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Systematic Review

Keywords: food security, systematic literature review, meta-analysis, projections

Posted Date: May 19th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-530565/v1>

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Version of Record: A version of this preprint was published at Nature Food on July 21st, 2021. See the published version at <https://doi.org/10.1038/s43016-021-00322-9>.

Systematic review and meta-analysis of global food security projections to 2050

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May 18, 2021

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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 conducted a systematic literature review and meta-analysis to assess the range of future global food security projections to 2050. We reviewed 57 global food security projection and quantitative scenario studies that have been published over the last two decades and discussed the methodology, underlying drivers, indicators and projections. We harvested quantitative information from 26 studies to compare future trends of the two most used global food security indicators: per capita food demand (593 projections) and population at risk of hunger (358 projections). We found that across five representative scenarios that span divergent but plausible socio-economic futures total global food demand is expected to increase by +35

1 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 (Alexandratos and Bruinsma 2012; Tilman et al. 2011), population at risk of hunger (Hasegawa et al. 2015; Parry et al. 2004), 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 methods (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 analyses of global food security projections have been presented. The aim of this paper is to provide a review of recent global food security projection and quantitative scenario studies that provide trends to 2050. By 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). 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 main question addressed in this review is: What is the range of future global food security projections to 2050? To answer this question and to better understand why projections differ, we also review the methods that have been used in the modeling studies and which drivers have been considered when projecting global food security.

We applied a systematic literature review approach to identify and collect relevant studies that were published between 2000 and early 2018, followed by a meta-analysis to assess the range of global food security projections to 2050. In comparison to standard literature reviews, systematic review approaches combined with meta-analysis have the advantage that they are guided by a well-defined methodology, which reduces bias and makes it possible to draw more general conclusions (Borenstein et al. 2009; Gough et al. 2012). we identified and analyzed 57 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 (593 projections) and global population at risk of hunger (358 projections), representing a wide range of plausible socio-economic and climate change futures. The Global Food Security Projections Database (van Dijk et al. 2021) 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.

2 Overview of studies

We selected 57 global food security projection studies for further review using a predetermined systematic review protocol with inclusion and exclusion criteria (Extended Data Figure 1, Supplementary Information and Methods). Figure 1 shows that the number of studies increased substantially over the last two decades. Between 2004, the year the first study in our database was published (Parry et al. 2004) and 2009, only six 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).

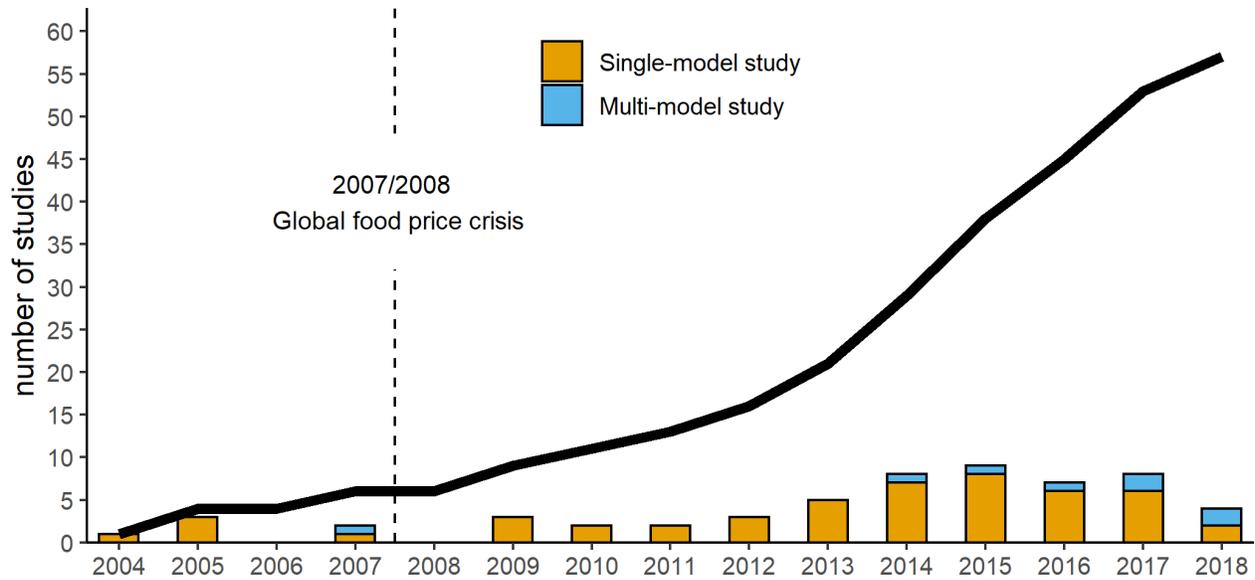


Figure 1: Total (cumulative) number and type of global food security studies per year. The bars show publication of new studies per year and type. Data for 2018 is incomplete as it only includes studies that were released in the first half of the year.

3 Review of methods and outcomes

3.1 Methods

Three different methodologies have been used to assess future global food security (Figure 2). The majority of studies ($n = 47$) employ simulation models, followed by statistical extrapolation approaches ($n = 9$) that use regression techniques to estimate future food security (e.g. Bodirsky et al. 2015; Tilman et al. 2011). Only one study (Alexandratos and Bruinsma 2012) mainly used expert input to prepare the projections. The IMPACT model (Robinson et al. 2015) was the most frequently used simulation model ($n = 16$). 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/CGE (Fujimori et al. 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 (van der Mensbrugge 2008).

The most frequently used type of models is partial equilibrium (PE) models ($n = 42$), followed by computable general equilibrium (CGE) market simulation models ($n = 28$). An advantage of PE models, such as IMPACT and GLOBIOM, is that they provide a detailed representation of 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/CGE, 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 (Robinson et al. 2014; Valin et al. 2014). Other types of models that have been less often used to project global food security include integrated assessment (IMAGE and T21, $n = 6$), biophysical (Agribiom, FSM and GRAFS, $n = 3$) and econometric (FEEDME and iAP, $n = 2$) models.

