Systematic review of global food security scenarios and projections to 2050

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Abstract

Abstract: Ending hunger and achieving food security - one of the UN sustainable development goals - is a major global challenge. To inform the policy debate, quantified global scenarios and projections are used to assess long-term future global food security under a range of socio-economic and climate change scenarios. However, due to differences in model design and scenario assumptions, there is uncertainty about the range of food security projections and outcomes. We reviewed 58 global food security modelling and projection studies that have been published over the last two decades and discussed the methodology and underlying drivers, and compared future trends in two key food security indicators. We found that across five representative scenarios that span divergent but plausible socio-economic futures global food demand is expected to increase by +34% to +53% between 2010 and 2050, which is a substantialy lower range than the often cited +60% to +110%. The latter range is based on earlier reference years and methodologies that are difficult to compare. We also found that population at risk of hunger is projected to decrease by -89% to -12%. For a subset of scenarios, food security outcomes worsen under climate change but comparison is difficult because of the small number of comparable projections. Finally, our review suggests that current modelling approaches can be improved by better incorporating several options that have been proposed to tackle global food security, in particular aquaculture and 'future foods', and expand the number of indicators to better cover the multiple dimensions of food security. The results of our systematic review can be used to benchmark new global food security projections and quantitative scenario studies and inform policy analysis and the public debate on the future of food.

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Main

The question on how to eradicate global hunger - one of the Sustainable Development Goals - and feed the future world population is a major global societal challenge. Since 1960 food supply has increased dramatically, resulting in the long-term decline in global undernourishment despite a doubling of total global population (Godfray et al. 2010; Roser and Ritchie 2020). Nonetheless more than 820 million people in the world are still hungry today (FAO et al. 2019). Climate change and increasing competition for land and water raise concerns about the future balance between food demand and supply and its impact on global hunger. To support the formulation of effective policies to ensure global food security a better understanding of the range in future outcomes and main driving forces is needed.

Global assessments have mainly used four broad indicators to measure the various dimensions of food (in)security: food demand (Tilman et al. 2011; Alexandratos and Bruinsma 2012), population at risk of hunger (Parry et al. 2004; Hasegawa et al. 2015), food prices (Baldos and Hertel 2016) and childhood undernutrition (Ishida et al. 2014). Often the results of these studies vary widely and are difficult to compare because of differences in methodology (Godfray and Robinson 2015), assumptions on driving forces (Reilly and Willenbockel 2010) and definitions of output indicators (Van Dijk and Meijerink 2014). To date, no comprehensive analysis of global food security projections has been presented.

The aim of this paper is to provide a systematic review of recent global food security projection and quantitative scenario studies that provide trends to 2050. With food security, we mean that "all people at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO 1996). Systematically collecting and comparing quantitative scenario results to assess model uncertainty has been common practice in the climate change literature (Huppmann et al. 2018) but has not been done for global food security assessments. The key questions addressed in this review are: Which methods have been used in the modeling studies? Which drivers are mainly considered when projecting global food security? And what is the 'bandwidth' of future global food security projections?

To answer these questions, we conducted a systematic literature review to identify, collect and analyze relevant studies that were published between 2000 and 2018 (see Methods and Supplementary Information for details about the methodology and overview of selected studies). In comparison to standard literature reviews, systematic review approaches have the advantage that they are guided by a well-defined methodology, which reduces bias and makes it possible to draw more general conclusions (Gough, Oliver, and Thomas 2012). we identified and analyzed 58 relevant studies and constructed a database with harmonized projections for two out of the four global food security indicators used in the literature: global food demand (320 projections) and global population at risk of hunger (182 projections), representing a wide range of plausible socio-economic and climate change futures. The Global Food Security Projections Database (Van Dijk et al. 2020) is publicly available and can be used by the research community to benchmark the results of new global food security projections and quantitative scenario studies.

We define projections as alternative quantitative results of running a statistical or simulation model based on different assumptions or inputs. In many global food security assessments the term “scenario” is used to refer to a plausible, comprehensive and consistent description of how the future might unfold (Nakicenovic et al. 2000). Scenario exercises often combine a narrative storyline that links important statements about the future with a model component, which provide a quantification (including projections) of the storyline. This review focuses on projections and quantified scenarios, rather than storylines.

Overview of studies

The number of global food security projection studies and related projections has substantially increased over the last two decades from 1 in 2004 to 58 in 2018 (Figure 1). Between 2004, the year the first study in our database was published (Parry et al. 2004) and 2009, only a handful of studies were released. The increase in publications after 2009, can almost certainly be attributed to the renewed interest in global food and nutrition research that was triggered by the 2007/2008 global food price crisis (Headey and Fan 2008). Most of the studies that were published in the 3-5 years after the food crisis were policy reports prepared by international institutions (e.g. Msangi and Rosegrant 2009; Nelson et al. 2010) which present an immediate response to ongoing discussions on the increase in food prices and implications for long-run global food security. Subsequent to that reaction, and up to the current period, a mixture of journal articles, book chapters and reports have been published, which often provided a more scientific analysis of future food security, including more discussion on methodologies, data and model design. There has been also a transition from studies that present the results of single-model to multi-model comparisons that present and discuss the results of an ensemble of models. Many of these studies are produced as part of the Agricultural Model Intercomparison and Improvement Project (AgMIP) that was initiated in 2010 and represent “a major international effort linking the climate, crop, and economic modeling communities with cutting-edge information technology to produce improved crop and economic models and the next generation of climate impact projections for the agricultural sector” (Rosenzweig et al. 2013, p 166).

