Nutrition Indicators for CGE Models

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Abstract

Computable general equilibrium (CGE) models have proven useful for simulating future economic activity and environmental indicators, especially in response to global drivers such as population, income, technology, and dietary preference. This paper demonstrates that output from CGE models can be converted to nutritional indicators such as calories, protein, fats, and micro-nutrients. In this paper, we cover post-simulation analysis of food demand, rather than how to specify food demand within a general equilibrium model. There are strong links between the specification of food demand in a model, and how that is calibrated, to the realism possible for reporting calories and other nutritional indicators. It turns out that modification to the underlying social accounting matrix (SAM) can improve the realism of projections of food demand, by increasing the consistency between monetary units in the SAM and physical units (metric tons) in food balance sheets such as those published by the Food and Agricultural Organization (FAO) of the United Nations. If model output by food commodity can be expressed by weight (e.g., consumption in terms of grams per person per day), then food conversion tables can be applied to obtain a comprehensive list of nutrient consumption, including macro- and micro-nutrients. This information can be summarized in a variety of nutritional indicators. We cover two key steps: (1) pre-processing of the SAM and food balance sheets; and (2) post-processing of CGE model output.

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Introduction

Computable general equilibrium (CGE) models have proven useful for analysis of alternative environmental policies, especially accounting for economy-wide and welfare effects of policies relative to a baseline. The baseline is important as a point of departure, and tells a story of how trends in population, income, and technology might influence food demand and nutrition over time. Baselines need not be unique, and the international global change research community has developed a set of Shared Socio-economic Pathways (SSPs) to cover a range of baseline scenarios.

We demonstrate that output from CGE models can be converted to nutritional indicators such as calories, protein, fats, and micro-nutrients. This paper covers post-simulation analysis of food demand, rather than how to specify food demand within a general equilibrium model. However, there are strong links between the specification of food demand in a model, and how that is calibrated, to the realism possible for reporting calories and other nutritional indicators.

It turns out that modification to the underlying social accounting matrix (SAM) can improve the realism of projections of food demand, by addressing the consistency between monetary units in the SAM and physical units (metric tons) in a food balance sheet. If model output by food commodity can be expressed by weight, in grams per person per day, then food conversion tables can be applied to obtain a comprehensive list of nutrient consumption, including macro- and micro-nutrients. This information can be summarized in a variety of nutritional indicators.

Pre-processing of social accounting matrix and food balance sheets

Analysis that follows depends on tracking food quantities within a CGE model over time. The model should be able to replicate FAO estimates of food available for consumption (by weight), at the level of aggregation used in a CGE model, for the model base year. We begin with the GTAP 9 SAM and FAO food balance sheets for 2011.

Since food balance sheets use units of metric tons, that is a good choice for units of agricultural products in a CGE model. One way to proceed is to replace agricultural rows in a country's input-output table with quantities from food balance sheets and recalculate the monetary values for each entry as if one price prevailed across all users of this agricultural commodity. However, some complications must be addressed: joint products (e.g., beef and dairy); maintaining plausible feed-to-meat conversion efficiencies; the price of imported goods may be very different than domestically produced goods; and the SAM must remain in monetary and physical balance throughout all time steps in model simulation. Once food demand is known in tons per year, it can be converted from tons to grams (by multiplying by 1,000,000) and then divided by population and by 365 days/year to obtain grams per person per day. Standard food conversion tables can then be directly applied to obtain kcal per person per day, grams of carbohydrates, protein, and fat, and milligrams of other nutrients.

Three key data sets provide empirical support for CGE models to simulate agricultural activity over time, report food consumption by food group, and convert food consumption to energy (kilocalories), macronutrients (protein and fat) and a long list of micronutrients. The three data sets are:

1. Base-year SAM with sufficient agricultural product detail
2. FAO food balance sheets
3. Food conversion tables

We begin with a global SAM provided by the Global Trade Analysis Project (GTAP). This provides several advantages: the GTAP project at Purdue University updates this data set every three or four years saving considerable time and expense for participating models, with 2007, 2011, and 2014 as the most recent base years; the GTAP data set provides a sufficient level of detail for agricultural products (Table 1), with 18 food products within 22 agricultural production sectors. A SAM is entirely in monetary units with no quantity information. A SAM defines the economic structure and scale for a model, including number of production sectors, number of world regions, and primary factors of production (land, labor, and capital).