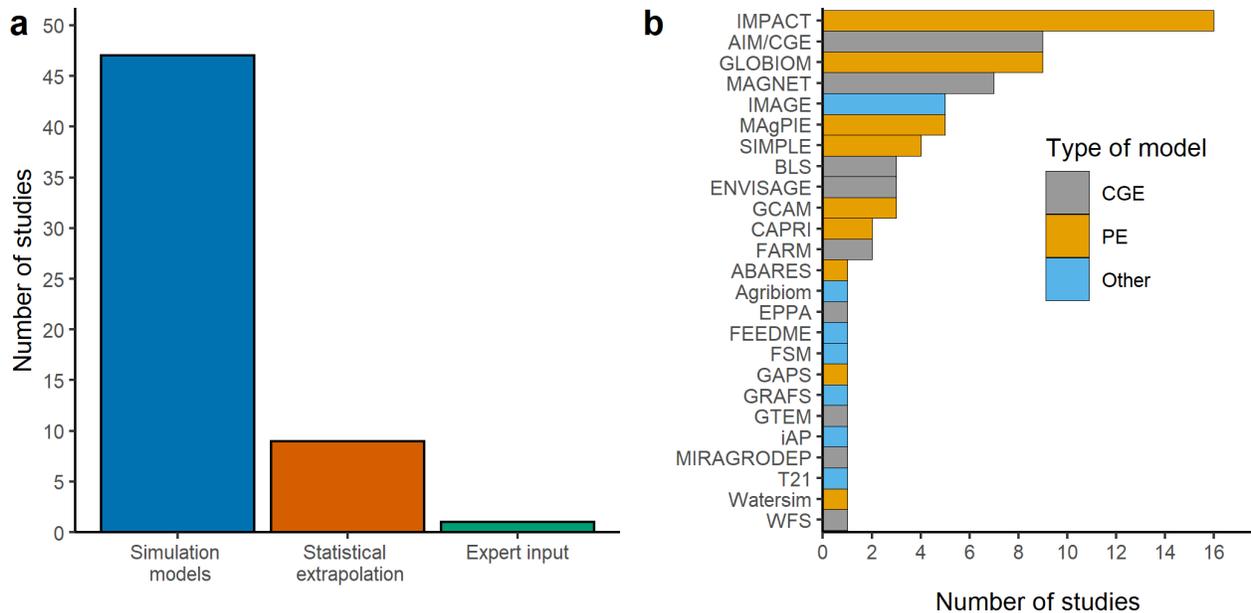


Figure 2: a Main method used per study and b list of simulation models used in the studies. The Other model type category include biophysical, econometric and integrated assessment models.

3.2 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 ($n = 57$) and income growth ($n = 52$), which are key drivers of food demand, and technical change (including total factor productivity growth, crop yield increase and adoption of advanced inputs) ($n = 52$), 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) ($n = 41$), diet change ($n = 39$), trade ($n = 37$) and

climate change (n = 32). Only a very small number of studies indicate they explicitly address the impact of aquaculture (n = 2) (FAO 2018; Linehan et al. 2013) and urbanization (n = 1) (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 (Extended Data Figure 2).

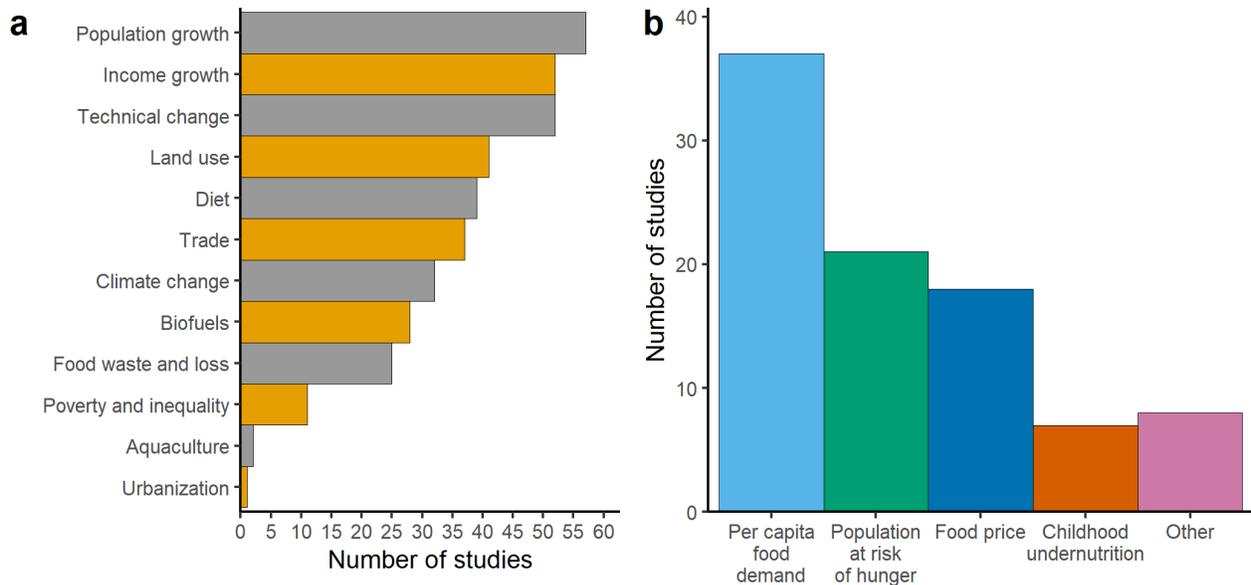


Figure 3: Global food security drivers a and indicators b. All studies incorporate multiple drivers and can produce multiple indicators. See text for a description of other indicators.

3.3 Indicators

A large number of the selected studies present future trends on two indicators. The first one is per capita food demand, in most cases measured as the average diet per person (sum of crops, dairy, fish and meat in kcal/cap/day) (n = 37). The second indicator is global population at risk of hunger (n = 21), 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 (Cafeiro 2014; FAO et al. 2013). Food price (n = 18) and, to a lesser extent, childhood undernutrition (n = 7), are other popular indicators. A few studies (n = 8) present alternative indicators, including protein consumption (Billen et al. 2015; Msangi

and Batka 2015), people at risk of protein deficiency (Medek et al. 2017) and recommended daily intake of macro-nutrients (Msangi and Batka 2015). 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.

3.4 Global food demand and population at risk of hunger projections

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 method (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, see Extended Table 1 for a summary of these scenarios) and the Representative Concentration Pathways (RCPs), a combination of socio-economic and climate change scenarios developed by the climate change community (O'Neill et al. 2017; van Vuuren et al. 2011; van Vuuren et al. 2014; van Vuuren et al. 2017), which are frequently used in global assessments (Leclère et al. 2020; Willett et al. 2019). For a subset of the selected studies, we were able to extract and harmonize projections for the two most used indicators: per capita demand ($n = 21$) and population at risk of hunger ($n = 14$). For the remainder we conducted a narrative analysis (Supplementary Table S5 and S6). All data were stored in a database, which includes 593 projections for per capita and total food demand and 358 projections for population at risk of hunger. For further analysis, all projections were divided into two types: baseline ($n = 323$ for per capita food demand and $n = 209$ for population at risk of hunger) and policy shock projections ($n = 270$ for per capita food demand and $n = 149$ for population at risk of hunger). The former correspond closely with the assumptions of the SSPs and RCPs and were used as input into a meta-regression analysis, presented below (See Supplementary Figure S8 for an evaluation of the policy shock projections, which are much harder to compare).

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 (Extended Data Figure 5). 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 point estimates from the meta-regression for the no climate change (NOCC) scenarios. In future worlds that are characterized by fragmentation (SSP3) and inequality (SSP4), per capita consumption will increase between +4% to +7%, while in scenarios that assume sustainability (SSP1), business-as-usual development (SSP2) and rapid growth (SSP5), the increase is +12% to +16%. Taking into account population growth, total food consumption increase is the lowest in SSP1 (+41%) and

the highest in SSP2 (+51%).

The distribution of projections within each SSP illustrates the uncertainty caused by methodological differences between studies. The figure shows that the results of several studies can be considered as less plausible because they are located outside the 95% confidence interval. If the confidence band of all SSPs is jointly taken into account, the plausible bandwidth of per capita food consumption becomes +0% to +20% and for total food consumption +35% to +56%. Figure 4 also compares the results between no climate change (NOCC) and extreme climate change (RCP8.5) scenarios (see Extended Data Figure 3 for a comparison with a wider range of RCPs). If the uncertainty related to climate change is also taken into account the range of per capita (-1% to +20%) and total food demand (+30% to +62%) projections changes slightly. However, a pairwise comparison did not provide evidence that climate change results in significantly different patterns of food demand compared to no climate change (Supplementary Figure S7).

