannot exceed 15% of its livestock output value. GTAP's primary-factor shares for agriculture build on a small set of literature estimates rather than country-by-country observation, and in the underlying studies land income is typically the residual of production value net of the other inputs' costs (Saeed, Hertel, and Fuglie, 2024). Computed within the GTAP database itself, the imputed pasture-rent share of livestock output reaches 0.19–0.36 in several developing regions, against 0.06–0.13 in every economy with observed

land rental markets, including New Zealand and Ireland, the world's most pasture-based systems. The cap of 0.15 is the upper envelope of the observed-market group; we report 0.10 and 0.20 as sensitivity values. The cap addresses over-imputation and cannot see under-imputation, so two countries with well-documented rental markets receive named overrides: New Zealand at 0.20 and Ireland at 0.12.[10]

One correction completes the feed and grass accounts. Livestock produces both food and non-food byproducts (wool, hides and skins, tallow, etc). Feed and pasture support both product lines, but the model's animal-food budget should carry only the food portion, so the byproduct value share of feed and grass is re-directed as non-food use of the input and added to the existing h_i^l. This mirrors the seed-cotton convention: the input keeps its full value, because land competes on total expected revenue, and the share supporting non-food byproducts exits through h_i^l, where the industrial use can reach.

G.6 The crop content of food and the allocation program

Once both crop and food accounts are prepared, we calculate ψ_i, the overall crop share of a food dollar following its definition:

$$\psi_i = \frac{\sum_l (1 - h_i^l) v_i^l X_i^l}{\sum_n p_i^n Q_i^n} \ , \tag{G.9}$$

the value of crops available to the food system over the total food produced. Across the 82 countries, ψ_i ranges from 0.11 to 0.84 with a median of 0.47. We use both FAOSTAT and GTAP information to split ψ_i into the category-level ψ_i^n.

We first compute the GTAP-based embodied crop content (CC) of every sector from the input–output structure, which gives us a first impression of how large each ψ_i^n should be. Let $S(m, a)$ be the input share of commodity m per dollar of activity a's output, computed from GTAP's domestic and imported firm purchases (the VDFB and VMFB arrays) divided by the activity's output value, and let $g(a)$ be the land payment per dollar of output (the EVFB array), nonzero only for livestock. Embodied content solves the recursion

$$CC(a) = \sum_m S(m, a)\, CC(m) + g(a), \qquad CC(\text{primary crop}) \equiv 1 \tag{G.10}$$

until the program converges. Every activity's input shares sum to less than one per dollar of

[10]For New Zealand, banks' sustainable-rental criterion of 20–25% of gross farm income is documented in Beef + Lamb New Zealand's leasing factsheet (*Leasing*, Knowledge Hub), and dairy lease rates against per-hectare revenue in the DairyNZ Economic Survey 2011–12 imply 17–22% of revenue. For Ireland, Eurostat's agricultural land prices and rents statistics and the Teagasc National Farm Survey 2012 put grassland rents against dairy output at about 10–12%, in line with GTAP's own France and Germany.

output, so the iteration converges geometrically. The embodied contents enter the calibration only as relative weights across food categories, which we call the *GTAP proportions* below.

Another piece of information we need is the *crop value split* from FAOSTAT, the five-piece allocation of crop value across food categories described in Section 3.3.4. With the crop account and the crop use information, each piece is measured directly. First, all crop value used as feed goes to the three animal categories. Second, we assume vegetable and fruit crops can only be used to produce "vegetables & fruits," so the crop value that category uses is also clear. Third, we have calculated the value of oilseeds used in the production of "vegetal oils & fats." Fourth, values of pulses, nuts, oilseeds, and spices go to "other foods." The residual crop value belongs to the remaining two categories, "starchy staples" and "sweeteners," which we call the *residual pair* below.

We then calibrate ψ_i^n by combining the crop value split and the GTAP proportions. The three vegetal pieces with a single category are calculated directly without GTAP information. The feed piece and the residual piece each cover several categories, and there the GTAP proportions decide the relative levels: within the animal block, each category's ψ_i^n is set proportional to its embodied content $CC(n)$ from Equation (G.10) and rescaled by one country-level factor so that the three animal categories together absorb exactly the measured feed value; the same rule splits the residual piece between "starchy staples" and "sweeteners." When a food category is not produced, its piece of crop value passes to the residual pair. Finally, the adding-up constraint (63) should be satisfied.