Table 1 Agricultural production sectors in GTAP social accounting matrix

Group	Subgroup	Symbol	Description
Primary agriculture	Crops	WHT	Wheat
		PDR	Paddy rice
		GRO	Other grains
		OSD	Oilseeds
		C_B	Sugar (cane and beet)
		V_F	Vegetables, fruits, nuts, roots and tubers
		PFB	Plant-based fibers
		OCR	Other crops
	Fisheries	FSH	Fish
	Forestry	FRS	Forestry
Animal products		CTL	Cattle and other ruminants
		RMK	Raw milk
		WOL	Wool
		OAP	Other animal products
Food processing		VOL	Vegetable oils
		PCR	Processed rice
		SGR	Sugar
		B_T	Beverages and tobacco products
		OFD	Other food
		CMT	Meat from cattle and other ruminants
		MIL	Dairy products
		OMT	Other meat products

In contrast to a SAM, a Food Balance Sheet (FBS) has only physical units (metric tons) and no monetary information. The Food and Agriculture Organization (FAO) of the United Nations is the source for annual food balance sheets for nearly all countries. Food balance sheets are organized with 98 rows, one for each food commodity, and columns with components of domestic supply and domestic utilization.

Table 2 displays the first four commodities in an FAO food balance sheet for the United States in 2013. Large quantities of maize in the U.S. are used for animal feed and ethanol production. The core of a social accounting matrix is an input-output table for each country or world region. An input-output table is constructed from a "use table" and a "make table" in monetary units (Miller and Blair, 2009). The use table has commodities as rows and activities as columns and shows the monetary value for each input to a given production activity. A make table has activities as rows and commodities as columns, and shows which commodities are produced by each production activity. If each activity produces only one commodity, then the make table is diagonal. A food balance sheet is essentially a "use table" in physical units instead of monetary units, with food commodities as rows and activities as columns.

Table 2 Standard Food Balance Sheet structure (thousand metric tons), USA 2013

	PROD	+IMP	+STOCK	-EXP	-FEED	-SEED	-WASTE	-PROC	-OTHER	= FOOD
Wheat	57,967	5,491	5,284	34,691	6,196	2,096			16	25,742
Rice	5,745	923	-27	3,522		109	200	464	142	2,203
Barley	4,683	864	16	696	1,440	107		3,161		160
Maize	353,699	3,595	-39,863	24,655	128,024	582		23,230	137,023	3,917

PROD = production; IMP = imports; STOCK = change in crop storage; EXP = exports; WASTE = waste during storage and transportation; PROC = processing into other food products; OTHER = non-food uses such as maize for ethanol; FOOD = food available for consumption

Beyond the core activities (columns), nutritional information is appended to the FBS with columns for dietary energy, protein, and fat (Table 3). The nutritional information is a national average expressed as kilocalories (kcal) per person per day for energy, and grams per person per day for protein and fat.

Table 3 Food Balance Sheet activities (columns)

Activity type	Activity	Notes
Supply	Production	
	Imports	
	Change in stocks	
	Exports	
	Available supply	Production + Imports + Change in stocks – Exports
Domestic utilization	Feed	
	Seed	
	Food manufacture	
	Other uses	
	Waste	Losses during storage and transportation
	Food	
Food supply per person	kg/person/year	
	grams/person/day	
	kcal/person/day	
	protein/person/day	grams
	fat/person/day	grams

If a CGE model replicates food balances in Table 2, with units of metric tons for each food commodity, then reporting of nutritional components only requires applying coefficients available from a food conversion table (FCT). A CGE model is designed to maintain monetary balance as it steps through time, but careful integration of SAM and FBS information is needed to replicate base-year food quantities and maintain food balance.[1]

Food balance sheets are available for download at

http://www.fao.org/faostat/en/#data/FBS

and a handbook is also available (FAO, 2001).

[1] The process of integrating monetary and food quantity information is similar to combining monetary and energy quantities in CGE models used for environmental policy analysis.

Hybrid units

The benchmark SAM for a CGE model is in monetary units, but monetary values might be inconsistent with quantity information obtained elsewhere. This problem has long been apparent in applications of CGE models to energy and climate policy, where monetary values of energy commodities were not consistent with energy balance tables from the International Energy Agency. The solution was to reconstruct the SAM so that energy commodities obey the law of one price (net of tax, transport, and distribution margins). If you know the price of an energy commodity, in dollars per gigajoule (GJ), you can always recover the quantity from a monetary value. In the early 1990s, individual modeling teams devised their own solution for merging energy balances with input-output tables, but the GTAP group later provided a solution built directly into the GTAP data set. This type of SAM reconstruction is similar in concept to a hybrid input-output table, which has hybrid units of dollars and joules (Miller and Blair, 2009). The goal was to maintain energy balance in the model, capturing direct energy consumption in a production process, as well as indirect energy consumption through other inputs.

We now face the same challenge with respect to agricultural products. Ideally, the SAM would be reconstructed with physical units for agricultural products (metric tons), energy units for energy carriers (joules), and real dollars for all other commodities. Food balance sheets are used for agriculture in the same way that energy balance tables were used for energy. In principle, CGE models should be able to reproduce FAO food balance sheets since the full value chain is modeled.

