Tracking calories in CGE models: from fork to farm

Ronald D. Sands

USDA Economic Research Service

Kansas City, Missouri, USA

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Email: ron.sands@usda.gov

https://orcid.org/0000-0002-2864-0339

Abstract

A major challenge for global economic modelers is matching monetary flows in the benchmark social accounting matrix (SAM) with quantity flows: energy (joules), agricultural commodities (calories), or land (hectares). For questions related to world food demand and food security, it is necessary to match flows of agricultural commodities, in physical units, to corresponding monetary flows. This paper describes a methodology developed for the Future Agricultural Resources Model (FARM), a global computable general equilibrium (CGE) model. We apply the methodology to three diet scenarios, with a demand-driven analysis of the implied demand for crops in each scenario. The range of demand for world crop calories is wider than the range of demand for food calories in any given year. With an income-driven diet, and population growth based on United Nations medium projections, the world demand for crop calories increases by 48 percent from 2010 to 2050.

Disclaimer

Introduction

A major challenge for global economic modelers is matching monetary flows in the benchmark social accounting matrix (SAM) with quantity flows: energy (joules), agricultural commodities (calories), or land (hectares). For questions related to world food demand and food security, it is necessary to match flows of agricultural commodities, in physical units, to corresponding monetary flows. This paper describes a methodology developed for the Future Agricultural Resources Model (FARM), a global computable general equilibrium (CGE) model. We apply the methodology to three diet scenarios, with a demand-driven analysis of the implied demand for crops in each scenario.

There is no unique measure of agricultural production – it could be tons, calories, or an economic quantity index with prices as weights. Tons are useful for aggregation of a limited number of similar agricultural products, such as grains. We use calories, which can be used to aggregate all agricultural products, and conversion factors from tons to calories available from food balance sheets. The Food and Agriculture Organization (FAO) of the United Nations is the primary source of national food balance sheets.

Dietary preference affects consumption of food calories, crop calories, and land use. The following diet scenarios provide a range of food consumption, one with decreasing per capita consumption of animal products and another with increasing consumption of animal products.

- 50 percent EAT-Lancet healthy 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.
- Static diet (reference scenario): All world regions maintain their 2011 historical diet. There is no income or price response in this scenario.[1]
- Income-driven diet: 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.

[1] Income elasticities for food products are set to zero for the 50 percent EAT-Lancet healthy diet and the static diet.

Economic framework

The Future Agricultural Resources Model (FARM) is a recursive dynamic CGE model: essentially a sequence of static equilibria with capital stocks updated between time steps, but lacking foresight of future economic variables. Land use can shift among crops, pasture, and managed forests in response to population growth and changes in income, with behavioral responses determined by price and income elasticities (Sands et al., 2014, 2017). Crop yield is endogenous in a CGE model, even with underlying productivity trends that are exogenous to the model. The model can substitute other inputs for land if land becomes expensive. The benchmark data set is from the Global Trade Analysis Project (GTAP). All 22 GTAP agricultural sectors are retained, as are all GTAP energy sectors (six energy-intensive industries).

The global economic model used for this study requires three key data sets: (1) a global social accounting matrix (SAM) from GTAP, (2) food balance sheets from the Food and Agriculture Organization (FAO) of the United Nations, and (3) tables for converting food consumption by weight to calories. 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). A SAM is entirely in monetary units, lacking quantity information. FAO food balance sheets provide the quantitative link between food consumption and derived demand for primary crops (FAO, 2001). The SAM used to benchmark FARM is a hybrid between economic data provided by GTAP and quantity data from FAO food balances. Food conversion tables provide the link between kilograms (kg) of food consumed and various nutrients. For this study, we only use the conversion factors for kilograms (kg) of food to kilocalories (kcal).[2]

The primary challenge is matching monetary flows in the benchmark SAM with energy flows (joules), agricultural commodities (calories), or land (hectares). If energy flows are accurately modeled, then CO_2 emissions can be calculated at the point of energy combustion. Maintaining energy balance in a CGE model requires adherence to the law of one price: all purchasers of a specific energy commodity pay the same price net of tax and transportation margins. This is done by combining energy balance tables from the International Energy Agency with input-output tables while constructing the benchmark SAM. The same process is applied to monetary flows in the GTAP SAM using FAO food balance sheets.

[2] Extensions to this study could include other macro-nutrients (e.g., protein and fat) and micro-nutrients (e.g., zinc and iron).