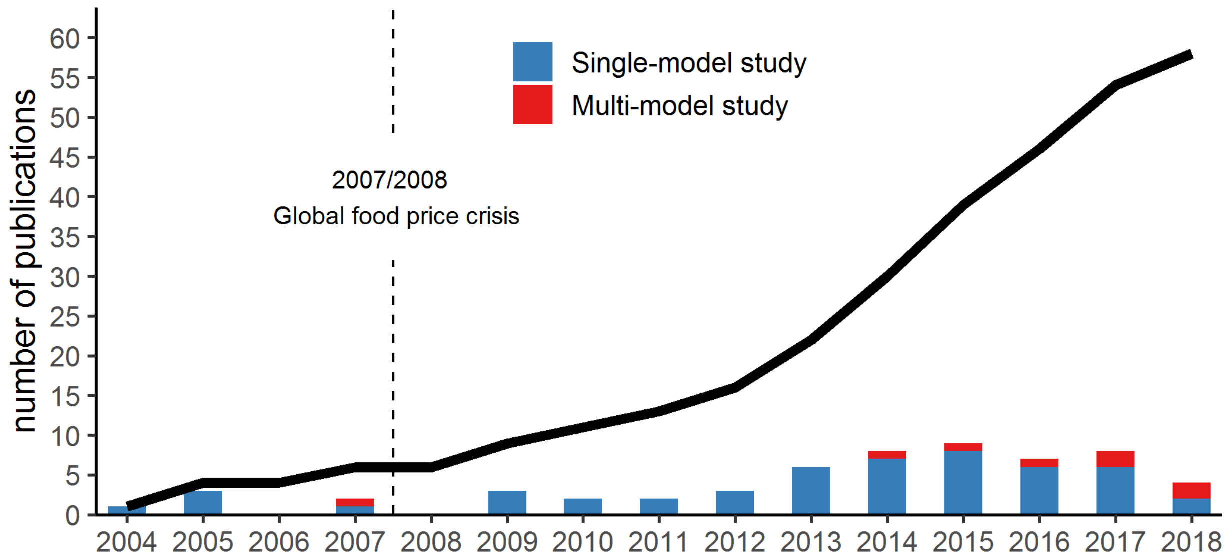

Figure 1: Total (cumulative) number and type of global food security studies per year. Bars show publication of new studies per year and type. Data for 2018 is incomplete as it only includes studies that were released in the first half of the year.

Methodologies

Three different methodologies have been used to assess future global food security (Figure 2). The majority of studies (48) employ simulation models, followed by statistical extrapolation approaches (9) that use regression techniques to estimate future food security (e.g. Tilman et al. 2011; Bodirsky et al. 2015). Only one study (Alexandratos and Bruinsma 2012) mainly used expert input to prepare the projections. The IMPACT model (Robinson et al. 2015) is the most frequently used simulation model. This is not surprising as it was already developed in the early 1990s by the International Institute of Food Policy Research (IFPRI) to analyze long-term hunger and poverty challenges. The model therefore frequently features in global food and hunger assessments that are commissioned by international organizations such as the Millennium Ecosystem Assessment (2005) and IAASTD (2009). The set of models that form the core of the global assessment component of AgMIP are also often applied in global food security assessments. Apart from the IMPACT model, these include GLOBIOM (Havlik et al. 2014), MAGNET (Woltjer et al. 2014), AIM (Fujimori, Hasegawa, and Masui 2017), IMAGE (Stehfest et al. 2014) and MagPIE (Lotze-Campen et al. 2008). Other often applied models are SIMPLE (Baldos and Hertel 2013), BLS (Parry et al. 2004) and ENVISAGE (Mensbrugghe 2008).

The most frequently used type of models is partial equilibrium (PE) models, followed by computable general equilibrium (CGE) market simulation models. An advantage of PE models, such as IMPACT and GLOBIOM, is that they provide a detailed representation in the agri-food sector, which makes them particularly suitable for food security assessments. This might explain why they are slightly more popular than CGE models, like MAGNET and AIM, which simulate the total economy and therefore account for interactions between the agricultural sector and the rest of the economy, albeit with limited detail. Across and within PE and CGE models, various approaches are used to specify and parameterize food supply and demand (Valin et al. 2014; Robinson et al. 2014). Other types of models that have been less often used to project global food security include biophysical accounting (Agribiom, FSM,and GRAFS), econometric (FEEDME and iAP) and integrated assessment (IMAGE and T21) models.