Table 4 World regions in the Future Agricultural Resources Model

Symbol	Region name	Notes
SSA	Sub-Saharan Africa	
IND	India	
OAS	Other Asia (south)	
BRA	Brazil	
OSA	Other South America	Including Central America, Caribbean, and Mexico
MEN	Middle East and North Africa	Including Turkey
EIT	Economies in Transition	Russia, Belarus, Ukraine, Kazakhstan, Kyrgyzstan, Armenia, Azerbaijan, Georgia, Tajikistan, Turkmenistan, Uzbekistan
CHN	China	
SEA	Southeast and East Asia	Including Japan
USA	United States	
CAN	Canada	
EUR	Europe	Including Estonia, Latvia, Lithuania
ANZ	Australia and New Zealand	Including Oceania

Source: FARM model documentation (Sands *et al.*, 2017)

Figure 1 Available macro-nutrients per capita (2011) by world region

Figure 1 displays historical consumption of macro-nutrients by world region (Table 4) across four major food groups. Low-income regions (sub-Saharan Africa, India, and other South Asia) are grouped to the left: these regions have the lowest per capita consumption of total calories and calories provided by animal products (fish are included in animal products). These regions also have the lowest per capita consumption of protein (second panel) and fat (third panel). The “oils and sweeteners” group provides substantial amounts of calories and fat, but little protein. The “fruits and vegetables” group provides substantial amounts of calories and protein, but little fat. The same holds for grains. Fat is provided mostly by oils and animal products.

Approaches for projecting baseline food consumption

A simple approach was used by (Valin *et al.*, 2014) to report kcal per person per day for major food groups and selected world regions, across a range of global economic models through 2050. Historical FAO data were used to set the level in 2005 by food group, and growth rates of food consumption from each model, regardless of unit, were used to project food consumption in kcal per person per day. Population and income projections were from SSP 2, the “middle of the road” scenario. This approach can be used regardless of units for agricultural products: real dollars, metric tons, or calories.

Future scenarios

We use the Future Agricultural Resources Model (FARM; Sands *et al.*, 2017) to demonstrate macro-nutrient consumption over time in seven scenarios.[2]

1. Static diet: All world regions maintain their 2011 historical diet. There is no income or price response in this scenario.
2. 50 percent EAT-Lancet Healthy Reference Diet: 50 percent convergence from 2011 historical diet toward the Healthy Reference Diet in Willet et al. (2019). With full convergence, average consumption of food calories becomes 2500 kcal/person/day within each world region, which is an increase for developing countries and a decrease for wealthy countries. Consumption of animal products increases in developing countries but declines in wealthy countries.
3. *Central income-driven diet scenario with medium income growth and medium population growth*: based on historical food consumption patterns in response to increasing per capita income. The general pattern is for total per capita calories to increase, along with a greater share of animal products in the diet.[3]
4. Income-driven diet with low income growth
5. Income-driven diet with high income growth
6. Income-driven diet with low population growth
7. Income-driven diet with high population growth

The machinery of a CGE model is not necessary for the first two scenarios: these are pre-specified diets. However, they provide a point of comparison for the income-driven diets. The response of animal product consumption to income at the world level is displayed in Figure 2a. Not surprisingly, the low-income and high-income scenarios bound the income-driven scenarios. Although the scenario variations for population have the same assumptions about income growth, there are price feedbacks to consumer demand that reduce consumption in the high-population scenario. Food prices are higher in that scenario because of resource constraints, primarily the amount of cropland. At the world level, the static scenario does not appear to be static: average per capita consumption of animal products falls over time. This is because population in low-income regions, especially sub-Saharan Africa, is growing faster than other world regions.

The same scenarios of animal product consumption are shown for sub-Saharan Africa in Figure 2b. At the regional level, per capita consumption for each food group is nearly constant over time in the static scenario. Consumption of animal products grows over time toward the world average but does not converge by 2050 in these simulations. Per capita consumption of animal products decreases at the world level in the EAT-Lancet diet scenario but increases in sub-Saharan Africa.

