Environment International 120 (2018) 93–103

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Review article

Forecasting future global food demand: A systematic review and meta-analysis of model complexity

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ARTICLE INFO

Handling Editor: Paul Whaley

Keywords:
Food demand
Prediction
Model complexity
Global
Aggregation
Gross domestic product (GDP)

ABSTRACT

Predicting future food demand is a critical step for formulating the agricultural, economic and conservation policies required to feed over 9 billion people by 2050 while doing minimal harm to the environment. However, published future food demand estimates range substantially, making it difficult to determine optimal policies. Here we present a systematic review of the food demand literature—including a meta-analysis of papers reporting average global food demand predictions—and test the effect of model complexity on predictions. We show that while estimates of future global kilocalorie demand have a broad range, they are not consistently dependent on model complexity or form. Indeed, time-series and simple income-based models often make similar predictions to integrated assessments (e.g., with expert opinions, future prices or climate influencing forecasts), despite having different underlying assumptions and mechanisms. However, reporting of model accuracy and uncertainty was uncommon, leading to difficulties in making evidence-based decisions about which forecasts to trust. We argue for improved model reporting and transparency to reduce this problem and improve the pace of development in this field.

1. Introduction

The ability to feed the world's growing population is reliant on the capacity of food supply to meet future food demand (Cirera and Masset, 2010). Current estimates show increasing demand per person, from an average of 2250 kilocalories (kcal) in the early 1960s, to ~2880 kcal in 2015 (Pardey et al., 2014). Coupled within these estimates are changes in the composition of diets, with a general shift away from traditional crops (e.g. tubers and pulses) towards more "luxurious" items like animal products, vegetable oils and stimulants (Kastner et al., 2012).

Food consumption patterns are having a tremendous impact on human and environmental health. Rising fat and calorie consumption worldwide, paired with decreasing activity levels of individual people, have contributed to problems of an increasing rate of obesity and non-communicable diseases (Popkin, 2004; Tilman and Clark, 2014). Further, agriculture is the largest contributor to tropical deforestation (Geist and Lambin, 2002) and is responsible for up to 35% of global greenhouse gas emissions (Foley et al., 2011). Intensive agriculture has been a major contributor to land-use change over the last century. With demonstrated negative impacts on air and water quality, biodiversity, carbon sequestration and infectious disease transmission (Foley et al., 2005).

Rising agricultural yields have, to date, kept pace with demand, but there is evidence that yields may be plateauing, especially in intensively cropped systems (Grassini et al., 2013). The steadily increasing per capita food demand, paired with a global population that is forecast to hit 9.8 billion by 2050 (United Nations, 2017), has led to concerns about how future global food demand will be met (Godfray et al., 2010) and what impact the effort to supply sufficient future food will have on the environment (Tilman et al., 2001).

Predictions about the amount and types of food consumed in the future can inform today's agricultural policies, but current predictions vary widely. For example, while some estimates for per capita kilocalorie demand in 2050 indicate averages around 3900 (Valin et al., 2014), other estimates are as low as 3070 (Alexandratos and Bruinsma, 2012). Furthermore, a small number of predictions are disproportionally cited in the literature. The decadal reports by the FAO (Alexandratos, 1995; Alexandratos and Bruinsma, 2012; Bruinsma, 2003) have been cited over 1000 times each, David Tilman's food demand predictions from 2011 and 2014 have already been cited over 2000 times combined, and the IFPRI studies have been cited hundreds of times each (Rosegrant et al., 1995, 1999). These three sources

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https://doi.org/10.1016/j.envint.2018.07.019
Received 2 March 2018; Received in revised form 9 July 2018; Accepted 11 July 2018

constitute the majority of our understanding of the future of global food demand but take very different modelling approaches.

At an individual level, food consumption is a consequence of many interacting factors, with behavioural, cultural, environmental and economic aspects (Alexandratos, 1995; Kearney, 2010; Rosegrant et al., 2002; UN Millennium Project, 2005). The aggregate consumption behaviour of populations is less variable than an individual's consumption decisions but is nonetheless influenced by a variety of components. Some models incorporate multiple variables to represent the mechanisms driving consumption choices (e.g. prices, crop yields, climate effects, and changing diets). These “complex mechanistic” models are often built on interacting economic, ecologic, demographic and/or climate sub-models (Alexandratos, 1995; Alexandratos and Bruinsma, 2012; Bijl et al., 2017; Schneider et al., 2011).

Alternatively, a simple mechanistic approach predicts demand based on the coarse (Engel's Law) relationship between income and kilocalorie consumption (Bodirsky et al., 2015; Tilman et al., 2011; Tilman and Clark, 2014). Finally, phenomenological models assume current trends of increasing kilocalorie consumption will continue (Leach, 1995). Here, we compare predictions from two mechanistic (complex and simple) and one phenomenological (time series) model types to determine how these model choices impact predictions.