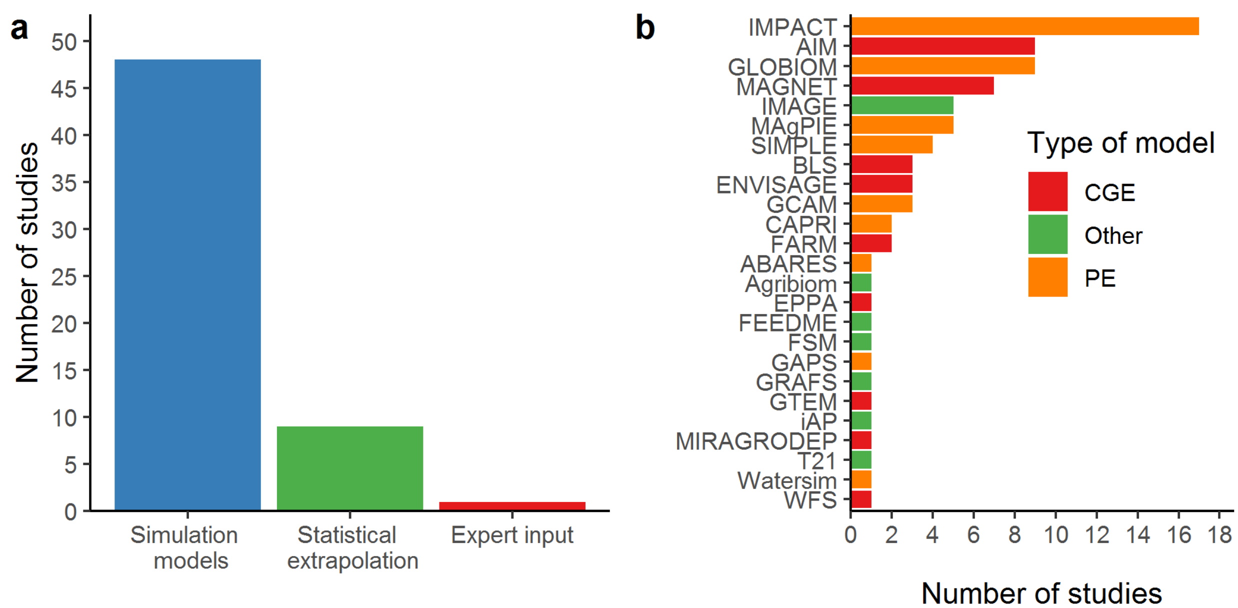

Figure 2: (a) Main methodology used per study and (b) list of simulation models used in the studies. The Other model type category include various types of models, such as biophysical, econometric and integrated assessment models.

Drivers

Global food security is a complex issue that is determined by the interaction of a multitude of driving forces that operate both on the demand and supply side. Nearly all studies include assumptions on future population and income growth, which are key drivers of food demand, and technical change (including total factory productivity growth, crop yield increase and adoption of advanced inputs), which is the main driver of food supply (3). Other drivers that are covered by more than half of the studies include land availability (e.g. protected areas and land degradation), diet change, trade and climate change. Only a very small number of studies indicate they explicitly address the impact of aquaculture (Linehan et al. 2013; FAO 2018) and urbanization (FAO 2018) on global food supply and demand projections. The design and sophistication of the models has clearly advanced over time. Early studies, such as Parry et al. (2004), Fischer et al. (2005) and Parry et al. (2005) were already quite sophisticated (i.e. simulating socio-economic and climate change scenarios including trade effects) but did not feature the impact of biofuels, diet change, poverty and inequality, and food waste and loss, which were introduced from around 2010 onward (Figure S2).