Approach

The following steps were used to track calories in the FARM model: (1) convert units for commodities in FAO food balances to calories; (2) aggregate 98 FAO food categories to 14 GTAP food categories; (3) for each food commodity row in the benchmark SAM, replace monetary values with food quantities (calories); (4) calculate average price for each food commodity and multiply by quantity to derive new monetary values; (5) rebalance SAM.

In wealthier countries, food commodities are generally not consumed directly, but as part of a bundle in processed foods, or away from home in a restaurant. This may be the most difficult of all issues to address in modeling food demand, and can require major restructuring of the input-output relationships in a SAM. First, we want to capture all food consumption in the consumer demand function so that it responds to prices and income. Second, dietary energy consumption must remain in a plausible range for large anticipated increases in per-capita income.

Essentially, food commodities are captured before they enter food processing sectors and can no longer be separated from other inputs to production. The food commodities are separated from food processing sectors and re-routed directly to consumer final demand. The consumer is modeled as if the food component is consumed separately from other inputs to food processing.

Demand driven analysis

The consumer demand system in FARM has two stages

- Linear Expenditure System (LES) for the first stage
- Constant Elasticity of Substitution (CES) for the second stage

Seven first-stage commodity groups are shown as the final seven columns in Table 1, which provide a way to group agricultural commodities. First-stage commodity groups are CES aggregates of individual commodities assigned to that group. Most of the commodities are food commodities; the exceptions are plant fibers, forestry, wool; and hay (included in "other crops"). However, all commodities in Table 1 influence the demand for land.

The most important requirement for the first stage is that food consumption not scale directly with per-capita income. This excludes Cobb-Douglas and CES demand systems, which would lead to impossibly high levels of individual calorie consumption with increases in per-capita income. The LES is derived from a shifted Cobb-Douglas utility function, with an extra shift parameter.

Table 1 Agricultural production sectors and first-stage mapping for demand system

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

Income-driven consumer demand

Demand for an individual commodity in the Linear Expenditure System is given by

$$x_i(\boldsymbol{p}, m) = \gamma_i + \frac{1}{p_i}\beta_i(m - \sum_k p_k \gamma_k) \tag{1}$$

where γ_i is the quantity of good *i* that is purchased regardless of price, sometimes called a "subsistence quantity." The β_i parameters are value shares of income remaining after minimum quantities of each commodity have been purchased. Income and price elasticities are not parameters of the demand system, but they can be calculated from parameters β and γ. The income elasticity of demand is calculated from (B1) by differentiating with respect to income.

$$\varepsilon_{im} = \frac{\beta_i m}{p_i x_i} = \frac{\beta_i}{s_i} \tag{2}$$

where s_i is the value share of commodity *i* in total expenditure *m*. Base-year calibration requires setting the β and γ parameters so that we replicate base-year data from the Global Trade Analysis Project (GTAP), including value shares for each commodity in total expenditure *m*. A convenient method of calibration is to set the base-year ratio γ_i/x_i, and then β_i parameters are calculated to match GTAP value shares. The ratio γ_i/x_i must be in the interval [0,1] and can be used to indirectly set income elasticities, especially for agricultural products. Note that income and price elasticities cannot be set independently in the LES: once the ratio γ_i/x_i is set, then income and own-price elasticities are already determined. Levels of the ratio γ_i/x_i close to 1 imply low income and own-price elasticities. The own- and cross-price elasticities of demand are calculated from equation (1) by differentiating with respect to prices.

$$\varepsilon_{ii} = -1 + \frac{(1-\beta_i)\gamma_i}{x_i} \tag{3}$$

$$\varepsilon_{ij} = -1 + \frac{(1-\beta_i)p_j\gamma_j}{p_i x_i} \tag{4}$$

Price elasticities for LES-CES nest

The second stage is a CES production function that combines individual commodities into a composite commodity. This provides limited flexibility for setting price elasticities for individual commodities with an additional parameter, the elasticity of substitution in the CES nest.

Let G represent "grains" as a first-stage composite of second-stage commodities wheat (w), rice (r), and maize (m). After taking partial derivatives and some algebra, we obtain own-price elasticities (5) and cross-price elasticities (6).

$$\varepsilon_{ww} = \varepsilon_{GG}^{LES} \frac{S_w}{S_{wrm}} + \varepsilon_{ww}^{CES} = \left[-1 + \frac{(1-\beta_G)\gamma_G}{x_G}\right] \frac{S_w}{S_{wrm}} + \sigma \left(\frac{S_w}{S_{wrm}} - 1\right) \tag{5}$$

Where σ is the elasticity of substitution in the CES nest and is always non-negative.

$$\varepsilon_{wr} = \varepsilon_{GG}^{LES} \frac{S_r}{S_{wrm}} + \varepsilon_{wr}^{CES} = \left[-1 + \frac{(1-\beta_G)\gamma_G}{x_G}\right] \frac{S_r}{S_{wrm}} + \sigma \frac{S_r}{S_{wrm}} \tag{6}$$

The own-price elasticity of demand is always negative. The cross-price elasticity can be positive or negative, depending on model parameters and value shares.