Figure 5 depicts the projections for population at risk of hunger. Nearly all projections point at a decrease in undernourishment in comparison to the base year. With no climate change point estimates of -71% to -68% the change is highest in SSP1 and SSP5, while it is smallest in SSP3 (-11%) and SSP2 and SSP 4 are located in the middle (-57% to -17%). The SSP2 results from Dawson et al. (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. We therefore excluded this study from the meta-regression. If the 95% confidence interval is considered, the projected change in population at risk of hunger lies between -91% and +8% for no climate change projections and -91% and +30% for climate change projections (Extended Data Figure 4). Like before, we did not find evidence that climate change projections are statistically different from no climate change projections (Supplementary Figure S7).

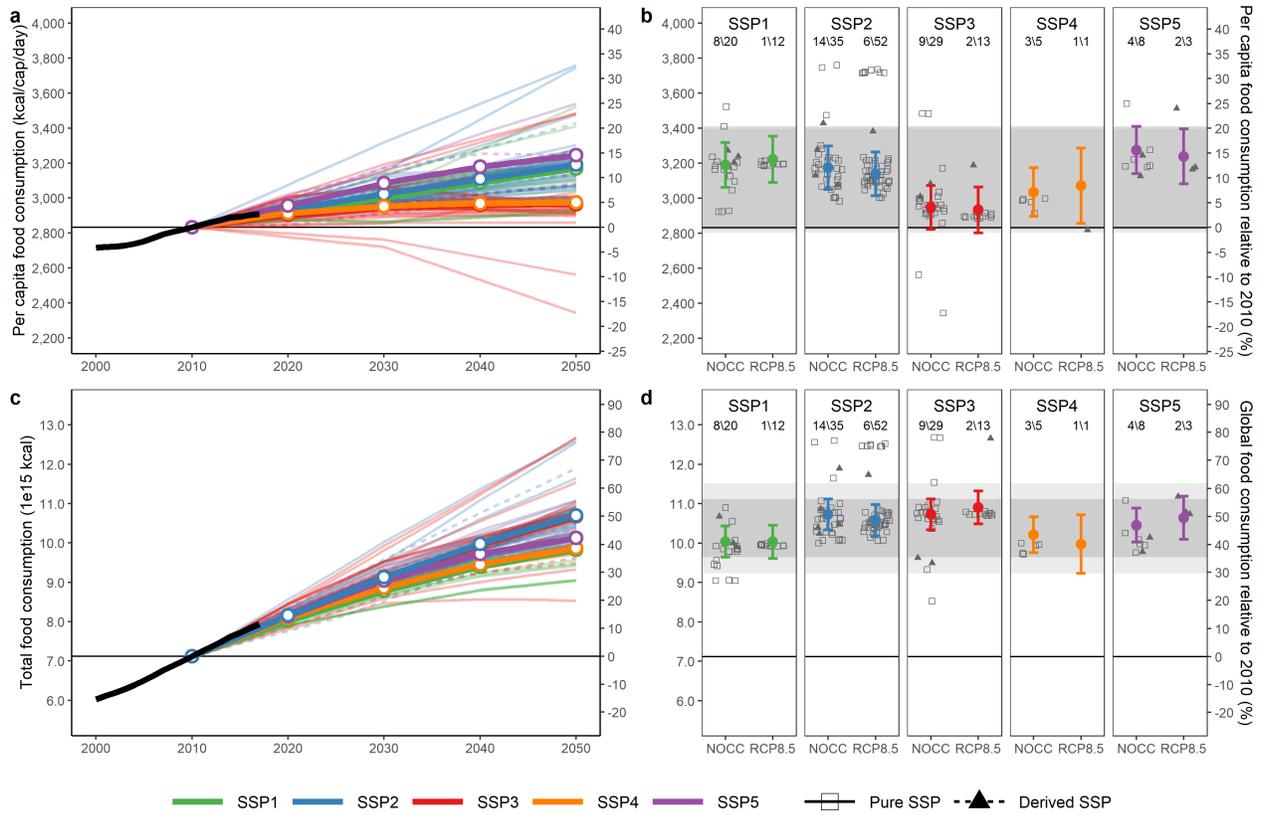


Figure 4: Per capita (a,b) and total (c,d) food consumption baseline projections for 2010-2050. All figures show the level of the selected food security indicator (left axis) as well as the percentage increase for the period 2010-2050 (right axis). a,c show baseline projections for the SSPs under no 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 point estimates and 95% confidence intervals taken from the meta-regression as well as all observations in 2050, comparing no climate change (NOCC) projections with projections based on the most extreme climate scenario (RCP8.5). The numbers on top refer to the number of studies/number of projections in the figure. The dark and light grey shaded areas demarcate the plausible range of baseline projections using the 95% confidence interval across all NOCC SSP and all RCP SSP projections, respectively (Extended Data Figure 3). Pure SSPs 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. Historical data from FAO (2020). Projections from the Global Food Security Projections Database (van Dijk et al. 2021).

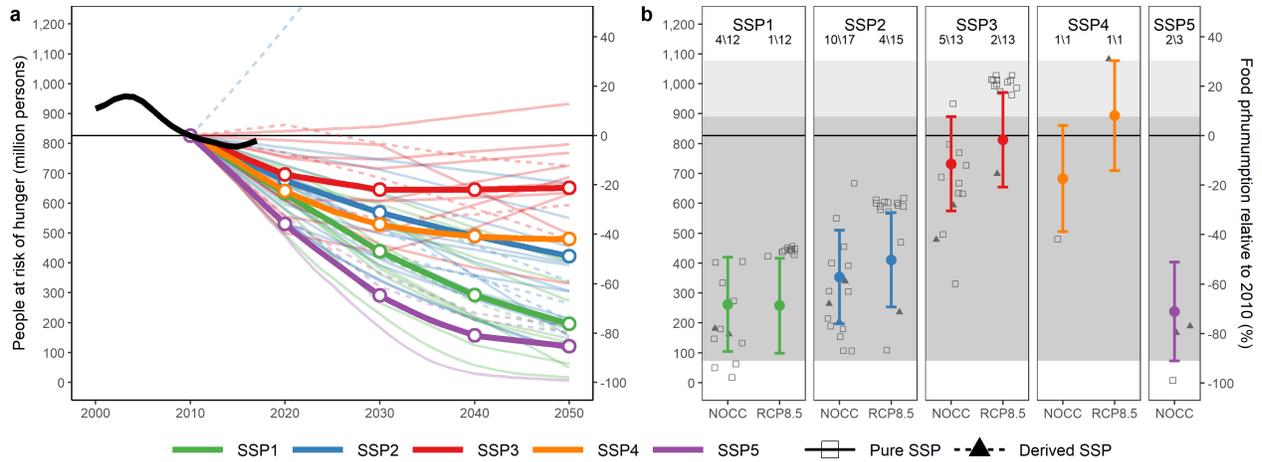


Figure 5: population at risk of hunger baseline projections for 2010-2050. See Figure 5 for a detailed explanation of the figure elements. The dark and light grey shaded areas demarcate the plausible range of baseline projections using the 95% confidence interval across all NOCC SSP and all RCP SSP projections, respectively (Extended Data Figure 4). Projections from Dawson et al. (2016) (blue dotted line heading upwards), are considered as outliers and therefore excluded from the meta-regression. Historical data from FAO (2020). Projections from the Global Food Security Projections Database (van Dijk et al. 2021).