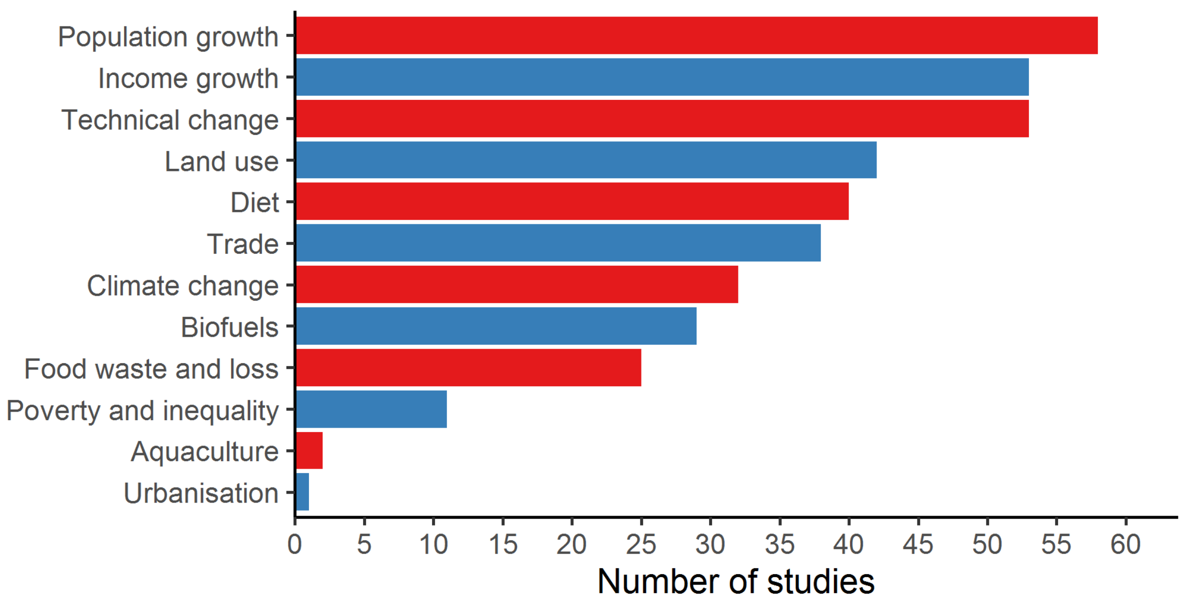

Figure 3: Global food security drivers captured by the selected studies. All studies include more than one driver.

Global food demand and population at risk of hunger projections

A large number of the selected studies present future trends on two indicators (See Figure S3). The first one is future food demand, in most cases measured as the average diet per person (sum of crops, dairy, fish and meat in kcal/cap/day) or as total population food demand (in calories). A few studies present alternative indicators. For example, Msangi and Batka (2015) present projections for the recommended daily intake of macronutrients to model how closely regions match healthy diet guidelines. Shutes et al. (2017) build on a set of historical food security indicators prepared by the FAO (e.g. share of calories from cereals and fruit and vegetables) to assess future global food security. Several studies present projections for protein consumption (Billen, Lassaletta, and Garnier 2015; Msangi and Batka 2015) and people at risk of protein deficiency (Medek, Schwartz, and Myers 2017). The second indicator is future trends in the global population at risk of hunger, which implements prevalence of undernourishment - FAO's key statistic to measure the number of hungry people - in a forward looking framework. Prevalence of undernourishment is defined as the probability that the calorie intake of an individual is lower than the energy needed to cover his or her requirement for an active and healthy life, the so-called minimum dietary energy requirement (FAO, IFAD, and WFP 2013; Cafeiro 2014).

The distribution of food security outcomes within and between studies is determined by the combination of (a) varying assumptions on key drivers, often related to a scenario storyline on how the future might unfold and (b) differences in methodology (e.g. type and parameterization of the model and how results are reported). To unravel these two factors, we mapped all projections to the Shared Socio-economic Pathways (SSPs), a set of five scenario storylines and related quantification of main drivers that describe a range of potential and plausible global futures (Vuuren et al. 2017; O'Neill et al. 2017). The five scenarios include: Sustainability (SSP1), Middle of the Road (SSP2, which is often considered as a business-as-usual scenario), Regional Rivalry (SSP3), Inequality (SSP4) and Fossil-fueled Development (SSP5) - see Table 1 for a summary of the storylines. The SSPs were originally designed as a framework for the recent climate change assessments but they have been increasingly used for the evaluation of other global challenges, including food security. Similar to the SSPs, we harmonized the various climate change assumptions in the projections by mapping them to the Representative Concentration Pathways (RCPs). The RCPs are a set of scenarios to reflect different potential climate outcomes (Vuuren et al. 2011) and were designed to be combined with the SSPs (D. P. van Vuuren et al. 2014). We were able to the extract information for 320 projections from 19 studies for food consumption and 182 projections from 12 studies for population at risk of hunger.

Figure 4 presents two indicators for the future trends in food demand: change in per capita consumption (kcal/cap/day) and change in total food consumption (in 1e15 kcal). The latter captures the combined impact of changes in the diet and growth in population (see Figure S6). Nearly all SSP scenarios project an increase in per capita and global food consumption in comparison to the 2010 levels but their relative size differs. We start by discussing the no climate change (NOCC) scenarios. In future worlds that are characterized by fragmentation (SSP3) and inequality (SSP4), per capita consumption will increase between +5% to +7% on average, while in scenarios that assume sustainability (SSP1), business-as-usual development (SSP2) and rapid growth (SSP5), the increase is +12% to +15% on average. Taking into account population growth, global food consumption increase is the lowest in SSP1 (+38%) and the highest in SSP2 and SSP3 (+50%).

The distribution of projections within each SSP illustrates the uncertainty caused by methodological differences between studies. The Figure clearly shows that the results of several studies can be considered less plausible because they are located outside the interquartile range. If this measure is taken into account, the bandwidth

Table 1: Shared Socio-economic Pathways scenario storylines taken from Table 2 in Riahi et al. (2017).

SSP	Scenario name and storyline
SSP1	Sustainability The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.
SSP2	Middle of the Road The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain
SSP3	Regional Rivalry A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions
SSP4	Inequality Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas
SSP5	Fossil-fueled Development This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

of per capita food consumption slightly increases to +3% to +15% and for total food consumption to +34% to +53%. Figure 4 also compares the results between no climate change (NOCC) and extreme climate change (RCP8.5) scenarios. A simple statistical comparison of the mean indicates that climate change does not result in significantly different patterns of food consumption.