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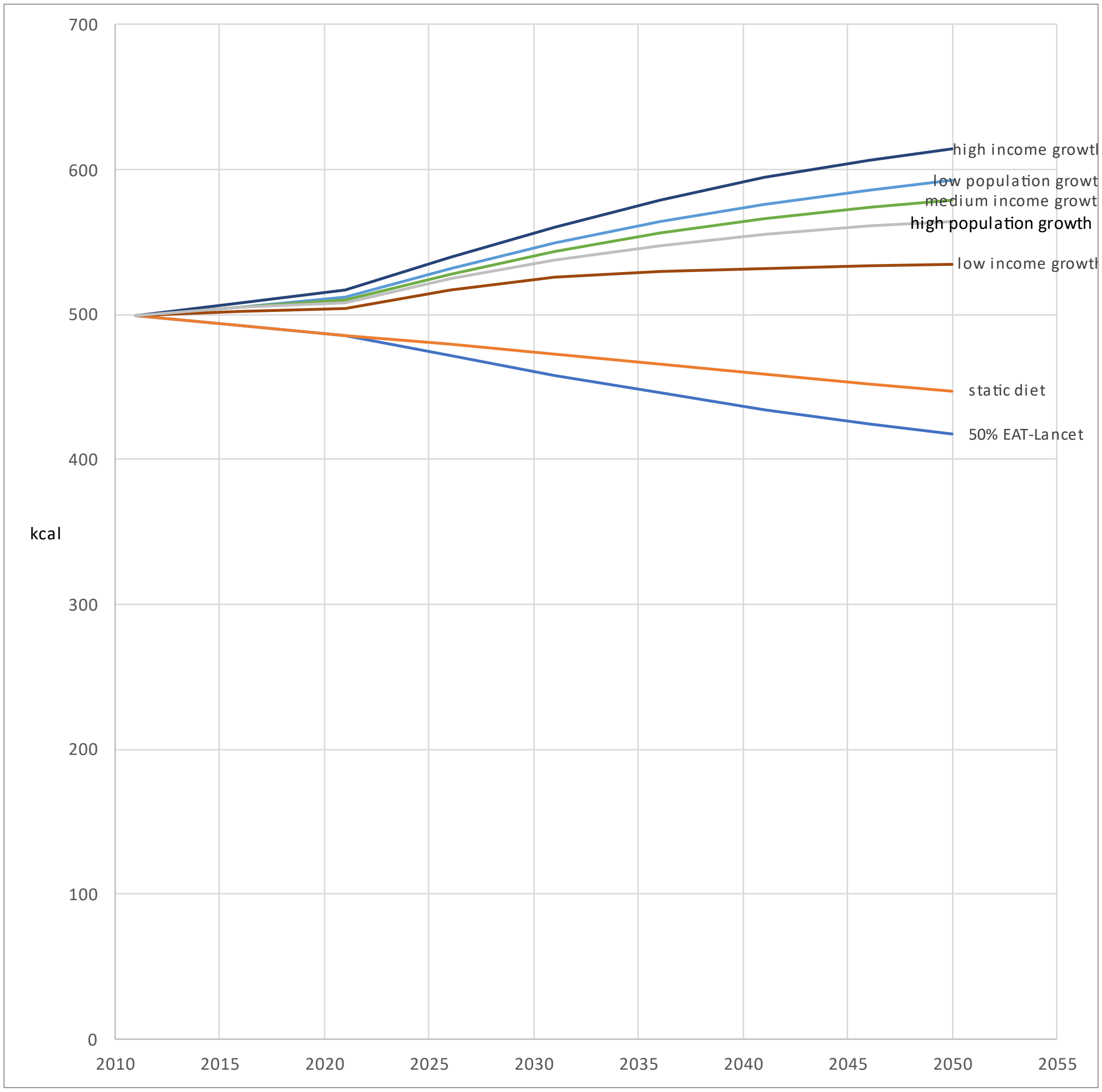
[2] Income scenarios are from the Shared Socio-economic Pathways (Dellink et al., 2017). Medium income growth corresponds to SSP2, the "middle of the road" scenario. High income growth is from SSP1, and low income growth is from SSP3.