4 Discussion

4.1 Comparison with the prevailing discourse on future global food demand

The expected increase in food production, and associated impacts on land use change, biodiversity and climate change heavily depends on projections of global food demand and consumption. The most cited figure, originating from a FAO briefing paper (FAO 2009), states 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 continues to be used as reference point by 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 (or its doubling, for short), erroneously frames global food security as a problem of supply (or even ‘scarcity’), closing off discussions on solutions that do not principally rely on increasing food production through technological innovation, such as the adoption of food sovereignty principles, including agro-ecological approaches that stress the value of indigenous knowledge, culture and peasant autonomy as well as radical non-market driven changes in diets (Claeys 2015; Holt-Giménez and Altieri 2013; Tomlinson 2013).

How does the +60% to +110% figures compare to our findings? We find that for SSP2, which, like the FAO projections, is regarded as a business-as-usual scenario, total food consumption will increase by +51%, with a 95% confidence interval of +45% to +56%. 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 et al. 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 just within the confidence interval 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 conversion efficiency rates (Wirsenius et al. 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.

4.2 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; Keating et al. 2014; Smith 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 so far largely

neglected by most modeling studies. Aquaculture, if produced sustainably, is an attractive source of protein because of its efficient feed-to-food conversion and potential to replace traditional plant-based feed sources with alternative feed ingredients (e.g. waste, insects and algae) (Costello et al. 2020). Furthermore, it has been estimated that aquaculture production will have to more than double from current levels by 2050 to maintain the role of fish in diets (World Resources Institute 2013). Aquaculture is therefore an important component of future food demand and supply that needs to be captured by global food security assessments. In anticipation of this, several of the identified models (Figure 2b) are in process of adding fishery and aquaculture extensions (Kobayashi et al. 2015; The Food and Land Use Coalition 2019).

A second, potential, driver of future food security that none of the selected studies tried to model is ‘future foods’, which are alternative food sources, such as insects, cultured meat, non-fed aquatic foods such as seaweed, and innovative plant-based meat substitutes (Parodi et al. 2018). These products are increasingly regarded as healthy and rich sources of protein and micronutrients on a par with animal-source meat. Their environmental impact is significantly lower than meat since they use land and water more efficiently and are associated with lower greenhouse gas emissions. Models accounting for the adoption of future foods are needed to assess their potential to replace animal-source food and how they would impact land use, food supply and demand, and climate change. However, the lack of data on future foods makes modeling challenging. For instance, the rate at which the cost of cultured meat might decrease to enable equitable access depends on uncertain or even speculative technological developments (Santo et al. 2020) and it is unclear whether a substantial percentage of the world population will accept to consume insects (Grasso et al. 2019). Nonetheless, a few studies have recently started to explore the future impact of future foods on land use change and greenhouse gas emissions (Alexander et al. 2017; Walsh et al. 2015).

Finally, several studies demonstrate that there is a clear difference in food consumption patterns between urban and rural populations (Popkin 1999; Regmi and Dyck 2001). According to the latest Revision of World Urbanization Prospects (UNDESA 2018), the urban population will growth by 2.5 billion people by 2050, with almost 90% of this growth occurring in Asia and Africa. Urbanization will therefore be a key driving factor in changing the pattern of future food demand. Surprisingly, we found only one study (FAO 2018) that explicitly includes urbanization as a driver of future food demand by accounting for its impact (1) on changes in future wages and income and (2) the loss of agricultural land. Given the availability of SSP-based urbanization projections (Jiang and O’Neill 2017; Jones and O’Neill 2016), other models could explore similar approaches.

4.3 Measurement of global food security

The Data4Diets platform (<https://index.nutrition.tufts.edu/data4diets>), building on Coates (2013) and the standard definition of food security (FAO 1996), presents a comprehensive framework of indicators that together provide a holistic picture of food security. The framework identifies six policy related dimensions: quantity, quality, preferability, safety, stability and sustainability that can be measured at the national, market, household and individual level. In the context of this framework, the selected studies cover only a very narrow part of the dimensions of global food security as they mainly present quantity, and to a lesser extent, quality indicators at national and market level.

A large number of indicators could probably be added if the global simulation models would take a more micro-approach and present individual and household level indicators of food security, diet and nutrition. An example of such an approach is Breisinger and Ecker (2014), who proposed 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. Also Laborde Debuquet et al. (2016) combined a global CGE model with household survey data to assess the costs of ending hunger in seven African countries. Finally recent studies, such as Springmann et al. (2018) and Willett et al. (2019), 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. It would be interesting to apply this type of approaches at global level in future food security assessments.

Apart from model innovations, there is also a need to increase the availability and accessibility of large household surveys (e.g. Household Income and Expenditure (HIES) and Living Standards Measurement (LSMS) Surveys) by national governments and international institutions. These complex surveys are an essential input for macro-to-micro modeling because they are often the only available source of nationally representative micro-level income and expenditure information, which are key to make the link with the national-level household projections that are produced by global simulation models (Bourguignon and Bussolo 2013). Unfortunately, for confidentiality reasons, HIES and LSMS data are in most cases only accessible to researchers that are affiliated with large international institutions, who often support the implementation of these surveys. A positive development in this regard is the World Bank's LSMS-ISA initiative (<https://www.worldbank.org/en/programs/lms/initiatives/lms-ISA>), which allows access to the LSMS of several African countries. Nonetheless, the global coverage of public household surveys is still very limited and more needs to be done to make the data available in an anonymized format.

4.4 Uncertainty and consistency in global food security projections

The 95% confidence intervals of the point estimates show there is a degree of uncertainty in the projections. 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. von 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 (Extended Data Figure 5).

Second, differences in methodologies to model long-run global food security can strongly influence the results. Godfray and Robinson (2015) discuss the strengths and weaknesses of simulation models and statistical extrapolation and how they contribute to disparity in outcomes. Hertel and Baldos (2016) found that apart from technological change, assumptions on income, capital, labor and land elasticities are critical determining factors of model output although they only have received very limited attention in the literature. Systematic model comparisons showed that structural differences between assumptions on technological change (Robinson et al. 2014), the way food demand is modeled (Valin et al. 2014) and the type of model (von Lampe et al. 2014), are important factors which explain differences in projections. Using our meta-regression, we formally tested the impact of model type on global food security projections but did not find convincing evidence to support this (Supplementary Section C).

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 95% confidence interval, 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 total food consumption. SSP3 represents an opposite world, characterized by the highest population at risk of hunger, the lowest per capita consumption and the highest total food consumption. In most cases the results for SSP2 and SSP4 are located in the middle of these extreme scenarios. The consistency of the SSPs is also supported by a pairwise comparison, which shows that the point estimates are statistically different for more than half of the SSP combinations (Supplementary Figure S6).

Our findings indicate that, under no climate change, per capita and total food demand are expected to change by +0% to +20% and +35% to +56% between 2010 and 2050, respectively, while population at risk of hunger is projected to change by -91% to +8%. Projections that account for climate change show a somewhat wider range of outcomes (-1% to +20% for per capita food demand, +30% to +62% for total food demand and -91% to +30% for population at risk of hunger). 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.

