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A physically-based model of long-term food demand

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ABSTRACT

Reducing hunger while staying within planetary boundaries of pollution, land use and fresh water use is one of the most urgent sustainable development goals. It is imperative to understand future food demand, the agricultural system, and the interactions with other natural and human systems. Studying such interactions in the long-term future is often done with Integrated Assessment Modelling. In this paper we develop a new food demand model to make projections several decades ahead, having 46 detailed food categories and population segmented by income and urban vs rural. The core of our model is a set of relationships between income and dietary patterns, with differences between regions and income inequalities within a region. Hereby we take a different, more long-term-oriented approach than elasticity-based macro-economic models (Computable General Equilibrium (CGE) and Partial Equilibrium (PE) models). The physical and detailed nature of our model allows for fine-grained scenario exploration. We first apply the model to the newly developed Shared Socio-economic Pathways (SSP) scenarios, and then to additional sustainable development scenarios of food waste reduction and dietary change. We conclude that total demand for crops and grass could increase roughly 35–165% between 2010 and 2100, that this future demand growth can be tempered more effectively by replacing animal products than by reducing food waste, and that income-based consumption inequality persists and is a contributing factor to our estimate that 270 million people could still be undernourished in 2050.

1. Introduction

Food plays a major role in discussions on sustainable development. While providing sufficient food for all people worldwide is a key human development objective (as expressed for instance in Goal 2 of the Sustainable Development Goals (UN, 2015)), at the moment still nearly 1 billion people suffer from undernourishment (FAO, 2015a). Moreover, the production of food plays a role in several environmental problems. Agricultural production is one of the main causes of land degradation, freshwater scarcity, loss of biodiversity, the imbalance in the nitrogen and phosphorus cycles, and climate change (Millennium Ecosystem Assessment, 2005). At the same time, several forms of global environmental change also impact agricultural production, such as climate change, ozone pollution and water scarcity (Millennium Ecosystem Assessment, 2005). In understanding these relationships, it is important to note that agricultural systems do not only produce food crops for direct human consumption. In 2011, 50% of food crops (not including grass) were used as food, 29% for industrial uses (including biofuels), 13% as animal feed, 2% as seed, and 6% were wasted during storage and distribution (rounded percentages by tonne (fresh) (FAOSTAT, 2014)). The share of animal feed is much higher when grass is included, i.e. around 60% in dry matter tonnes (Stehfest et al., 2014). For studying the future role of the food system in the context of sustainable development, it is therefore important to account for complex interactions between development, dietary patterns, and the productive capacity of natural resources.

At the moment, several types of models look into future food demand, including economic Computable General Equilibrium (CGE) or Partial Equilibrium (PE) models. In these models, the future structure of an economy and the resulting demand for goods and services are estimated based on macro-economic data, income elasticities, own-price and cross-price elasticities, and substitution elasticities. The strong point of such macro-economic models is the consistent description of the agricultural sector, the connection between the supply and the demand side via price-mediated equilibriums, and the representation of food demand as part of the economy as a whole, allowing also to assess the propagation of indirect effects of future food demand across economic sectors. However, this approach also has limits, especially for

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long-term projections of food demand. First of all, the income, price and substitution elasticities used in these models are often hard to calibrate empirically: it is not clear that published elasticity estimates accurately reflect the behaviour of consumers and producers (Woltjer et al., 2011). Secondly, while the detailed structure of macro-economic models adds value if production and consumption patterns remain close to the range of historical behaviour, it becomes progressively less suitable for longer-term projections, also because it is difficult to incorporate physical constraints which lie outside the historical range. Finally, it is not easy to account for income inequality and other heterogeneities among the population within these aggregated CGE approaches, though some have included a representation of inequality recently.

Other approaches for determining future food demand have been developed that focus more on the food systems in terms of physical flows. Many of these take the concept of so-called Engel curves describing relationships between food expenditure and income, and apply this concept to physical food consumption. One advantage of this approach is the ability to model non-rational behavioural trends and cultural preferences. Existing physical flow models, however, also have important limitations. Many of them only cover a limited number of products and do not capture local heterogeneity (neither urban-rural nor income differences). One of the more advanced physical, Engel-curve based food-demand models is described by Tilman and Clark (2014). We take a similar approach, but we explicitly include local income inequality and use a much more fine-grained set of regions based on geographic, political and cultural similarity. This allows the development of scenarios that better take into account the heterogeneity across the world. Further, we include various types of animal feed and their efficiencies to calculate the actual production volumes; the purpose in Tilman and Clark (2014) was to provide a more rough set of indicators of greenhouse gas emissions and consumer health.