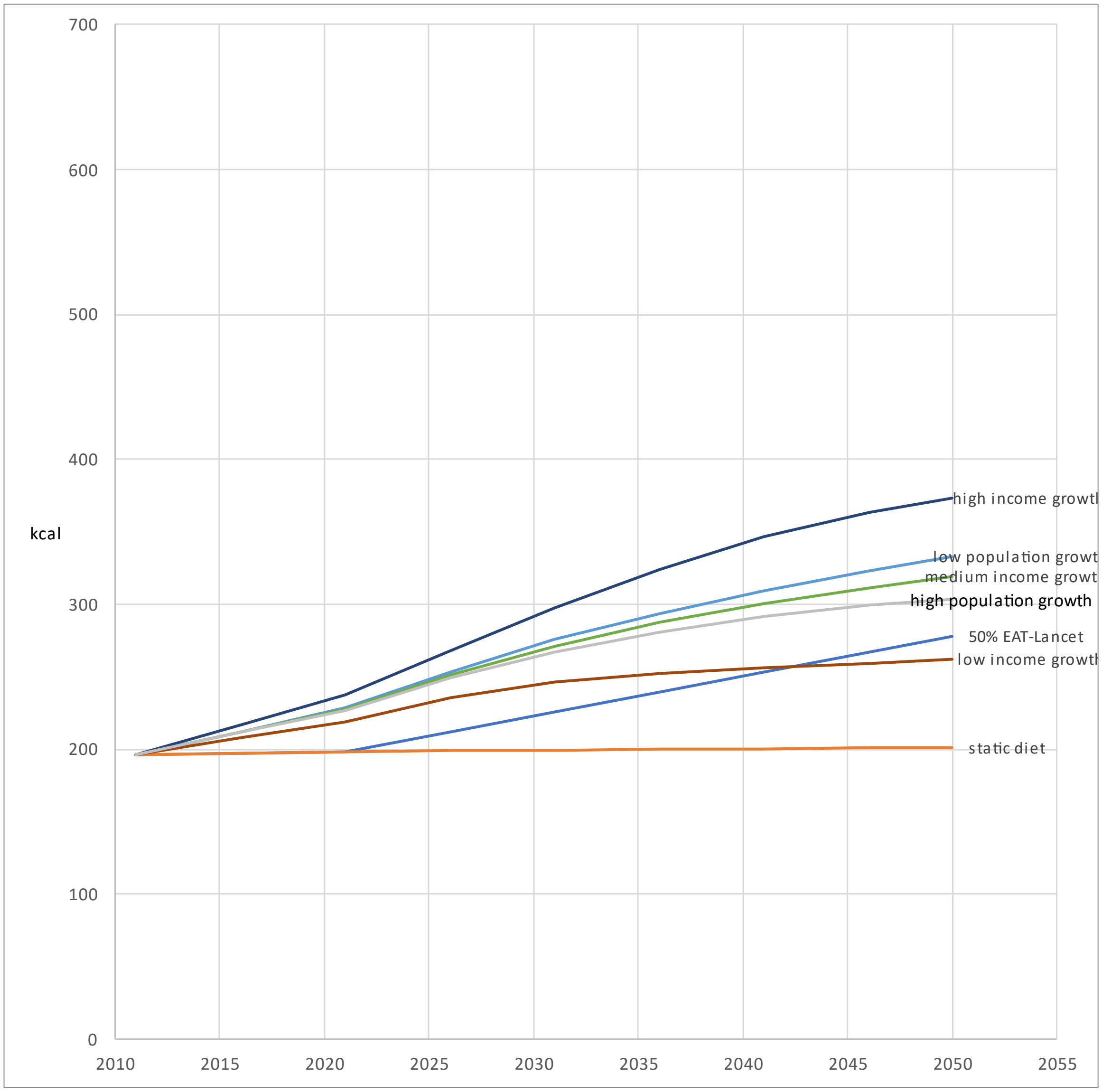
[3] Demand system parameters in the central scenario are calibrated so that per capita food calorie consumption in 2050 approximates projections by FAO (Alexandratos and Bruinsma, 2012), as a function of per capita income.

Figure 2a Per capita consumption of animal products (World)



Notes: Units are per capita calories of animal products available for consumption per day.

Figure 2b Per capita consumption of animal products (sub-Saharan Africa)



Notes: Units are per capita calories of animal products available for consumption per day.

The following figures provide scenario results as a world average and for sub-Saharan Africa, covering calories (Figure 3), protein (Figure 4), and fat (Figure 5). In each figure, results for the static diet also represent the beginning diet in 2011. At the world level, total per capita calorie consumption is about the same in the 50 percent EAT-Lancet diet compared to the static diet, but the composition across food groups is different: the quantity of calories from grains and animal products is lower and calories from fruits and vegetables is higher. Total calories and calories from animal products increase along with income in the income-driven scenarios. The pattern for calories in sub-Saharan Africa differs from the world average: total calories are greater in the 50 percent EAT-Lancet diet compared to the static diet, and calories from animal products increase.

The distribution of protein across the four food groups in Figure 4 differs from that of calories, partly because sweeteners provide essentially zero protein. Animal products provide a much larger share of protein than of calories. Total protein consumption in sub-Saharan Africa starts in 2011 below the world average (static diet) and stays below the world average in all scenarios. Convergence toward the world average of total protein is greatest in the high-income scenario.

Consumption of fat is driven mostly by animal products and vegetable oils (Figure 5). As with protein, sweeteners provide zero fat. Consumption of fat in sub-Saharan Africa differs from the world average mainly because of a lower consumption of animal products.