Calibration of income response

To provide a plausible transition of food consumption to 2050, especially with rapidly growing per-capita incomes, income and price elasticities decline over time. This implies that underlying β and γ parameter must also change over time. For calibration of an income response, the most important elasticity is the first-stage (LES) income elasticity. The LES does not have the flexibility to calibrate income and price elasticities independently: once income elasticities are set, price elasticities are pre-determined. The following equation can be derived from (1) and (2) and is useful for calibrating LES demand to beginning and ending income elasticities.

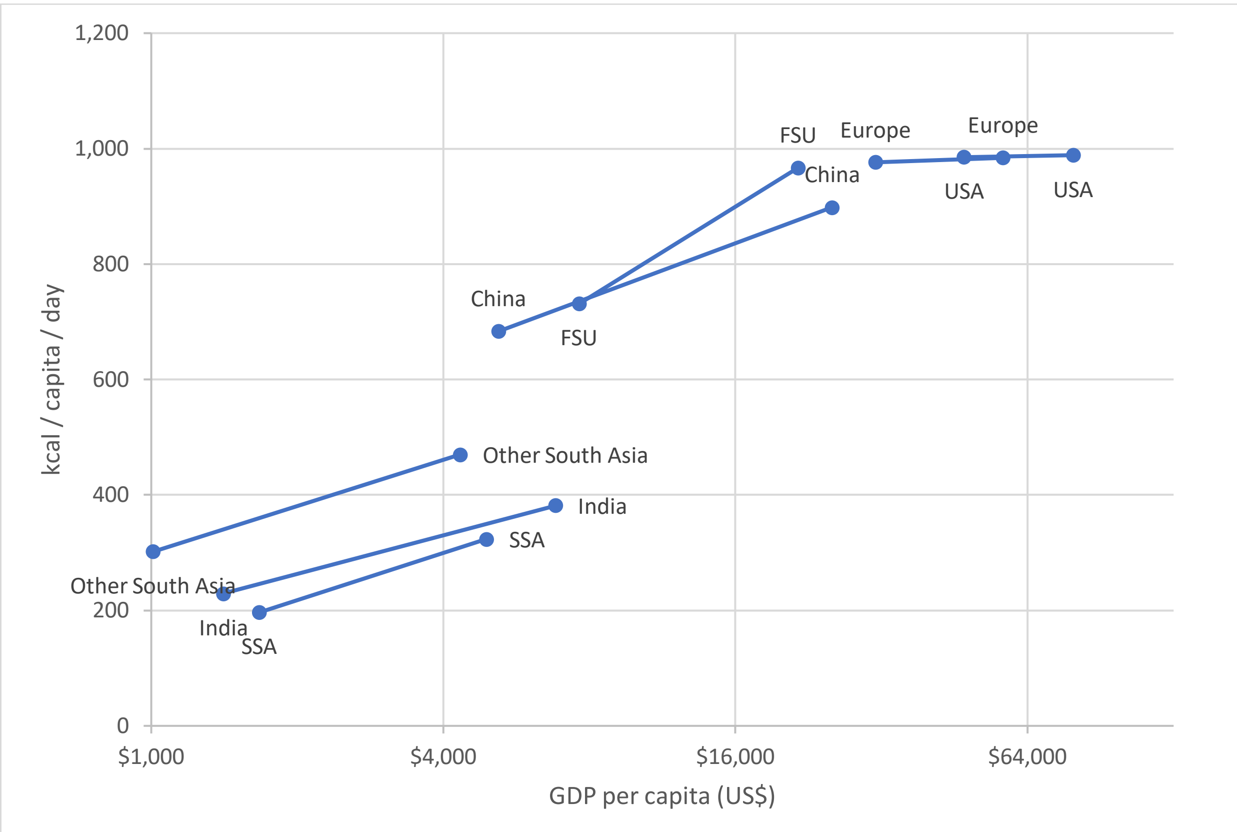
$$\frac{\gamma_i}{x_i} = 1 - \varepsilon_m \frac{sup}{m} \tag{7}$$

where “supernumerary income” $sup = m - \sum_k p_k \gamma_k$. This provides guidance for setting the base-year ratio γ_i / x_i. Since *sup* is a function of γ_i, we solve (7) iteratively for base-year γ_i, updating *sup* during each iteration using model output. For any desired income elasticity, we can find parameter γ_i to calibrate the beginning income response.