The main purpose of this research is therefore to develop a global food demand model which is aimed (1) at long-term developments, (2) is therefore physically based by simulating calories, proteins and grams of food consumed per person per day, (3) incorporates heterogeneities between regions and income inequality in urban and rural populations within regions, and (4) has sufficiently detailed food categories in order to run dietary change scenarios with Integrated Assessment Models (IAMs) that project land use and other environmental impacts. The model is used to investigate how physical food demand based on Engel curves may develop in the long-term future, and to evaluate options for making the food system more sustainable.

First we introduce the overall structure of the new food demand model (Section 2.1), followed by a more detailed description (Section 2.2) and the scenario definition (Section 2.3). In Section 3 we present the main results, including heterogeneity between and within regions (Section 3.1.2), the number of undernourished people (Section 3.1.3) and the impact of measures that could reduce demand growth relative to the baseline scenario (Section 3.2). In Section 4 we discuss advantages and limitations of the model, including a sensitivity analysis and comparisons with other projections and household survey micro-data. Section 5 concludes with the main findings.

2. Methods

2.1. General model description

The model presented in this paper focuses on future food consumption. Here, 'consumption' is defined as the total amount of food actually consumed by humans. The term 'food use' includes consumption and 'waste in households' (including restaurants etc.). The calculation of food use is driven by a set of key drivers, i.e. population and income. The model is based on Engel's law, which states that households with lower incomes generally spend a larger share of their income on food (Engel, 1857). In Engel's study and many subsequent empirical studies, it is also shown that the absolute expenditure on food increases with income (albeit less than proportionally). In general, the average expenditure per calorie also increases with income, since richer households buy more luxury items and spend more on 'value added' such as service in restaurants or premium brands in supermarkets. This means that food use in physical terms (calories, weight or volume) increases even less proportionally with income. The income elasticity of demand is the percentage that demand increases (or decreases) for each percentage point increase in income. In other words, it is the sensitivity of demand to income changes, and should therefore decrease for higher incomes, regardless of whether demand is defined in physical or monetary terms. Since real income can increase dramatically over long time periods, decreasing income elasticities are an essential part of our long-term food demand model (see Section 2.2). Modelled food consumption is modified for scenario assumptions and leads to animal production and feed demand. Animals can be fed with grass ('grass use') or with crops such as maize or soy, which is called 'feed use'. Subsequently, feed, food and industrial use of crops are summed to total crop use. Finally, 'waste in distribution' is calculated, which includes waste in storage, distribution and retail, but excludes losses on the field (e.g. due to weather or pests) since these are accounted for in agricultural production models. Throughout this paper, we use the term 'use' for actual use as revealed by historical data and 'demand' (potential use) for future projections. We cannot project actual use for the future without explicitly considering supply constraints, and therefore call it 'demand'. Fig. 1 shows a conceptual diagram of the model.

2.1.1. Food categories

In the model, we have defined six major and 46 minor food categories in such a way that they (1) relate to the functions of food for end-users (Table 1), (2) relate to crop characteristics used in food production models, (3) show similar behaviour within the 6 major categories, and (4) allow detailed behavioural scenarios such as the substitution of pulses and soy for cattle meat. See Supporting information for the mapping of minor to major categories.

The major category 'luxuries' is mainly composed of the calorie-heavy food type sugar, and will be only marginally influenced by tea, coffee and spices. We decided to cluster these food types together because they serve roughly the same purpose, and because demand for these food types would increase with income in roughly the same way.

2.2. Calibration and detailed model description

2.2.1. Demand for major food categories

The FAO provides data in very detailed food categories, allowing the model to be calibrated. Fig. 2 shows historical food use for each of the six major categories aggregated from the Food Balance Sheets (FAOSTAT, 2014), plotted against logarithmic average income per region for the SSP-2 scenario in IMAGE regions (Dellink et al., 2015; Stehfest et al., 2014). Although there is much variation between regions and variability for each region, some very broad patterns can be observed. Historical food use increases with income for most categories, slightly decreases for pulses and remains constant for staples.

We use a log-linear relation between food demand and income because (1) it roughly matches the data in Fig. 2 and (2) log-linear relations with income are widely used in food demand modelling for their Engel behaviour (Aitchison and Brown, 1954; Banks et al., 1997) and the resulting lower income elasticity for higher incomes (see Supporting information).

The relation between income and demand is calibrated separately for our six major food categories. First, for each major food category a global slope is calibrated using linear least squares on yearly regional data weighted by population size, as shown in Fig. 2. A dummy variable is used for each region. With this approach we are able to distinguish whether low-income regions seem to follow the behaviour of high-income regions (which is the case for animal products) or whether