Figure 5 depicts the projections for population at risk of hunger. All projections point at a decrease in undernourishment in comparison to the base year. With -85% to -77% on average the change is highest in SSP1 and SSP5, while it is smallest in SSP2 and SSP3 (-28% to -19%) and SSP 4 is located in the middle (-49%). The spread in projections is relatively large for SSP2 in comparison to the other SSPs. The SSP2 results from Dawson, Perryman, and Osborne (2016) are a clear outlier. This is mainly caused by the type of model that is used, which is not able to incorporate the impact of technological change and trade, two important drivers that are captured by most other model simulations. If the interquartile range is considered, the projected change in population at risk of hunger lies between -89% and -12% for the period 2010-2050. In two out of the three SSPs for which there is data (SSP1 and SSP3), climate change results in substantially higher levels of population at risk of hunger.

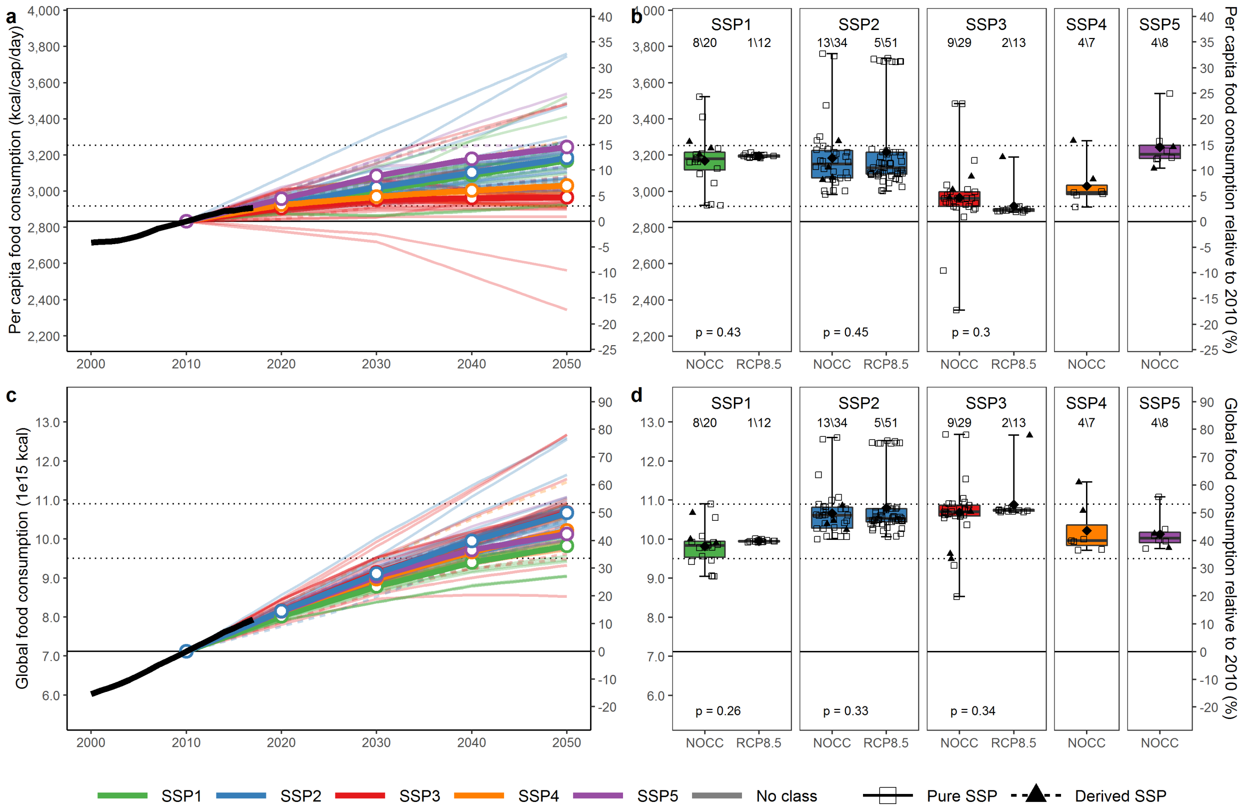

Figure 4: Per capita (a,b) and global (c,d) food consumption projections for 2010-2050. (a,c) show individual model projections for the SSPs under no climate change (thin colored lines), the average for each SSP (the bold colored lines with circles) and the 3-year average historical trend (bold black line). (b,d) present boxplots comparing no climate change (NOCC) and the most extreme climate scenario (RCP8.5) per SSP. The diamond in the boxplot indicates the mean value and the whiskers indicate the maximum and minimum range of observations. The numbers on top refer to the number of studies/number of projections depicted. p-values are reported for Welch's t-tests to compare the difference of the mean between the NOCC and RCP8.5 scenarios. SSP4 and SSP5 results for RCP8.5 are not reported because of the limited number of observations (see Figure S4 for a comparison with a wider range of RCPs). The NOCC boxplots in (b,d) depict the same information as the values for 2050 in (a,b).Both figures are aligned horizontally and show the level of the selected food security indicator (left axis) as well as the percentage increase for the period 2010-2050 (right axis). The dotted horizontal lines demarcate the plausible bandwidth of projections using the interquartile range across SSPs as criterion. 'Pure' SSP are projections that take their assumptions from the SSPs, where relevant combined with RCP-based climate impact scenarios. 'Derived' SSPs are projections that belong to the same SSP and RCP scenario families but use somewhat different assumptions. Projections that could not be mapped to one of the SSP scenario families are labelled 'No class'. Historical data from FAO (2020). Projections from the Global Food Security Projections Database (Van Dijk et al. 2020).