5 Methods

5.1 Systematic literature review design

To select relevant studies on global food security projections, we followed the guidelines for the qualified application of systematic review by the EPPI-centre (<https://eppi.ioe.ac.uk>, see Gough et al. 2012). Our approach includes five steps: (1) definition of research questions and preparation of research protocol, (2) search for relevant studies, (3) screening and selection of studies; (4) data extraction and (5) analysis. The core of the literature review was conducted between September and December 2017 but an additional search using the same approach was conducted around mid-2018 to cover the studies that were published in the first half of 2018. The main steps are summarized below. Additional details can be found in the review protocol (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, (2) we used Google scholar but only including the first two pages with references, (3) we consulted websites of organizations and institutions (e.g. FAO, OECD, World Bank and IFPRI), which occasionally prepare global food security assessments, (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.

The literature search generated a list of potentially relevant studies that were subsequently screened by applying a set of exclusion criteria. The query of the scientific literature repositories resulted in 3,667 unique studies. After abstract and full text screening, a total of 57 studies were selected to be included in the systematic literature review (Extended Data Figure 1, also see Supplementary Section E for the list of studies). Finally, we used a questionnaire to systematically extract and code relevant information, including meta-data, methodologies used, scenario information, food security indicators and main drivers. All data were stored in a database that is available for download.

5.2 Global Food Security Projections Database

For practical purposes, we decided to limit the collection and harmonization of data to two indicators that were presented in the majority of studies: per capita food consumption (in kcal/cap/day) and population at risk of hunger (in million persons). We also collected information on population projections to prepare total food consumption projections (in kcal). For a variety of reasons (Supplementary Section A.1), we were able to extract quantitative and comparable information on global food security projections from only 26 (46%) out of the 57 studies that resulted from the systematic literature review. All data was subsequently cleaned, harmonized and stored in a database (Supplementary Section A). The Global Food Security Projections Database (van Dijk et al. 2021) contains 593 projections for food consumption per capita and total food consumption and 358 projections for population at risk of hunger.

In order to make the data comparable across studies and over time we mapped the projections to the Shared Socio-economic Pathways (SSPs) (O’Neill et al. 2017; van Vuuren et al. 2017). The SSPs were originally designed as a framework for the recent climate change assessments but have been increasingly used for the evaluation of other global challenges, including food security. Around 88-90% of the projections (Supplementary Figure S4) already use the SSPs to produce food security projections. For all other projections, we built upon van Vuuren et al. (2012) and 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’. We assumed that projections based on the SSPs and projections based on

scenarios with the same characteristics (i.e. belonging to the same ‘family’) can be directly compared. However, as the assumptions underlying these scenarios are not exactly the same as those of the SSPs, we labeled them as Derived SSPs. We used the tables in van Vuuren et al. (2012) and van Vuuren and Carter (2014) to map the majority of these projections to the SSPs. For all remaining studies, we added the mapping by comparing the storylines and direction of drivers with the description of the scenario families (Supplementary Table S1). We used a similar approach, drawing upon van Vuuren and Carter (2014), to map all climate change projections to the Representative Concentration Pathways (RCPs) (Supplementary Table S2). A small number of projections could not be mapped to one of the SSP scenario families. We labeled them as ‘No class’ and excluded them from further analysis but added them to the Global Food Security Projections Database for further reference.

Finally, we divided the projections into ‘baseline’ and ‘policy shock’ projections (Supplementary Figure S5). The first type is based on the assumptions of baseline scenarios, which assume that socio-economic development, including global food security will be determined by future changes in the socioeconomic drivers (and associated major policy changes that can be regarded as exogenous to the analysis) (Dellink et al. 2020). The SSPs are generally considered as baseline scenarios. The second type is used to investigate the impact of specific policies on global food security. This is usually done by comparing the results of a baseline projection with those of a policy shock projection. Their difference can be regarded as a measure of potential policy impact (Börjeson et al. 2006). For the meta-regression (see below), we only used the sample of baseline studies, which used the same or very similar assumptions and therefore could be harmonized and compared. The policy shock projections, on the other hand, use widely different assumptions to model a large number of policies, which makes it hard to include them in the meta-regression. To analyze these projections, we grouped them by policy and compared the results with the estimated range that resulted from our meta-regression (Supplementary Figure S8). The comparison shows that nearly all policy shock projections fall within the estimated bandwidth, confirming our main findings.

5.3 Meta-regression

After removal of outliers and ‘No class’ projections (Supplementary Figure S2), we conducted a meta-regression (Borenstein et al. 2009) on the baseline projections to estimate point estimates for the percentage change in per capita consumption, total food consumption and population at risk of hunger for the period 2010-2050 taking into account differences between SSPs and RCPs. To control for the clustering of observations into groups (e.g. projections conducted with the same model or harvested from the same study), we estimated separate linear mixed-models (Fox and Weisberg 2019) for each of the three food security indicators:

$$y_{ij} = \beta_0 + \beta_1 x_{1ij} + \dots + \beta_p x_{pij} + b_{i1} z_{1ij} + \dots + b_{iq} z_{qij} + \epsilon_{ij} \quad (1)$$

where y_{ij} is the j th projection expressed as the percentage change between 2010 and 2050 in the i th group; β_0 is the intercept; β_1, \dots, β_p are the fixed effect coefficients; x_{1ij}, \dots, x_{pij} are the fixed effects regressors. We included fixed effects for all SSP-RCP combinations and dummy variables for pure (as opposed to derived) SSP and RCP scenarios; b_{i1}, \dots, b_{iq} are the random effects for group i ; z_{1ij}, \dots, z_{qij} are the random effects regressors. We added random effects for both study and model as we assume that, although comparable, outcomes will vary both across studies and models because of differences in study design and model specifications. The projections in our sample can be regarded as random samples of all projections that could have been observed. Under these assumptions a random effects model (as opposed to a fixed effects model) is recommended for meta-regression analysis (Borenstein et al. 2009); ϵ_{ij} is the error for projection j in group i .

The model was estimated using a Restricted Maximum-Likelihood (REML) routine as implemented by the lme4 R package (Bates et al. 2015) in combination with the lmerTest package (Kuznetsova et al. 2017), which implements the Satterthwaite’s degrees of freedom method for mixed models. The results of the model were used to derive point estimates and 95% confidence intervals based on standard errors for all SSP-RCP combinations for which data is available (Extended Data Figure 3 and Extended Data Figure 4). The point estimates and confidence intervals were calculated by evaluating equation 1 at the population weighted average values of the fixed effects and zero mean for random effect variables using the R effects package (Fox and Weisberg 2018). We used the step-down strategy (Diggle et al. 2002; Kuznetsova et al. 2017; Zuur et al. 2009) to select the model with the best fit. Independent variables, such as method, model base year and type of study were dropped as a result of this procedure (Supplementary Section B). Point estimates for the percentage change were multiplied with base year values to derive level values for 2050.

5.4 Selection bias

There is a risk that the results of our study were affected by selection bias. To account for publication bias, we conducted an extensive search for both academic and grey literature. Out of the 57 studies 18 (32%) were unpublished at the time of our analysis. Additional estimations did not provide support for differences between projections from published and unpublished studies (Supplementary Table S5).

Another type of selection bias that potentially influenced our results is related to the fact that we were only able to extract quantitative information from a limited number of selected studies. This is not a problem by itself as the mixed model we used for the meta-regression is designed to deal with data that

represents a random sample of the total population. Only in case of non-random selection, the results of the meta-regression will be biased. A comparison of the main characteristics between studies for which quantitative data was extracted with those for which data was missing does not suggest major structural differences between both groups and, hence, does not provide evidence for selection bias (Supplementary Figure S9). Where possible, we also compared the findings of these studies with the estimated SSP confidence bands from our meta-regression (Supplementary Table S6 and S7). The strong overlap between the two provides additional evidence against the existence of selection bias in our analyzed sample.