Figure 3 Variation in 2050 calorie consumption across scenarios

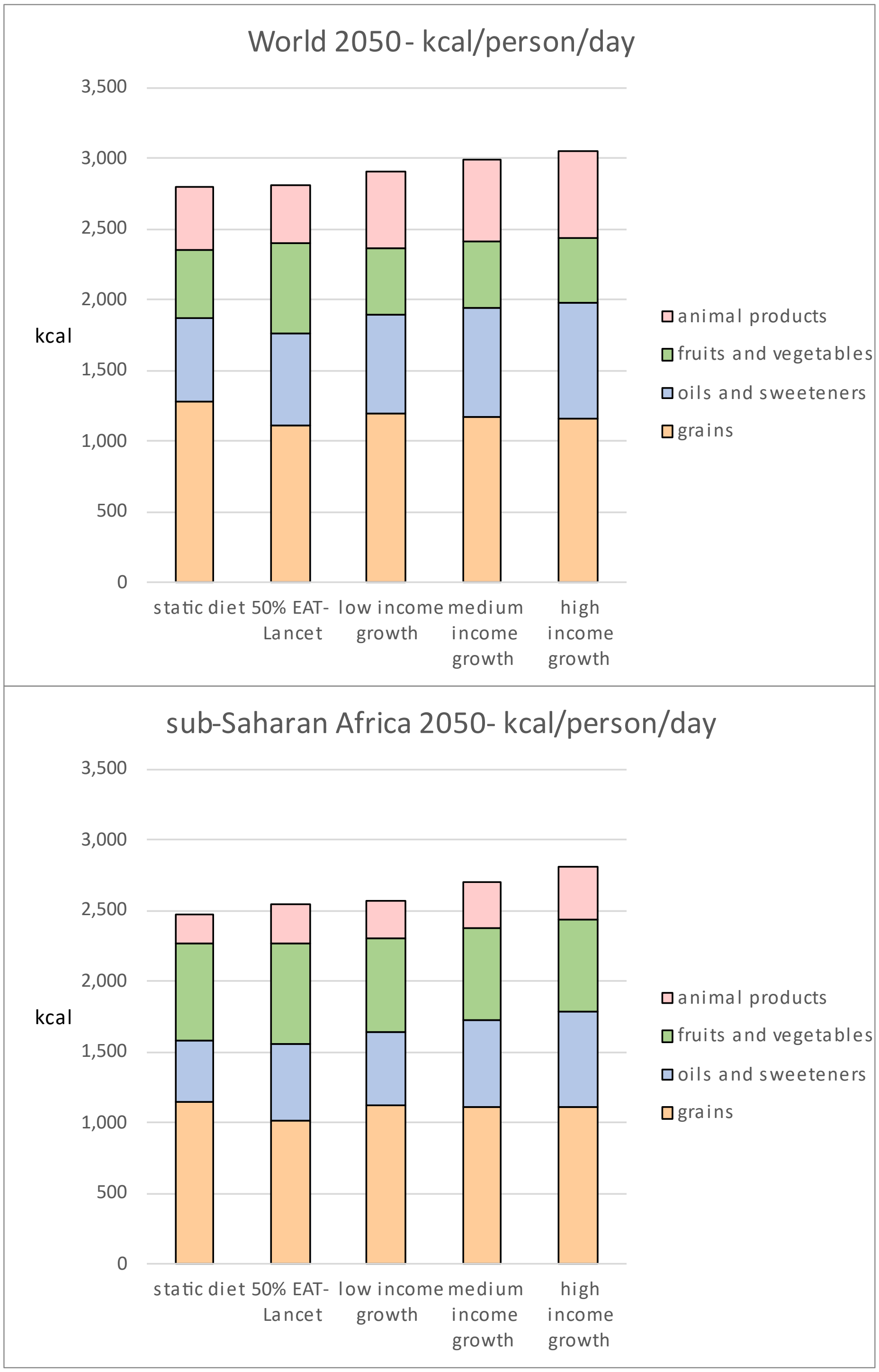


Figure 4 Variation