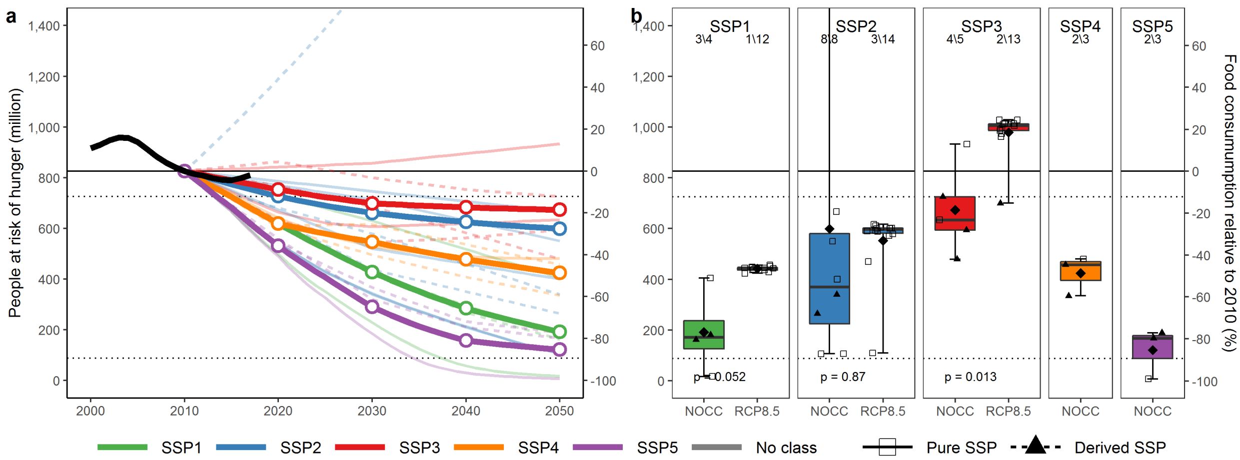

Figure 5: population at risk of hunger projections for 2010-2050. See Figure 5 for a detailed explanation of the figure elements. SSP4 and SSP5 results for RCP8.5 are not reported because of the limited number of observations (see Figure S5 for a comparison with a wider range of RCPs). One extreme value for SSP2 is not depicted. Historical data from FAO (2020). Projections from the Global Food Security Projections Database (Van Dijk et al. 2020).

Comparison with the prevailing discourse on future global food demand

Projections on global food demand and consumption provide information on the expected increase in food production and associated impacts on land use change, biodiversity and climate change. For this reason, these figures are frequently cited by popular media, scientists, policy makers and business. The most cited number, originating from a FAO briefing paper (FAO 2009), is that world food production needs to increase by 70% to feed the world population in 2050. Although this number was reduced to 60% in a revision of the original study (Alexandratos and Bruinsma 2012), it remains to be used as the main reference point by some several companies (e.g. The John Deere Journal 2015) and scientific papers (e.g. Carvajal-Yepes et al. 2019). Another widely cited paper is Tilman et al. (2011), who present a much higher increase in global food demand of 100-110% between 2005 and 2050. Opponents of mainstream agriculture often dismiss global food futures projections and scenarios because they believe that the cited 60%-110% increase in food demand, which is often translated as the need to double food production by 2050, erroneously frames global food security as a problem of supply, closing off discussions on solutions that do not principally rely on increasing food production through technological innovation (e.g. Tomlinson 2013). How does the 60-110% figure compare to our findings?

We find that for SSP2, which, like the FAO projections, is regarded as a business-as-usual scenario, food consumption will increase by 50% on average, with an interquartile range of 44-52%. This is substantially lower than the FAO and Tilman et al. (2011) projections of 60%-110%. There are at least two reasons for the difference (Grethe, Dembele, and Duman 2011; Hunter et al. 2017). The main reason is that the FAO trend is estimated using the earlier base year 2005/2007 and therefore overestimates the expected increase in food consumption in comparison to the 2010 base year that is used in our review. A second reason is that it measures food consumption in value terms using food prices as weights instead of the preferred calorie-based measure (Kearney 2010). The value-term measure tends to overestimate food consumption in case of a diet shift from low-prices staples towards to higher value products that might have occurred since 2005/2007.