Finally, we investigated potential selection bias related to the No class projections, which were excluded from the analysis because the underlying scenario assumptions are different from the SSP/RCP framework. A comparison shows that for all three indicators almost all No class projections fall within the estimated plausible range of global food security projections (Supplementary Figure S10). Hence, excluding them had probably little impact on our results.

5.5 Limitations

To better interpret the results of our analysis, it is important to discuss a number of limitations. First, in order to summarize and compare the methods of the global food security studies, we distinguished between three major approaches (simulation models, statistical extrapolation and expert input) of which the first was further decomposed into computable general equilibrium (CGE), partial equilibrium (PE) and other models. In practice this classification was not always straightforward. For example, a number of studies (e.g. Ishida et al. 2014; Nelson et al. 2010) combine simulation modeling with statistical extrapolation to project future food security indicators. In several other studies, statistical approaches are used to estimate future food consumption, which is then used as an input into a larger simulation model. Examples of this approach are the iAP (Pardey et al. 2014) and MagPIE models (Lotze-Campen et al. 2008). To be consistent, we decided to use ‘simulation models’ for all studies in which food security indicators are presented in the context or as part of a model simulation study, while stand-alone statistical approaches, even when they are used as part of a model in other studies (e.g. Bodirsky et al. 2015) were classified as ‘statistical extrapolation’. Finally, in some studies the models are linked with other models to deepen the analysis and cover a wider range of outcome indicators (Popp et al. 2017) to enrich the analysis. In such cases, we assumed the model is still comparable to its stand-alone version.

Second, the information on the drivers of global food security should be interpreted with care. Not all studies provide full details on the model specification and, hence, which drivers can be incorporated in the model. Occasionally, we took information on the incorporation of driving forces from other studies in which the same

model was used.

Third, most of the high-ranking models used for global food security analysis (Figure 2b) are (part of) large-scale integrated assessment tools that are used, among others, for global climate change (Riahi et al. 2017), biodiversity (Leclère et al. 2020) and land use (Elke Stehfest et al. 2019) studies. Such models are continuously updated and expanded in order to respond to new research questions. The reviewed studies do not offer sufficient information to track changes in model design and input data from one study to the other. Nonetheless, we think it is reasonable to assume that the core of the models does not change over time and cross-model comparison is possible.

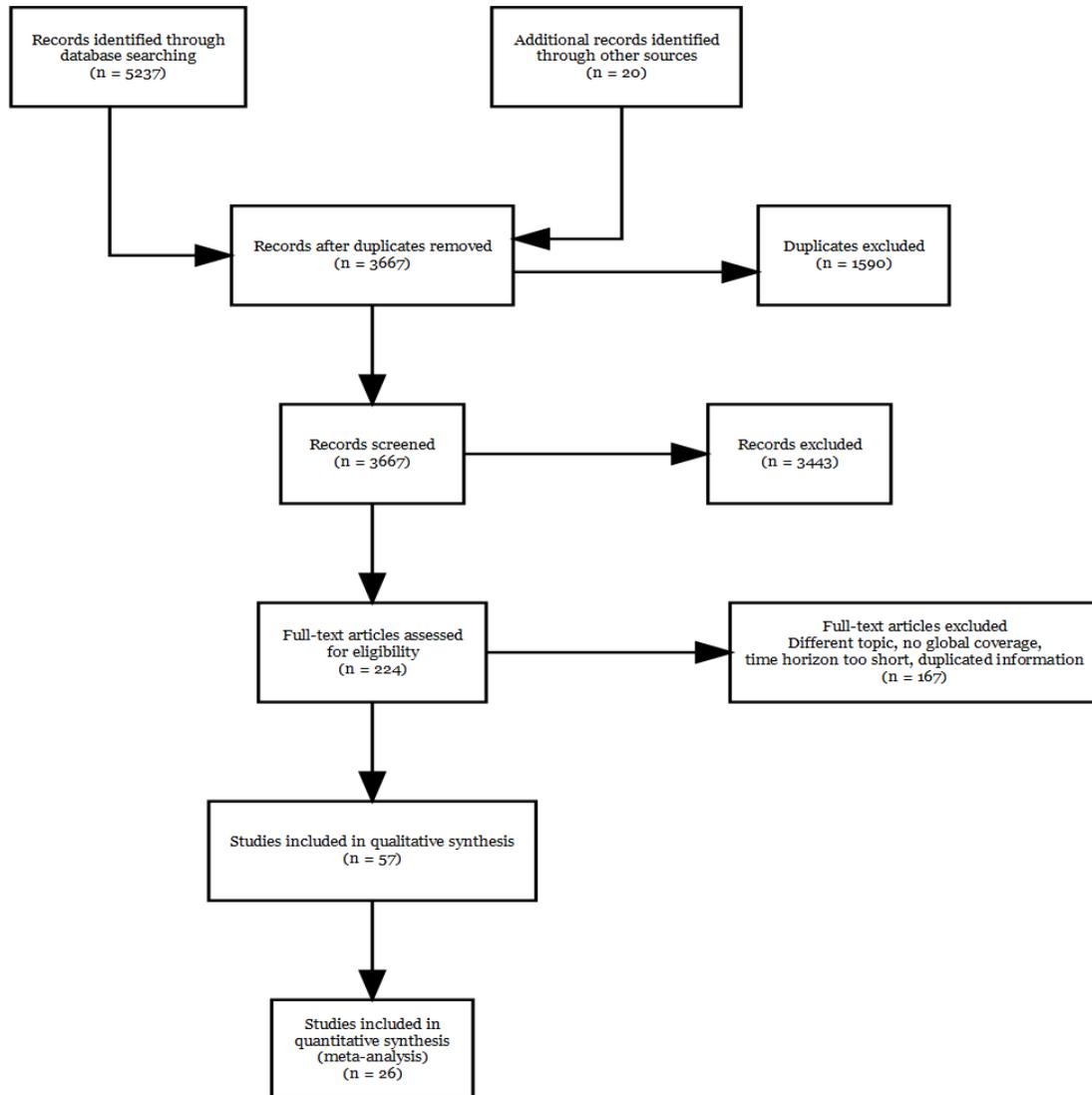
Fourth, we were not able to map a small number of projections to the SSP/RCP framework because the underlying scenarios were not compatible with the SSP storylines and/or RCP climate change assumptions (Supplementary Section A.2). The SSPs cover only four out of the six scenario families identified by van Vuuren and Carter (2014), which means that projections, which belong to one of these families (or even other not yet identified scenario families) are not captured by our analysis. A comparison shows that projections for missing scenario families are positioned within the plausible range of SSP/RCP-based global food security projections and therefore do not affect our results (Supplementary Figure S10). If a sufficient number of projections from new scenario families becomes available, we can easily incorporate them in our assessment.

Finally, our analysis only deals with global level projections. Several of the selected studies present food security projections at the broad regional level (e.g. Bodirsky et al. 2015; Hasegawa et al. 2018; Popp et al. 2017) that clearly indicate different patterns and futures, which we are unable to analyze. We tried to collect comparable information at the regional level but as only a small number of studies cover and present such an analysis, and often use different regional aggregations, more disaggregated analysis was not feasible. For similar reasons we were not able to distinguish between the demand for different food commodities. Only a few studies (Bijl et al. 2017; Gouel and Guimbard 2017) present detailed information on the shifts in diet and in most cases the results are not comparable due to differences in the composition of food groups, making wider comparison impossible.