A similar process is used to calibrate the model to a target end-year income elasticity. Depending on the diet scenario, we specify in advance the per-capita growth of x_i, so we know the ending x_i. Ratio sup/m can be approximated using output from previous model runs, providing enough information to iteratively solve for end-year γ_i. The β_i are calculated using (2).

To keep future per-capita calorie consumption within reasonable bounds, we rely on Alexandratos and Bruinsma (2012) for projections to 2050. Combined with income projections from the Shared Socioeconomic Pathways (Dellink et al., 2017), we can plot beginning and ending combinations of income and calorie consumption for each world region in FARM. This plot is shown in Figure 1 for animal products. From this, a long run income elasticity for animal products can be calculated for each region. The slopes of the line segments in Figure 1 correspond to average income elasticities over 40 years. At higher income levels, as in Europe or the United States, the income elasticity for calories of animal products approaches zero (i.e., the line segments for Europe and the United States are nearly flat).

Figure 1 Long-run income response of animal product consumption to per-capita income



Relationship between FAO food balance sheets and input-output tables

An understanding of the difference between final (food) calories available for consumption and primary (crop) calorie production is necessary to interpret the analysis that follows. Final calories are those that can be consumed as food, covering all food products. Primary (crop) calories are produced from the land, before processing into animal or food products. Crop calories are greater than food calories, due to losses as feed is converted to meat, dairy products, and eggs. At the country level, crop calories produced may be different than crop calories utilized, due to international trade. At the world level, international trade nets to zero, and production of crop calories equals utilization of crop calories.

Food Balance Sheets published by the Food and Agriculture Organization (FAO) of the United Nations are the primary data source for historical food consumption by food type and country. In each food balance sheet for each food commodity, domestic supply equals domestic utilization, measured in tons. Domestic supply is the quantity of food produced (PROD), plus imports (IMP), less exports (EXP), adjusted for change in crop storage (STOCK). Domestic utilization includes crops used for seed, animal feed, processed food, non-food uses, and waste during storage and transportation. The remainder is food available for consumption (FOOD), which is greater than food consumed due to waste at home or in restaurants. FAO food balance sheets do not provide estimates of food waste at home or in restaurants but do estimate waste during storage and transportation. Except for statistical error, domestic supply should equal domestic utilization in each country.

Table 2 displays the first four commodities listed in an FAO food balance sheet from 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; STCH = change in crop storage; EXP = exports; WASTE = waste during storage and transportation
PROC = food processing; OTHER = other uses, mostly corn for ethanol; FOOD = food available for consumption

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 knew the price of an energy commodity, in dollars per gigajoule, you could always back out its 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 conservation 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.

Since food balance sheets use units of metric tons, that is a good choice for units of agricultural products in a hybrid input-output structure. 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: the price of imported goods may be very different than domestically produced goods; joint products (e.g., beef and dairy); maintaining plausible feed-to-meat conversion efficiencies; and the SAM must remain in monetary and physical balance.

Once food demand is known in tons, it can be divided by population and 365 to obtain grams per person per day. 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.

Tracking calories

FAO food balance tables provide national food consumption levels in calories for 98 commodities. These were mapped to 14 GTAP food production sectors, which are the blue rows in Table 3. Some of these are primary agricultural sectors and some are secondary (food processing). FAO food balances also provide information on calories used as feed and as inputs to other production processes. Some calories end up as biofuels (e.g., corn to ethanol).

A hybrid input-output table is then constructed by replacing monetary values with calories in the 14 rows with FAO calorie data. All calorie accounting is done within these rows, either as an input to another production process or as final demand. The input-output table is then rebalanced so that these 14 rows can be expressed either as monetary values or as calories. The hybrid input-output table becomes part of the benchmark SAM for each world region. Even though the SAM is entirely in monetary values, physical quantities (calories) that match FAO food balances can be recovered by applying prices. Some challenges remain: we have not accounted for the energy content of hay or other forage crops; exports and imports may trade at prices that differ from domestic production.