Fallback rules handle a small set of import-dominated markets where the recovered food-production denominator of ψ_i^n is unusable. All fallbacks are triggered when ψ_i^n would otherwise exceed one, which means that a category's crop cost exceeds its production value. The problem case is best seen in Bangladesh, where imports cover 95% of the consumption of "vegetal oils & fats". Recovered production is then the small difference between consumption and imports and is mostly noise. For this category, we therefore replace the recovered denominator with the country's own SUA production value of vegetal oils and cap ψ_i^n at one; for the few countries whose SUA records no oil production at all, we set $\psi_i^n = 0.7$. For "other foods" and "vegetables & fruits," no alternative own-country denominator exists, so the number is capped at one. Every wedge these rules open is reassigned to the residual pair, so the adding-up constraint (63) continues to hold exactly. The residual pair is the designed pressure valve of the system and absorbs every wedge, with the GTAP proportions setting the relative levels of its two categories.

The allocation shares s_i^{nl} are then solved by a convex quadratic program (66), which minimizes the squared distance to the priors subject to the structural constraints (each category's crop budget, $\psi_i^n a_i^n (1 - h_i)$, equals the crop value allocated to it) and the share

constraints (each crop's allocation sums to one). The priors give crop destination structures as the main text describes: each crop's feed share is divided equally among the three animal categories, and its food share is split between the oil destination and the crop's family bucket, so the prior of every crop the country grows sums to one. The solved shares stay close to these priors and change only where a category's crop budget requires.

Zero restrictions remove inadmissible destinations in three layers before the program runs. We do not allow production of "vegetables & fruits" to use crops classified as cereals, oilseeds, roots, pulses, nuts, and olives. Production of "sweeteners" does not use crops belonging to pulses, oilseeds, nuts, olives, vegetables, and fruits. "Starchy staples" does not contain crops classified as vegetables, fruits, and olives. Other channels, such as maize and roots entering "sweeteners" through high-fructose syrups and starch glucose, are still allowed. Grass is fixed at zero for every vegetal category. And a crop with no measured oil destination in a given country cannot supply "vegetal oils & fats" there.

Countries are independent in program (66), so the program solves 82 country-level quadratic programs, and all 82 return optimal solutions. After the solve, the crop cost shares of food production follow from the identity $c_i^{nl} = \psi_i \, \alpha_i^l \, (1 - h_i^l) \, s_i^{nl} \, / \, \left[\psi_i^n \, (1 - h_i) \, a_i^n\right]$.

G.7 Consistency checks and validation

The program enforces its account balancing at each run. For example, the five pieces of the crop value split must add up to ψ_i after all fallbacks (Section G.6); the prior of every crop a country grows must sum to one; the adding-up identities of Table 3 hold in all 82 countries; all 82 quadratic programs solve to optimality. ψ_i lies in $(0, 1)$ in every country, and φ_i equals the GTAP land-rent share everywhere, below 0.64 in all countries.

Two measurement tensions still exist. First, at the category level, ψ_i^n exceeds one for 14 of the 656 country–food pairs, with thirteen for "starchy staples" and one for "sweeteners." The maximum is 1.43 for the starchy staples of Rest of South America. The concentration in the residual pair is by construction: the directly measured categories are bounded by their own accounts or capped at one, so whatever wedge remains between the FAOSTAT levels and the GTAP proportions ends up in the residual pair, which the adding-up constraint (63) forbids us to cap. A ψ_i^n above one says that the crop value assigned to the category exceeds the category's measured production value, which can be explained as producing such food yields some unobserved benefits. In equilibrium, such a ψ_i^n implies that food category's price is more elastic than its crop bundle's price.

Second, at the crop level, the rent ratio φ_i^l exceeds one in 165 (4.1%) of the 4,058 nonzero country–crop pairs. The maximum is 13.5 for Korean rapeseed. These pairs are

concentrated in minor grain, pulse, and oilseed crops of high-protection economies (Korea, Japan, Taiwan, and Egypt account for a third of them), where the harvested-area share of the crop is too large relative to its value share, so Equation (69) attributes more rent to the crop than its producer price collects. This could also be because farmers receive subsidies, so crop value does not have to fully cover the land rent, and crop-price changes amplify rather than dampen land-rent changes in these cells. The affected pairs carry small value shares ρ_i^l by the same construction: together they hold 0.5 percent of world crop value, half a percent of the median affected country's crop value, and at most 16 percent of an economy's crop value (Taiwan).