Interestingly, the latest update of the FAO study (Alexandratos and Bruinsma 2012) also presents a projection of 54% for the global change in calories, which we added to the Global Food Security Database. Using a base year of 2010, this translates to an increase in consumption of 44%, which is within the interquartile range for SSP2. This shows that the FAO projections are comparable to other studies but results are highly sensitive to the selection of the base year. Without adding the reference period, statements about future increases in food demand and production can be severely misleading.

The projections in Tilman et al. (2011) cannot easily be compared with most of the studies in our review because of differences in approach. In contrast to most other studies, which use diet projections, food consumption is approximated by total crop calories. This includes the crops that are used for direct human consumption as well as the feed that is required to produce dairy, fish and meat products, resulting in much higher kcal/cap/day per capita projections. The study implicitly assumes that food and feed have the same relationship with income per capita. This deviates from most model studies, which assume an increase in feed-to-food efficiency rates (Wirsenius, Azar, and Berndes 2010) and, hence, a lower relative future demand for feed. Not accounting for potential efficiency improvements in the livestock sector might explain why the food consumption projections in Tilman et al. (2011) are nearly twice as large in comparison to most other studies.

Discussion

Missing drivers of global food security

A number of strategies and options have been proposed to feed the 9-10 billion people by 2050, in particular promoting sustainable intensification, often combined with agroecology, reducing food loss and waste, shifting towards low-meat diets and expanding aquaculture (Godfray et al. 2010; Smith 2013; Keating et al. 2014;

World Resources Institute 2013). A number of studies have made efforts to simulate the impact of the first three solutions as they are an integral part of SSP1 (the sustainability scenario). However, the fourth option - aquaculture - is largely neglected by most modeling studies. In addition, none of the selected studies tries to model the impact of “future foods” (Parodi et al. 2018). These are alternative food sources, such as insects, cultured meat, innovative plant-based meat substitutes or seaweed that are increasingly regarded as healthy and sustainable alternatives to mainstream food products. In order to adequately project global food security and assess solutions to feed the world in 2050, models need to be able to capture the major driving forces of food demand and supply, including aquaculture and future foods.

Measurement of global food security

The FAO has prepared a comprehensive list of around 25 national-level indicators that aim to capture the four dimensions of food (in)security: availability, access, stability and utilization (FAO 2020). Comparing this list with the indicators published in the selected studies suggests a very narrow view on food security. None of the studies presents and indicator on stability and only a few studies address the utilization dimension (i.e. Lloyd et al. (2011) and Ishida et al. (2014), who include a stunting indicator). Some of indicators proposed by FAO (2020) are probably difficult to model due to lack of global data (e.g. household level indicators). Others, however, can be added as illustrated by Shutes et al. (2017), who present projections for share of dietary energy supply derived from cereals, share of calories from fruits and vegetables and supply of protein of animal origin. Similarly, recent studies, such as Springmann et al. (2018) and Willett et al. (2019), have started to analyze the impact of a global change in diets on nutrition and health outcomes, widening the analysis to include both food and nutrition security.

All model studies take a strong macro-approach and therefore only present food security results at the national or regional level. They are therefore unable to take into account differences in wealth, assets and behavior of households, which are among the main determinants of the access component of food security. Only recently model simulation studies have started to explicitly incorporate household-level food security in their analysis. Breisinger and Ecker (2014) propose a macro-micro approach in which a dynamic computable general equilibrium model is combined with household- and individual-level regression models to assess food security for the period 2012-2020 in Yemen. Another example is Laborde Debucquet et al. (2016), who combine a global CGE model with household survey data to assess the costs of ending hunger in seven African countries. It would be interesting to apply this type of approaches at global level in future food security assessments.

Uncertainty and consistency in global food security projections

The distribution of projections is wide for most global food security indicators, pointing to a high degree of uncertainty. Three factors may explain the high variety in observed food security outcomes (Van Dijk and Meijerink 2014). First, in contrast to model comparison exercises (e.g. Lampe et al. 2014), where all models use harmonized assumptions on drivers and attempt to align the implementation of qualitative scenario assumptions, the input data of the studies in our review are not fully aligned despite our effort to map all projections to the SSP scenario framework. It appears that even 'pure' SSP studies use slightly different projections for core SSP building blocks, such as population growth, resulting in a variation of outcomes (Figure S6).

Second, differences in methodologies to model long-run global food security can strongly influence the results. Systematic model comparisons showed that structural differences between the type of model (Lampe et al. 2014), assumptions on technological change (Robinson et al. 2014) and the way food demand is modeled (Valin et al. 2014) are important factors which explain differences in projections. Hertel and Baldos (2016) found that apart from technological change, assumptions for income, capital, labor and land elasticities are critical determining factors of model output although they only have received very limited attention in the literature. Godfray and Robinson (2015) discuss the strengths and weaknesses of simulation models and statistical extrapolation and how they contribute to disparity in outcomes.

Finally, differences in the way results are reported, such as differences in base year or definition of indicators, potentially explains the wide range of outcomes. As one of the main aims of this study was to harmonize the food security projections to make them comparable, we do not expect this factor to be of major influence.