Table 3 Calorie map between production sectors

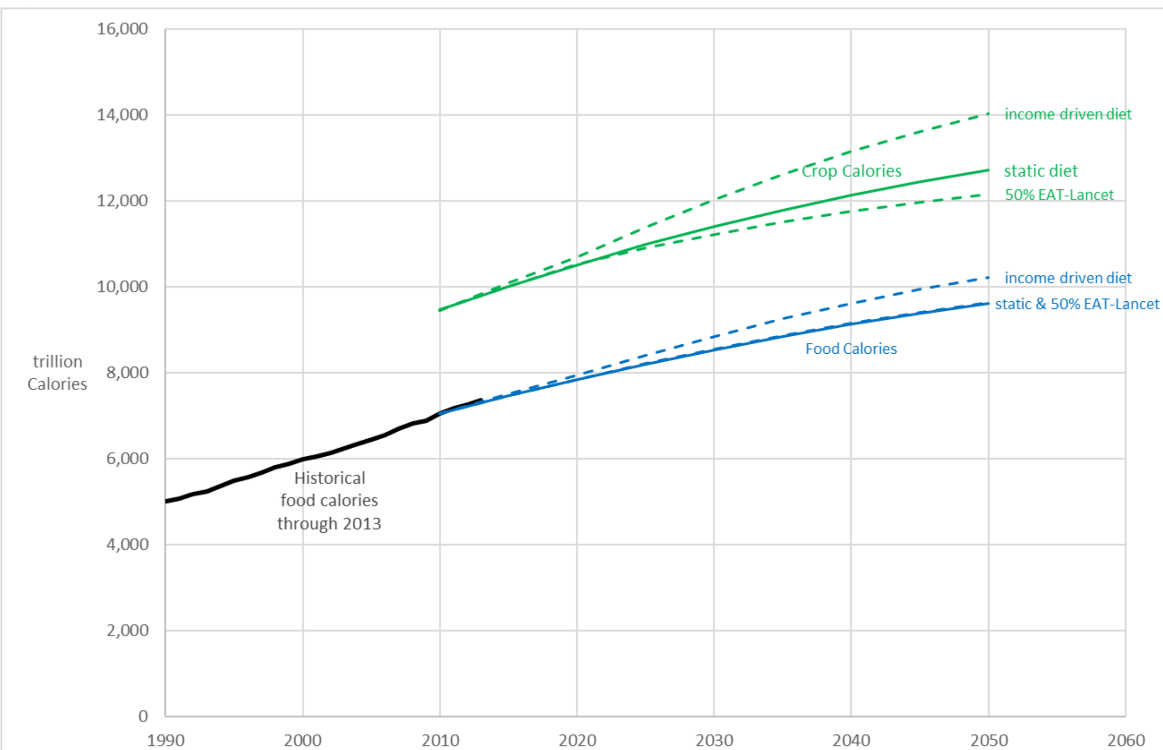
Subgroup	Symbol	feed	VOL	PCR	SGR	B_T	CMT	MIL	OMT	LUM PPP	other	Consumer Demand
Crops	WHT	kcal				kcal						kcal
	PDR	kcal		kcal								kcal
	GRO	kcal									kcal	kcal
	OSD	kcal	kcal								kcal	kcal
	C_B	kcal			kcal							(kcal)
	V_F					kcal						kcal
	PFB											$
	OCR	$										$
Fisheries	FSH											kcal
Forestry	FRS									$		-
Ruminant	CTL						kcal					(kcal)
	RMK							kcal				(kcal)
	WOL											$
Non-ruminant	OAP								kcal			kcal
Food processing	VOL											kcal
	PCR											$
	SGR											kcal
	B_T											kcal
	CMT											$
	MIL											$
	OMT											kcal
	OFD											$
Forest products	LUM											$
	PPP											$

Notes: Forest products (lumber, pulp and paper) are included because they influence the demand for land and the amount of land available for crops. LUM = lumber. PPP = pulp and paper products.

Results

The EAT-Lancet healthy reference diet highlights the distinction between food calories and crop calories: they can move in opposite directions. World food calories increase slightly with this scenario, but crop calories decline relative to the reference (static diet) scenario. With the income-driven diet, per capita consumption of food calories increases in developing countries, but the effect is magnified in the demand for crop calories due to feed requirements of animal products. This study provides a methodology for projecting the demand for crop calories implied by alternative diet scenarios. The range of demand for world crop calories is wider than the range of demand for food calories in any given year. With an income-driven diet, and population growth based on United Nations medium projections, the world demand for crop calories increases by 48 percent from 2010 to 2050.

Figure 2 World food calories and crop calories in three diet scenarios



Notes: Crop calories are always greater than food calories due to losses in conversion of feed to meat. One large Calorie equals 1 kilocalorie (kcal). Historical food calories are based on FAO food balances. Population projections are from the United Nations medium scenario. Food and crop calorie projections are calculated in the FARM model.

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