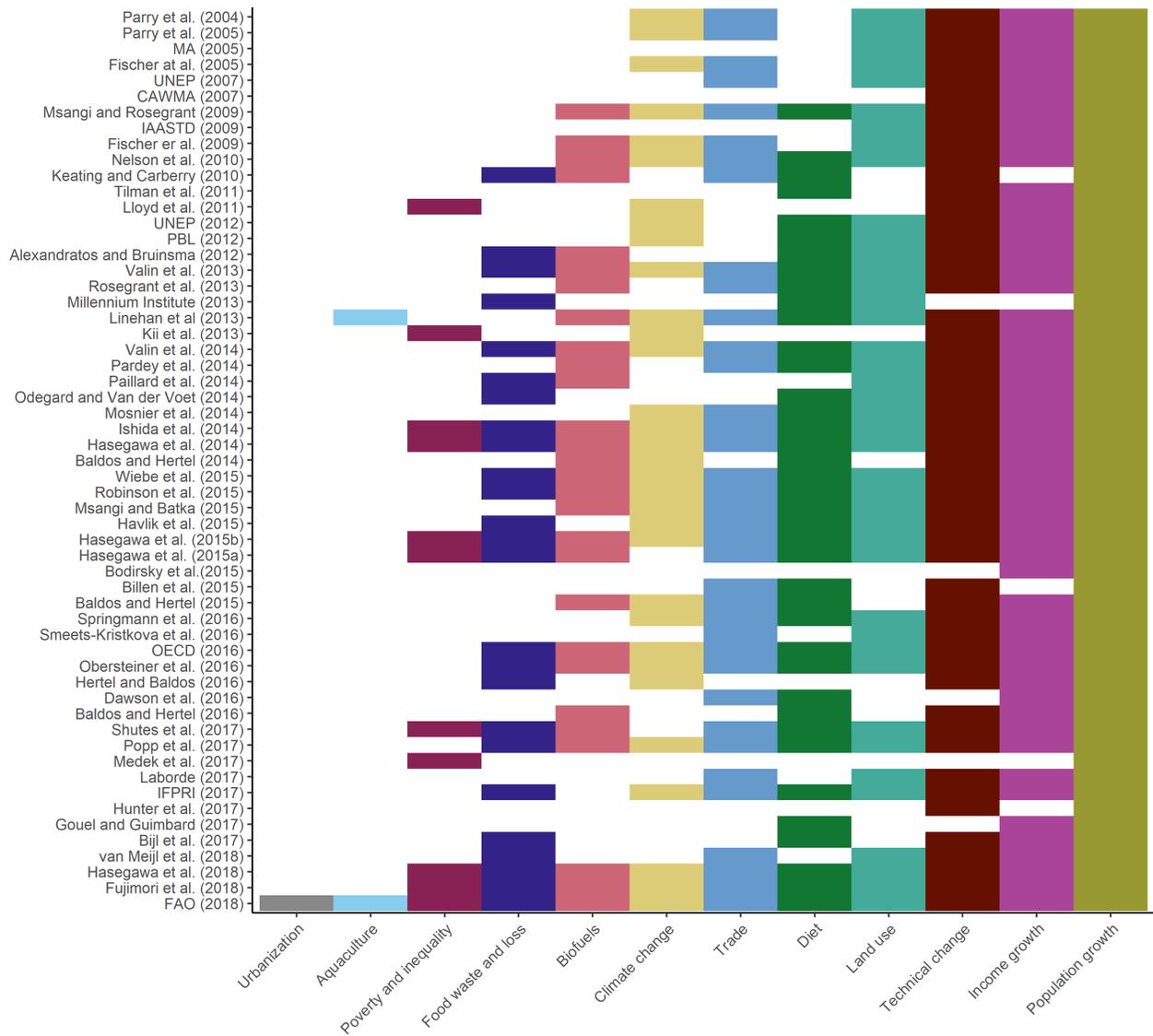
5.6 Extended data figures and tables

Extended Data Table 1: Shared Socio-economic Pathways scenario storylines. Source: Table 2 in Riahi et al. (2017).

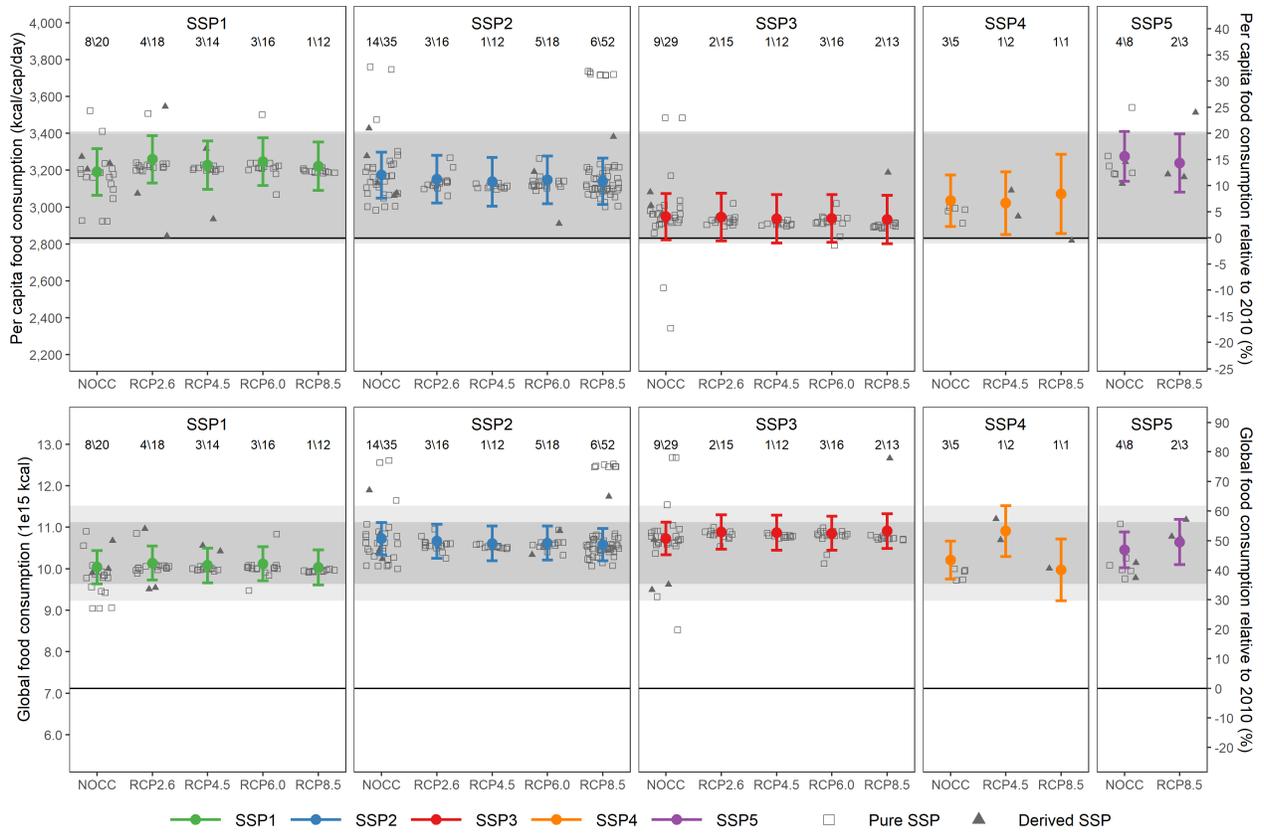
SSP	Scenario name and storyline
SSP1	<p>Sustainability</p> <p>The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health 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, low-meat diets and lower resource and energy intensity.</p>
SSP2	<p>Middle of the Road</p> <p>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</p>
SSP3	<p>Regional Rivalry</p> <p>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</p>
SSP4	<p>Inequality</p> <p>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</p>
SSP5	<p>Fossil-fueled Development</p> <p>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.</p>