After harmonizing all projections and discarding observations outside the interquartile range which can be considered as less plausible, projections are largely consistent. SSP1 and SSP5 represent futures in which global food security will improve, reflected by a sharp decrease in population at risk of hunger, high food consumption per capita levels and low global food consumption. SSP3 represents an opposite world, characterized by the highest population at risk of hunger, the lowest per capita consumption and the highest global food consumption. In most cases the results for SSP2 and SSP4 are located in the middle of these extreme scenarios.

A comparison between no climate change and RCP8.5 results showed that socio-economic drivers (as defined by the SSPs) have a much larger influence on food security outcomes than climate change scenarios (as defined by the RCPs). Only for population at risk of hunger the mean between scenarios with and without climate change was significantly different. This finding, however, has to be interpreted with care as we used basic statistics to compare the difference in means. Our approach does not account for differences in sample size, nor does it control for within group effects (e.g correlation in results between projections produced by the same authors, model or study). More advanced meta-analysis approaches such as random effect models (Borenstein et al. 2009) are needed to tackle these issues and provide more in-depth analysis

Our findings indicate that global food demand is expected to increase by +34% to +53% between 2010 and 2050, while the population at risk of hunger is projected to decrease by -89% to -12%. These figures reflect global food security outcomes in five vastly different but plausible future worlds with respect to sustainability, equality, and technological development. We believe that these findings are more reflective of the current state of the literature than the often cited range of +60% to 110% range for food demand, which represents only business-as-usual scenarios.

Moreover, in the light of the current Coronavirus pandemic, which undoubtedly will have a lasting impact on all aspects of future global development (including food supply and demand), business-as-usual scenarios can no longer be considered plausible, nor realistic. According to the World Food Programme, trade barriers put up by some countries to safeguard national food security in combination with an economic slowdown are expected to double acute hunger by the end of 2020 (World Food Programme 2020). Although, it is too early to oversee and understand the full impact and consequences of the Coronavirus pandemic, current developments show some resemblance with the SSP3 Regional Rivalry scenario, which is characterized by slow economic development, focus on domestic security and sovereignty, and increasing inequality within and between nations. The recent developments, underscore the need for (quantitative) scenario analysis and comparison as a tool to inform policy analysis, coordination and planning for the future of food and wider societal issues.

Methods

To select relevant studies on global food security projections, we followed the guidelines for the qualified application of systematic review by the Evidence for Policy and Practice Information and Co-ordinating Centre (EPPI centre, University of London, https://eppi.ioe.ac.uk) and the Cochrane Handbook for Systematic Reviews of Interventions (http://training.cochrane.org/handbook). The core of the review was conducted between September 2017 and December 2017. However, following expert input, we included several studies that were published during the first half of 2018. The main steps to collect, screen and process the studies are described below. Additional details are presented in the Supplementary Information.

We combined a number of search strategies to identify relevant studies: (1) we searched five electronic search engines of bibliographic databases (Scopus, Econlit, CAB abstracts, Agricola and Agris) using a combination of search terms (See Supplementary Information); (2) We used Google scholar but only including the first two pages with references; (3) We consulted websites of organisations and institutions (e.g. FAO, OECD, World Bank and IFPRI) that have published this type of research; (4) We consulted experts working on the topic to inquire about relevant studies; and (5) We conducted a 'snowballing' exercise on all references from several global food security review studies as they are assumed to bring together important literature (See Supplementary Information for list of review studies).

The literature search generated a list of potentially relevant studies that were subsequently transferred to the EPPI tool, a specialized piece of software to support systematic literature reviews, to assess their relevance by applying a set of exclusion/inclusion criteria. The screening was done in two phases. A first selection was made by screening the title and abstract. This was followed by a full text screening for studies that were identified as being relevant. In case of doubt, the study was evaluated by a second reviewer and, if needed, further discussed by the research team.

The query of the scientific literature repositories resulted in 3647 studies. In addition, 20 studies were identified by means of snowballing, expert consultation and literature search. After abstract and full text screening, a total of 58 studies were selected to be included in the systematic literature review. We used a questionnaire to systematically analyse, extract and code key relevant information, including meta-data, methodologies used, scenario information, food security indicators and main drivers.

For 24 out of the 58 studies that resulted from the systematic literature review of global food security projection studies, we were able to extract quantitative and comparable information on food security projections. In order to make the data comparable across studies and over time we mapped the scenarios that were used to create the projections to the Shared Socio-economic Pathways (SSPs). We built upon Vuuren et al. (2012) and D. P. van Vuuren and Carter (2014), who demonstrated that assumptions of many global socio-economic scenarios (including the SSPs) are similar and can be classified into five archetypal scenario 'families'. Similarly, drawing upon D. P. van Vuuren and Carter (2014), we mapped climate change projections to the Representative Concentration Pathways (RCPs). The RCPs are a set of scenarios to reflect different potential climate outcomes used in recent IPCC climate assessment reports (Vuuren et al. 2011). They were designed to be combined with the SSPs as part of a scenario 'matrix' that encompasses the full spectrum of future socio-economic and climate change pathways (D. P. van Vuuren et al. 2014).

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