There is also debate over what scale of spatial and calorie disaggregation is best for modelling purposes. Some researchers argue that complex, disaggregated models better represent reality (Alexandratos, 1995; Alexandratos and Bruinsma, 2012; Schneider et al., 2011) while others claim that coarser, simpler analyses can avoid some of the idiosyncrasies and possibly arbitrary assumptions in fine-scale or complex models (Doos and Shaw, 1999; Tilman et al., 2011).

To improve our understanding of what shapes current perceptions of future food demand, we asked four empirical questions: 1) at what spatial scale are current food demand predictions being made, 2) what is the geographic distribution of food demand predictions, and with a meta-analysis: 3) what impact does model complexity (i.e. number of covariates and disaggregation of data) have on global food demand predictions and 4) how valid are those predictions? To answer questions 1 and 2, we examine the spatial scale and scope of published studies. For question 3, our meta-analysis compares the predictions of complex, integrated mechanistic models with simple correlative-based models (which predict food demand using GDP) and purely phenomenological models (which assume current demand trends will continue), to determine the effect of these additional data on predictions. Finally for question 4, we investigate the degree to which the various models follow current best practice in statistical analysis including model averaging (incorporating information from multiple models; Burnham, 2015; Burnham et al., 2004), model validation (reporting how well the model fits or predicts the data) and reporting of model uncertainty (using confidence intervals or standard errors). The outcome of our analyses can help inform efforts to predict future food demand patterns.

2. Materials and method

2.1. Identifying, screening & classifying papers

We frame our review questions, search strategy and inclusion/exclusion criteria using the PICOTS system (Box 1). To identify relevant papers, we used a combination of search engines that would identify both peer-reviewed and grey literature: Web of Science, Scopus and Google Scholar. A systematic search strategy was developed that would identify all relevant papers. After an iterative keyword screening process, the following keyword(s) were selected as optimal and were used for this analysis: ([“Food demand” OR “crop demand” OR “human food consumption” OR “human crop consumption”] AND [trend OR historic OR predict* OR projected OR projections OR future OR model]). No time period was set for this search so all relevant papers through to June 20, 2017 were returned. This process yielded 670 papers from Web of Science, 998 papers from Scopus and 17,600 results from Google Scholar. We extracted the top 100 relevant results from Google Scholar for screening. We then supplemented the search with potentially relevant papers suggested by content experts (n = 11). After duplicates were removed, this search yielded 1190 novel references (Appendix A, Fig. 1). All references were screened by one researcher (EJF) for relevance according to the following question: “Is a major focus of this paper understanding patterns of human food consumption/demand?” All papers that were classified as “y” according to the screening question were categorized according to the spatial scale of the analysis (Table 1, Fig. 2), whether they predicted future food demand, and the level of calorie disaggregation (Fig. 1). In this process, papers were excluded when predictions were not made or reported (i.e., addressed historic patterns or used others' predictions), or when predictions were made for a subset of food types or countries. If any of the selected papers referenced the food demand predictions of another study, the referenced paper was added to the meta-analysis (n = 11). This step ensured that the literature; a) included data and forecasts from primary sources and b) included ‘grey’ literature sources, including reports prepared for the United Nations Food and Agriculture Organization (FAO) and the International Food Policy Research Institute (IFPRI), which are not present in Web of Science. No language was set in the search terms but only papers that were published in English were progressed beyond the initial screening stage.

2.2. Critical appraisal

Currently, no critical appraisal tool exists to guide data extraction and assess the risk of bias for non-medical predictive models, as is the focus of this review (Box 1). Therefore, a new tool was developed, modelled after the CHARMS (Debray et al., 2017; Moons et al., 2014), TRIPOD (Collins et al., 2015), REMARK (Mcshane et al., 2005) and the Cochrane (Higgins et al., 2011) internal validity tools. Our critical appraisal system has two main domains (model data, and methodology) with seven signaling questions (Table 2) to identify possible sources of error or bias in the development and reporting of future food demand. All included papers were critically appraised (and had data extracted) by two reviewers (EJF and either LB or JB).

We do not conclude this appraisal with a “bias rating” for each paper because the type of bias inherent in each data source and model method is different. Consequently, a subjective “high or low” rating of bias would not be informative nor would it enhance the meta-analysis. Therefore, the results of our critical appraisal (Table 2) did not quantitatively impact the meta-analysis but rather were used to guide the narrative comparison of the included papers.

2.3. Synthesis and meta-analysis

The purpose of the meta-analysis was to understand how model complexity influences average global food demand predictions. We only included studies that estimated future demand using definitions similar to the FAO's food balance sheets/supply utilization accounts (FAO, 2016). These predictions include all food available for human consumption (i.e. production + imports − exports ± stock variations) which excludes food used for non-human consumption (e.g., animal feed, seeds) or industry losses and wastage in the production system, but includes household-level waste. A small number of authors considered the values provided by their papers to be scenario values, not “projected” values (e.g., von Lampe et al., 2014). In these cases the authors' aim was not to forecast future demand, but rather provide a ‘what if’ scenario. However, these “what if” scenarios are possible futures and as such, were included in our meta-analysis.

There was only one study that reported predictions based on time trends alone. To increase the sample size for this category, we supplemented this family of predictions with our own time-trend models,