in 2050 protein consumption across scenarios

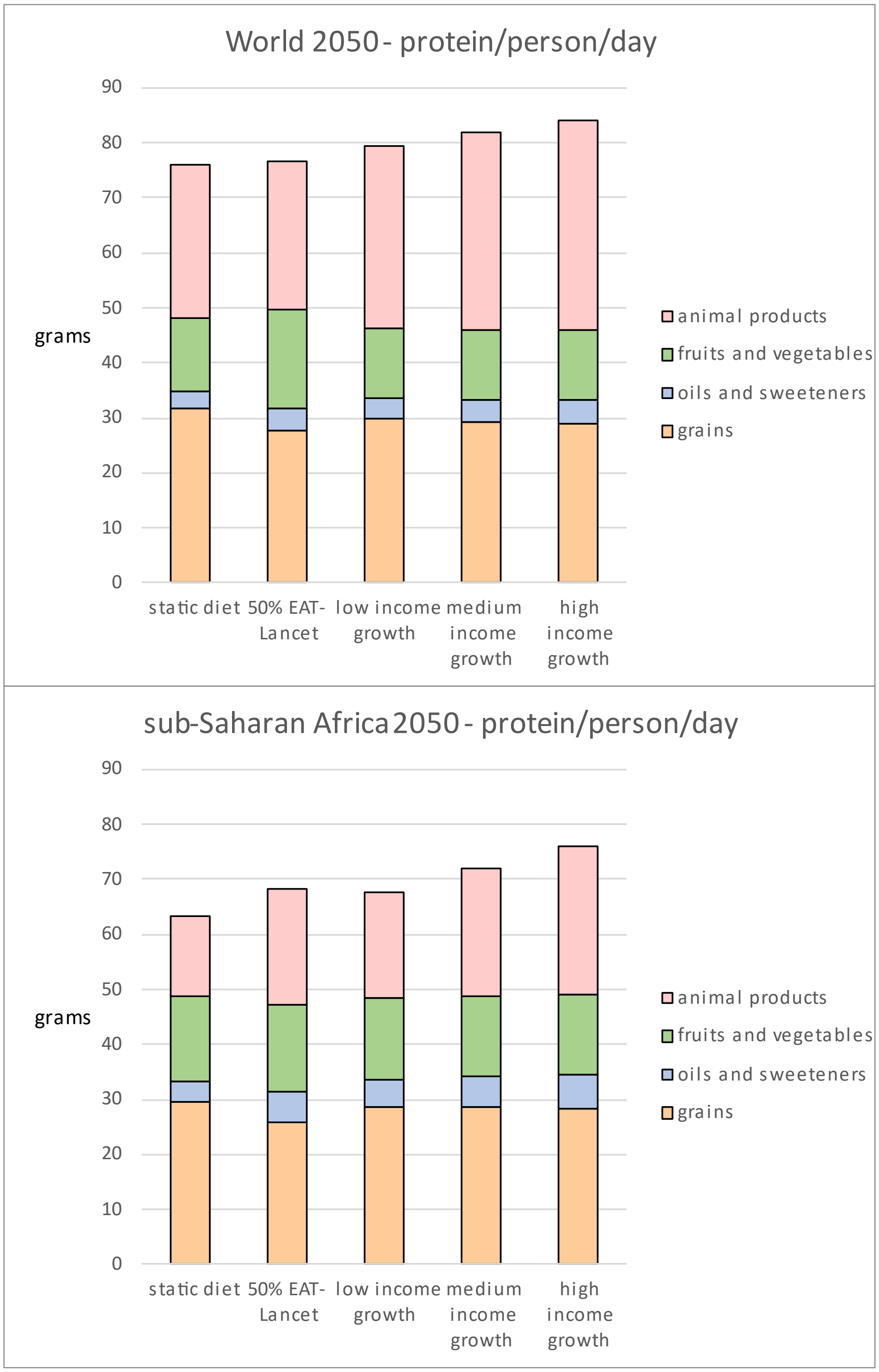
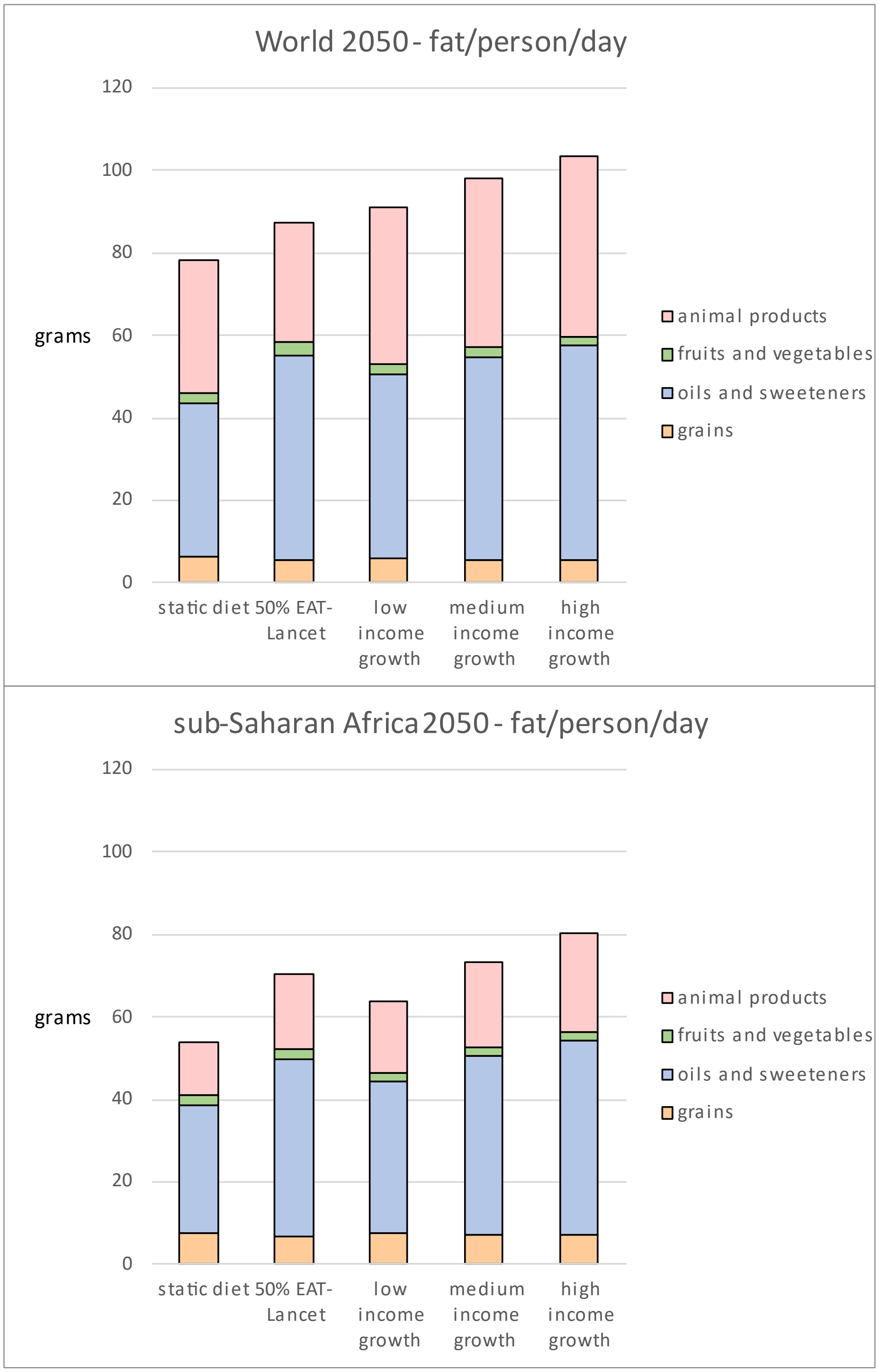