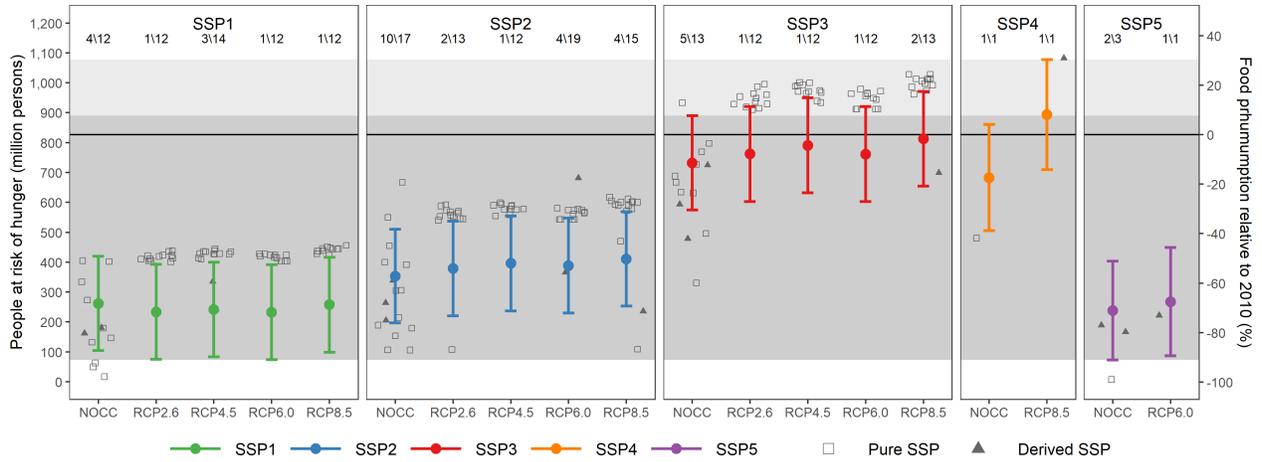
Extended Data Figure 1: Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram. The diagram shows the different phases of the literature search and screening as well as the number of studies that have been included in the systematic literature review and the number of studies for which data could be extracted for the construction of the Global Food Security Projections Database (van Dijk et al. 2021). See Methods and Supplementary Information for the details of the systematic literature review approach, protocol and selected studies.



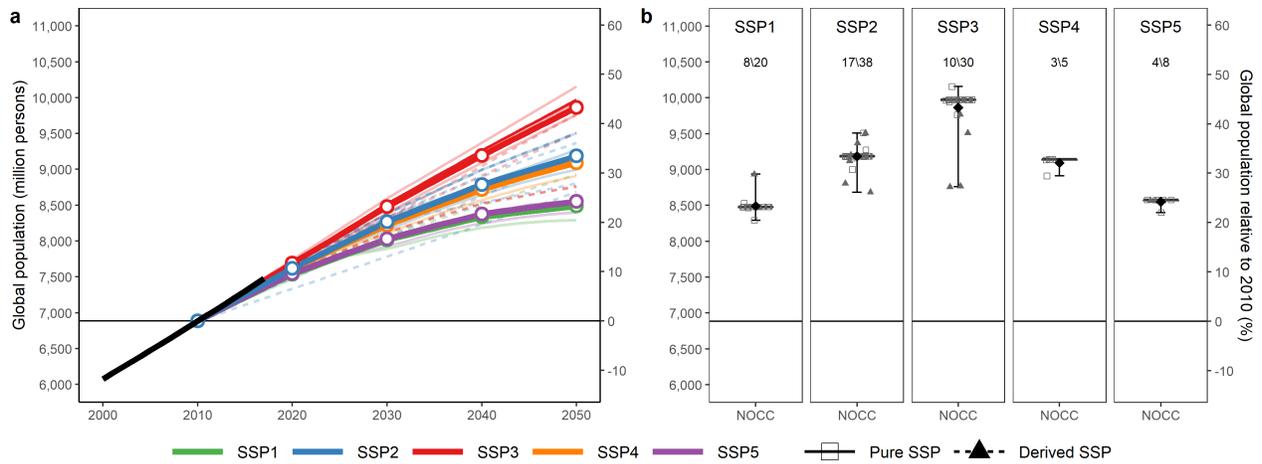
Extended Data Figure 2: Global food security drivers incorporated by the selected studies, ranked by year of publication.



Extended Data Figure 3: Per capita food consumption (a) and total food consumption (b) projections comparing no climate change (NOCC) with RCP projections for 2050. The dark and light grey shaded areas demarcate the plausible range of projections using the 95% confidence interval across all NOCC SSP and all RCP SSP projections, respectively. See Figure 4 for a detailed explanation of the figure elements. Projections from the Global Food Security Projections Database (van Dijk et al. 2021).



Extended Data Figure 4: Population at risk of hunger projections comparing no climate change (NOCC) with RCP projections for 2050. The dark and light grey shaded areas demarcate the plausible range of projections using the 95% confidence interval across all NOCC SSP and all RCP SSP projections, respectively. See Figure 4 for a detailed explanation of the figure elements. Projections from the Global Food Security Projections Database (van Dijk et al. 2021).



Extended Data Figure 5: Population projections for 2010-2050. a shows individual model projections for the SSPs (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 presents boxplots for the population projections. The diamond in the boxplot indicates the mean value and the whiskers indicate the maximum and minimum range of observations. SSP Population projections are independent of climate change and therefore only no climate change (NOCC) projections are presented. Projections from the Global Food Security Projections Database (van Dijk et al. 2021).

5.7 Data availability

The core data used in the study was obtained from the selected studies (Supplementary Section E) including their supplementary information and data files. For a few studies additional information was supplied by the authors upon request. Historical data for the selected food security indicators was taken from FAO (2020). The database with information from the 57 selected studies as well as the Global Food Security Projections Database are publicly available at the Zenedo repository: <https://doi.org/10.5281/zenodo.3706990>. A dashboard to visualize the projections is available at: https://michielvandijk.shinyapps.io/gfsp_db_dashboard/.

5.8 Code availability

We used R (R Core Team 2020) for visualization and analysis. The complete code to reproduce all figures as well as the meta-analysis is publicly available at the Zenedo repository: <https://doi.org/10.5281/zenodo.3706990>.

Acknowledgments: We like to thank Joke Webbink, Caterina Barrasso and Winand de Jong for their support with the systematic literature review. We like to express our gratitude to Tomoko Hasegawa, Kieth Wiebe, Daniel Mason Croz, Andrzej Tabeau and Martin von Lampe for making available unpublished data, and Hugo Valin and three anonymous reviewers for useful suggestions to improve the paper. This research was funded by a grant from the Stavros Niarchos Foundation as part of the Johns Hopkins Global Food Ethics Berman Institute of Bioethics' and Policy Program and a grant from Wageningen University and Research.

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