Figure 5 Variation in 2050 fat consumption across scenarios



Future Directions

Data available from FAO food balance tables and GTAP allow expansion of the number of food commodities that can be tracked for calories, protein, and fat. GTAP data cover five types of animal products: ruminant meat, dairy, nonruminant meat, other animal products (eggs), and fish. The fruit and vegetable group could be partitioned based on Chepeliev *et al.* (2021). To expand this set of indicators to micro-nutrients and other macro-nutrients requires food conversion tables.

Food conversion tables have one row for each food commodity, and columns for each of the macro- and micro-nutrients. Units are weight of nutrient (grams, milligrams, or micro-grams) per 100 grams of food consumed. If CGE models can provide consumption of each food commodity by weight, then entries in the food conversion table can be directly applied to obtain per capita consumption of nutrients. Food composition tables from the GENuS model (Smith *et al.*, 2016), with 225 commodities and 23 nutrients (Table 4), are well suited. The quantity of each nutrient, per person per day, can be derived by multiplying coefficients in the food conversion table for each model region by weight of each food commodity consumed in that region. The 225 food commodities in GENuS are mapped to 98 FAO food commodities, which in turn are mapped to GTAP agricultural products.

Table 4 Nutrients in GENuS Food Conversion Tables

	Nutrient	Unit (per 100 g food)
Macro-nutrients	Calories	kcal
	Protein	g
	Carbohydrates	g
	Fat	g
	Saturated fat	g
	Monounsaturated fat	g
	Polyunsaturated fat	g
	Dietary fiber	g
Micro-nutrients	Vitamin C	mg
	Vitamin A	micrograms RAE
	Folate	micrograms
	Calcium	mg
	Iron	mg
	Zinc	mg
	Potassium	mg
	Copper	mg
	Sodium	mg
	Phosphorus	mg
	Thiamin (B1)	mg
	Riboflavin (B2)	mg
	Niacin (B3)	mg
	B6	mg
	Magnesium	mg

Further processing of model output is possible; the following are examples (Nelson et al., 2018):

- Food expenditure share of per-capita income
- Acceptable Macro-nutrient Distribution Range
- Adequacy ratio

Summary

The strategy for this study is to model food consumption in two stages: first as food groups and then as foods within each group. This provides guidance for the structure of a consumer demand system in a CGE model and for presentation of nutrition indicators. The primary macro-nutrients are energy (calories per person per day), protein (grams per person per day), and fat (grams per person per day). The first challenge is to replicate FAO calculations of food available for consumption in the model base year (in this case 2011). The second challenge is to simulate food consumption over time in response to drivers of global change while maintaining food balance (in quantities) during all time steps through 2050. Further, per capita food consumption should remain in a plausible range. Once defensible results are obtained for calorie consumption over time and across world regions, results can be extended to other nutritional indicators.

This study follows naturally from the GTAP 2021 presentation and conference paper “Tracking calories in CGE models: from fork to farm” (Sands, 2021). The 2021 paper documents a methodology for projecting the demand for crop calories implied by alternative diet scenarios, based on merging food balance tables with SAMs.

Finally, some humility is needed for global economic modelers venturing into nutrition indicators: nutrition is a complex subject. We can construct basic indicators and how they change over time in response to drivers of global change. Climate change is one of these drivers and nutrient density of crops could change along with climate (Mariem et al., 2021).

Abbreviations

- Computable General Equilibrium (CGE)
- Food and Agriculture Organization (FAO) of the United Nations
- Food Balance Sheet (FBS)
- Food Conversion Table (FCT)
- gigajoule (GJ)
- Global Trade Analysis Project (GTAP)
- kilocalories (kcal)
- kilograms (kg)
- Social Accounting Matrix (SAM)
- Shared Socio-economic Pathway (SSP)

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